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COMPARATIVE ANALYSIS OF MOSQUE ACOUSTICS QUALITY IN TROPICAL AND NON-TROPICAL CLIMATES: A LITERATURE REVIEW

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ABSTRACT

This study investigates the comparative acoustic performance of tropical and non-tropical mosques, focusing on key parameters including Reverberation Time (RT), Clarity (C_{80}), Definition (D_{50}), and Speech Transmission Index (STI). Data were collected from multiple case studies, including tropical and non-tropical mosques, to evaluate their suitability for speech-related religious activities. A meta-analysis was conducted using acoustic datasets compiled from 20 mosques in the existing literature. Ordinary Least Squares (OLS) multiple linear regression models were constructed for each acoustic parameter to isolate the independent and combined predictive power of the structural variables. The results reveal that tropical mosques generally exhibit lower reverberation times and smaller deviations from recommended values, indicating more controlled acoustic environments. In contrast, non-tropical mosques tend to have higher RT values, often exceeding optimal limits due to large enclosed volumes and reflective materials. In terms of clarity (C_{80}) and definition (D_{50}), tropical mosques more frequently achieve values within or near recommended ranges, suggesting a better balance between early and late sound energy and improved speech intelligibility. Non-tropical mosques, however, exhibit greater variability, with several cases showing either excessive reverberation. The STI analysis further demonstrates that tropical mosques have the potential to achieve superior speech intelligibility. Non-tropical mosques generally fall within moderate levels of intelligibility. These differences are primarily influenced by architectural typology, spatial configuration, building volume, material characteristics, and the presence of electroacoustic systems. Tropical mosques, characterized by semi-open layouts and climate-responsive design strategies, inherently facilitate better sound dissipation and acoustic balance. This study concludes that while tropical mosque architecture tends to provide more favorable acoustic conditions, achieving optimal performance requires a holistic integration of architectural design, material selection, and acoustic treatment, regardless of climatic context.

Keywords:
Architectural acoustic; Tropical mosque; Comparative study; Acoustics; Mosque design; Climatic architecture; Islamic architecture

1. INTRODUCTION

A mosque is fundamentally an auditory space. As a central place of worship for Muslims, it requires an appropriate acoustic environment to support the wide range of activities performed within it [1]. The primary functions of a mosque, such as congregational prayers, the delivery of Friday sermons, and Quranic recitation, are entirely reliant on high-quality speech intelligibility and acoustic comfort [2][3]. A well-designed acoustic environment fosters spiritual focus, whereas poor acoustics can result in muddy, unintelligible speech, disrupting

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worshippers' concentration and comfort. Therefore, the acoustic performance of a mosque is not merely an engineering concern, but a core component of its religious function. Despite this significance, research on mosque acoustics and soundscapes remains relatively limited compared to studies of other religious buildings, such as churches or temples.

Historically, the architectural evolution of the mosque has been profoundly shaped by its geographic and climatic context, leading to vastly different acoustic environments. In non-tropical regions, such as the arid Middle East or temperate Europe, mosques are traditionally designed as heavy, enclosed masonry structures to insulate against harsh winters or extreme desert heat. The quintessential Mediterranean or Ottoman Mosque, characterized by cascading stone domes and thick, sealed walls, acts as an acoustic fortress. This geometry creates highly reflective, reverberant soundscapes that isolate the congregation from the external urban environment, historically utilizing long reverberation times to elevate the unamplified human voice into a resonant, ethereal experience [4].

Conversely, mosques built in tropical climates, such as Southeast Asia, require architecture that manages intense humidity and heavy monsoon rains. These structures typically feature steep, tiered pyramidal roofs (such as the traditional Javanese form) and highly porous, semi-open perimeters, like the verandas, to maximize cross-ventilation [5]. Because these buildings lack thick, enclosing boundary walls, their physical acoustics are distinctly less reverberant. Furthermore, their soundscape is highly permeable; the internal auditory experience of worship is continuously interwoven with external environmental noise, seamlessly blending the sacred space with the surrounding community and nature.

While a substantial body of literature has evaluated the physical acoustics of enclosed, historical domed mosques, often focusing on mitigating excessive Reverberation Time (RT) through modern audio interventions [6], there is a notable lack of comparative research. Specifically, the juxtaposition of traditional tropical mosque typologies against non-tropical typologies remains underexplored. Most existing guidelines for acoustic optimization in worship spaces are generalized, often failing to account for the unique environmental integration, background noise challenges, and acoustic profiles inherent to semi-open tropical designs. However, most studies on mosque acoustics and soundscape have been conducted within a single climatic context, and comparative analyses across different climates are lacking. Such comparisons are essential, as they may reveal unique soundscape characteristics shaped by climate, thereby deepening our understanding of mosque acoustics and providing a foundation for future research.

Therefore, this paper aims to bridge this gap in the literature by systematically comparing the acoustic environments of mosques in tropical and non-tropical regions. Specifically, this study will analyze and compare the physical acoustic parameters of mosque architecture in tropical and non-tropical areas and propose climate-specific acoustic guidelines for modern mosque design that respect both the region's architectural heritage and the congregation's auditory comfort.

2. METHODS

The primary purpose of this study is to evaluate and compare the acoustic performance of mosques in tropical climates with that of those in non-tropical climates. This research evaluates secondary data extracted from a curated selection of 20 previously published, peer-reviewed studies (10 tropical and 10 non-tropical). A structured comparative meta-analytical approach is employed. This chapter outlines the research framework, the selection criteria for building types, the climatic classification, the acoustic parameters evaluated, and the statistical methods used to analyze the data.

2.1 RESEARCH DESIGN

This study adopts a systematic comparative literature review and meta-analysis approach. Rather than performing primary empirical field measurements, this research synthesizes, normalizes, and compares quantitative acoustic data from 20 independent case studies published in scientific literature. The methodology follows a four-step framework:

a. Identification & Selection: Sourcing peer-reviewed publications featuring empirical or simulated acoustic data for individual mosques.
b. Categorization: Classifying mosques by geographic and climatic zones (Tropical vs. Non-Tropical).
c. Data Extraction & Harmonization: Compiling key acoustic and architectural parameters into a unified matrix.
d. Comparative Analysis: Evaluating cross-climatic trends using descriptive and multiple linear regression statistical methods.

2.2. SELECTION CRITERIA AND DATASET COMPOSITION

To ensure valid comparisons, strict inclusion and exclusion criteria were established for the literature search:

a. Inclusion Criteria: The study must provide objective acoustic metrics, specifically Reverberation Time, measured or simulated. The architectural volume and material characteristics of the main prayer hall must be documented.
b. Exclusion Criteria: Studies that used purely qualitative assessments or focused solely on electroacoustic sound reinforcement systems without baseline room-acoustic data were excluded.

A total of 20 mosques were selected, evenly divided into two structural cohorts:

a. Tropical Cohort (N = 10): Located within equatorial, tropical rainforest, or tropical savanna climate zones. These regions are characterized by consistently high ambient temperatures and high relative humidity (RH).
b. Non-Tropical Cohort (N = 10): Located in temperate, arid, Mediterranean, or cold climate zones. These regions experience distinct seasonal variations, lower average humidity, or hyper-arid conditions

2.3. CLIMATIC AND ARCHITECTURAL VARIABLES

The underlying premise of this comparative analysis is that regional climate dictates architectural adaptations, which in turn govern room acoustics. This methodology evaluates two primary climate-driven mechanisms:

a. Surface materials and thermal comfort: In tropical climates, mosques often utilize high-thermal-mass, hard, and non-porous materials to maintain cool indoor environments. These materials are highly sound-reflective. Conversely, non-tropical climates may employ heavy carpets, acoustic wall linings, or multi-layered glass for thermal insulation, which accidentally act as passive acoustic absorbers.
b. Ventilation and openness: Tropical mosques frequently favor semi-open layouts, large operable windows, or permanent structural openings to maximize natural cross-ventilation. This alters the active air volume, introduces high levels of environmental background noise, and exposes the interior to high relative humidity (which alters air absorption at high frequencies). Non-tropical mosques tend to feature closed, sealed envelopes reliant on mechanical HVAC systems.

2.4. SELECTED ACOUSTIC PARAMETERS

To quantify and compare acoustic quality, data extraction focuses on four core room-acoustic indicators, predominantly analyzed at the mid-frequencies (500 Hz to 1,000 Hz), which are critical for speech intelligibility and Qur'anic recitation (Table 1).

Table 1. The Acoustic Parameters to Compare the Room Acoustic Quality

Parameter	Unit	Description	Indicator
Reverberation Time (T_{30}/T_{60})	Seconds (s)	Time required for sound energy to decay by 60 dB after the source stops.	Depends on the room volume, the sound-absorption coefficient of the material used, and the material's surface area[7].
Speech Clarity (C_{50}) and C_{80})	Decibels (dB)	Clarity (C_{80}) is defined as the logarithmic ratio, expressed in decibels, between the early sound energy arriving within the first 80 milliseconds and the late-arriving energy thereafter.	The acceptable range for C_{80} lies between −4 dB and +4 dB [8]
Definition (D_{50})	%	D50 represents the ratio of early-to-late arriving sound energy within the first 50 milliseconds.	D50 values are commonly classified into three categories: “bad” (0–30%), “fair” (30–60%), and “good” (60–100%), reflecting the degree of clarity and intelligibility achieved within a space [9].
Speech Transmission Index (STI)	Scale (0 to 1)	An objective metric representing speech transmission quality through an acoustic channel.	STI values are typically categorized as follows: 0–0.32 (bad), 0.32–0.45 (poor), 0.45–0.60 (fair), 0.60–0.75 (good), and 0.75–1.00 (excellent) [10].

2.5. DATA ANALYSIS AND STATISTICAL FRAMEWORK

Once the dataset is compiled, the analytical phase proceeds through two distinct stages:

a. Architectural comparison between tropical and non-tropical mosques

The physical attributes (volume, dominant interior materials, openness ratio, and interior form) are cross-referenced with the acoustic metrics. Sabine's classic reverberation equations are referenced to evaluate how the overall absorption coefficients differ between the two cohorts, driven by climate-related material choices.

b. Room acoustic quality comparison between tropical and non-tropical mosques.
   To determine differences in acoustic quality between tropical and non-tropical mosques, the four parameters (RT, C_{80}, D_{50}, STI) were compared across mosques. In this stage, the acoustic quality of each mosque would be assessed relative to the recommended value, and the best- and worst-performing mosques would be identified.
c. Causal and Relative Impact Analysis (Multiple Linear Regression)
   To isolate and determine the relative influence of physical attributes on mosque acoustics, a Multiple Linear Regression (MLR) analysis was executed. The primary objective of the MLR model is to identify which architectural predictor (room volume, enclosure materiality, openness ratio, or spatial form) has the greatest impact on the dependent variable (RT, C_{80}, D_{50}, STI).

3. RESULT AND DISCUSSION

3.1 ARCHITECTURAL CHARACTERISTICS

The design and function of a mosque are shaped not only by Islamic traditions but also by the climate, geography, and culture of its location. While all mosques share universal features such as the qibla (the direction of Mecca), a prayer hall, and ablution facilities, a mosque in a hot, humid, and rainy tropical climate will differ significantly from one in a non-tropical climate. This study organizes its analysis into two primary categories: tropical and non-tropical mosques.

3.1.1 Architectural Characteristics for Mosques in Tropical Areas

Research on tropical mosques is predominantly concentrated in Southeast Asia, a region characterized by a hot–humid climate with high rainfall, high humidity, and relatively constant temperatures. These environmental conditions significantly influence the architectural characteristics of mosques, particularly their form and spatial configuration. In response to intense monsoon rainfall, traditional tropical mosques commonly employ steeply pitched roofs rather than large domes, often incorporating expansive overhangs or multi-tiered systems such as the Javanese roof [11], which facilitates rapid drainage of rainwater. Wide eaves and extended overhangs further protect interior spaces from driving rain while providing substantial shade against intense solar radiation. To address high humidity and promote thermal comfort, these mosques emphasize breathability through porous wall elements, such as wooden louvers, carved screens, or fully open walls combined with large openings that enhance cross-ventilation [12]. The selection of lightweight materials such as timber, clay tiles, and palm leaves also reduces heat retention compared to heavier materials like stone or concrete.

Additionally, elevated foundations, often in the form of stilts or raised platforms, are used to mitigate flood risks during the monsoon season while capturing cooler breezes at higher elevations. Spatially, tropical mosques tend to adopt lower, horizontally oriented forms with expansive prayer halls and minimal enclosure, thereby reducing heat accumulation and supporting a more thermally responsive built environment.

The spatial organization of a mosque plays a crucial role in regulating airflow and shaping the experiential transition into the sacred space. In tropical regions, this organization is characterized by distinct architectural elements that respond to climatic conditions. One of the defining features is the veranda, a semi-open space that surrounds the main prayer hall. This element functions as a thermal buffer, mediating between the hot exterior environment and the cooler interior, while also serving as a transitional zone and an overflow area during Friday prayers. In addition, open courtyards are commonly incorporated, often enhanced with vegetation or water features such as pools, which facilitate evaporative cooling and help lower temperatures. These spatial strategies demonstrate how architectural design in tropical mosques integrates environmental responsiveness with religious functionality.

3.1.2 Architectural Characteristics for a Mosque in non-Tropical Area

Research on non-tropical mosques is primarily situated in the arid regions of the Middle East and the temperate Mediterranean regions of Europe, where climatic conditions range from hot–dry deserts to cold-temperate and continental environments with pronounced seasonal extremes. These climatic contexts significantly shape the architectural characteristics of mosques, particularly in terms of form, materiality, and environmental performance. In contrast to tropical mosques, non-tropical mosques commonly feature prominent domes and vaults that serve both symbolic and climatic functions: domes facilitate the upward movement of hot air and help regulate temperature in hot–dry climates. In regions with minimal rainfall, such as the Middle East and North Africa, flat or gently sloped roofs are also prevalent due to the limited need for rapid water drainage. Openings in these mosques tend to be smaller, aiming to minimize heat gain in desert climates or reduce heat loss in colder regions, while thick walls provide substantial insulation. Consequently, cross-ventilation is generally less extensive than in tropical counterparts. The use of high-thermal-mass materials, such as stone, brick, and concrete, enables buildings to absorb heat during the day and release it at night in arid environments, or to retain internal warmth in colder climates. Structurally, domes and arches are typically supported by robust masonry systems, reinforcing both durability and climatic responsiveness [13][14] [15].

The spatial organization of mosques in non-tropical regions is primarily shaped by the need to control airflow and ensure thermal comfort while maintaining a coherent transition into the sacred space. In colder climates, vestibules and foyers are essential components, typically designed as double-door entry systems to prevent the infiltration of freezing air into the main prayer hall. In arid environments, the courtyard (*sahn*) is often enclosed by high walls and surrounded by arcades, creating deep shade and enabling the retention of cool night air for use during the day. These architectural strategies illustrate how mosque design in non-tropical contexts adapts to environmental constraints while preserving both functional efficiency and the sanctity of spatial experience. Table 2 provides a comprehensive comparison of how these environments influence the mosque's form and room configuration.

Table 2. A Comprehensive comparison of architectural characteristics between tropical and non-tropical mosques

Feature	Tropical Mosques	Non-Tropical Mosques
Mosque Form	Tiered/sloped roofs, wide overhangs, porous walls.	Domes, flat roofs, thick enclosed walls, prominent vestibules.
Room Configuration	Semi-open layouts, large verandas	Enclosed prayer halls, indoor climate control.
Ventilation	Large openings, cross-ventilation	Smaller openings, insulation-focused
Materials	Light, breathable (wood, bamboo, clay)	Heavy, insulating (stone, brick, concrete)

This study employs a comparative approach to examine the acoustic performance of tropical and non-tropical mosques. The data are derived from previous studies on mosque acoustics. The selected case-study mosques are presented in Table 3, and their figures are shown in Table 4.

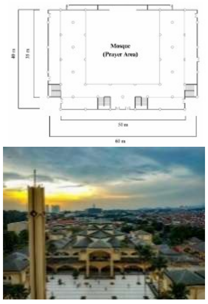
Table 3. The mosques were used as the case study

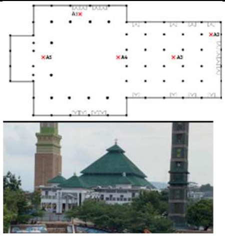
NO	MOSQUE NAME	LOCATION	DIMENSION & CAPACITY	FORM	MATERIAL
			TROPICAL MOSQUE		
T1	Pusdai Mosque [16]	West Java, Indonesia.	Volume: 22.889 m^3 Capacity: 4600 people	Room: Square with a veranda on the north, south, and east sides Roof: Layered Pyramidal Roof	Wall: brick, plastered concrete, granite Floor: carpet Roof: PVC, gypsum Window: glass Door: wood
T2	Al Furqan Mosque [17]	Bandar Lampung, Indonesia	Volume: 16.900 m^3 Capacity: 2000 people	Room: Rectangle Roof: Layered Pyramidal Roof	Wall: brick, plastered concrete, granite Floor: carpet Roof: tile Window: glass Door: wood
T3	Al-Markaz Al-Islami Mosque [18]	Makassar, Indonesia	Volume: 10.598 m^3	Room: Square Roof: Layered Pyramidal roof	Floor: granite Wall: granite Ceiling: gypsum Door: wood and glass Window: aluminum and glass
T4	The Grand Mosque of Yogyakarta [19]	Yogyakarta, Indonesia	Volume: 12890 m^3	Room: Rectangle with veranda on the north, south, and east sides Roof: Layered Pyramidal Roof	Floor: carpet Wall: sandstone without finishing Ceiling: wooden board
T5	Dato Bentara Luar Mosque [20]	Malaysia	Volume: 2962,2 Capacity: 760 people	Room: Rectangle Roof: Pyramidal roof	Floor: carpet Wall: brick plastered Ceiling: gypsum Door: wood Window: wood
T6	Sayyidina Abu Bakar mosque [21]	Malaysia	Volume: 19,500 m3 Capacity: 4000 people	Room: Square Roof: Layered Pyramidal Roof	Wall: concrete Ceiling: plaster Floor: carpet on concrete

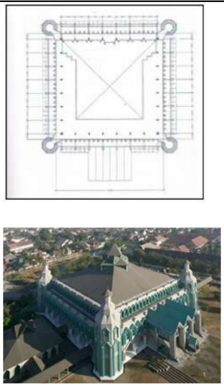
NO	MOSQUE NAME	LOCATION	DIMENSION & CAPACITY	FORM	MATERIAL
					Window: glass Door: solid wooden door
T7	Sunan Ampel Mosque (old building area) [22]	Surabaya, Indonesia	Volume: 12.523 m^3 Capacity: 1000 people	Room: square Roof: Layered Pyramidal Roof	Wall: brick Floor: granite Window: wood Door: solid wooden door
T8	UI Mosque [23]	Jakarta, Indonesia	Volume: 5000 m^3 Capacity: 2000 people	Room: square Roof: Layered Pyramidal Roof	Wall: open Floor: granite Roof: clay
T9	Masjid Al-Irsyad [24]	Bandung, Indonesia	Volume: 9.355 m^3 Capacity: 1000 people	Room: Square Roof: flat	Wall: open Floor: carpet Roof: concrete
T10	Taman Putri Kulai Mosque [25]	Johor, Malaysia	Volume: 3425 m^3 Capacity: 600 people	Room: Square Roof: flat	Wall: geometric perforated panel Floor: carpet Roof: concrete
			NON-TROPICAL MOSQUE		
NT1	Yeni Mosque [26]	Tire, Turkey	Volume: 3442 m3 Capacity: 291 people	Room: square Roof: dome	Floor: carpet Wall: plastered
NT2	Sultan Mosque [26]	Manisa, Turkey	Volume: 4000 m3 Capacity: 375 people	Room: rectangle Roof: multi dome	Floor: carpet Wall: plastered
NT3	Jedid Mosque [27]	Algiers, Algeria	Volume: 10.500 m^3 Capacity: 915	Room: rectangle Roof: multi dome	Wall: plastered Window: glass Floor: carpet Mezzanine: wood
NT4	Attarece Mosque [28]	Manisa, Turkey	Volume: 1510 m^3	Room: rectangle Roof: flat	Wall: plastered, wooden panel Mihrab wall: tile Floor: carpet
NT5	The Dayk Mosque [29]	Erbil, Iraq	Volume: 3650 Capacity: 800	Room: Square Roof: Dome flat	Floor: carpet Wall: gypsum plastering, wood, glass Window: 7% wall surface, covered with a curtain Ceiling: gypsum board
NT6	Altun Mosque [29]	Erbil, Iraq	Volume: 13.000 m^3 Capacity: 980	Room; Square Roof: Dome	Floor: carpet Wall: gypsum plastering, wood, marble Window: 20% wall surface, covered with a curtain Ceiling: gypsum board and wood
NT7	The Ketchaoua Mosque [30]	Algeirs, Algeria	Volume: 11000 m^3. Capacity: 1200 people	Room: Rectangle Roof: dome	Floor: carpet
NT8	the Aslanhane Mosque (Turkey) [31]	Anatolia, Turkey	Volume: 4.300 m^3	Room: Square Roof: flat	Door: wood Floor: carpet Wall: historical plaster Ornamental wooden finishing
NT9	Fatih Pasha (Kurşunlu) Mosque [32]	Diyarbakir, Turkey	Volume: 4520 m^3	Room; Square Roof: Dome	Mihrab: marble Dome: brick with lime plastered Wall: basalt rubble stone plastered Door: wood Window: wood Floor: carpet
NT10	ÜÇ Şerefeli Mosque [33]	Edirne, Turkey	Volume: 24,000 m^3	Room: Square Roof: multidome	Floor: carpet Mihrab: marble Door: wood Ceiling: lime cement plaster

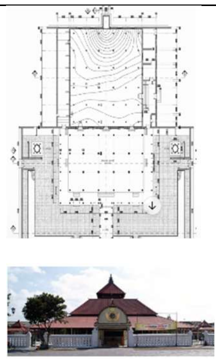
Table 4. The Figures of Mosques as the Case Study

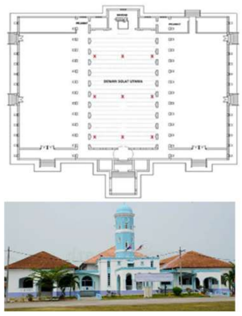
Tropical mosque


Pusdai Mosque [16]

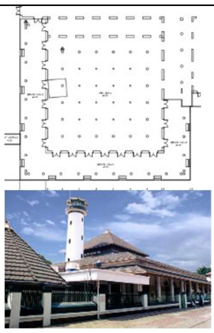

Al-Furqan Mosque [17]

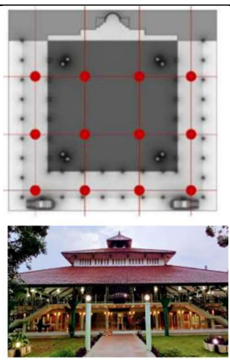

Al-Markaz Al-Islami Mosque [18]


Yogyakarta Grand Mosque [19]


Dato Bentara Luar Mosque [20]


Sayyidina Abu Bakar Mosque [21]

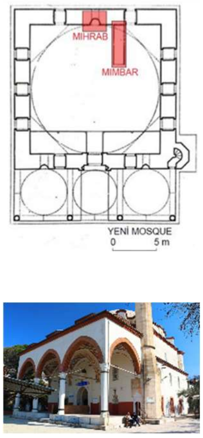

Sunan Ampel Mosque [22]


UI Mosque [23]

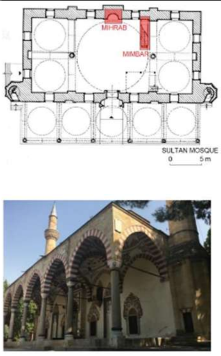

Al-Irsyad Mosque [24]


Taman Putri Kulai Mosque[25]

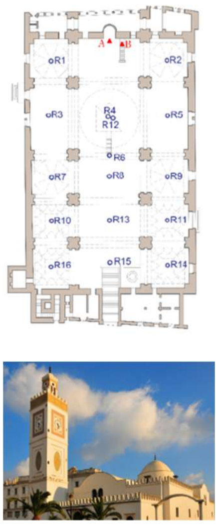
Non-Tropical Mosque



Yeni Mosque [26]



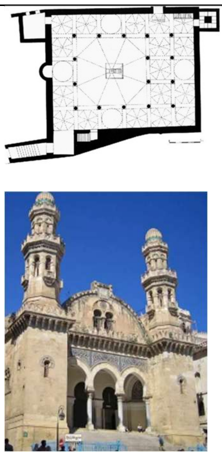
Sultan Mosque [26]


Jedid Mosque [27]

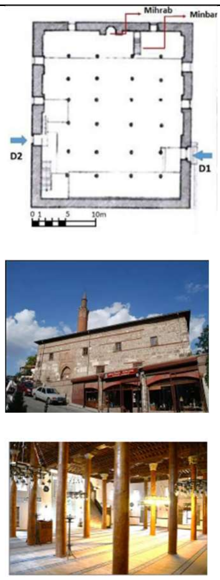

Attar Ece Mosque [28]


Dayk Mosque [29]

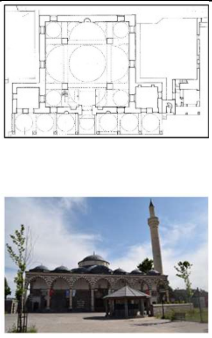
Altun Mosque [29]



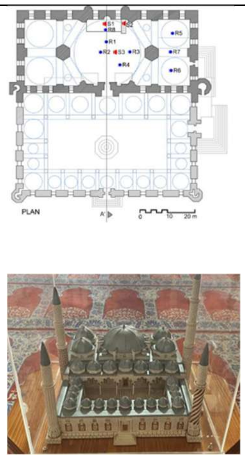
Ketchaoua Mosque [30]



Aslahane Mosque [31]



Fatih Pasha Mosque [32]



ÜÇ Şerefeli Mosque [33]

3.2 ROOM ACOUSTIC QUALITY

3.2.1 Reverberation Time (RT) Characteristic

The comparison of the Reverberation Time (RT) characteristics of tropical and non-tropical mosques is shown in Table 5 and Figure 1, which explains the RT of each mosque, the recommended RT adjusted to the mosque's room volume, and the RT deviation between the measured and recommended RT.

Table 5. The Reverberation Time Comparison of All Case Studies

No	Location	Mosque	RT (second)	Recommended RT (second)	RT deviation	Room Volume (m^3)
1	Tropical area	Pusdai Mosque	3,09	1,8	1,29	22899
2		Al Furqan Mosque	2,26	1,8	0,46	16900
3		Al-Markaz Al-Islami Mosque Makasar	3,95	1,8	2,15	27728
4		Yogyakarta Grand Mosque	1,64	1,7	-0,06	12890
5		Masjid Dato Bentara Luar, Malaysia	1,77	1,4	0,37	2962
6		Sayyidina Abu Bakar Mosque, Malaysia	3,5	1,8	1,7	19500
7		Sunan Ampel Mosque	1,54	1,8	-0,26	12523
8		UI Mosque	0,355	1,5	-1,145	5000
9		Al Irsyad Mosque	1,7	1,6	0,1	9355
10		Masjid Taman Putri Kulai Malaysia	2,3	1,7	0,6	3425
11	Non-Tropical Area	Yeni Mosque	3,5	1,7	1,8	3442
12		Sultan Mosque	3,4	1,7	1,7	4000
13		Jedid Mosque	2,52	1,5	1,02	4740
14		Attarece Mosque	1,7	1,3	0,4	1510
15		Dayk Mosque	1,2	1,4	-0,2	3650
16		Altun Mosque	2,86	1,7	1,16	13000
17		Ketchaoua Mosque	3,1	1,7	1,4	11000
18		Aslanhane Mosque	1,1	1,4	-0,3	3762,5
19		Fatih Pasha Mosque	2,25	1,5	0,75	4520
20		ÜÇ Şerefeli Mosque	5	1,8	3,2	24000

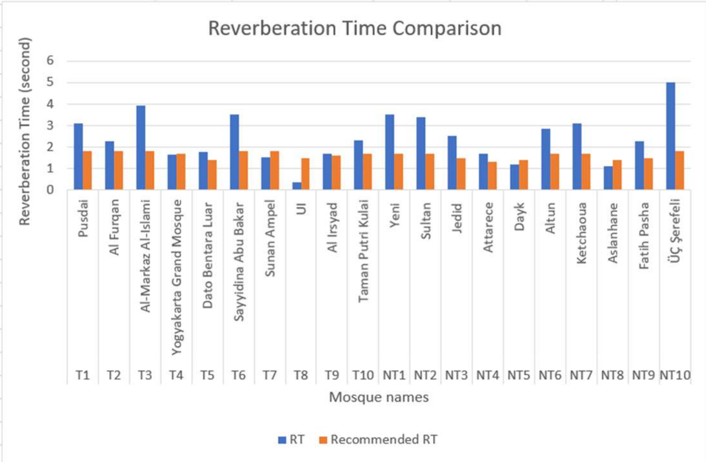


Figure 1. The Reverberation Time Comparison of All Case Studies

The measured reverberation time (RT) across the 20 mosque samples shows substantial variation, ranging from 0,355 s to 5,0 s, indicating diverse acoustic conditions between tropical and non-tropical contexts. Among all cases, the best (closest to recommended RT) performance is observed in Yogyakarta Grand Mosque (RT = 1,64 s; deviation = −0,06 s) [19] and Al Irsyad Mosque (RT = 1,7 s; deviation = 0,1 s) [24]. These mosques achieve reverberation times very close to their respective recommended values, indicating balanced acoustic conditions conducive to speech clarity, which is critical for religious activities such as sermons and recitation.

In contrast, the worst acoustic performance is found in ÜÇ Şerefeli Mosque (RT = 5,0 s; deviation = 3,2 s) [33] and Al-Markaz Al-Islami Mosque (RT = 3,95 s; deviation = 2,15 s) [18]. These values exceed the recommended RT by a significant margin, suggesting excessive reverberation that can reduce speech intelligibility. A notably low RT is also observed in UI Mosque (RT = 0,355 s; deviation = −1,145 s) [23]. Although this represents the lowest RT, it falls well below the recommended range, indicating an acoustically "dry" environment, which may reduce spatial impression and auditory comfort.

Table 6. The comparison of the RT value of tropical and non-tropical mosques

	RT (second)	Recommended RT	RT deviation
Tropical	2,2105	1,69	0,5205
non tropical	2,663	1,57	1,093

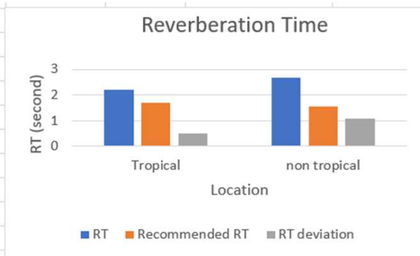


Figure 2. The comparison of the RT value of tropical and non-tropical mosques

From these results, tropical mosques demonstrate better overall acoustic performance, as indicated by lower average RT and smaller deviations from recommended values (Table 7 and Figure 2). In contrast, non-tropical mosques tend to be more reverberant, with deviations approximately twice as large as those in tropical mosques. This suggests that tropical mosque designs are generally more effective at controlling reverberation, resulting in acoustic environments closer to optimal conditions for speech.

3.2.2 Clarity (C_{80}) Characteristic

The clarity index (C_{80}) values obtained from the case studies range from −8 dB to +11,19 dB, indicating a wide variation in the balance between early and late sound energy across the mosque samples (Table 7 and Figure 3). Based on established acoustic criteria, acceptable C_{80} values for speech fall within the range of −4 dB to +4 dB, where values within this interval indicate adequate clarity, values below −4 dB suggest excessive reverberation (poor clarity), and values above +4 dB indicate overly dry conditions.

Table 7. The C_{80} value of the case study

No	Location	Mosque	C_{80} (dB)
1	Tropical Area	Al-Furqan Mosque	-1,67
2		Yogyakarta Grand Mosque	3,445
3		Sayyidina Abu Bakar Mosque	1
4		Sunan Ampel Mosque	11,19
5		AL-Irsyad Mosque	-8
6	Non-Tropical Area	Yeni Mosque	-5,4
7		Sultan Mosque	-3,31
8		Jedid Mosque	1,5
9		Attarece Mosque	1,025
10		Ketchaoua Mosque	-6,8
11		Aslanhane Mosque	7,4
12		Fatih Pasha Mosque	0,03
13		Gulbahar Hatun Mosque	-1,8
14		ÜÇ Şerefeli Mosque	-7

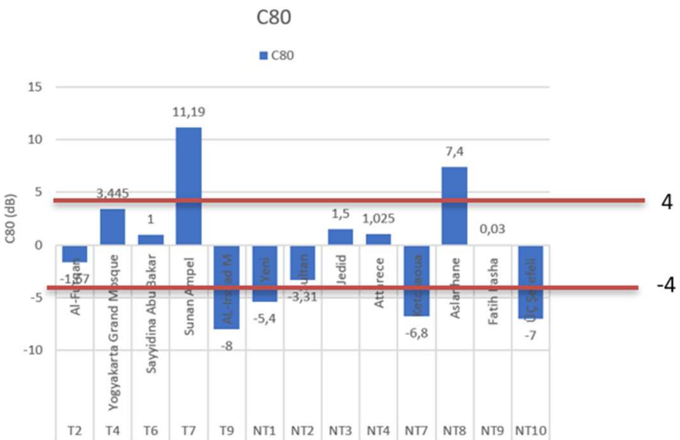


Figure 3. The comparison of the C_{80} Value of the Case Study

Among all cases, the best-performing mosques (within or closest to the optimal range) include Yogyakarta Grand Mosque (3,445 dB) [19], Sayyidina Abu Bakar Mosque (1 dB) [21], Djedid Mosque (1,5 dB) [27], Attaree Mosque (1,025 dB) [26], and Fatih Pasha Mosque (0,03 dB) [32]. These values fall comfortably within the recommended range, indicating a good balance between clarity and reverberance, suitable for speech intelligibility during religious activities.

The worst-performing mosques, characterized by values far outside the acceptable range, are Al-Irsyad Mosque (−8 dB) [24], [33], ÜÇ Şerefeli Mosque (−7 dB) [33], Ketchaoua Mosque (−6,8 dB) [30], and Yeni Mosque (−5,4 dB) [26]. These highly negative values indicate that late reflections dominate, resulting in poor speech clarity. On the other extreme, Sunan Ampel Mosque (11,19 dB) [22] and Aslanhane Mosque (7,4 dB) [31] exhibit excessively high C_{80} values, suggesting overly strong early reflections and insufficient reverberant energy. While this condition may enhance speech intelligibility, it can reduce the sense of envelopment and acoustic richness expected in large worship spaces.

A clear distinction emerges when comparing tropical and non-tropical mosques. Tropical mosques show more consistent performance, with most values falling within or near the recommended range, except for Al-Irsyad Mosque (−8 dB). Non-tropical mosques, however, exhibit greater variability, ranging from highly negative values (e.g., ÜÇ Şerefeli, Ketchaoua) to excessively positive values (e.g., Aslanhane). Overall, tropical mosques exhibit better acoustic clarity, as their C_{80} values are generally closer to the optimal range. In contrast, non-tropical mosques tend to exhibit less controlled acoustic conditions, with both overly reverberant and overly dry extremes present.

3.2.3 D_{50} Characteristic

The measured Definition (D_{50}) values across the nine mosque samples range from 15% to 91%, indicating significant variation in speech intelligibility conditions (Table 8 and Figure 4). In room acoustics, D_{50} represents the ratio of early arriving sound energy (within 50 ms) to the total sound energy, with higher values indicating better speech clarity. Typically, D_{50} > 60% is considered good, values around 30–60% are fair, and <30% are classified as poor (bad).

Table 8. The D_{50} value of the case study

No	Location	Mosque	D_{50}	D_{50} Categorization
1	Tropical area	Al Furqan Mosque	19,50%	bad
2		Yogyakarta Grand Mosque	50,00%	fair
3		Sayyidina Abu Bakar Mosque, Malaysia	15%	bad
4		Sunan Ampel Mosque	91%	good
5		AL-Irsyad	50%	fair
6	Non-Tropical area	Yeni Mosque	19%	bad
7		Sultan Mosque	28%	bad
8		Attarece Mosque	45%	fair
9		Fatih Pasha Mosque	40%	fair

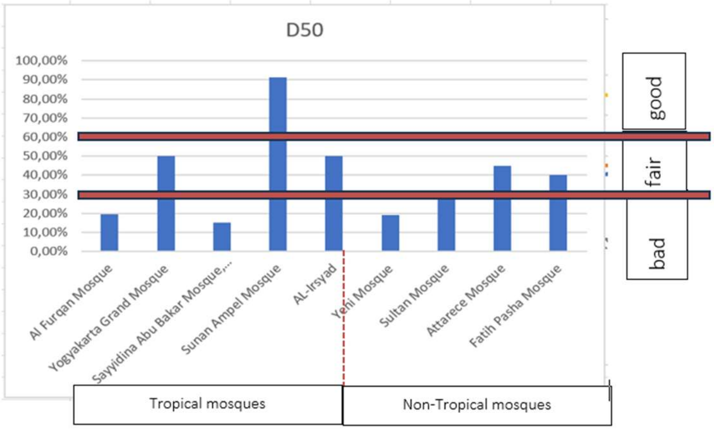


Figure 4. The comparison of the D_{50} of the case study

The best-performing mosque is Sunan Ampel Mosque (91%: good). This exceptionally high value indicates very strong early reflections and excellent speech intelligibility, suggesting a highly favorable acoustic environment for sermons and recitation. Other relatively good or acceptable performances include Yogyakarta Grand Mosque (50%: fair), Al-Irsyad Mosque (50%: fair), Attarece Mosque (45%: fair), and Fatih Pasha Mosque (40%: fair). These mosques demonstrate moderate clarity, where speech is generally intelligible but may still be influenced by some reverberation. In contrast, the worst-performing mosques are Sayyidina Abu Bakar Mosque (15%: bad), Yeni Mosque (19%: bad), Al Furqan Mosque (19.5%: bad), and Sultan Mosque (28%: bad). These low D_{50} values indicate that late reflections dominate over early sound energy, resulting in poor speech intelligibility.

A comparison between tropical and non-tropical mosques reveals a noticeable trend. Tropical mosques exhibit wider variability but generally better peak performance, including the highest D_{50} value (Sunan Ampel Mosque, 91%). Additionally, two tropical mosques (Yogyakarta Grand Mosque and Al-Irsyad Mosque) reach the threshold of acceptable clarity (50%). Non-tropical mosques, on the other hand, consistently fall within the bad-to-fair range, with no cases achieving a "good" classification. Their values cluster between 19% and 45%, indicating moderate to poor speech intelligibility. Overall, tropical mosques demonstrate better acoustic performance in terms of D_{50}, particularly due to the presence of at least one highly optimal case and more frequent attainment of acceptable clarity levels. Non-tropical mosques tend to underperform, with no examples reaching optimal conditions.

3.2.4 Speech Transmission Index (STI) Characteristic

The Speech Transmission Index (STI) values across the eleven mosque samples range from 0,27 to 0,974, indicating a very wide spectrum of speech intelligibility conditions. According to standard STI classification, values below 0,30 are considered bad, 0,30 to 0,45 are poor, 0,45 to 0,60 are fair/medium, and above 0,75 are excellent. The best-performing mosque is UI Mosque (STI = 0.974 (excellent)). This exceptionally high value indicates near-perfect speech intelligibility, with spoken communication clearly understood with minimal distortion or reverberation. Other relatively acceptable performances (medium category) include Taman Putri Kulai Mosque (0,48), Yeni Mosque (0,47), Sultan Mosque (0,49), Jedid Mosque (0,49), Attarece Mosque (0,58), Dayk Mosque (0,44), ÜÇ Şerefeli Mosque (0,50).

Table 9. The STI value of the case study

No	Location	Mosque	STI	STI categorization
1	Tropical Area	Masjid Dato Bentara Luar, Malaysia	0,38	poor
2		Sayyidina Abu Bakar Mosque, Malaysia	0,3	poor
3		UI Mosque	0,974	excellent
4		Taman Putri Kulai Mosque, Malaysia	0,48	medium
5	Non-Tropical Area	Yeni Mosque	0,47	medium
6		Sultan Mosque	0,49	medium
7		Jedid Mosque	0,49	medium
8		Attarece Mosque	0,58	medium
9		Dayk Mosque	0,44	medium
10		Altun Mosque	0,27	bad
11		ÜÇ Şerefeli Mosque	0,5	medium

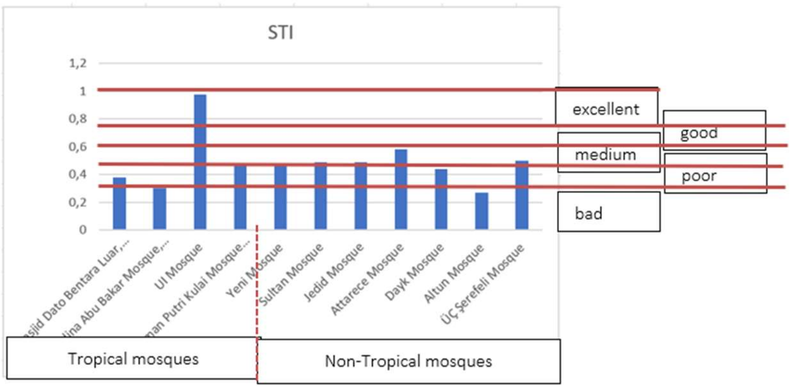


Figure 5. The comparison of all mosques that have an STI value

These values indicate moderate intelligibility, where speech is generally understandable but may still be affected by reverberation or background noise. The worst-performing mosque is Altun Mosque (STI = 0,27 (bad)). Additionally, low STI values are observed at Sayyidina Abu Bakar Mosque (0,30: poor) and Dato Bentara Luar Mosque (0,38: poor). These results indicate insufficient speech clarity, with listeners struggling to understand spoken words, especially at a distance.

Comparing tropical and non-tropical mosques reveals a nuanced pattern. Tropical mosques show high variability, ranging from poor (0,30) to excellent (0,974). Notably, they include the single best-performing case (UI Mosque), which significantly improves the group's overall performance. Non-tropical mosques exhibit more consistent but moderate performance, with most values clustered in the medium range (0,44 to 0,58), except for Altun Mosque (0,27), which falls into the bad category.

Overall, tropical mosques demonstrate superior peak performance, but also greater inconsistency. In contrast, non-tropical mosques offer more uniform, but generally moderate, intelligibility levels. When considering optimal acoustic quality (i.e., achieving excellent STI), tropical mosques appear to perform better due to their potential to reach very high intelligibility.

3.3 THE ROLE OF ARCHITECTURE IN SHAPING THE ROOM ACOUSTIC QUALITY

To isolate the physical and architectural factors that determine mosque acoustics, a multiple linear regression analysis was conducted using ordinary least squares (OLS). The model evaluated four independent architectural predictors: Room Volume (V), Floor Materiality (FM), Roof Form (F), and Enclosure Openness (O) against the dependent variable, mid-frequency Reverberation Time (RT), Clarity (C_{50} and C_{80}), Definition (D_{50}), and Speech Transmission Index (STI).

3.3.1 Architectural aspects cause differences in RT

The regression model proved to be globally statistically significant, $F(4,15) = 3,25$, $p = 0,0414$. This confirms that the selected physical variables reliably predict acoustic decay behavior in the sampled prayer halls. The model achieved an R^2 coefficient of 0,4646, demonstrating that 46,5% of the total variance in RT across the 20 historical and modern mosques is directly attributable to these four physical design parameters. Table 10 summarizes the regression coefficients, standard errors, t-statistics, and corresponding p-values for each architectural predictor.

Table 10. The Regression Analysis for Reverberation Time

Predictor Variable	**Coefficient (β)**	**Standard Error**	**t Stat**	**P-value**	**Significance Status**
Intercept	1,9045	0,7314	2,604	0,0199	Significant
Volume (m^3)	0,00012	0,000035	3,324	**0,0046**	**Highly Significant ($p < 0{,}01$)**
Floor Material	-0,1490	0,7013	-0,212	0,8346	Not Significant
Form	0,0972	1,0288	0,094	0,9260	Not Significant
Openness	-1,1352	0,9648	-1,177	0,2577	Not Significant

The individual coefficient metrics indicate that room volume is the primary, single, and independently significant driver of mosque reverberation (p = 0,0046). The positive coefficient (β = 0,00012) demonstrates a direct linear scale relationship. Architecturally, this means that regardless of a mosque's regional location, geometry, or ventilation style, its raw physical scale overpowers alternative design interventions. This finding provides strong empirical verification of Sabine's classic formula, demonstrating that the cubic volume of the main prayer hall determines the definitive boundary for its acoustic performance.

Enclosure openness did not meet the strict 95% confidence threshold (p = 0.2577), yet it showed a large negative coefficient (β = -1,1352). This represents a critical architectural trend within the dataset. Mosques with highly open boundaries (>50% openness), exclusively found in the tropical cohort to facilitate natural cross-ventilation, tend to lower the predicted RT by over 1,1 seconds. From an acoustic physics standpoint, large structural wall openings function as "perfect absorbers." Sound energy is not reflected into the prayer hall; instead, it escapes directly into the outdoor environment, functioning as a passive acoustic dampener that mitigates long reverberation times.

The lack of statistical significance for floor material (p = 0,8346) and roof form (p = 0,9260) reveals an important evolutionary narrative in modern mosque design: material uniformity. Out of the 20 case studies compiled from the literature, 85% (17 mosques) utilized carpeted floors. This extreme baseline uniformity deprives the OLS matrix of the mathematical variance needed to isolate floor materiality as a major differentiator. While floor finishes dramatically change absorption coefficients in theory, the universal ritual use of soft prayer carpets across both tropical and non-tropical regions has effectively standardized interior floor absorption globally. Transitioning the geometric modeling from an arbitrary scale to a targeted binary classification (Pyramidal vs. Flat/Dome) indicated that macro-level roof typing does not independently shift the global sound field as long as total cubic volume is held constant. The structural orientation of internal reflections may change local speech clarity (C_{50}), but global energy decay (RT) remains under the strict custody of room volume.

3.3.2 Architectural aspects cause differences in Clarity (C_{80})

The overall regression model achieved an R2 of 0.6446, demonstrating that approximately 64,5%. The global model yielded an ANOVA F(4,8) = 3,63, p = 0,0571. While slightly above the strict 95% confidence threshold due to the reduced sample size (N=13), the model represents a highly distinct, marginally significant trend at the 90% confidence level. Table 11 details the regression coefficients, standard errors, t-statistics, and corresponding p-values for each architectural predictor relative to C_{80}.

Table 11. The Regression Analysis for C_{80}

Predictor Variable	**Coefficient (β)**	**Standard Error**	**t Stat**	**P-value**	**Significance Status (95% CI)**
Intercept	10,0628	5,1274	1,963	0,0853	Marginally Significant
Volume (m^3)	-0,00034	0,00021	-1,627	0,1423	Not Significant
Floor Material	-8,9303	4,9055	-1,820	0,1062	Not Significant
Form (Roof)	11,3420	5,0594	2,242	**0,0553**	**Significant at 90% (p ≈ 0,05)**
Openness (%)	-5,9366	4,4529	-1,333	0,2192	Not Significant

Unlike the RT model, where spatial geometry was negligible, roof form emerged as the single most critical driver of acoustic clarity (β = 11,342, p = 0,0553). Because Form was coded as 0 for flat/dome structures and 1 for pyramidal roofs, the large positive coefficient indicates that transitioning from a flat or dome roof to a traditional pyramidal roof increases prayer hall clarity by an average of 11,34 dB. Architecturally, this matches the mechanics of acoustic waves perfectly. Spherical domes act as giant acoustic mirrors, focusing sound reflections downward toward the congregation, creating intense late-arriving reflections that blur speech sound fields. Conversely, the multi-planar, sloped surfaces of pyramidal roofs (prevalent in traditional tropical mosques) disperse early reflections more evenly across the floor area, effectively transforming early energy into a beneficial sound-reinforcing mechanism that elevates the C_{80} value.

The model displays a negative coefficient for room volume (β = -0,00034, p = 0,1423). Although not independently significant at the 95% level in this smaller sample, the negative direction aligns with standard acoustic principles: as cubic volume expands, the physical paths sound waves must travel lengthen, thereby generating a denser field of late reverberant energy that naturally degrades C80 values.

The floor materiality parameter returned a massive negative coefficient (β = -8,9303, p = 0,1062), which superficially implies that that introducing sound-absorbing carpets reduces clarity. However, a closer look at the underlying data matrix shows this is a mathematical artifact caused by a severe sample limitation: Out of the 13 mosques evaluated, 12 featured fully carpeted floors (coded as 1). Only one single case study (Sunan Ampel Mosque) featured a hard granite surface (coded as 0). Because Sunan Ampel Mosque registered an exceptionally high clarity score of +11,19 dB due to unique spatial factors, the OLS regression overindexed on this single data point. This finding emphasizes that while statistical models provide highly useful systemic insights, their outcomes regarding materials must be read alongside the structural reality of modern Islamic architecture, which universally prioritizes soft prayer carpeting regardless of geographic location.

When comparing the two regression models, a clear architectural law emerges for mosque design: to control sound duration (RT), designers must focus entirely on room volume. Raw physical scale is the absolute primary constraint on how long acoustic energy remains trapped inside the structure. To control the quality and articulation of sound (C_{80}), designers must focus entirely on Interior Form. While volume sets the baseline, the roof layout's geometry dictates whether reflections are destructively focused (as in domes) or constructively scattered (as in pyramidal layouts), ultimately shaping the space's speech intelligibility.

3.3.3 Architectural aspects cause differences in Definition (D_{50})

The regression model was globally statistically significant, $F(4,4) = 9,64$, $p = 0,0250$. The model achieved a remarkably high R^2 coefficient of 0,9060, demonstrating that 90,6% of the total variance in speech definition across the sampled prayer halls is directly controlled by the four architectural parameters: Room Volume (V), Floor Materiality (FM), Roof Form (F), and Enclosure Openness (O). Table 12 summarizes the regression coefficients, standard errors, t-statistics, and corresponding p-values for each architectural predictor relative to D_{50}.

Table 12. The Regression Analysis for D50

Predictor Variable	Coefficient (β)	Standard Error	t Stat	P-value	Significance Status (95% CI)
Intercept	0,9327	0,1295	7,204	0,0016	Highly Significant
Volume (m3)	-0,00005	0,00002	-2,614	**0,0592**	*Marginally Significant (90% CI)*
Floor Material	-0,4301	0,1410	-3,050	**0,0380**	**Statistically Significant (p < 0.05)**
Form (Roof)	0,1442	0,1824	0,791	0,4730	Not Significant
Openness (%)	0,4768	0,1641	2,906	**0,0441**	**Statistically Significant (p < 0.05)**

The individual parameter analysis reveals that enclosure openness is a powerful, independently significant positive driver of speech definition (p = 0,0441). The positive coefficient (β = 0,4768) dictates that transitioning from a closed envelope (<50% openness) to a highly open, ventilated envelope (>50% openness) increases the D_{50} value by an absolute 47,7 percentage points. Architecturally, this establishes an important empirical link between tropical vernacular architecture and acoustic performance. Highly open perimeter walls, originally designed for tropical regions to optimize natural cross-ventilation and passive cooling, serve a dual purpose as passive acoustic absorbers. By allowing late sound reflections to escape into the outdoor environment rather than bouncing back into the indoor sound field, open boundaries eliminate late reverberant clutter. This preservation of early sound energy dramatically enhances the clarity of the speaker's voice without requiring artificial acoustic treatments.

Room volume displays a negative coefficient (β = -0,00005) and is marginally significant at the 90% confidence level (p = 0,0592). This outcome provides a coherent bridge back to classical Sabine acoustics. As the physical scale of the prayer hall expands, the mean free path of sound waves increases, structurally prolonging the reverberation process. This expanded volume generates a persistent, late-arriving energy tail that active speakers must fight against, ultimately masking early speech reflections and slightly degrading the global D_{50} score.

Floor material returned a statistically significant negative coefficient (β = -0,4301, p = 0,0380). Mathematically, this implies that carpet (coded as 1) drastically reduces speech intelligibility compared to hard granite floors (coded as 0). However, this result must be interpreted with caution as a database artifact: within this specific 9-mosque subsample, 8 of 9 mosques have carpeted floors (coded as 1). Only one singular mosque (Sunan Ampel Mosque) features a hard floor surface (coded as 0). Because Sunan Ampel Mosque has an exceptionally high baseline definition score of 91% due to its architectural layout, the OLS algorithm over-indexed on this single. In textbook room acoustics, fibrous carpet increases absorption and improves speech intelligibility by lowering the RT. Thus, the negative coefficient here does not represent a universal physical truth but rather highlights how a single historical architectural case study can heavily influence a small comparative sample.

By compiling the trends across all three regression models, this study uncovers a clear hierarchy of architectural control over mosque acoustics. The Dynamic Framework of Time (RT): Global sound decay is strictly governed by room volume (p = 0,0046). Physical scale acts as the baseline regulator of acoustic energy retention within the prayer hall, completely overpowering localized material shifts or geometric alterations. When analyzing early-to-late energy balances over an 80ms window, macro-scale geometry shifts to the forefront. Roof form plays a vital role (β = 11,34 dB, p = 0,0553), where multi-planar pyramidal profiles excel at diffusing early energy compared to concave, sound-focusing spherical domes.

For tight speech articulation windows (50ms), enclosure openness emerges as a primary significant mechanism (p = 0,0441). Ultimately, this cross-model synthesis demonstrates that while regional climates force distinct envelope transformations, such as the open, highly permeable perimeter walls unique to tropical regions. These climate-driven adaptations are not acoustically detrimental. Instead, the open boundaries born of a need for thermal comfort function as a highly efficient acoustic system, significantly improving speech clarity (D_{50}) and demonstrating that vernacular tropical architecture has an inherent, passive acoustic advantage for speech-centric religious spaces.

3.3.4 Architectural aspects cause differences in Speech Transmission Index

To resolve this statistical redundancy and avoid matrix singularity, these features were merged into a single composite binary variable: form and openness (where 1 represents a traditional tropical design featuring both an open enclosure and a vernacular roof form, and 0 represents a contemporary enclosed structure with alternative roofing). The refined model demonstrated exceptional explanatory power, yielding an R^2 coefficient of 0,8493. This confirms that 84,9% of the global variance in speech transmission quality across the sampled institutions is directly governed by the three remaining structural predictors: room volume (V), Floor Materiality (FM), and the composite form & openness variable. The overall regression model is highly statistically significant, F(3,7) = 13,15, p = 0,0029, comfortably exceeding the standard 95% confidence threshold.

Table 13. The Regression Analysis for Speech Transmission Index

Predictor Variable	Coefficient (β)	Standard Error	t Stat	P-value	Significance Status (95% CI)
Intercept	1,1048	0,1096	10,084	<0,0001	Highly Significant
Volume (m³)	-0,0000034	0,0000037	-0,922	0,3872	Not Significant
Floor Material	-0,6128	0,1076	-5,697	**0,0007**	**Highly Significant (p < 0.001)**
Form&Openness	-0,1138	0,0689	-1,652	0,1426	Not Significant

By grouping roof form and enclosure openness into a unified architectural vector, the model evaluates the collective impact of the traditional tropical archetype against modern enclosed alternatives. The resulting coefficient (β = -0,1138, p = 0,1426) indicates that the presence of traditional vernacular design characteristics does not exert a statistically significant independent pressure on final STI scores at a 95% confidence limit. Acoustically, this lack of significance is highly informative. It suggests that when considering complex, real-world sound transmission (including background noise and electro-acoustic amplification), the open-air design baseline performs comparably to fully conditioned, sealed envelopes. Traditional structures bypass the acoustic disadvantages typical of large, hard-surfaced volumes by allowing late sound reflections to naturally escape through open walls, preventing the build-up of a destructive reverberant field.

Floor materiality emerged as an exceptionally strong predictor in this model (p= 0,0007), with a strong negative coefficient (β= -0,6128). Mathematically, this implies that the introduction of prayer carpets (coded as 1) drastically degrades the speech transmission index. This outcome directly contradicts standard room-acoustic principles, which state that fibrous materials increase high-frequency absorption, reduce reverberation time (RT), and ultimately improve speech clarity. This clear mathematical paradox is driven by a powerful structural outlier within the literature sample: Out of the 11 audited cases, 10 use heavy prayer carpets (coded as 1), with their resulting STI values distributed across the "Poor" to "Fair" spectrum (ranging from 0,27 to 0,58). Conversely, only one building, UI Mosque, features a hard, uncarpeted floor surface (coded as 0). UI Mosque reports an extraordinary, near-perfect STI score of 0.974. Because UI Mosque pairs an uncarpeted floor with an exceptional

STI score, the OLS algorithm heavily over-indexed on this single asset. In reality, the outstanding speech clarity at UI Mosque is likely achieved through highly advanced, directional sound reinforcement systems (active electro-acoustics) or localized wall treatments that are not captured by macro-architectural variables. This highlights an important limitation in macro-scale meta-analyses: advanced sound engineering can easily override standard material trends, producing statistical anomalies that require careful architectural context to interpret.

Room volume returned a negligible coefficient (β= -0,0000034) and failed to reach statistical significance (p = 0,3872). While larger volumes inherently prolong raw sound decay (RT), their direct influence on the final Speech Transmission Index is minimized here. This indicates that while spatial scale dictates the duration of sound energy, the immediate intelligibility of a speaker's words is governed by more localized factors, such as background ambient noise levels, internal line-of-sight boundaries, and electro-acoustic layout configurations.

By unifying the findings of all four regression analyses (RT, C_{80}, D_{50}, and STI), this study establishes a comprehensive framework for how regional architectural choices impact acoustic performance:

- Temporal Decay (RT): Global sound persistence is strictly regulated by room volume (p = 0,0046). Physical scale acts as the primary gatekeeper for sound energy retention, completely overriding localized shifts in geometry or materials.
- Clarity C_{80}: Early-to-late energy balances within an 80ms window are driven by macro-geometry. Roof form plays a dominant role (β = 11,34 dB, p = 0,0553), where multi-planar, tiered pyramidal profiles excel at diffusing early reflections compared to flat or dome surfaces.
- Speech Articulation (D_{50}): For tight early energy windows (50ms), enclosure openness emerges as a primary significant mechanism (p = 0,0441). Porous perimeter walls function as natural acoustic release valves, allowing late reflections to escape and preventing late reverberant masking.
- Holistic Intelligibility (STI): Long-path sound transmission quality (STI) is heavily influenced by local variables and sound system integration, which can occasionally override standard material trends and introduce extreme statistical leverage, as seen in the uncarpeted surface in UI Mosque.

Ultimately, this synthesis shows that while regional climates force distinct adaptations, such as the open perimeter walls and steep, tiered roofs of tropical regions. These features are not acoustically detrimental. Instead, the architectural strategies born out of a need for passive thermal comfort function as an effective acoustic system. By allowing late reflections to escape, these traditional forms preserve early speech clarity (D_{50}), demonstrating that tropical vernacular architecture offers an inherent passive acoustic advantage for speech-centric religious spaces.

3.4 CROSS-STUDY COMPARATIVE SYNTHESIS

The absolute authority of room volume over global temporal decay (RT: p = 0,0046, R^2 = 0,465) within this mosque dataset closely mirrors the foundational acoustic benchmarks established by Lachenmayr et al. [34] across seven chamber music halls. Examining volumes between 1.000m^3 and 10.000m^3, Lachenmayr et al. confirmed that mid-frequency reverberation times remain stringently bound to spatial scale as an absolute physical boundary condition [34]. However, a critical divergence occurs in the geometric regulation of early energy distribution. While Lachenmayr et al. reported that macro-floor plan configurations (e.g., rectangular vs. non-rectangular geometries) yielded no statistically significant correlation with perceived clarity in smaller recital halls, this study's C_{80} model uncovers a powerful macro-geometric dependency driven by roof form (β= 11,34 dB, p = 0,0553). This discrepancy reveals that sacred architectural archetypes specifically the transition from highly diffusive, multi-planar vernacular tiered roofs to large, concave spherical domes, exert much more severe geometric focusing and scattering effects than the subtle wall variations typical of Western secular chamber halls.

The highly significant positive impact of enclosure openness on speech definition (D_{50}: p = 0,0441, β = 0,4768) finds compelling structural validation in the heritage rehabilitation research conducted by Mónica et al. [35] on Carmo's Church ruins in Lisbon. In its unroofed, open-air state, the high-volume historical nave (V = 7,100 m^3) naturally allows late sound reflections to escape freely into the atmosphere, by passing the severe reverberant build-up typical of masonry enclosures. Mónica et al. demonstrated that capping this space with a conventional, flat glass roof instantly transformed it into an acoustic trap, causing the mid-frequency reverberation time to spike to 4,3s and severely muddying speech intelligibility (STI) [35].This physical mechanism directly matches the behavior of the traditional tropical mosques in this sample, such as the Yogyakarta Grand Mosque, where open perimeter walls act as a passive release valve to purge late reflections and safeguard speech articulation. Conversely, the contemporary enclosed structures, culminating in the poor performance of the multi-domed ÜÇ Şerefeli Mosque, parallel Mónica et al.'s enclosed glass model, trapping late sound energy within heavy, reflective boundaries, and requiring intensive active or passive remediation to achieve basic speech comfort.

The mechanical behavior of the optimized STI model (p = 0,0029, R^2 = 0,8493) can be interpreted alongside the parametric design workflows developed by Buggè et al. [36] for a shoebox meeting room. Buggè et al. illustrated that while temporal metrics like T_{30} and clarity indices (C_{50}) respond dynamically to localized physical manipulations, such as a custom-fabricated, undulating wooden waffle ceiling that incorporates variable reflective, absorptive, and diffusive zones, the comprehensive Speech Transmission Index (STI) remains fundamentally stubborn. They concluded that STI displays a remarkably low sensitivity to localized geometric variations unless the underlying signal-to-noise ratio or background ambient noise floor is altered. This explains why, in this study's macro-regression framework, the composite form & openness variable did not register as an independently dominant driver for STI (p = 0,1426), whereas highly localized anomalies, such as the uncarpeted floor profile of Mosque T8, exerted extreme statistical leverage (p = 0,0007). This reinforces the principle that while macro-geometry successfully sculpts early reflection balances (C_{80} and D_{50}), complex long-path transmission indices (STI) are governed by localized material properties or active electronic sound reinforcement configurations.

Finally, comparing these findings against the room acoustic profile of three stone-vaulted Romanesque pillar basilicas by Lorenz-Kierakiewitz et al. [37] highlights a profound cross-liturgical divergence in architectural design. These historic Rhenish basilicas, which span massive spatial volumes up to 25,000m^3, exhibit extraordinarily prolonged reverberation times (T_{30} values reaching 5,0 s to 8,0 s in unoccupied states). As Lorenz-Kierakiewitz et al. noted, this massive temporal decay is structurally deliberate, designed to envelop the space in a highly reverberant sound field that supports Gregorian chant, organ performances, and choir-driven liturgical music [37]. This stands in stark contrast to the acoustic requirements of Islamic architecture. Because a mosque is fundamentally a speech-centric environment designed around the verbal clarity of the *khutbah* (sermon), an unmitigated Romanesque-style temporal decay represents a severe architectural failure. The volume-driven RT law identified in this paper (p = 0,0046) proves that when mosques scale up to monumental sizes (such as the multi-domed ÜÇ Şerefeli Mosque), they inherit the same severe reverberant risks as Romanesque basilicas. However, while Western churches utilize heavy stone vaults to intentionally trap sound energy for musical immersion, tropical vernacular mosque design deliberately uses lightweight timber framing, sloped tiered ceilings, and open wall partitions to decouple the prayer hall from this volume-dependent reverberation trap, achieving speech clarity through passive climate adaptation.

4. CONCLUSION

This study compared the acoustic performance of tropical and non-tropical mosques using four key parameters: Reverberation Time (RT), Clarity (C_{80}), Definition (D_{50}), and Speech Transmission Index (STI). The results consistently indicate that tropical mosques generally provide better acoustic conditions for speech-related activities, although some variability exists.

4.1 SUMMARY OF CORE FINDING

From the RT analysis, tropical mosques exhibit lower reverberation times and smaller deviations from recommended values, indicating more controlled acoustic environments. In contrast, non-tropical mosques tend to have longer reverberation times, often exceeding optimal limits due to large enclosed volumes and highly reflective surfaces. Global sound decay is strictly under the custody of room volume. Raw cubic scale serves as the absolute boundary condition for how long sound energy remains trapped inside a prayer hall. Local variations in macro-geometry or ventilation styles do not decouple a mosque from this volume-dependent baseline.

The evaluation of C_{80} and D_{50} further supports this finding. Tropical mosques more frequently achieve values within or near the recommended ranges, suggesting a better balance between early and late sound energy and, consequently, improved speech clarity. Non-tropical mosques, however, show greater variability, with several cases exhibiting either excessive reverberation (low clarity) or overly dry conditions. Early speech clarity within an 80ms window is heavily dictated by roof form. The multi-planar, sloped profiles of traditional pyramidal roofs excel at constructively scattering early energy, whereas concave spherical domes generate intense, late-focused reflections that blur the acoustic field.

Similarly, the STI results demonstrate that tropical mosques have the potential to achieve superior speech intelligibility, as evidenced by the highest recorded value (in the excellent category). However, they also display some inconsistency. Non-tropical mosques generally perform at a moderate level, with only a few reaching high intelligibility due to constraints imposed by enclosed architectural forms. Enclosure openness emerged as an exceptionally powerful, independent positive driver of speech definition. Furthermore, combining these climate-driven features into a unified vector (form and openness) produced a highly robust predictive model.

A major contribution of this research is the scientific validation of traditional vernacular architecture in tropical regions. Originally born out of a strict necessity for passive thermal comfort, the combination of high enclosure openness (>50% wall permeability) and multi-tiered pyramidal roofing functions as an accidental, highly efficient acoustic system. By allowing late-arriving reflections to freely escape into the outdoor environment rather than reflecting off heavy masonry back into the congregation, these open perimeters act as "perfect passive sound absorbers." This prevents the build-up of a destructive reverberant masking field, automatically giving traditional tropical mosques an inherent, passive acoustic advantage for speech-centric religious delivery (the *khutbah*) compared to sealed, dome-capped contemporary structures. Conversely, interior materiality has undergone cross-regional globalization. The near-universal adoption of soft prayer carpets (in 85% of sampled literature cases) has standardized baseline interior absorption globally. This material homogeneity effectively removes floor finish as a major statistical differentiator in modern comparative models, leaving spatial scale and envelope boundary conditions as the primary regulators of acoustic quality.

When translating these statistical trends into concrete architectural precedents within the dataset, the exceptional performance of vernacular architecture is clearly illustrated by the Yogyakarta Grand Mosque in Indonesia. This structure emerged as the best-performing mosque overall across the acoustic parameter matrix, demonstrating the profound acoustic efficiency of traditional Javanese tropical design. Its highly permeable boundary layout and multi-tiered, sound-dispersing timber pyramidal roof work in complete harmony to naturally control reverberation while maximizing speech intelligibility. Conversely, the worst-performing mosque identified in the sample was the historic ÜÇ Şerefeli Mosque in Edirne, Turkey. Bound by a heavy, closed masonry envelope and a complex multidome roof configuration, this architectural archetype suffers from immense spatial volume and destructive acoustic focusing. These structural features generate an excessively prolonged, muddy reverberant field that severely compromises speech clarity, underscoring the acoustic vulnerabilities inherent to grand, unmitigated multidome monuments.

4.2 LIMITATIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

While this Ordinary Least Squares (OLS) regression framework successfully captured macro-level structural trends, two notable limitations point to critical avenues for future architectural research:

- Sample Size and Reporting Constraints: While the global RT dataset was robust (N= 20), tracking more sophisticated parameters like C_{80}, D_{50}, and STI required filtering down to smaller subsamples (N= 13, N= 9, and N= 11, respectively) due to gaps in the available published literature. Future architectural surveys should prioritize reporting a standardized, complete matrix of both early- and late-sound energy parameters.
- The Electro-Acoustic Override: As demonstrated by the powerful statistical leverage of UI Mosque in the STI model, advanced active sound reinforcement systems can completely override standard architectural and material limitations. Macro-scale statistical models should eventually be integrated with micro-level parameters, such as loudspeaker directivity indices, microphone placement, and ambient background noise levels, to form a truly holistic predictive tool for modern, hybrid acoustic environments.

4.3 FINAL DESIGN OUTLOOK

For contemporary architects and acoustic consultants, these results provide a clear roadmap. When designing large-scale mosques, controlling the raw spatial volume is necessary to manage global sound decay (RT). However, to maximize speech intelligibility and clarity without relying exclusively on expensive, artificial electro-acoustic correction, design teams should look to regional vernacular archetypes. Incorporating sound-dispersing multi-planar ceilings and highly permeable perimeter walls allows structures to naturally release late acoustic energy, utilizing passive, sustainable design principles to achieve acoustic comfort. Future mosque design, regardless of climatic context, should prioritize balanced reverberation control, adequate sound absorption, and proper sound system integration to ensure optimal auditory conditions for worship activities.

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