Acoustics Australia (2024) 52:191–208
https://doi.org/10.1007/s40857-024-00320-4

ORIGINAL PAPER

# Acoustic Characterization of Hemadpanti-Style Hindu Temples: A Case Study of the Markanda and Mrikunda Temples

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Received: 14 December 2023 / Accepted: 27 March 2024 / Published online: 8 May 2024


**Abstract**
This article presents the acoustic characterization of two well-known Hemadpanti-style Indian Hindu temples in Maharashtra, India, built during the twelfth century. The studies of architectural acoustics in Indian Hindu temples are sparse. Therefore, characterizing the acoustic nature of such historical Hindu temples is vital. This study may provide insight into the role of architectural characteristics that support the desired sound field, ensuring that the music ritual, singing of devotional songs, and Vedic chanting are suitable in Hemadpanti-style Hindu temples. The research aimed to report and investigate the acoustic behavior of the Hindu temples through in-situ measurements in an unoccupied condition. Virtual acoustic models were developed and validated using the in-situ measurements under the same conditions. Objective room acoustic indicators considered are reverberation time (T30), clarity of music (C80), and Speech Transmission Index (STI), which are later simulated and analyzed for two sound source positions in occupied conditions. The results report that the spatially and spectrally unoccupied averaged values for reverberation time (T30) and clarity of music (C80) of the Markanda temple are 0.98 s and 3.98 dB, and the Mrikunda temple (T30) and (C80) values are 0.73 s and 5.62 dB respectively. The values obtained for both temples are within the optimum range adopted for this study. The average subjective rating for speech intelligibility of the Markanda and the Mrikunda temples is "good". After analyzing indicators, the results emphasize the influence of architectural features on the acoustic characteristics of the Hemadpanti style of Hindu temples.

**Keywords** Indian Hindu temples · Acoustic characteristics · 3D simulation · Reverberation time · Clarity of music (C80) · Speech transmission index (STI)

## 1 Introduction

Historically, worship spaces have held significance in communities as they represent a society's religious and spiritual beliefs. Worship spaces also serve as notable examples of architectural history and contribute to the visual appeal of cities with their grandeur and ornate features. More than a visual experience, the auditory experience significantly impacts the spiritual atmosphere and sense of space during religious rituals [1]. The sound of a worship space fundamentally shapes the acoustic experience of an individual [2]. Worshipper's needs differ significantly based on these spaces' specific functions and religious practices. Worship spaces require challenging acoustic characteristics [3, 4] and, therefore, have been the focus of many researchers. In recent years, there has been significant interest in examining the acoustic characteristics of worship spaces, particularly churches, cathedrals, basilicas, mosques, Hän Chinese, Japanese, and Buddhist Temples. Several researchers have dedicated their efforts to exploring this subject and its various dimensions.

In literature, churches are often characterized by their acoustically reverberant spaces due to their large volume and the use of acoustically reflecting materials in the interiors [4, 5]. Long reverberation in churches has improved congregational engagement by improving organ music and hymn listening [6, 7]. The sound of temple bells and chanting in Buddhist temples creates a unique spiritual atmosphere that resonates with visitors when they participate in religious activities [8, 9], and such acoustic conditions have contributed to the growth of Buddhism. Similar acoustical studies include individual mosque cases [10–13], or some

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involve comparing mosques to other mosques [14, 15], which were often built in enormous volumes using high and wide dome structures [16]. Within this framework, the acoustics of basilicas [17, 18], Han Chinese temples [19], and cathedrals [20–23] have also been an attractive research topic for acousticians. Acoustic behavior in these worship spaces is fundamentally different [10]. A recent study [24] provides a comprehensive overview of the current status of acoustics in heritage religious buildings, and it was observed that there is a substantial research gap in architectural acoustics of Indian sites. India is known for its diverse culture and religion; one of its most significant cultural aspects is its temple architecture. These structures have been crucial in preserving and shaping the country's history and cultural heritage. However, despite their importance, there is a lack of research on the acoustic characteristics of Indian Hindu temples. As a result, it presents an exciting opportunity to delve into and broaden acoustics knowledge within the context of Indian Hindu temple spaces.

In Hindu temples, sound plays a fundamental role. In every Hindu temple, a bell is set in place, and the recitation of Vedic chants invokes the presence and manifestation of deities, highlighting the crucial role of sound in the worship rituals [25]. Vedic Hinduism gives great importance to sound, comprising music and chanting. The acoustic characteristics and the clear phonetic articulation of chants profoundly influence the worshippers in a Hindu temple [26, 27]. Praying requires individuality, whereas the congregation needs to recite the Vedic chanting and singing devotional songs known as *bhajan and kirtan.* The atmosphere inside these temples is often filled with vocal music and a combination of various musical instruments, creating a dominant environment mainly during festivals. Priests in Hindu temples are professional voice users who use their voices to perform regular worship, such as *puja* (Hindu prayer), *arthi* ceremony (deity songs while presenting lamps), and *homa* (fire ritual) at temples and houses [28]. Prayer rituals require clear speech, while musical rituals may require a more reverberant environment. In Hindu temples, the main focus of the priest and worshippers during prayer is to ensure precise and understandable music and speech [29]. All of these activities necessitate a high level of speech audibility and intelligibility [30].

Some studies in the literature discuss the architectural elements and components within Hindu temples that contribute to musical sound production. Such studies include the effect of Vedic chants and the evaluation of acoustic characteristics of musical instruments, such as conch shells, bells, and gongs, studied in the anechoic and community halls of a contemporary-style Hindu temple in New Jersey [25]. In another study, a scientific examination of the acoustic characteristics exhibited by the musical stone pillars of the Maha mandapam in the Vitthala temple, Hampi, was investigated to identify whether these stone pillars can produce musical sound when tapped with a finger. The research systematically examines the acoustic properties of the musical pillars using non-destructive testing techniques [31]. In addition, a scientific study discovered that the temple's pillars produce a bell-like sound, suggesting a significant resemblance between the resonance properties of the pillars and an actual bell [32]. Previous related research is specific to architectural elements in a Hindu temple and significantly differs from the sound field characteristics of Hindu temples subject to spatial configuration, volume, ceiling type, and construction materials. Therefore, research on the acoustic characteristics of a Hindu temple is still lacking. There is a critical need to investigate these unexplored areas of Hindu temples and their acoustic characteristics.

India has various Hindu temples, with each state having its own set of notable and renowned places of worship. The architectural style of the Hindu temple is a varied and diverse tradition that has developed over many centuries, shaped by its religion and local influences. Therefore, for our initial exploration of the acoustic characteristics, the typical Hemadpanti-style of the Hindu temple in Maharashtra state of India, which is well-known for its unique, distinctive architectural features and size variation, has been identified for this study.

### 1.1 Hemadpanti-Style of Hindu Temple

The Hemadpanti-style of Hindu temples is one of the prominent styles built around the twelfth century in Maharashtra, India. They are characterized by their unique star-shaped and zig-zag pattern outer walls. These temples are constructed in small to medium sizes, either enclosed or semi-open spatial configurations, using sandstone or black basalt gneiss stone as construction materials, depending on their regional characteristics [33]. The interior of these temples is intricately carved with sculptures and motifs of Hindu Vedic stories. The tiered ceiling in these temples' sanctum and pavilion space is another essential characteristic. The ceiling comprises three main sections that recede upward and inward toward the middle: (1) the outer square-shaped section, (2) the rhombus section in the middle, and (3) the circular section in the center with a lotus flower motif. The square and rhombus sections are assembled of separately carved parts that fit together around the central circular section from a single large piece of stone [34].

The internal organization of Hemadpanti-style Hindu temples typically comprises three interconnected spaces: the sanctum (*garbhagriha*), a vestibule (*antarala*), and a pavilion (*mandapa*). These spaces are designed to have separate volumes and are acoustically coupled.

Acoustically coupled apertures refer to interconnected spaces typically consisting of two or more volumes connected by an opening [35]. These interconnected spaces frequently possess varying sound absorption characteristics, resulting in distinct durations of sound decay [36]. Therefore, sound behavior in performance spaces is a complex subject. Coupled reverberation chambers can lead to non-exponential decay of sound energy in the main source room. In-room acoustics, it is not uncommon to observe multi-rate decays, which occur when different volumes are connected and result in non-linear decay curves. This phenomenon is particularly noticeable in churches during the initial decay process [37].

This paper investigates the objective room acoustic indicators for two Hemadpanti-style Hindu temples in the Maharashtra state of India. The paper aims to report and investigate the acoustic characteristics of these temples and compare the results with those in unoccupied (*unocc*) and occupied (*occu)* conditions. The study examines the key indicators of room acoustics: Reverberation Time (T30), Clarity of Music (C80), and Speech Transmission Index (STI). The primary inquiries that we seek to address in this research are as follows:

1. To report the acoustic characteristics of the identified Hemadpanti-style Hindu temples in their original condition.
2. How do the temple's architectural features, like spatial configuration, coupled volume, ceiling style, and construction material, contribute to distinctive acoustic characteristics suitable for its intended purpose?

## 2 Acoustic Indicators

Worship spaces and their acoustics have a significant relationship [38]. There are various historical structures worldwide, with differences in architectural style and construction materials used within the interior space. This difference in such spaces complicates the acoustical evaluation process. Therefore, more specific evaluation criteria or defined optimum values need to be published as standards for Indian Hindu temple spaces. Several studies have been conducted about acoustical requirements and evaluation indicators for large-volume such as mosques, churches, and cathedrals. Since Hindu temples have a relatively medium to small volume with hard reflecting walls, they may cause long reverberation times and fluttering echo [39, 40]. Therefore, for our initial exploration, in this study, the choice of metrics considered are reverberation time (T30), Clarity of Music (C80), and Speech Transmission Index (STI).

### 2.1 Reverberation Time

The reverberation time is the duration for the sound level to decrease by 60 dB after the sound source has stopped abruptly. In this study, reverberation time in terms of T30 has been evaluated. T30 has a decay range of 30 dB, spanning from − 5 dB to − 35 dB [41–43]. Small spaces with a T30 value below 0.3 s are classified as acoustically "dead," whereas spaces with a T30 value exceeding 2 s are considered "echoic.". The reverberation time may vary depending on any religious or worship space's architectural design, size, and purpose. Therefore, the intended use of the space defines the optimal value of the reverberation time [44]. The current literature lacks the optimal reverberation time T30 values suitable for Hindu temples, depending on the enclosure's overall volume and material. However, Prasada et al.[25] theoretically estimated the reverberation time for Hindu temples in New Jersey to be approximately in the range of 0.63 to 1.12 s. Therefore, in this study, the optimal reverberation time is adopted in the range of 0.6 to 1.12 s for unoccupied conditions.

### 2.2 Clarity of Music (C80)

Clarity of music (C80) is a metric used to assess how the room affects the perception of musical clarity [41, 45]**.** In music analysis, the term "Clarity" serves as a metric for evaluating the perceived quality of sound. Specifically, it refers to the logarithmic relationship between the initial sound energy received within the first 80 ms and the subsequent good energy received after this initial time frame. The optimal C80 levels for religious music should range from − 2 dB to + 3 dB for locations near the sound source, while for greater distances, the C80 levels can fall within the optimal range of 0 to + 5 dB [46]. The Hemadpanti-style Hindu temples are characterized by medium to small volumes. Therefore, the optimal C80 range for nearby locations, between − 2 dB and + 3 dB, is adopted for this study.

### 2.3 Speech Transmission Index (STI)

The Speech Transmission Index (STI) indicates speech intelligibility regarding physical measurements deriving from the modulation transfer function (MTF) [47]. The resulting Speech Transmission Index (STI) value falls from 0 to 1, with 0 representing completely unintelligible speech and 1 representing excellent speech intelligibility (Table 1). When aiming for high speech intelligibility, the main objective should be to achieve a low T30 value. On the contrary, T30 should also be sufficiently high to maintain a sense of religious ambiance. Therefore, T30 needs to be balanced [16]. The Speech Transmission Index (STI) is expected to be favorable for a smaller room. However, for our initial

**Table 1** Subjective Interpretation of the STI Measurements [47]

| | Bad | Poor | Fair | Good | Excellent |
|---|---|---|---|---|---|
| STI | 0–0.30 | 0.30–0.45 | 0.45–0.60 | 0.60–0.75 | 0.75–1.00 |

exploration in this study, we aim to assess the intelligibility of spoken words at each receiver position. It is critical to balance the acoustic qualities of a worship space, which frequently contributes to its spiritual ambiance and ensures that speech remains clear and understandable to the worshippers [48].

## 3 Study Area

In this study, Markanda and Mrikunda, the Hemadpanti-style Hindu temples, are identified to investigate their acoustic characteristics. Markanda temple complex is well-known for its historical, architectural, aesthetic, and heritage significance. The Archaeological Survey of India (ASI), Nagpur Circle protects, conserves, and maintains the entire Markanda temple site (Fig. 1). It is a pilgrimage site for Lord Shiva's followers during the annual Mahashivratri festival. During this festival, temples host various activities, such as Vedic chanting and congregational activities, such as singing devotional songs. These temples have unique, distinctive characteristics and are currently under the restoration process of the temple's outer walls [49]. Hence, this is also one of the key factors for selecting these temples for reporting and investigating the acoustic characteristics of the Hemadpanti-style Hindu temples in their original condition through on-site measurements and computer-aided simulations.

The following section will briefly overview the historical background and significance of the Markanda and Mrikunda temples.

### 3.1 Markanda Temple

The Markanda temple complex, known as the "Khajuraho of Vidarbha," is located in the Chamorshi town of Gadchiroli district, Maharashtra, India. The 12th-century temple complex is situated on the banks of the Wainganga River. The temple complex has a rectangular layout, with dimensions of 35.9 m in width and 30.10 m in length, extending from the north to south direction [49]. The main Markanda temple is surrounded by twenty-four smaller temples of various sizes (Fig. 1). The temple complex is a heritage site, creating a distinct and impressive form of temple architecture (Fig. 2a). It is a Shiva temple dedicated to Markanda; a saint known for his profound devotion to Lord Shiva, as seen in Fig. 2b. This temple has a designated space for congregational activities such as (*bhajan and kirtans*) occupied during major festivities [50] (Fig. 2c).

Markanda temples have intricate carvings on the exterior and interior walls. The temple suffered significant damage around two centuries ago when lightning struck it. As a result of the strike, the upper spire, the shikhara, collapsed onto the pavilion's roof, damaging the outer shikhara (Fig. 2d). Approximately 120 years ago, the Gond rulers restored the exterior roof of the pavilion, but the methods employed were considered unethical. However, the original internal structure was preserved, making it a suitable case example for its acoustic study. The temple has an eastern side entrance porch leading into the main pavilion with two additional side entrances in the north and south directions [51]. The temple's layout consists of three interconnected spaces: the sanctum (*garbhagriha*), which contains Lord Shiva's idol; a Vestibule (*antarala*), which generally holds the temple bell; and the pavilion (*mandapa*), the main hall for worshippers and congregational activities.

### 3.2 Mrikunda Temple

The Mrikunda temple is situated behind the Markanda temple and is dedicated to Mrikunda, a saint and brother of Markanda and a devotee of Lord Shiva (Fig. 3a). This temple layout comprises a two-thirds open pavilion, a vestibule, and a sanctum. The main pavilion hall of Mrikunda temple is square and externally measures 8.0 × 8.0 m (Fig. 3b). Four small pillars are positioned symmetrically at the entrance on a low-height wall**.** The main pavilion Hall has four intricately carved stone pillars supporting the tiered ceiling (Fig. 3c). The Mrikunda temple exhibits a slightly smaller footprint than the Markanda temple, and the interior walls and pillars are intricately stone carved (Fig. 3d). Figure 4 represents the floor plan and section of Markanda temple (left) and Mrikunda temple (right). Table 2 summarises the primary geometric characteristics of the Markanda and Mrikunda temples.

## 4 Research Methods

This study is divided into two parts to address the primary inquiries:

1. To record in-situ room impulse responses (RIR), reporting the objective room acoustic indicators necessary to

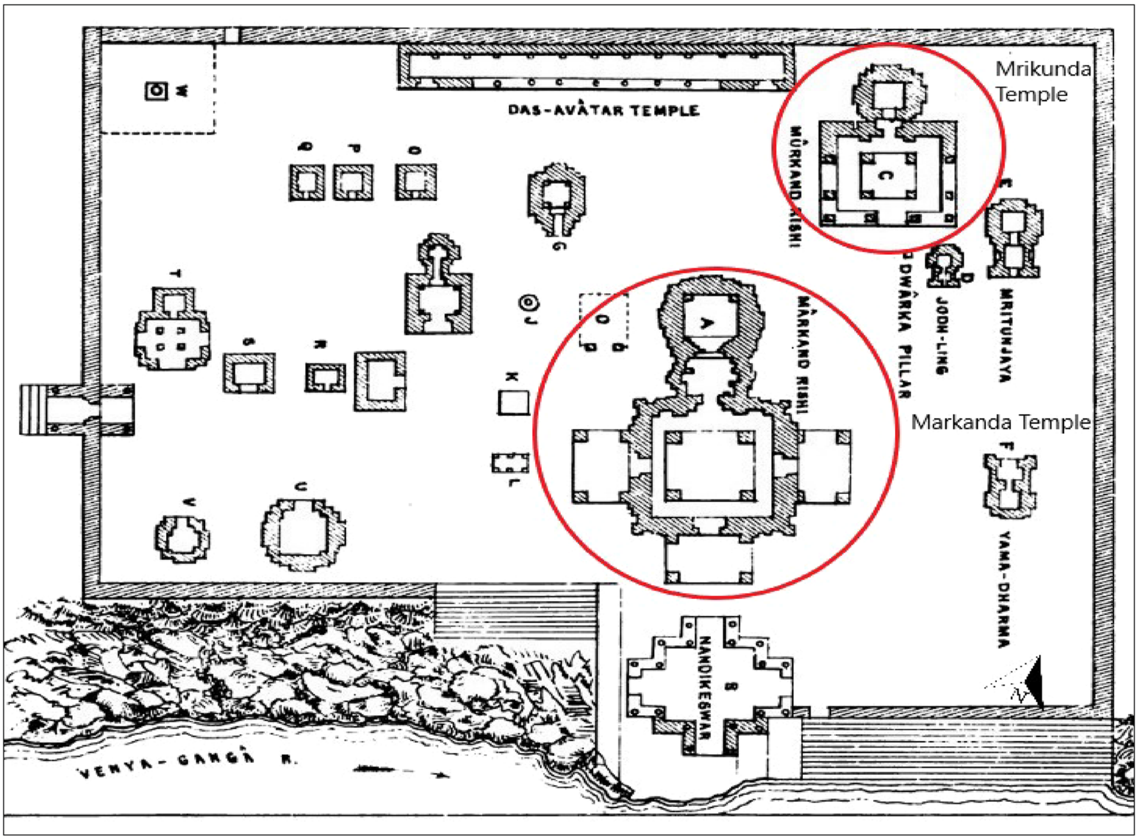


**Fig. 1** Site plan of the Markanda temple complex in Maharashtra, India (report on central tour) [49]

characterize the sound field of the Markanda and the Mrikunda temples.
2. To conduct computer-aided simulations to investigate the acoustic characteristics of both unoccupied (*unocc*) and occupied (*occu*) conditions.

### 4.1 Measurement Condition

The acoustic study was conducted following the ISO 3382-1:2009 [41] standards. Figure 5 illustrates the framework of the study's methodology in detail. First, the in-situ acoustic measurements of the Markanda and the Mrikunda temples were carried out between 7:00 a.m. and 10:00 a.m., ensuring no worshippers or priests were present within the temple.

An omni power sound source (Brüel and Kjaer type 4292-L), connected to a power amplifier (Brüel and Kjaer type 2734-A), was placed at the center of the pavilion (S1) in both the temple cases (refer Fig. 4). The sound source was placed at the height of 1.5 m from the floor to represent the position of the worshippers while reciting Vedic chanting and singing devotional songs. The receiver positions are strategically placed to dominate the prayer space in these temples. Room impulse responses (RIR) were recorded using an omnidirectional microphone (Brüel and Kjaer Type 4189ZC-0032) that integrated with the handheld analyzer (Brüel and Kjaer-Type 2270-A) for all the receiver positions (R1-R6). All receivers were placed at the height of 1.2 m, representing the height of the ear of a person praying in the temple space (Fig. 6). To ensure accurate results, the calibrated DIRAC 6.0 acoustical analysis program by (Bruel and Kjaer Type 7841) was used to generate sine sweep excitation signals with a more extended period than the estimated reverberation time of the temples volume across the desired frequency range 125 Hz to 4000 Hz. Figure 7 shows a schematic representation of the Dirac measurement setup. The environmental conditions temperature at 25–30 °C and relative humidity of 50% were continuously monitored and maintained during the in-situ measurements. These signals were then recorded and analyzed for three-room acoustic indicators: Reverberation Time (T30*unocc*), Clarity of Music (C80*unocc*), and Speech Transmission Index (STI*unocc*). The analysis was conducted for six-octave band frequencies: 125 Hz, 250 Hz, 500 Hz, 1000 Hz, 2000 Hz, and 4000 Hz.

In addition, SketchUp software was employed to develop the 3D virtual models of the Markanda and the Mrikunda

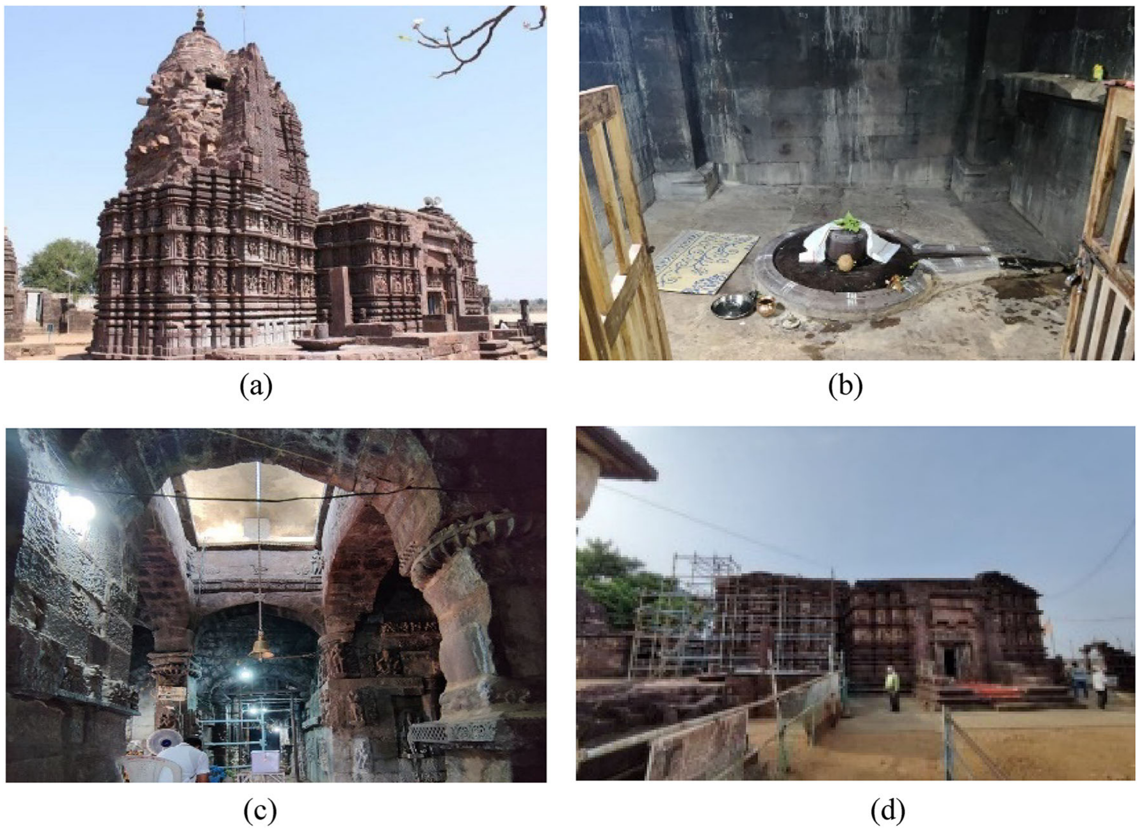


**Fig. 2** **a** Markanda temple's external view, **b** Lord Shiva sanctum, **c** the pavilion space for congregational activities, and **d** the temple's current restoration

temples. The SU2Odeon Sketchup plugin was used to convert the models into the parametric file format (.par), which was imported to Odeon 12.10 software to simulate both temple's sound fields. Figure 8 shows the imported 3D virtual models of the Markanda (a) and the Mrikunda (b) temples. Hindu temples have intricately carved interiors, and detailed geometric models do not guarantee greater accuracy in calculating the acoustic indicators. Complex geometric models can significantly increase computation time without improving the accuracy of the results [52, 53]; therefore, the temple models were simplified to the greatest extent. The number of surfaces in the Markanda temple model are 752, and the number of surfaces in the Mrikunda temple model are 388. The calculation indicators were adjusted to match the temple's dimensions and the desired reverberation time. The absorption coefficients of the surfaces within the temple were meticulously established through a comprehensive scientific literature review [44, 54]. The scattering coefficient was determined by considering the material's surface condition and the simplification of the acoustic model; the coefficient was then repeatedly adjusted based on differences between the measured and simulated values of the sound fields. This method determined reference values for absorption and scattering coefficients of materials most commonly used for ancient temples. Lastly, the sound sources and receivers were placed in the 3D virtual model to carry out the simulations. The occupied simulations were conducted with the sound source positioned at two locations. First, the sound source was placed at the center of the pavilion (S1), a space for musical activities that match the in-situ measurements. In the second simulation, the sound source was placed inside the sanctum (S2) at a height of 1.5 m, where a single priest chants Vedic mantras and performs (*aarti*), standing before the deity.

The 3D virtual models were calibrated using in-situ measurements and altering the absorption and scattering coefficients. The resulting absorptions and scattering coefficient are presented in Table 3. To evaluate the accuracy of the simulation results, the errors for selected indicators were calculated considering its Just Noticeable Difference (JND): the simulated errors should be less than its JND. This iterative calibration process was repeated until the T30, C80, and STI values were within the range of 1 JND. The discrepancies equivalent to 1 JND are a 5% relative difference for T30, 1 dB for C80, and 0.3 for STI [55–57]. The spatially averaged in-situ measurement and computer-aided simulation findings for the T30*unocc*, C80*unocc*, and STI*unocc* indicators of the

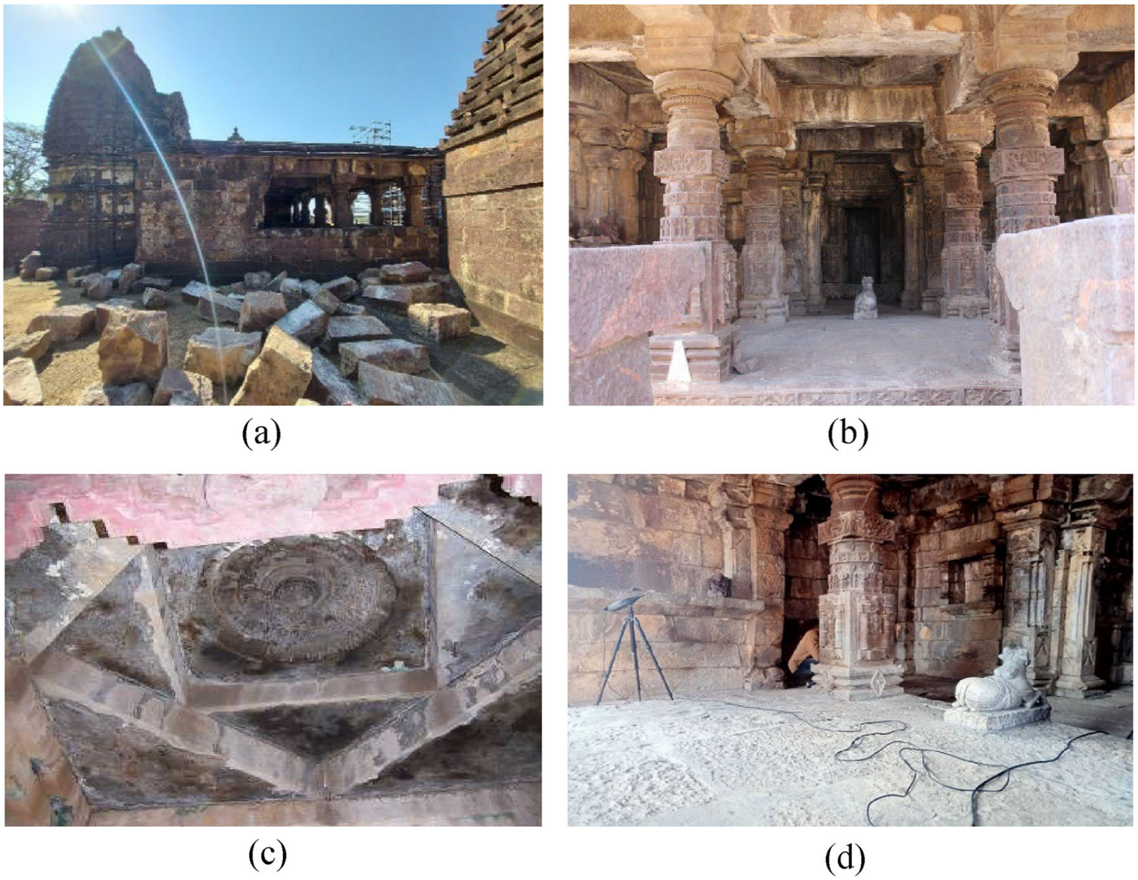


**Fig. 3** **a** Mrikunda temple's external view, **b** the entrance to the semi-open pavilion, **c** the tiered ceiling at the pavilion, and **d** stone carved columns

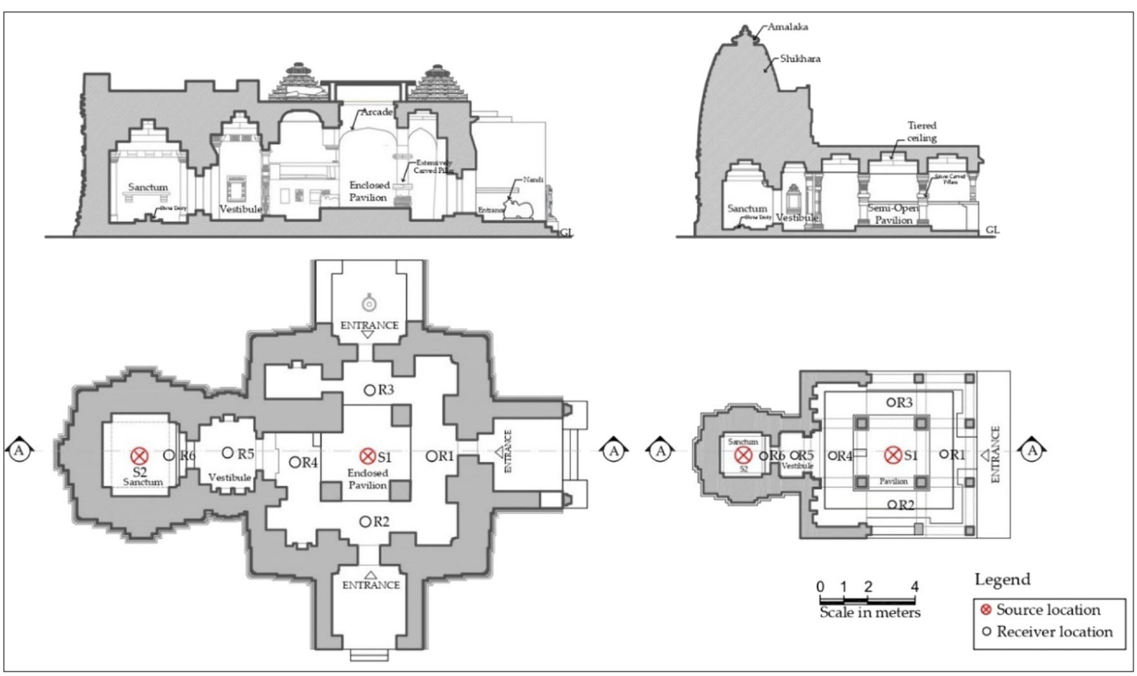


**Fig. 4** Shows the floor plans of Markanda temple (left) and Mrikunda temple (right), indicating the sound source (S1), (S2), and receiver positions (R1–R6), along with a cross-section above each floor plan

**Table 2** Summary of the primary geometric characteristics of the Markanda and the Mrikunda temple

| | Internal spatial organization | Construction date | Plan typology | Internal volume ($m^3$) | Total surface area ($m^2$) | Construction material | Ceiling Type |
|---|---|---|---|---|---|---|---|
| Markanda Temple | Sanctum | Twelfth century | Enclosed from three sides | 63.7 | 97.3 | Basalt gneiss | Tiered |
| | Vestibule | | Enclosed from two sides | 31.25 | 64 | | Tiered |
| | Pavilion | | Enclosed | 332.8 | 394.4 | | Arcade |
| | Combined | | Enclosed | 427.75 | _ | | _ |
| Mrikunda Temple | Sanctum | Twelfth century | Enclosed from three sides | 25.62 | 53.4 | Basalt gneiss | Tiered |
| | Vestibule | | Enclosed from two sides | 12.3 | 36.34 | | Tiered |
| | Pavilion | | Semi-open | 152.56 | 150.46 | | Tiered |
| | Combined | | Semi-open | 190.48 | – | | – |

Markanda and the Mrikunda temples are shown in Tables 4, 5 and 6, respectively. The results indicate that the differences between the measured and simulated values for the three acoustic indicators were less than 1 JND. Hence, it can be inferred that the simulation results are validated and acceptable for further investigation in this study.

## 5 Results and Discussion

### 5.1 Unoccupied In-Situ Measurements Results

This section presents the results of in-situ measurement for the sound source position (S1) placed in the center of the pavilion of the Markanda and the Mrikunda temples. The indicators analyzed were T30*unocc*, C80*unocc*, and STI*unocc*. The findings of the T30*unocc* measurements are presented in Table 7. The spatially averaged T30*unocc* results for six receiver positions (R1–R6) of Markanda temples ranges between 0.84 to 1.04 s. The T30*unocc* values show a relatively consistent increase from 125 to 1000 Hz, with a peak at (500 Hz and 1000 Hz) showing consistent and moderate values of 1.04 s. This suggests the temple has a higher reverberation time in the lower and mid-frequency ranges. The reverberation times decrease at higher frequencies (2000 Hz and 4000 Hz), indicating a shorter decay time in the high-frequency range. The receiver position R6 in the Markanda temple consistently shows a higher T30*unocc* value in all frequency ranges. This indicates a more prolonged decay of sound as sound travels to the distant areas of the temple. These T30*unocc* results for Markanda temple are within the optimal range between 0.6 to 1.12 s as adopted for this research, even though no occupants were present during measurements. The relatively low T30*unocc* values can be attributed to the enclosed pavilion and the highly reflecting properties of basalt stone entirely used in the construction of the Markanda temple. Additionally, it can also be said that the low ceiling height of approximately 5.0 m for its overall volume of 427.75 $m^3$ contributes to lower T30*unocc* values. The average T30*unocc* values at low, medium, and high frequencies show a more moderate reverberant sound field in the Markanda temple.

On the other hand, the Mrikunda temple shows much lower T30*unocc* values than the Markanda temple, with an average range between 0.59 to 0.97 s for six receiver positions (R1-R6). T30*unocc* values are high at lower frequencies (125–250 Hz) and decrease at higher frequencies (2000–4000 Hz). The mid-frequency range (500 Hz and 1000 Hz) shows moderate and relatively consistent T30*unocc* values. Higher T30 values in low-frequency help to create a more appropriate environment for musical rituals [30]. Since the spatial configuration of the Mrikunda temple exhibits semi-open pavilion, most of the sound energy is absorbed through the openings. Mrikunda temple, which has comparatively low T30*occu* values, results in a less reverberant environment. Overall, such acoustic conditions enhance the intelligibility of rituals and facilitate clear communication between priests and worshippers. The actual T30 values during the prayers would be much lower due to the worshippers' higher absorption and diffusion, which were evaluated in the next section via computer-aided simulations.

The results of the clarity of music (C80*unocc*) indicator are presented in Table 8. The results are interpreted based on speech and musical clarity. As mentioned earlier, the optimal level of clarity is (between − 2 and + 3 dB) if the sound source is close to the receiver for the satisfactory performance of both speech and music. The averaged C80*unocc* results of the Markanda temple range from + 2.82 to + 5.48 dB. The highest C80*unocc* values are observed at higher frequencies (2000 Hz and 400 Hz). The findings suggest that

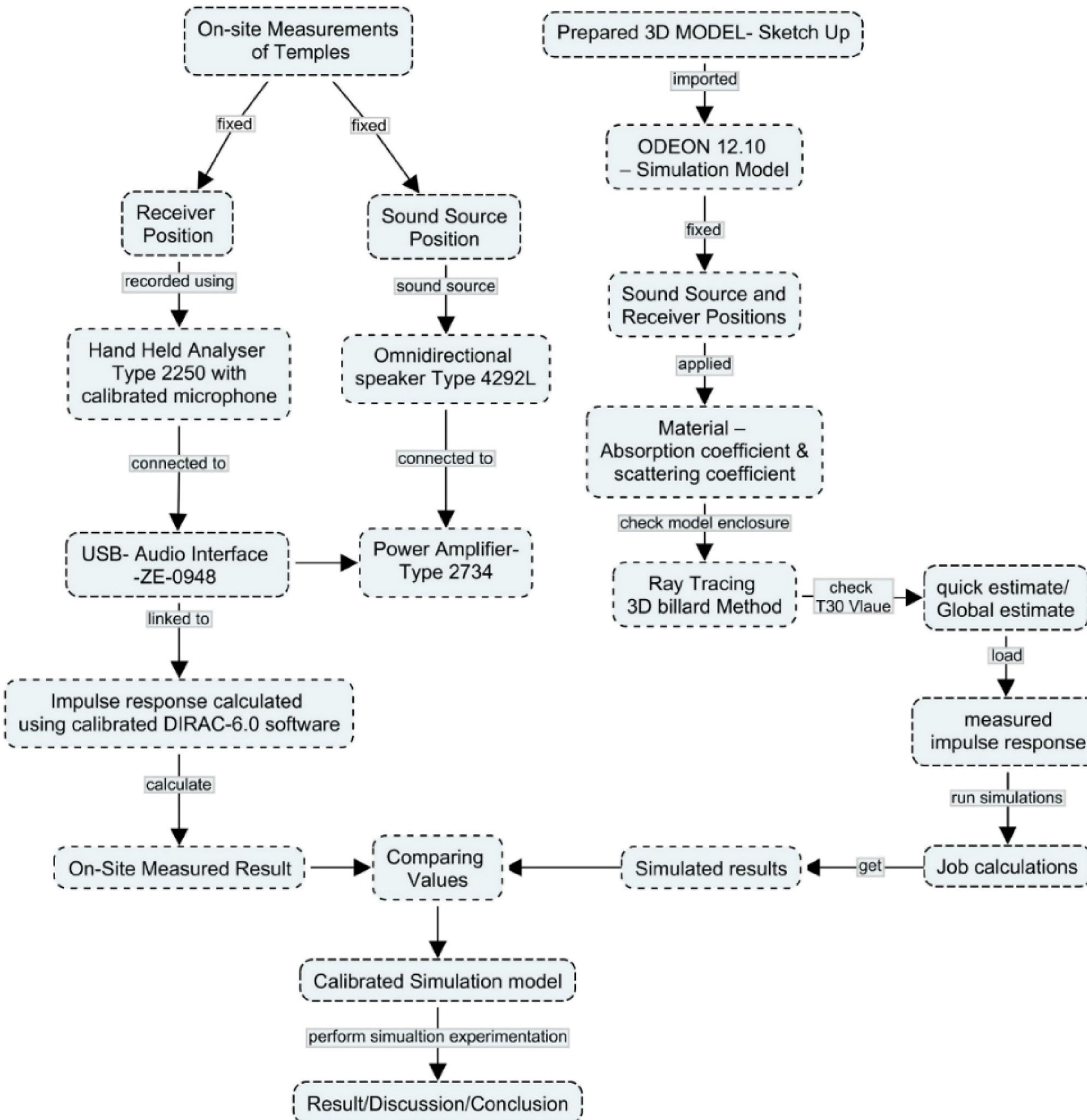


**Fig. 5** A framework of the methodology adopted for this research

early sound energy reaching the worshippers in the pavilion space is more dominant than late sound energy. R1-R5 position shows a positive C80*unocc* value, indicating clarity in the pavilion and vestibule space of the Markanda temple. A negative C80*unocc* value is observed at the R6 position across all frequency ranges and exceptionally low at 125 Hz. The C80 values depend on the distance between the source and the receiver [58], contributing to the negative C80 value observed at the R6 position where the sound source is placed in the center of the pavilion and the receiver is positioned inside the sanctum.

The average C80*unocc* results of the Mrikunda temple range from + 3.68 dB to + 7.51 dB. Higher C80*unocc* was observed at 500 Hz, 1000 Hz, 2000 Hz, and 4000 Hz, suggesting better clarity for mid to high-pitched sounds. In comparison, the C80*unocc* value for the Mrikunda temple shows positive values for all receiver positions (R1-R6),

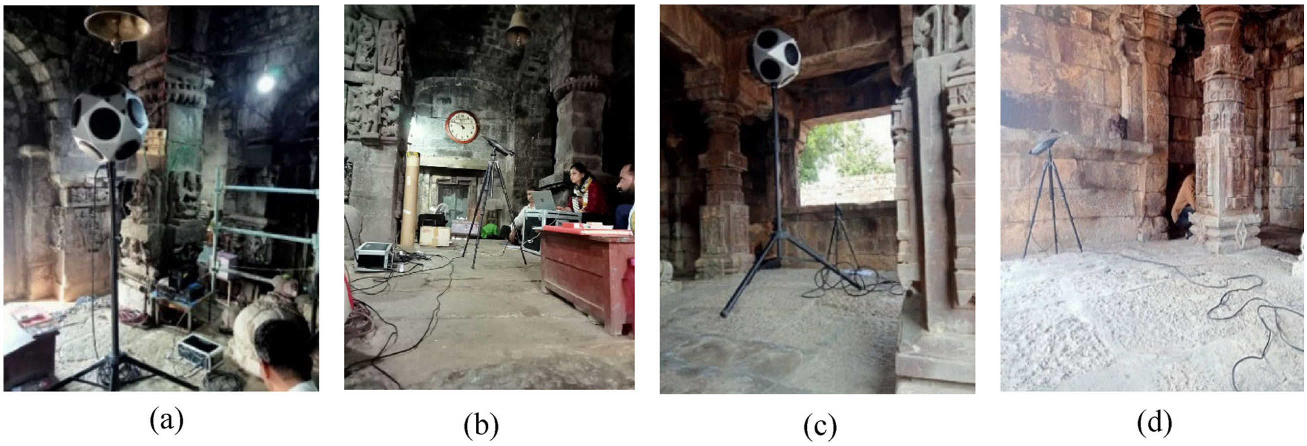


**Fig. 6** **a** Markanda temple sound source (S1) (center of the pavilion) and the **b** Markanda temple receiver position **c** Mrikunda temple sound source (S1) (center of the pavilion) **d** Mrikunda temple receiver position

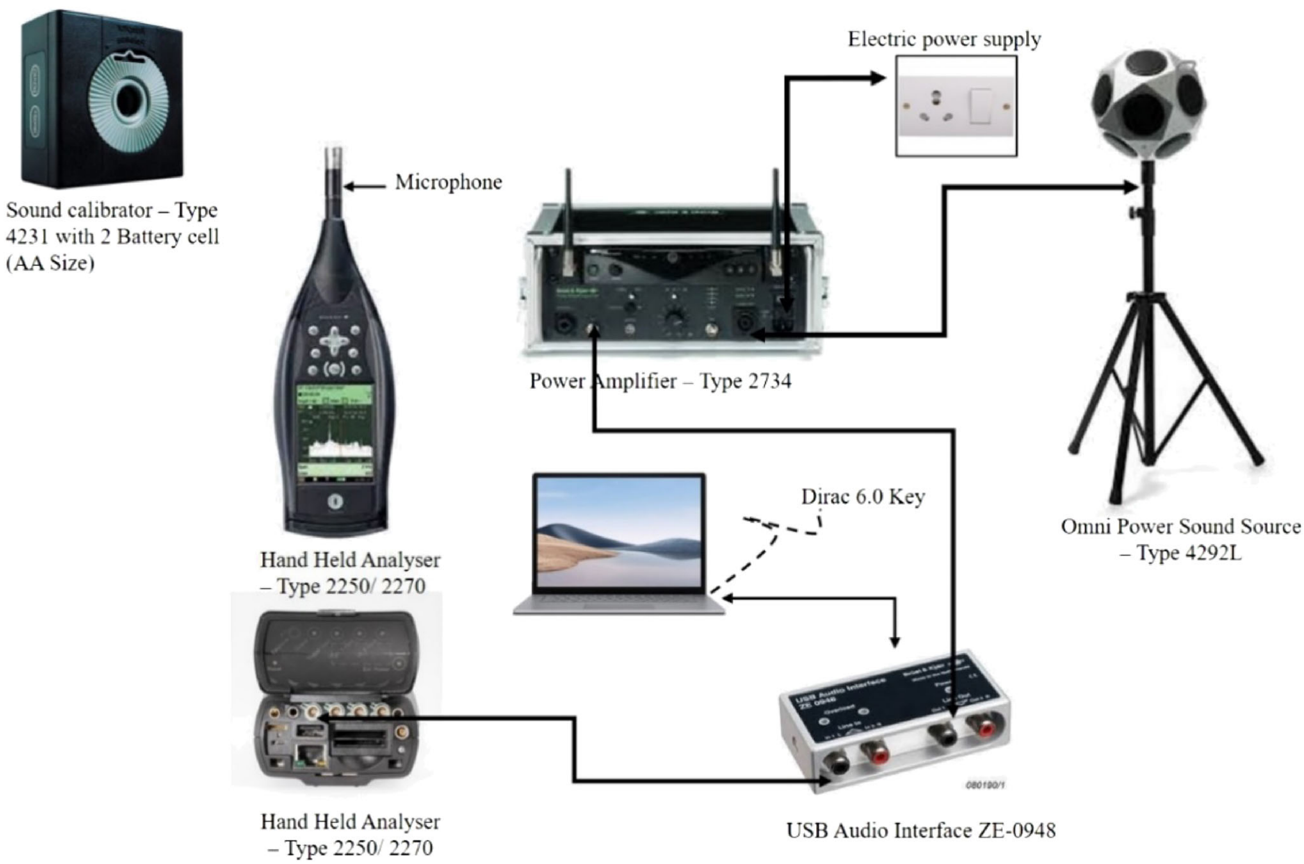


**Fig. 7** Schematic representation of Dirac 6.0 measurement setup

resulting from the semi-open pavilion, absorptive characteristics enhancing speech and better musical clarity as expected. Overall, the small volume and the position of columns in the semi-open pavilion space are relatively close to the receivers, causing strong early reflection and, therefore, resulting in positive results for C80*unocc*. In this research, the average C80*unocc* values in both temples are higher than the adopted optimal values for musical and speech clarity.

Speech Transmission Index (STI) is directly related to speech. A higher order of STI includes understanding the percentage of words/sentences/phonemes by the listeners [59]. The results of average STI*unocc* of the Markanda and the Mrikunda temples are presented in Table 9. The STI val-

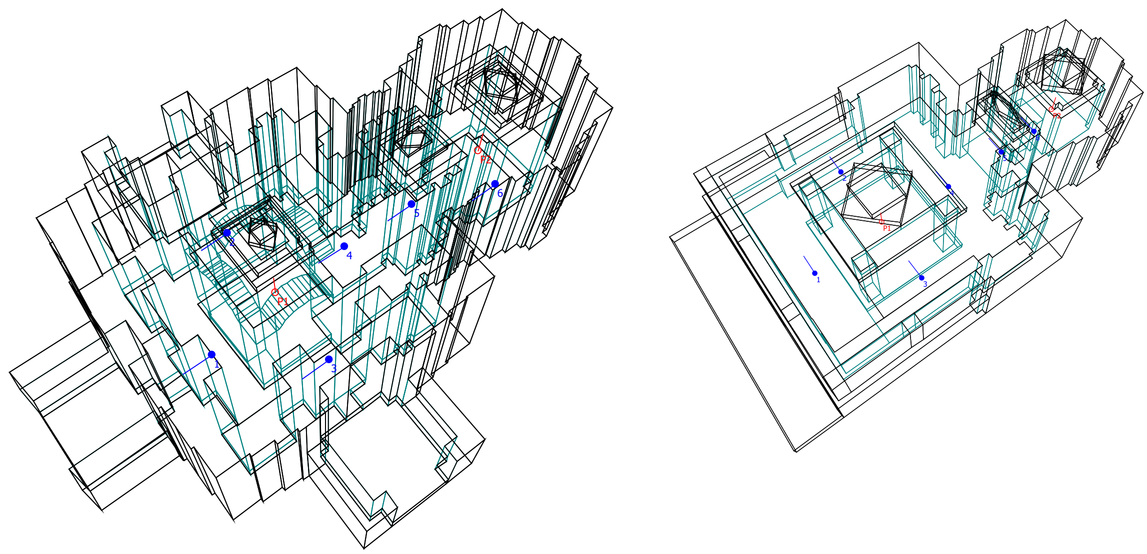


**Fig. 8** Virtual acoustic models of Markanda Temple (**a**) and Mrikunda Temple (**b**) with sound sources (S1), (S2), and receivers (R1–R6)

**Table 3** Sound absorption and scattering coefficient (SC) of materials assigned to the surfaces in a virtual model of the Markanda and the Mrikunda temples

| Band (Hz) | 125 | 250 | 500 | 1000 | 2000 | 4000 | (SC) |
|---|---|---|---|---|---|---|---|
| Stonewall | 0.02 | 0.03 | 0.03 | 0.04 | 0.05 | 0.05 | 0.70 |
| Ceiling | 0.12 | 0.12 | 0.11 | 0.12 | 0.12 | 0.12 | 0.70 |
| Standing occupants (density: 1.07 persons/$m^2$) | 0.15 | 0.26 | 0.61 | 1.00 | 1.00 | 1.00 | 0.70 |

**Table 4** compares the spatially averaged T30*unocc* values between in-situ measurements and computer-aided simulation of the Markanda and the Mrikunda temples

| | Band (Hz) | 125 | 250 | 500 | 1000 | 2000 | 4000 |
|---|---|---|---|---|---|---|---|
| Markanda temple | Measured (sec) | 0.91 | 1.10 | 1.04 | 1.04 | 0.98 | 0.84 |
| | Simulated (sec) | 0.93 | 1.05 | 1.08 | 1.02 | 0.97 | 0.81 |
| | Difference (sec) | – 0.02 | 0.05 | – 0.04 | 0.02 | 0.01 | 0.03 |
| | JND % | 2.19 | 4.5 | 3.8 | 1.92 | 1.02 | 3.5 |
| Mrikunda temple | Measured (sec) | 0.97 | 0.83 | 0.69 | 0.66 | 0.64 | 0.59 |
| | Simulated (sec) | 0.95 | 0.80 | 0.72 | 0.68 | 0.66 | 0.61 |
| | Difference (Sec) | 0.02 | 0.03 | – 0.03 | – 0.02 | – 0.02 | – 0.02 |
| | JND % | 2.06 | 3.61 | – 4.34 | – 3.03 | – 3.12 | – 3.3 |

**Table 5** compares the spatially averaged C80*unocc* values between in-situ measurements and computer-aided simulation of the Markanda and the Mrikunda temples

| | Band (Hz) | 125 | 250 | 500 | 1000 | 2000 | 4000 |
|---|---|---|---|---|---|---|---|
| Markanda temple | Measured (dB) | 3.64 | 4.69 | 2.82 | 3.32 | 3.93 | 5.48 |
| | Simulated (dB) | 3.60 | 4.62 | 2.74 | 3.27 | 3.80 | 5.44 |
| | Difference (dB) | 0.04 | 0.07 | 0.08 | 0.05 | 0.13 | 0.04 |
| | JND | 0.04 | 0.07 | 0.08 | 0.05 | 0.13 | 0.04 |
| Mrikunda temple | Measured (dB) | 4.05 | 3.68 | 6.01 | 5.77 | 6.72 | 7.51 |
| | Simulated (dB) | 4.07 | 3.74 | 6.04 | 5.81 | 6.77 | 7.42 |
| | Difference (dB) | – 0.02 | – 0.06 | – 0.03 | – 0.04 | – 0.05 | 0.09 |
| | JND | – 0.02 | – 0.06 | – 0.03 | – 0.04 | – 0.05 | 0.09 |

**Table 6** compares the spatially averaged STI*unocc* values between in-situ measurements and computer-aided simulation of the Markanda and the Mrikunda temples

| | | | | | |
|---|---|---|---|---|---|
| Markanda temple | Measured | 0.60 | Mrikunda temple | Measured | 0.67 |
| | Simulated | 0.59 | | Simulated | 0.66 |
| | Difference | 0.01 | | Difference | 0.01 |
| | JND | 0.1 | | JND | 0.1 |

**Table 7** Unoccupied reverberation time (T30*unocc*) measurement results for the six receiver (R1–R6) positions of the Markanda and the Mrikunda temples

| Markanda temple T30*unocc* | | | | | | |
|---|---|---|---|---|---|---|
| Band (Hz) | 125 | 250 | 500 | 1000 | 2000 | 4000 |
| R1 | 0.85 | 0.87 | 0.83 | 0.89 | 0.83 | 0.74 |
| R2 | 0.79 | 0.87 | 0.90 | 0.86 | 0.85 | 0.74 |
| R3 | 0.77 | 0.82 | 0.83 | 0.85 | 0.82 | 0.73 |
| R4 | 0.82 | 0.93 | 0.97 | 1.00 | 0.93 | 0.81 |
| R5 | 0.91 | 1.11 | 1.22 | 1.21 | 1.10 | 0.88 |
| R6 | 1.30 | 1.44 | 1.51 | 1.46 | 1.33 | 1.17 |
| Average | 0.91 | 1.01 | 1.04 | 1.04 | 0.98 | 0.84 |
| Mrikunda temple T30*unocc* | | | | | | |
| Band (Hz) | 125 | 250 | 500 | 1000 | 2000 | 4000 |
| R1 | 0.93 | 0.77 | 0.60 | 0.70 | 0.65 | 0.60 |
| R2 | 0.72 | 0.81 | 0.72 | 0.68 | 0.62 | 0.58 |
| R3 | 1.09 | 0.73 | 0.72 | 0.63 | 0.63 | 0.58 |
| R4 | 1.28 | 0.97 | 0.72 | 0.64 | 0.64 | 0.58 |
| R5 | 0.84 | 0.85 | 0.73 | 0.66 | 0.64 | 0.59 |
| R6 | 0.96 | 0.88 | 0.66 | 0.67 | 0.66 | 0.62 |
| Average | 0.97 | 0.83 | 0.69 | 0.66 | 0.64 | 0.59 |

**Table 8** Unoccupied clarity of music (C80*unocc*) measurement results for the six receiver (R1–R6) positions of the Markanda and the Mrikunda temple

| Markanda temple C80*unocc* | | | | | | |
|---|---|---|---|---|---|---|
| Band (Hz) | 125 | 250 | 500 | 1000 | 2000 | 4000 |
| R1 | 3.6 | 4.26 | 4.18 | 3.66 | 4.78 | 5.81 |
| R2 | 6.53 | 6.06 | 5.28 | 4.26 | 5.08 | 6.93 |
| R3 | 4.95 | 4.27 | 5.61 | 4.9 | 6.63 | 8.72 |
| R4 | 3.84 | 4.59 | 3.83 | 5 | 5.5 | 6.74 |
| R5 | 3.2 | 4.96 | 1.84 | 2.81 | 2.67 | 3.99 |
| R6 | − 0.26 | − 2.03 | − 3.8 | − 0.72 | − 1.1 | 0.69 |
| Average | 3.64 | 3.69 | 2.82 | 3.32 | 3.93 | 5.48 |
| Mrikunda temple C80*unocc* | | | | | | |
| Band (Hz) | 125 | 250 | 500 | 1000 | 2000 | 4000 |
| R1 | 2.03 | 1.18 | 2.37 | 3.64 | 3.82 | 4.12 |
| R2 | 4.2 | 5.98 | 9.1 | 9.03 | 8.51 | 9.43 |
| R3 | 6.57 | 5.24 | 6.83 | 6.67 | 7.91 | 9.56 |
| R4 | 3.67 | 4.24 | 7.05 | 5.58 | 8.46 | 9.09 |
| R5 | 3.99 | 3.67 | 5.88 | 5.3 | 6.8 | 7.1 |
| R6 | 3.85 | 1.74 | 4.85 | 4.39 | 4.92 | 5.76 |
| Average | 4.05 | 3.68 | 6.01 | 5.77 | 6.72 | 7.51 |

**Table 9** Unoccupied speech transmission index (STI*unocc*) measurement results for the six receiver (R1–R6) positions of the Markanda and the Mrikunda temple

| Markanda temple | |
|---|---|
| Receiver positions | STI |
| R1 | 0.65 |
| R2 | 0.64 |
| R3 | 0.66 |
| R4 | 0.62 |
| R5 | 0.57 |
| R6 | 0.47 |
| Average | 0.60 |
| Mrikunda temple | |
| Receiver positions | STI |
| R1 | 0.69 |
| R2 | 0.71 |
| R3 | 0.69 |
| R4 | 0.68 |
| R5 | 0.67 |
| R6 | 0.63 |
| Average | 0.67 |

ues of the Markanda temple range from 0.47 to 0.66, with an average STI*unocc* of 0.60 for six receiver positions (R1–R6). Receiver positions (R1–R4) exhibit "moderate" to "good" speech intelligibility with an STI above 0.60 (Table 1). On the contrary, speech intelligibility decreases at the R5 and R6 positions, with an STI below 0.60 corresponding to "fair" speech intelligibility. The STI*unocc* values of the Mrikunda temple range from 0.63 to 0.71, with an average STI*unocc* of 0.67. The STI*unocc* values are generally higher compared to the Markanda temple. All receiver positions (R1–R6) of the Mrikunda temple exhibit "excellent" speech intelligibility with STI values above 0.60. It is important to note that these findings could differ if the temples are occupied, as covered in the next section.

## 5.2 Occupied Acoustic Simulation Results

This section presents the occupied simulation results of the Markanda and the Mrikunda temples. Two simulations were conducted. First, the sound source was placed in the center of the pavilion (S1), and the second sound source was placed inside the sanctum (S2). The T30*occu*, C80*occu*, and STI*occu* room acoustic indicators were analyzed for both sound source positions. The T30*occu* measurement values for sound source position (S1) and (S2) of the Markanda temple are shown in (Fig. 9) and the Mrikunda temple (Fig. 10).

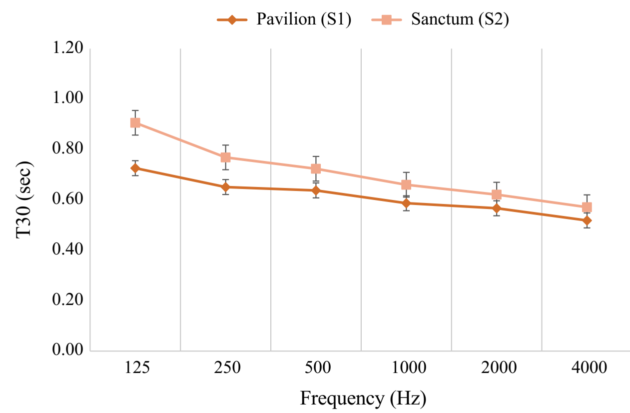


**Fig. 9** Compares the occupied reverberation time (T30*occu*) indicator between the two sound source positions: center of the pavilion (S1) and inside the sanctum (S2) of the Markanda temple

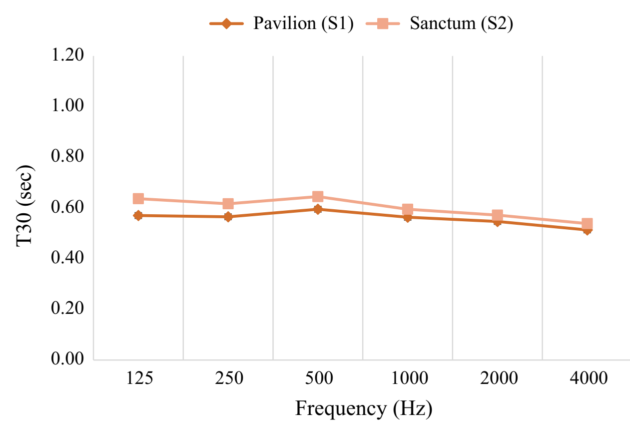


**Fig. 10** Compares the occupied reverberation time (T30*occu*) indicator between the two sound source positions: center of the pavilion (S1) and inside the sanctum (S2) of the Mrikunda temple

The Markanda temple averaged T30*occu* value for the sound source in the sanctum (S2) has a significantly higher value of 0.91 s compared to the sound source at the center of the pavilion (S1) value of 0.73 s at 125 Hz. In comparison, both sound source positions show a decreasing T30*occu* value of 0.52 s for (S1) and 0.57 s for (S2) sound source position at higher frequency (4000 Hz). The simulations showed higher T30 values at low frequencies, a significant increase below 250 Hz. This can be explained by the absorptive characteristics of occupants in the pavilion space of the temple used in the computer simulations. Additionally, it can be said that the relatively high T30*occu* values observed for the sound source in the sanctum (S2) tend to have longer sound decay times, potentially caused by the coupled volume with highly reflective material and the tiered ceiling in the sanctum. The tiered ceiling contributes to the retroreflection phenomenon, where little sound energy is reflected in locations not near the sound source [60], which may be beneficial for the clear speech intelligibility of high-pitched

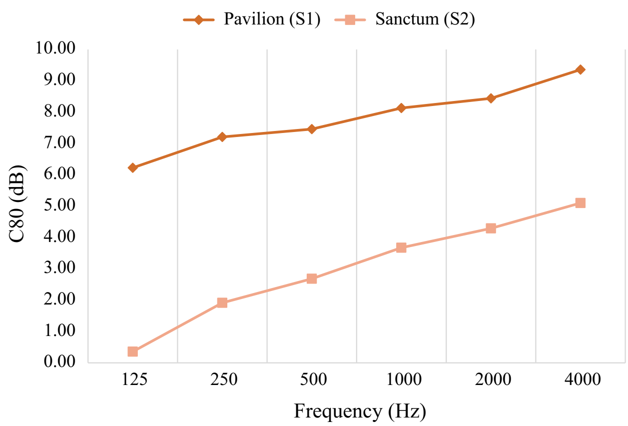


**Fig. 11** Compares the occupied clarity of music (C80*occu*) indicator between the two sound source positions: center of the pavilion (S1) and inside the sanctum (S2) of the Markanda temple

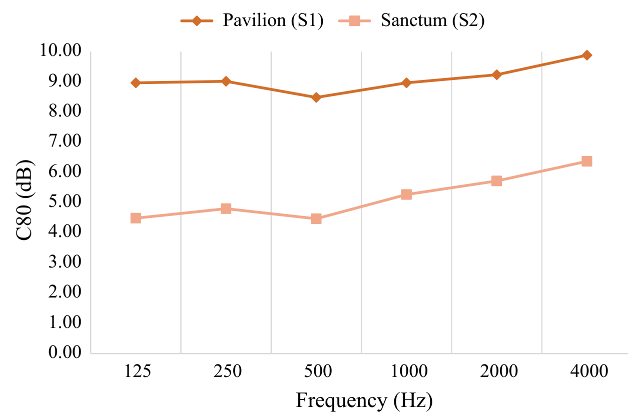


**Fig. 12** Compares the occupied clarity of music (C80*occu*) indicator between the two sound source positions: center of the pavilion (S1) and inside the sanctum (S2) of the Mrikunda temple

sounds like temple bells and Vedic chanting by a priest within the sanctum with specific musical instruments such as gong and conch shells.

Similar to the Markanda temple, the Mrikunda temple sound source position (S2) exhibits higher T30*occu* values across all frequencies than the sound source position (S1). A slight peak is observed at the mid-frequency octave band (500 Hz) of 0.65 s for the sound source (S2) and 0.60 s for the sound source (S1). The lowest T30*occu* value for the sound source (S1) is 0.51 s, and the sound source (S2) is 0.54 s at 4000 Hz. The results suggest that the sound source (S2) placed in the sanctum decayed slightly longer than the sound source in the pavilion (S1). Overall, the Mrikunda temple's average T30*occu* values are lower than the Markanda temple. A low T30*occu* value above 500 Hz improves speech intelligibility with the number of worshippers within the temple space.

The results of the C80*occu* measurements of the Markanda and Mrikunda temples are shown in Figs. 11 and 12, respectively. The results are discussed for the sound source positions (S1) and (S2). Figure 13 presents the spatial map of the C80*occu* indicator for the mid-frequency octave band (1000 Hz) of the Markanda and Mrikunda temples. The simulation results of the Markanda temple showed that the highest spatially averaged C80*occu* values are significantly higher for the sound source (S1) than the sound source (S2) across all frequency ranges. The sound source inside the sanctum (S2) of Markanda temple has a very low C80*occu* value of + 0.36 dB at 125 Hz, indicating less clarity, while (S1) showed a higher value of + 6.23 dB for similar frequency. The C80*occu* values decrease with the frequency, particularly below 250 Hz, showing an inverse relationship with the T30. At higher frequencies, (S1 and S2) show increasing C80 values, with the sound source (S1) having consistently higher clarity. The higher clarity at high frequency leads to improved speech intelligibility. A lower C80*occu* value in the sanctum (S2) suggests a reverberant sound field suitable for Vedic chanting but detrimental to the music. However, the acoustic characteristics of the sanctum space with restricted entry limited to a single priest are suitable for its intended purpose of Vedic chanting. The C80*occu* value is above the adopted optimal levels for speech and musical clarity, particularly at higher frequencies, owing to the pronounced early strong reflections resulting from the temple's enclosed pavilion with highly reflecting and diffusive surfaces. In the Mrikunda temple, the sound source (S1) and sound source (S2) show increasing C80*occu* values at higher frequencies, with (S1) consistently having higher clarity. The C80*occu* value of + 8.97 dB at 125 Hz is observed for sound source (S1), indicating high clarity, while sound source (S2) shows slightly lower clarity of + 4.48 dB at a similar frequency. Similarly, for the sound source position (S2), the highest C80*occu* value is + 6.37 at 4000 Hz, and the lowest is + 4.47 at 500 Hz. The sound source (S1) generally provides higher clarity across all frequencies than the sound source (S2). It is worth noting that when the sound source is placed at the (S2) position, the side aisle in the pavilion exhibits very low clarity, which can be attributed to the coupled volume of the Mrikunda temple (refer to Fig. 13).

The results of the Speech Transmission Index (STI) of both temples in occupied conditions are presented in the form of a spatial map in Fig. 14. The averaged STI*occu* values for the Markanda temple range from 0.66 to 0.76 for the sound source position (S1), with an average STI*occu* value of 0.73 for the receiver (R1–R6), indicating good speech intelligibility. The average STI*occu* value for the sound source position (S2) ranges from 0.56 to 0.74, with an average STI*occu* value of 0.63 for the receiver (R1–R6). However, speech intelligibility was decreased to 0.56 for the receiver (R1–R3), indicating fair speech intelligibility. This can be attributed to the position of the sound source in the sanctum, the uneven

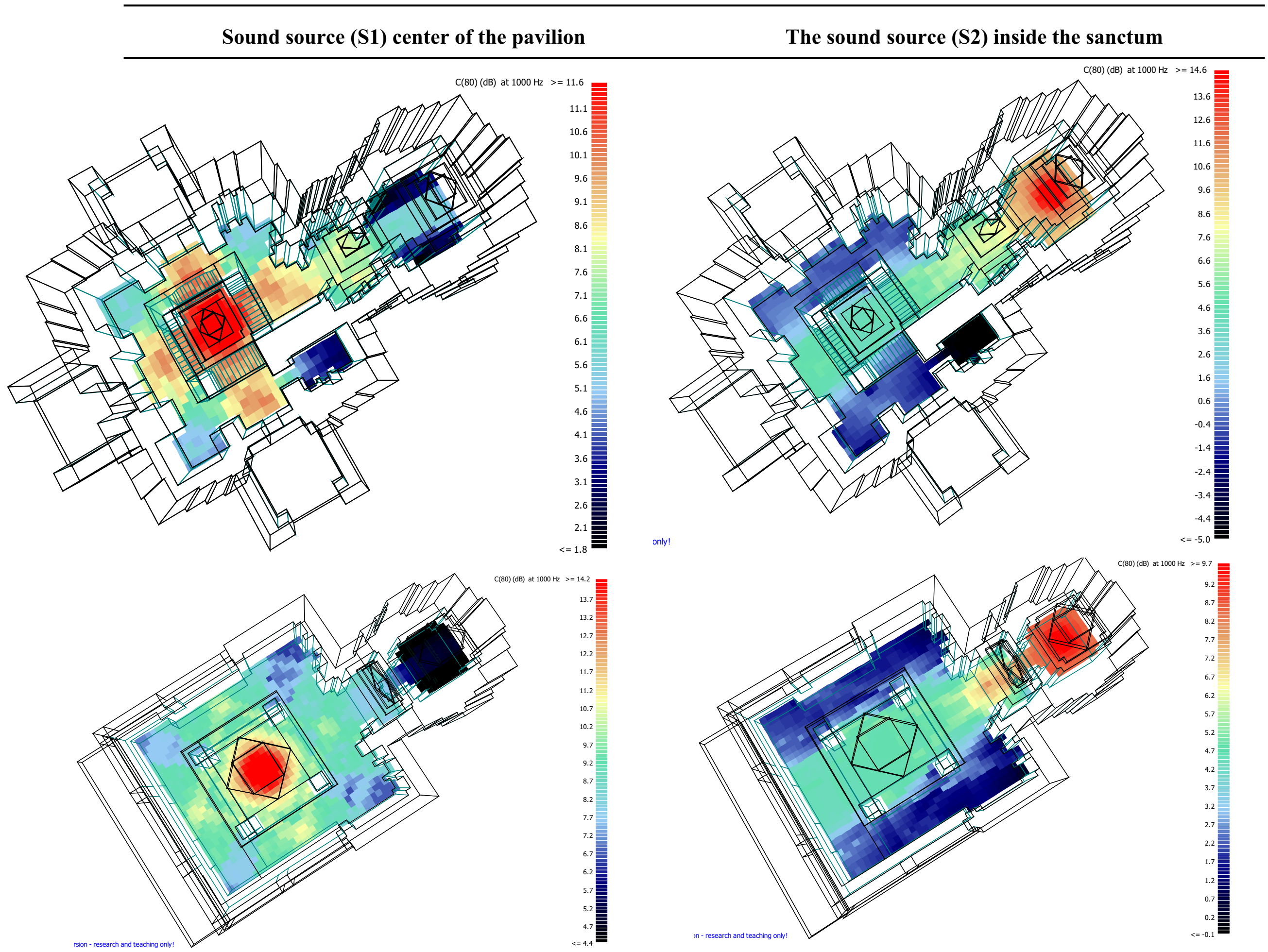


**Fig. 13** Shows the spatial map for clarity of music (C80*occu*) indicator between the two sound source positions: center of the pavilion (S1) and inside the sanctum (S2) of the Markanda temple (above) and the Mrikunda temple (below)

distribution of sound energy caused by the coupled volume, and the placement of columns and edges in the pavilion. On the other hand, all receiver positions R1–R6 of Mrikunda temple exhibit "good to excellent" speech intelligibility with STI*occu* values above 0.60.

## 6 Conclusion

This study investigated acoustic characteristics of the two Hemadpanti-style Hindu temples, Markanda and Mrikunda temple, through in-situ measurement employing room impulse response (RIR) techniques and computer-aided simulation results. Room acoustic indicators examined were T30, C80, and STI. Based on the results and discussions, the main findings are listed below:

- The average unoccupied (*unocc*) and occupied (*occu*) reverberation time T30 of the Markanda and the Mrikunda temples are within the optimum T30 value adopted in this study.
- In the Markanda temple, T30*occu* values are higher, and clarity C80*occu* values are lower at low frequencies below 250 Hz. This suggests that prolonged sound decay can contribute to a moderate reverberant sound field in the Markanda temple and is desirable for its intended use, such as Vedic chanting and singing devotional songs. The temple's enclosed pavilion and highly reflective and diffusive properties of basalt stone contribute to a more immersive sound field for worshippers inside the temple for music rituals. Rituals performed inside the sanctum by a priest remain largely confined to that space, allowing a more focused approach towards praying and Vedic chanting.
- The Mrikunda temple's overall low volume and the semi-open pavilion's absorptive characteristics absorb most of the sound energy, resulting in lower reverberation time and a less reverberant sound field than the Markanda temple.

| Sound source (S1) center of the pavilion | The sound source (S2) inside the sanctum |
|---|---|

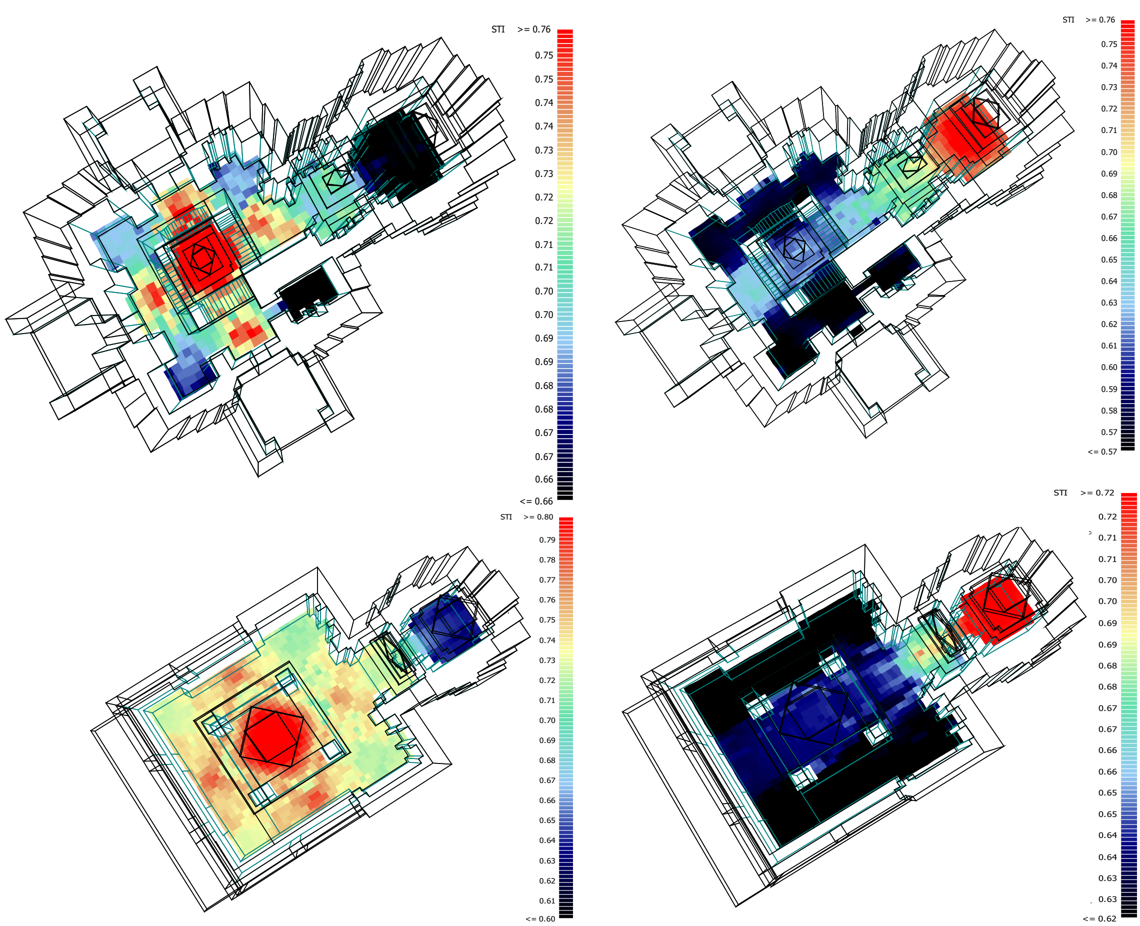


**Fig. 14** shows a spatial map for the Speech Transmission Index (STI*occu*) indicator between the two sound source positions: center of the pavilion (S1) and inside the sanctum (S2) of the Markanda temple (above) and the Mrikunda temple (below)

- According to the results of higher C80*occu* values, the sound field within both temples is conducive to musical rituals. Overall, both temples have medium to small volumes, with the lesser distance between the sound source and receivers beneficial for maintaining clarity. Additionally, a tiered ceiling in the pavilion space contributes to sound diffusion and even distribution, enhancing clarity within the space.
- The average subjective rating for speech intelligibility in the occupied condition of the Markanda and the Mrikunda temples is “good.” However, due to the coupled volume, the distribution of sound energy is not uniform, affecting speech intelligibility for a few receivers’ positions in the pavilion when the sound source is placed inside the sanctum of the Markanda temple.

Overall, the results indicate that the Markanda and the Mrikunda temples have distinct acoustic characteristics, which are significant due to their architectural features. The recorded data can be a valuable source of objective acoustical indicators and comparative information for further investigations of Hindu temple acoustics. In addition, using in-situ measurements, such as those reported in the study, combined with computer-aided simulation studies, can be useful for gaining insight into the acoustics of Hemadpanti-style Hindu temples.

**Acknowledgements** The authors wish to thank Visvesvaraya National Institute of Technology, Nagpur, India, for providing Bruel & Kjaer instruments and the Archaeological Survey of India (ASI), Nagpur Circle, for allowing them to conduct acoustical measurements. They also want to acknowledge the valuable contributions of Dr. Amit Wahurwagh, Ar. Prateek Barsagade, Ar. Surabhi Mendhe, and Ar. Parikshit Mudholkar, for their assistance with on-site measurements. Additionally, they are appreciative of Ar. Shivani Sharma for providing the architectural drawings. This research is part of a full-time Ph.D. Program at the Department of Architecture and Planning, Visvesvaraya National Institute of Technology, Nagpur, India.

**Authors Contribution** All Authors have contributed sufficiently to the scientific work and share collective responsibility and accountability for the results.

**Funding** No funding was received for conducting this study.

## Declarations

**Conflict of interest** The authors have no conflicts of interest to declare relevant to this article's content.

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