

ACOUSTIC EVALUATION OF MOSQUES WITH TWO LOUDSPEAKERS: INFLUENCE OF GEOMETRY, SIZE, CEILING MATERIALS, LOUDSPEAKER POSITION, AND OCCUPANCY

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Abstract

Introduction. This study presents a comprehensive investigation of the acoustic characteristics of mosques equipped with two loudspeakers under varying conditions. It addresses the widespread challenge of poor acoustics in Indonesian mosques, which often results from architectural features, material choices, and suboptimal sound system design. **Methods.** Using acoustic simulation, the research systematically varied several parameters: geometry, prayer area size (ranging from 100 m² to 625 m²), ceiling material (acoustic tile ceiling vs. gypsum tile ceiling), loudspeaker position, and occupancy level (unoccupied vs. fully occupied). The primary focus is the optimisation of the Speech Transmission Index (STI) for speech intelligibility and Sound Pressure Level (SPL) uniformity. **Results.** The key findings indicate that loudspeaker placement (corner vs. center-front) does not significantly affect either STI or uniformity. However, in larger hall volumes (e.g., 3,516 m³ and 6,086 m³), minor differences in sound uniformity (SPL Max–Min) were observed depending on loudspeaker position. In contrast, room volume, ceiling material, and occupancy significantly influence STI; larger volumes and lower absorption are associated with reduced clarity. Sound uniformity is also negatively affected by increased room volume and reflective, complex ceiling shapes (e.g., pyramidal), whereas increased absorption can heighten the dominance of the direct sound field, potentially diminishing uniformity. **Conclusions.** The study establishes that to achieve an STI > 0.5 and SPL variation < 6 dB across all occupancy conditions, the mosque volume should not exceed 1,125 m³. Furthermore, to ensure adequate speech intelligibility (STI > 0.5) in the unoccupied (worst-case) condition, the maximum reverberation time (RT) at 1 kHz should be limited to 2.5 seconds. These findings provide practical, evidence-based guidelines for the acoustic design of small- to medium-sized Indonesian mosques.

Keywords: mosque, room acoustics, loudspeakers, simulation, sound uniformity, speech transmission index.

Introduction

The acoustical performance of mosques, as significant religious and architectural structures, profoundly impacts the spiritual experience of congregants during various rituals, including prayer, sermons, and Quran recitation (Sert and Karaman, 2021; Kaygısız, Semerci and Sayın, 2024). This necessitates a comprehensive understanding of how architectural features, material properties, and sound system design interact to shape the aural environment within these unique spaces (Sert and Karaman, 2021; Handryant, 2021). The intricate interplay of these factors is especially critical in mosques, where auditory clarity is paramount for the comprehension of religious texts and sermons, thereby enhancing the spiritual engagement of worshippers (Aydın, Kocyigit and Dalkılıç, 2021).

In Indonesia, the mosque has historically been the most significant structure in Islamic civilisation. As the most populous Muslim country, Indonesia is home to over three hundred thousand mosques (Sistem Informasi Masjid, 2025). Given this vast number, ensuring optimal acoustic conditions for speech intelligibility and overall sound quality within these structures presents a significant challenge,

particularly considering their diverse architectural styles and construction materials (Adnan et al., 2018; Sert and Karaman, 2021). The study conducted by Sudarsono et al. (2019) shows that acoustic problems are still prevalent in Indonesian mosques. Several factors contribute to this issue, including the lack of prior acoustic considerations during the design phase, the use of inappropriate building materials, and suboptimal loudspeaker placement within worship halls (Prawirasasra and Mubarak, 2017). Moreover, a common misconception persists in Indonesia that good acoustic design can be achieved solely by installing a high-quality sound system, without due consideration of the room's inherent acoustic properties (Sudarsono et al., 2019). This situation is further exacerbated by the tendency of many mosque committees to prioritise aesthetic appeal or budget constraints over expert acoustic planning (Latifah et al., 2023; Handryant, 2021). These challenges underscore the urgent need for simplified, evidence-based guidance to facilitate effective acoustic design without requiring comprehensive specialised expertise.

Sound reinforcement systems have become an integral component of room acoustic design,

particularly in modern mosques. However, most studies on mosque acoustics have predominantly focused on architectural parameters and material properties, often neglecting the comprehensive impact of loudspeaker systems on overall acoustic comfort and speech intelligibility (Abdou, 2003; Othman et al., 2016; Pratiwi et al., 2023; Kaygısız, Semerci and Sayın, 2024). Therefore, an integrated strategy that addresses both the inherent architectural acoustics of mosques and the design of sound reinforcement systems is essential for improving speech intelligibility and achieving uniform sound distribution.

One of the challenges in the acoustic design of mosques in Indonesia is the dynamic nature of occupancy, which significantly affects acoustic conditions. In general, two main occupancy states can be distinguished: Jumah prayer and normal congregational prayer. Jumah prayer is characterised by a significantly higher occupancy rate, which increases sound absorption, resulting in good speech intelligibility but often poor sound uniformity. In contrast, normal congregational prayer typically has a lower occupancy, leading to decreased sound absorption and potentially longer reverberation times that can compromise clarity (Latifah et al., 2023). This dynamic shift in occupancy underscores the need for a robust acoustic design that can maintain optimal speech intelligibility and sound uniformity across varying absorption levels.

Several studies have investigated the acoustic quality of mosques through field measurements (Kitapci and Çelik Başok, 2021; Masih et al., 2021; Arinta et al., 2022; Syazana et al., 2023). These studies provide valuable information about existing conditions and enable comparisons with established standards. However, such measurements are typically conducted in unoccupied mosques, which may not accurately reflect the acoustic experience during congregational prayers, when occupancy significantly alters sound absorption characteristics. Furthermore, field measurements cannot be used to evaluate the effect of parameter variations on acoustic conditions. This highlights the need for advanced acoustic modeling techniques capable of simulating diverse scenarios, including varying occupancy levels and material configurations (Pratiwi et al., 2023; Sudarsono et al., 2023).

The aim of this study is to comprehensively investigate the acoustic characteristics of mosques under varying occupancy levels, with a specific focus on optimising speech intelligibility and sound uniformity through strategic loudspeaker placement and material selection using acoustic simulation. The study focuses on mosques equipped with two loudspeakers, owing to their widespread adoption in smaller to medium-sized prayer halls. The findings of this study are expected to provide practical,

evidence-based guidelines for the acoustic design of Indonesian mosques, ensuring enhanced speech intelligibility and uniform sound distribution across diverse occupancy scenarios and architectural configurations.

Method

This study evaluates the acoustic conditions inside a mosque by systematically varying several parameters, including mosque geometry, size, application of acoustic materials, loudspeaker positions, and occupancy levels, as detailed in Table 1. Acoustic simulation employing loudspeakers as sound sources was used to assess acoustic performance, with a particular focus on speech intelligibility and sound uniformity. The simulations were conducted using Fohhn Designer, a web-based simulation tool capable of modeling acoustic conditions with loudspeakers as sound sources (Fohhn Designer, 2025). This approach enables a systematic analysis of how each variable contributes to overall acoustic quality, thereby facilitating the development of evidence-based design recommendations for various mosque typologies.

The prayer area size was varied between 100 m² and 625 m² to represent the typical range of community mosque sizes, which are predominant in Indonesia (Sistem Informasi Masjid, 2025). The prayer area was modelled with a rectangular shape, as this geometric configuration is frequently encountered in existing mosque designs. The rectangular plan is highly efficient for organising worshippers into neat, straight rows, all facing the Qibla (the direction of the Kaaba in Mecca) (Lukman et al., 2023; Ali and Mustafa, 2023). Furthermore, a study on Javanese mosques found that the majority of mosque plans were typically square (Budi, 2006).

The ceiling shape was varied between flat and pyramidal configurations. The flat ceiling was chosen to represent a common prayer room design, while

Table 1. Variable evaluated in the study

Variables	Variation	Remarks
Prayer area size	10 m x 10 m 15 m x 15 m 20 m x 20 m 25 m x 25 m	Wall height: 5 m
Ceiling shape	Flat Pyramid Shaped	Pyramidal ceiling angle: 40°
Ceiling material	Gypsum Acoustic tile	
Occupancy	Fully occupied Unoccupied	Occupancy was simulated by modifying the absorption coefficients of the floor surface
Loudspeaker position	Front walls Front corners	Loudspeaker height: 3 m

the pyramidal ceiling was selected to reflect the typical roof forms of traditional Indonesian mosques, particularly in Java (Fikriyati, 2023). In the simulation, the ceiling angle was set to 40° , and the pyramidal ceiling dimensions were scaled proportionally to the prayer area. Visualisations of the ceiling shapes are presented in Fig. 1. The wall height was fixed at 5 m across all models.

Room volume is one of the critical factors influencing reverberation time and speech intelligibility, necessitating careful consideration in mosque design (Latifah et al., 2023). In this study, the room volume was calculated based on the variations in ceiling shape and prayer area size, yielding values ranging from 500 m^3 to $6,086 \text{ m}^3$.

The materials used in the mosque models were selected to represent typical construction practices. Walls were defined as painted concrete. Two ceiling types were examined: a hard, reflective ceiling representing standard construction (gypsum tile), and an acoustically absorptive ceiling (acoustic tile) to investigate the impact of sound-absorbing materials. Occupancy was also varied by modifying the sound absorption characteristics of the floor surface. The unoccupied condition was represented by carpet flooring, while the fully occupied condition was simulated by defining the floor as fully occupied by seated congregants, based on absorption coefficients reported by Oldham, Elkhateeb, and Science (2008). Detailed absorption coefficients for all materials used in this study are presented in Table 2. This approach effectively models the varying acoustic absorption characteristics between an unoccupied space and a fully populated prayer

hall, which is crucial for assessing dynamic acoustic performance.

This study incorporates two loudspeakers to investigate the effect of their placement on acoustic parameters within the mosque environment. As the simulation software (Fohhn Designer) only includes a database of Fohhn loudspeakers, the models were selected carefully to represent typical loudspeakers used in mosques. For this study, two 5-inch box loudspeakers (Fohhn Arc AT-05) were used in the simulations, as shown in Fig. 2. Each loudspeaker has a nominal coverage angle of 90° horizontally and 90° vertically, along with a frequency response tailored for speech applications, ensuring a realistic representation of sound reinforcement systems commonly found in mosques. The loudspeakers were positioned at a height of 3 m above the floor, aimed toward the rear wall. Two different placement configurations were simulated: at the front corners and at the center of the front wall, as illustrated in Fig. 3. This approach enables a comprehensive evaluation of how varying source locations interact with room acoustics and influence critical parameters, such as sound pressure level distribution and clarity, which are essential for effective speech communication in congregational settings.

This study focused on speech intelligibility and sound uniformity, which are essential parameters for khutbah (sermon) and congregational prayers (Sudarsono et al., 2019; Othman et al., 2016; Kitapci and Çelik Başok, 2021; Sarwono et al., 2020). Speech intelligibility was evaluated using the Speech Transmission Index (STI), a standardised method for the objective assessment of speech transmission

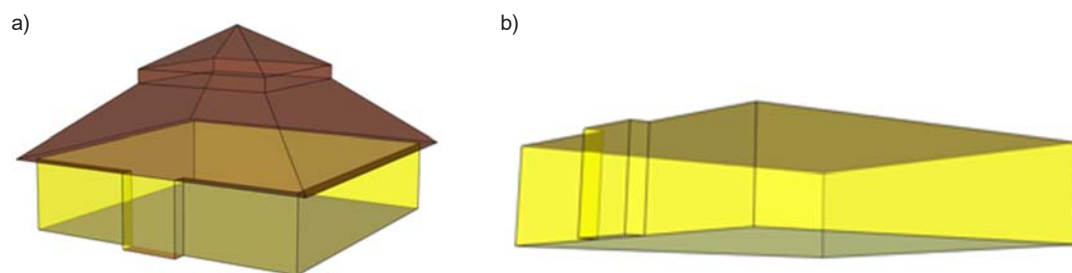


Fig. 1. Ceiling configurations simulated in this study: (a) pyramidal, (b) flat

Table 2. Sound absorption coefficients of materials used in the study

Type of Variations	Variations	Frequency						
		125	250	500	1000	2000	4000	8000
Walls	Painted concrete wall / floor (Fohhn Designer, 2025)	0.08	0.05	0.08	0.09	0.10	0.09	0.09
Ceiling	Generic, gypsum board, thickness of 0.625, 2 layers, 16-inch OC, 2x4 wood studs (Fohhn Designer, 2025)	0.28	0.12	0.10	0.08	0.14	0.09	0.06
	Acoustic ceiling (Fohhn Designer, 2025)	0.46	0.60	0.60	0.72	0.68	0.52	0.52
Floor	Carpet, commercial on concrete, floor (Fohhn Designer, 2025)	0.04	0.06	0.10	0.22	0.40	0.48	0.7
	The absorption coefficient of the fully occupied mosque (seated congregation) (Oldham et al., 2008)	0.19	0.19	0.75	0.89	0.86	0.97	0.99



Fig. 2. Fohhn Arc AT05 loudspeaker

quality (IEC 60268–16, 2003; Bjor, 2023; Jørgensen, 2014; Kobayashi and Kondo, 2019). The STI values used for analysis represent the spatial average across the prayer hall. Sound uniformity was assessed by calculating the difference between the maximum and minimum sound pressure levels (SPL) across the prayer area. In addition to these two parameters, reverberation time (RT) at 1 kHz was also examined, as optimal reverberation is crucial for both recitation and sermon / speech intelligibility in mosque environments (Elkhateeb and Eldakdoky, 2022).

The STI targets were selected with consideration of two occupancy scenarios: fully occupied and unoccupied. STI is closely related to the sound absorption within the mosque, with the worst-case condition typically occurring in the unoccupied scenario due to the absence of acoustic damping provided by the congregation. Accordingly, this study establishes a lower STI target for the unoccupied condition, acknowledging the practical challenges of achieving optimal intelligibility without the absorptive effect of worshippers. An STI target above 0.5 was selected for the unoccupied condition to ensure that intelligibility remains adequate even in the most demanding acoustic state, with further improvement expected under full occupancy (Farrasti, Sarwono, and Mangkuto, 2024). An STI of 0.5 is generally regarded as the minimum acceptable value for delivering complex messages with familiar context, and is commonly used as a design target for spaces

such as shopping malls and public offices (ANSI/ASA S3.5, 2017). This scenario-specific approach to STI targets ensures that the acoustic design is optimised for both peak congregational events and regular daily use, reflecting the diverse functional demands of a mosque.

To ensure good sound uniformity, the difference between the maximum and minimum sound pressure levels should ideally remain within a narrow range, typically less than 6 dB, to avoid significant variations in perceived loudness (Zohra, 2016). A difference of 6 dB is generally considered the maximum acceptable variation before a typical listener begins to consciously notice that the sound level differs significantly from one seat to another (American National Standards Institute, 2017).

Results

Effect of Parameter Variations on STI

The effect of parameter variations on the Speech Transmission Index (STI) was analysed using linear regression models, revealing quantitative relationships between architectural parameters, material properties, loudspeaker configurations, and the resulting speech intelligibility. The linear regression analysis indicated that STI values are significantly influenced by room volume, ceiling material, and occupancy, with a correlation coefficient of $R = 0.965$, as shown in Table 3. The results demonstrate that larger room volumes are associated with lower STI values. This relationship can be attributed to the proportional dependence of reverberation time on room volume; reverberation time is a critical determinant of speech intelligibility, as excessively long reverberation times cause overlapping of successive sounds, thereby diminishing clarity (Kunchur, 2019).

The STI is also influenced by ceiling material and occupancy, as both factors affect the sound absorption within the space. Specifically, materials with higher sound absorption coefficients — such as acoustic ceiling tiles or the presence of a congregation — effectively reduce reverberation time, leading to improved STI values (Galbrun and Kitapçı, 2014).

The use of acoustic tiles on the ceiling significantly enhances speech intelligibility, with

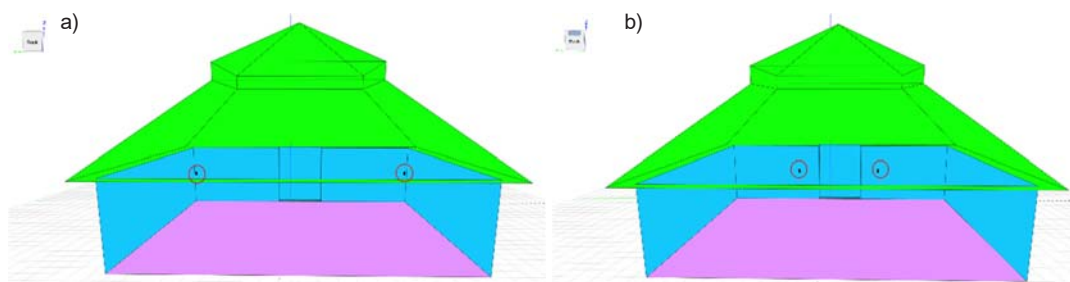


Fig. 3. Loudspeaker positions: (a) at the corner of the front wall, (b) at the centre of the front wall

Table 3. Multiple linear regression model for STI

Model Fit		
Model	R	R ²
1	0.965	0.932

Model Coefficients – STI

Predictor	Estimate	SE	t	p
Intercept ^a	0.537	0.00769	69.82	<.001
Room volume	-1.27e ⁻⁵	2.02e ⁻⁶	-6.31	<.001
Ceiling material:				
acoustic tile — gypsum	0.156	0.00699	22.34	<.001
Occupancy:				
fully occupied — unoccupied	0.118	0.00699	16.86	<.001

STI values exceeding 0.6, which indicates good speech intelligibility. This improvement was not observed in simulations with gypsum ceilings. These findings highlight the benefit of incorporating acoustic materials on ceilings, particularly given that most mosque designs typically feature hard-surface materials for walls and floors. The implementation of such materials can optimise acoustic conditions by reducing excessive reverberation, thereby improving speech clarity for sermons and recitations (Eldakdoky, 2016).

Effect of Parameter Variations on Sound Uniformity

The effect of parameter variations on sound uniformity was evaluated using a linear regression model. This analysis aimed to quantify how modifications to mosque geometry, acoustic material application, loudspeaker positioning, and occupancy levels influence the evenness of sound distribution throughout the prayer hall. The model indicated that sound distribution is significantly affected by room volume, occupancy, ceiling material, and ceiling shape, with a correlation coefficient of $R = 0.942$, as shown in Table 4. The sound from two loudspeakers can only be distributed effectively over a limited area, which reduces sound uniformity in larger rooms. The non-uniformity in sound distribution becomes more pronounced in larger volumes, where the inverse square law dictates more rapid attenuation of sound intensity with increasing distance from the source (Yang and Kang, 2021).

Sound uniformity is also significantly affected by ceiling shape. The results demonstrate that better sound uniformity is achieved with a flat ceiling. In contrast, complex ceiling geometries, such as pyramidal or vaulted structures, tend to produce uneven reflections, leading to significant variations in sound pressure levels across the space (Adnan et al., 2018).

Another factor affecting sound uniformity is the addition of absorptive surfaces, resulting from

Table 4. Multiple linear regression model for sound uniformity

Model Fit		
Model	R	R ²
1	0.942	0.887

Model Coefficients – SPL Max-Min

Predictor	Estimate	SE	t	p
Intercept	-0.788	0.284	-2.77	0.007
Occupancy:				
fully occupied — unoccupied	1.928	0.252	7.66	<.001
Ceiling material:				
acoustic tile — gypsum	2.757	0.252	10.96	<.001
Ceiling shape:				
pyramidal — flat	1.790	0.273	6.57	<.001
Room volume	9.23e ⁻⁴	7.86e ⁻⁵	11.74	<.001

full occupancy or the use of sound-absorbing materials on the ceiling. The introduction of sound-absorbing materials reduces the reflected sound field, making the direct sound more dominant and thereby contributing to uneven sound distribution (Setiyowati, 2012).

Acoustic Evaluation of Mosques in Unoccupied Condition

The unoccupied condition was evaluated to represent scenarios with a small number of worshippers. In this condition, sound uniformity was found to be adequate across all variations; therefore, the analysis focused primarily on the STI parameter. Ceiling type did not significantly affect STI values; rather, STI was predominantly influenced by room volume. This observation is consistent with prior research highlighting that larger volumes inherently increase reverberation time, thereby degrading speech intelligibility in unoccupied spaces (Abdullah and Zulkefli, 2014).

Fig. 4(a) presents the simulation results for mosques with an acoustic ceiling. The application of acoustic ceiling tiles improves STI across all room volumes, with values exceeding 0.5 in all cases. This improvement is attributed to reduced sound reflections from the ceiling, which increase the dominance of direct sound. The relationship between STI and room volume for mosques with acoustic ceilings is expressed in Equation (1):

$$STI = -9 \times 10^{-6} * Room\ volume + 0.7031 \quad (1)$$

Fig. 4(b) shows the simulation results for mosques without acoustic treatment (gypsum ceiling). In this configuration, STI is primarily influenced by room volume, with an R^2 of 0.84, indicating a strong relationship. The predictive model for STI in unoccupied mosques without absorptive ceiling materials is given in Equation (2):

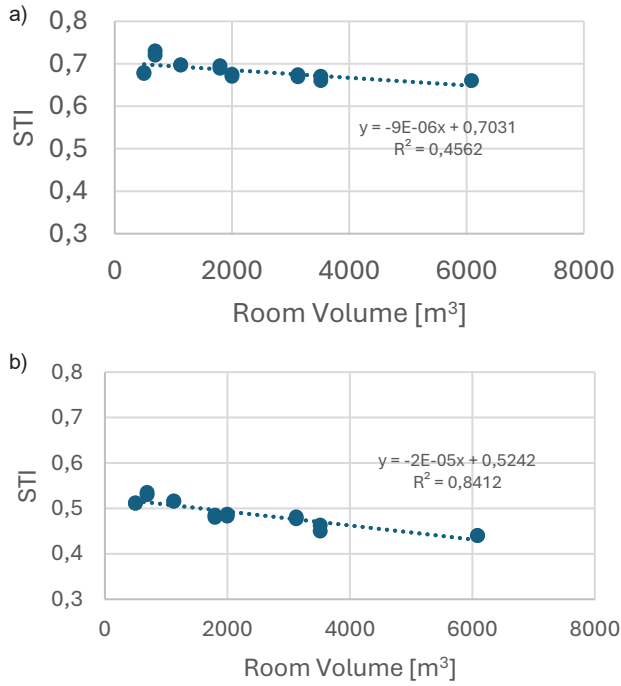


Fig. 4. Relationship between room volume and STI in unoccupied condition: (a) with acoustic tile ceiling, (b) with gypsum tile ceiling

$$STI = -2 \cdot 10^{-5} \cdot \text{Room volume} + 0.5242 \quad (2)$$

These results indicate that the use of acoustic tiles on the ceiling is generally effective in achieving good speech intelligibility, owing to reduced reflections from the ceiling surface. Under fully occupied conditions, STI values are expected to improve further due to the additional sound absorption provided by the congregation.

Acoustic Evaluation of Mosques in Fully Occupied Condition

The fully occupied condition was evaluated to represent the scenario of Jumah (Friday) prayer. In this condition, the analysis focused primarily on sound uniformity, as STI targets were already achieved across all variations in the unoccupied state. The main challenge was observed in sound uniformity, which varied significantly with room volume. This finding emphasises the critical need for more sophisticated acoustic design in larger mosques during periods of high occupancy, to ensure adequate sound coverage and clarity for all worshippers.

Fig. 5 illustrates the relationship between room volume and sound uniformity in the fully occupied condition. In general, sound uniformity deteriorates with increasing room volume. It should be noted that these results were obtained using only two loudspeakers; different outcomes may be expected with a greater number of loudspeakers.

The relationship between sound uniformity and room volume for fully occupied mosques is expressed in Equations (3) and (4). Equation (3) corresponds to

rooms with gypsum tile ceilings, while Equation (4) corresponds to rooms with acoustic tile ceilings:

$$\text{Sound Uniformity} = 0.001 \cdot \text{Room volume} + 1.9253 \quad (3)$$

$$\text{Sound Uniformity} = 0.0015 \cdot \text{Room volume} + 3.3211 \quad (4)$$

Sound uniformity is influenced by the reflective characteristics of the room. Greater reflection tends to distribute sound more evenly throughout the space. Consequently, as shown in Fig. 5(a), gypsum tile ceilings — which are more reflective — provide more uniform sound distribution compared to acoustic tile ceilings, as shown in Fig. 5(b). This suggests a trade-off: materials that enhance speech intelligibility by reducing reflections may simultaneously diminish sound uniformity in expansive spaces, particularly when only a limited number of loudspeakers are used (Din, Yong, and Razak, 2016).

Robust Design Recommendation for Mosques with Two Loudspeakers

This section synthesises the findings into design principles, offering practical guidance for architects on achieving optimal acoustic performance in mosque environments. Based on the results, a robust design recommendation is proposed that balances speech intelligibility with sound distribution.

The study systematically varied prayer hall areas from 100 m² to 625 m² with a standard wall height of 5 m, yielding volumes ranging from 500 m³ to 3,125 m³ for flat ceiling configurations. For more complex geometries, such as pyramidal ceilings, volumes reached up to 6,086 m³, as detailed in Table 5. Although a broad range was investigated,

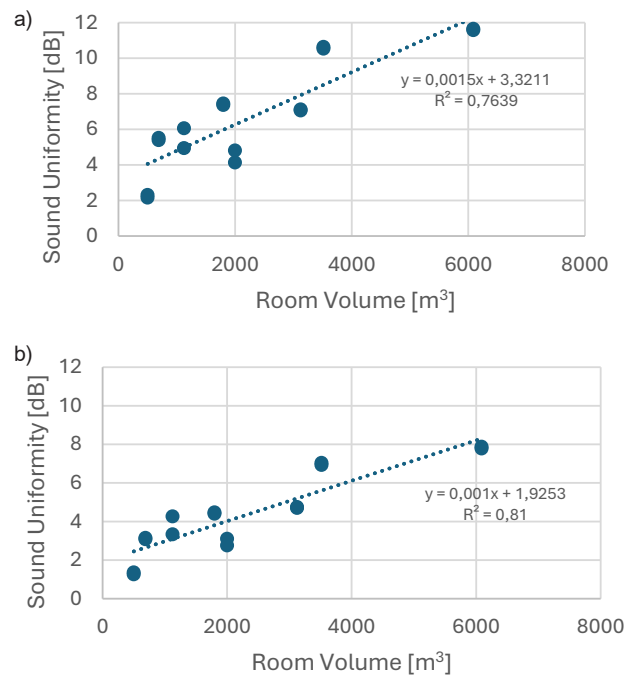


Fig. 5. Relationship between room volume and sound uniformity on fully occupied condition: (a) with acoustic tile ceiling (b) with gypsum tile ceiling

Table 5. STI and sound uniformity data from different variations. Grey shading indicates values that meet the design criteria

No.	Prayer area size [m ²]	Room volume [m ³]	Loudspeaker position	Ceiling shape	Ceiling material	Room occupancy	STI	SPLmax–SPLmin [dB]
1	100	500	Front wall	Flat	Gypsum	Fully occupied	0.663	1.26
2	100	500	Front corners	Flat	Gypsum	Fully occupied	0.662	1.36
3	100	500	Front wall	Flat	Gypsum	Unoccupied	0.512	0.48
4	100	500	Front corners	Flat	Gypsum	Unoccupied	0.511	0.52
5	100	500	Front wall	Flat	Acoustic tile	Fully occupied	0.757	2.15
6	100	500	Front corners	Flat	Acoustic tile	Fully occupied	0.756	2.3
7	100	500	Front wall	Flat	Acoustic tile	Unoccupied	0.679	1.36
8	100	500	Front corners	Flat	Acoustic tile	Unoccupied	0.677	1.46
9	100	689.5	Front wall	Pyramidal	Gypsum	Fully occupied	0.66	3.08
10	100	689.5	Front corners	Pyramidal	Gypsum	Fully occupied	0.66	3.15
11	100	689.5	Front wall	Pyramidal	Gypsum	Unoccupied	0.54	1.5
12	100	689.5	Front corners	Pyramidal	Gypsum	Unoccupied	0.53	1.54
13	100	689.5	Front wall	Pyramidal	Acoustic tile	Fully occupied	0.79	5.39
14	100	689.5	Front corners	Pyramidal	Acoustic tile	Fully occupied	0.78	5.51
15	100	689.5	Front wall	Pyramidal	Acoustic tile	Unoccupied	0.73	4.21
16	100	689.5	Front corners	Pyramidal	Acoustic tile	Unoccupied	0.72	4.31
17	225	1125	Front wall	Flat	Gypsum	Fully occupied	0.682	3.33
18	225	1125	Front corners	Flat	Gypsum	Fully occupied	0.694	4.26
19	225	1125	Front wall	Flat	Gypsum	Unoccupied	0.516	1.37
20	225	1125	Front corners	Flat	Gypsum	Unoccupied	0.516	1.55
21	225	1125	Front wall	Flat	Acoustic tile	Fully occupied	0.779	4.94
22	225	1125	Front wall	Flat	Acoustic tile	Unoccupied	0.697	3.45
23	225	1125	Front corners	Flat	Acoustic tile	Unoccupied	0.697	4.24
24	225	1125	Front corners	Flat	Acoustic tile	Fully occupied	0.778	6
25	225	1797.4	Front wall	Pyramidal	Gypsum	Fully occupied	0.69	4.47
26	225	1797.4	Front corners	Pyramidal	Gypsum	Fully occupied	0.61	4.4
27	225	1797.4	Front wall	Pyramidal	Acoustic tile	Unoccupied	0.7	5.96
28	225	1797.4	Front corners	Pyramidal	Acoustic tile	Unoccupied	0.69	5.88
29	400	2000	Front wall	Flat	Gypsum	Fully occupied	0.662	2.76
30	400	2000	Front corners	Flat	Gypsum	Fully occupied	0.656	3.1
31	400	2000	Front wall	Flat	Acoustic tile	Fully occupied	0.837	4.13
32	400	2000	Front corners	Flat	Acoustic tile	Fully occupied	0.757	4.8
33	400	2000	Front wall	Flat	Acoustic tile	Unoccupied	0.675	2.55
34	400	2000	Front corners	Flat	Acoustic tile	Unoccupied	0.67	2.96
35	625	3125	Front wall	Flat	Gypsum	Fully occupied	0.66	4.75
36	625	3125	Front corners	Flat	Gypsum	Fully occupied	0.656	4.7
37	625	3125	Front wall	Flat	Acoustic tile	Unoccupied	0.674	4.95
38	625	3125	Front corners	Flat	Acoustic tile	Unoccupied	0.669	4.9
39	225	1797.4	Front wall	Pyramidal	Gypsum	Unoccupied	0.49	2.21
40	225	1797.4	Front corners	Pyramidal	Gypsum	Unoccupied	0.48	2.17
41	225	1797.4	Front wall	Pyramidal	Acoustic tile	Fully occupied	0.76	7.45
42	225	1797.4	Front corners	Pyramidal	Acoustic tile	Fully occupied	0.75	7.36
43	400	2000	Front wall	Flat	Gypsum	Unoccupied	0.487	1.05
44	400	2000	Front corners	Flat	Gypsum	Unoccupied	0.483	1.06
45	625	3125	Front wall	Flat	Gypsum	Unoccupied	0.481	1.86
46	625	3125	Front corners	Flat	Gypsum	Unoccupied	0.477	1.83
47	625	3125	Front wall	Flat	Acoustic tile	Fully occupied	0.764	7.11
48	625	3125	Front corners	Flat	Acoustic tile	Fully occupied	0.759	7.05
49	400	3516.4	Front wall	Pyramidal	Gypsum	Fully occupied	0.6	7.04
50	400	3516.4	Front corners	Pyramidal	Gypsum	Fully occupied	0.59	6.93
51	400	3516.4	Front wall	Pyramidal	Gypsum	Unoccupied	0.46	3.88

Table 5 (Ending)

No.	Prayer area size [m ²]	Room volume [m ³]	Loudspeaker position	Ceiling shape	Ceiling material	Room occupancy	STI	SPLmax–SPLmin [dB]
52	400	3516.4	Front corners	Pyramidal	Gypsum	Unoccupied	0.45	3.81
53	400	3516.4	Front wall	Pyramidal	Acoustic tile	Fully occupied	0.74	10.63
54	400	3516.4	Front corners	Pyramidal	Acoustic tile	Fully occupied	0.74	10.53
55	400	3516.4	Front wall	Pyramidal	Acoustic tile	Unoccupied	0.67	8.89
56	400	3516.4	Front corners	Pyramidal	Acoustic tile	Unoccupied	0.66	8.79
57	625	6086.9	Front wall	Pyramidal	Gypsum	Fully occupied	0.58	7.87
58	625	6086.9	Front corners	Pyramidal	Gypsum	Fully occupied	0.58	7.78
59	625	6086.9	Front wall	Pyramidal	Gypsum	Unoccupied	0.44	4.43
60	625	6086.9	Front corners	Pyramidal	Gypsum	Unoccupied	0.44	4.35
61	625	6086.9	Front wall	Pyramidal	Acoustic tile	Fully occupied	0.73	11.65
62	625	6086.9	Front corners	Pyramidal	Acoustic tile	Fully occupied	0.72	11.57
63	625	6086.9	Front wall	Pyramidal	Acoustic tile	Unoccupied	0.66	9.84
64	625	6086.9	Front corners	Pyramidal	Acoustic tile	Unoccupied	0.65	9.74

the final “robust design” recommendation is based on a volume of 1,125 m³. This specific value serves as a critical acoustic threshold: below this volume, achieving an STI > 0.5 and SPL variation < 6 dB remains feasible across various occupancy levels. Beyond this threshold, acoustic degradation becomes substantially more difficult to mitigate with a standard two-loudspeaker configuration. This is exemplified by data points 39 and 40 in Table 5, which show that STI values fall below 0.5 in unoccupied conditions for rooms with a volume of 1,797.4 m³. These results suggest that for larger mosque volumes, a more sophisticated acoustical design approach — potentially involving distributed loudspeaker systems or advanced acoustic treatments — would be necessary to meet the robust criteria.

Statistical analysis and regression models (Tables 3 and 4) indicate that, for the general dataset, the choice between corner and center-front loudspeaker placement does not significantly affect STI or sound uniformity. However, in larger hall volumes (e.g., 3,516 m³ and 6,086 m³, as shown in Table 5), minor differences in sound field unevenness (SPL Max – Min) were observed depending on speaker position. Therefore, while the influence of loudspeaker placement is negligible in small to medium-sized rooms compared to room volume and ceiling material, its impact may become more noticeable in larger halls and warrants further investigation.

Speech intelligibility is typically evaluated in relation to the reverberation time, which is normally measured in unoccupied conditions and reflects the level of sound reflections within the mosque. According to the data, STI values are negatively correlated with reverberation time, indicating that longer reverberation times reduce speech clarity (Kaygısız, Semerci, and Sayın, 2024). This relationship was modeled using linear regression,

yielding a strong correlation coefficient of $R = 0.97$. Since an STI above 0.5 is desired in unoccupied conditions, the maximum permissible reverberation time can be derived from the simulation data. To achieve good speech intelligibility in unoccupied conditions, the recommended upper limit for reverberation time is 2.5 seconds, as shown in Fig. 6. This value aligns with recommendations from several previous studies, which typically suggest ranges of 1.6 to 1.8 seconds (Sudarsono et al., 2023; Ismail, 2013). Furthermore, the presence of worshippers during occupancy reduces reverberation time, thereby enhancing speech intelligibility. Congregants act as a substantial sound-absorbing mechanism, which can improve acoustic parameters such as clarity and the speech transmission index, both crucial for the functional performance of a mosque (Gül and Çalışkan, 2013).

Sound optimisation is particularly crucial for large mosques, largely due to their increased volume and surface areas, which necessitate more sophisticated acoustic treatments and sound

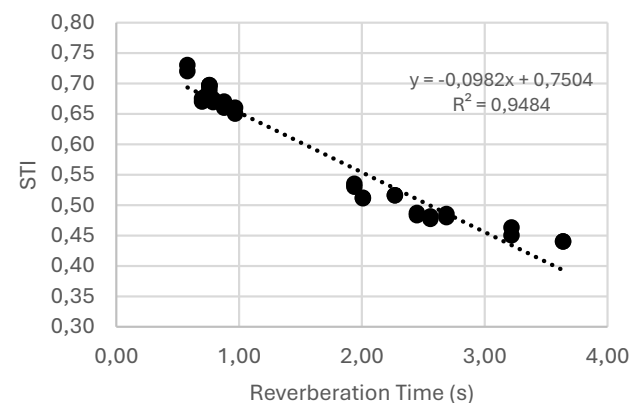


Fig. 6. Relationship between STI and reverberation time

reinforcement strategies to maintain desirable intelligibility and sound pressure levels across the entire prayer hall (Adnan et al., 2018). The use of absorptive materials is key to controlling sound reflections, thereby improving speech clarity and reducing excessive reverberation (Zohra, 2016). However, excessive use of absorptive materials can compromise sound uniformity and diminish the sense of a sacred space by substantially reducing natural reverberation. Therefore, a careful balance must be struck between reverberation control and maintaining sufficient sound reflection to preserve the mosque's architectural acoustics and spiritual ambiance (Elkhateeb and Eldakdoky, 2022). This optimal condition can be achieved by iterating through various design options using simulation during the design stage. Such simulations allow designers to predict key acoustic parameters, such as reverberation time and speech transmission index, under various occupancy and material conditions before physical construction, thus enabling proactive optimisation of the acoustic environment (Zohra, 2016; Benferhat et al., 2024).

Conclusion

This study utilised acoustic simulation to investigate the acoustic performance of mosques equipped with two-loudspeaker systems under various architectural and occupancy conditions. The findings provide critical, practical insights for architects and mosque committees aiming to optimise the aural environment, particularly in small to medium-sized prayer halls.

The research established that the most significant determinants of acoustic quality are room volume,

ceiling material, ceiling shape, and occupancy, while the specific placement of the two loudspeakers (corner vs. center-front) had only a negligible practical effect on both the Speech Transmission Index (STI) and sound uniformity.

STI was found to be strongly and negatively correlated with room volume, and positively correlated with sound absorption from ceiling materials and occupancy. Larger volumes and reflective materials significantly reduce speech clarity due to reduced sound absorption within the room. Sound uniformity is negatively affected by room volume, pyramidal ceiling shapes, and the presence of high absorption from acoustic ceilings or full occupancy.

A robust acoustic design that maintains acceptable speech intelligibility ($STI > 0.5$) and sound uniformity ($SPL \text{ variation} \leq 6 \text{ dB}$) across both unoccupied and fully occupied conditions is achievable only when the mosque volume is limited to $1,125 \text{ m}^3$ or less. For larger volumes, a more sophisticated, distributed sound reinforcement system and advanced acoustic treatments are necessary to meet these criteria.

For the unoccupied condition, a maximum reverberation time of 2.5 seconds is recommended. This represents the critical limit necessary to ensure that STI remains above 0.5, which is suitable for complex messages with familiar context. The presence of a full congregation, acting as a substantial sound absorber, will naturally reduce reverberation time, thereby ensuring enhanced clarity and spiritual comfort during congregational prayers.

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АКУСТИЧЕСКАЯ ОЦЕНКА МЕЧЕТЕЙ С ДВУМЯ ГРОМКОГОВОРИТЕЛЯМИ: ВЛИЯНИЕ ГЕОМЕТРИИ, РАЗМЕРА, МАТЕРИАЛОВ ПОТОЛКА, РАСПОЛОЖЕНИЯ ГРОМКОГОВОРИТЕЛЯ И ЗАПОЛНЕННОСТИ ПОМЕЩЕНИЯ

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Аннотация

Введение. В данном исследовании представлено всестороннее изучение акустических характеристик мечетей, оборудованных двумя громкоговорителями, в различных условиях. Рассматривается распространенная проблема плохой акустики в индонезийских мечетях, которая часто является результатом архитектурных особенностей, выбора материалов и неоптимального проектирования звуковой системы. **Методы.** В ходе исследования с использованием акустического моделирования систематически варьировались несколько параметров: геометрия, размер молитвенной зоны (от 100 м² до 625 м²), материал потолка (акустическая плитка против гипсокартона), расположение громкоговорителей и уровень заполненности (пустое помещение против полностью заполненного). Основное внимание уделялось оптимизации индекса передачи речи (ИПР) для обеспечения разборчивости речи и равномерности уровня звукового давления (УЗД). **Ключевые результаты** показывают, что расположение громкоговорителей (в углу или в центре передней части зала) не оказывает существенного влияния ни на ИПР, ни на равномерность. Однако в больших залах (например, 3516 м³ и 6086 м³) наблюдались незначительные различия в равномерности звука (максимальный–минимальный УЗД) в зависимости от положения громкоговорителей. Напротив, объем помещения, материал потолка и уровень заполненности существенно влияют на ИПР; большие объемы и меньшее поглощение звука связаны с уменьшением четкости. На равномерность звучания также негативно влияют увеличение объема помещения и отражающие, сложные формы потолка (например, пирамидальные), тогда как повышенное поглощение может усилить доминирование прямого звукового поля, потенциально снижая равномерность. **Выводы.** Исследование показало, что для достижения ИПР > 0,5 и изменения УЗД < 6 дБ во всех условиях присутствия людей объем мечети не должен превышать 1125 м³. Кроме того, для обеспечения адекватной разборчивости речи (ИПР > 0,5) в условиях пустого помещения (худший случай) максимальное время реверберации (ВР) на частоте 1 кГц должно быть ограничено 2,5 секундами. Эти результаты предоставляют практические, основанные на фактических данных рекомендации по акустическому проектированию малых и средних мечетей в Индонезии.

Ключевые слова: мечеть, акустика помещения, громкоговорители, моделирование, равномерность звучания, индекс передачи речи.