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Sound Quality inside Mosques: A Case Study on the Impact of Mihrab Geometry

Hany Hossameldien and Abdulrahman Abdullah Alshawan

Abstract

This chapter presents a detailed analysis to identify the best Mihrab (prayer niche of Imam) geometry with respect to acoustic performance of mosques. Mihrab geometry has an impact on daily prayer recitation and orders, as the Imam (prayer leader) faces this semicircular shape. Sound pressure level (SPL) has been simulated to compare different well-known designs and geometries of Mihrab by ODEON. A typical mosque in an educational campus was considered for the study, and it is found that Safavid Mihrab geometry has the best performance followed by Chinese, Mughal, and Tulunid Mihrab geometries, while the worst performance is found in Almoravid Mihrab geometry. This study obviously guides the mosque designers to choose the appropriate Mihrab geometry with regard to the acoustic performance.

Keywords: mosque acoustics, prayer niche, Mihrab geometries

1. Introduction

The term masjid (mosque) refers to the “place for prostration,” which is used by Muslims as houses of worship. Muslims have to execute five prayers daily, which are supposed to be performed congregationally in masjids. Masjids are exclusively essential structures in every Muslim community. They normally have a certain size and location in relation to the public. In general, they could be categorized as large national masjids, major landmark buildings, community focal point, and small local neighborhood masjids. Although their uses are clearly varied, they have several consistent characteristics. Mihrab (prayer niche) is the prayer place in Arabic, and it is the architectural feature of front wall (to which the Imam faces during the daily prayer) of any masjid.

Few studies on mosque acoustics have been reported by Topaktaş [1]. In general, the literature on mosque acoustics could be categorized as follows [2]:

- A. Researches on academic studies that concentrated on the analysis of existing mosques
- B. Studies on acoustic renovation and modification
- C. Studies on real or virtual mosques to develop acoustic design criteria

The first category (A) contains assessment researches including single mosque cases, comparisons of mosque to another mosque, or comparisons of mosques to churches or chapels. The second category (B) contains recommended architectural modifications on floor plan geometry and materials in contrast to common utilized internal finishes or shapes. Rare cases applied solely electronic sound reinforcement systems with no modifications on interior design, while both approaches were used in some cases. The third category (C) aims either to propose particular architectural parameters/features that are effective on the acoustics of the mosque typology or to specify acoustic parameter limits specifically to be applied for mosque typology [2].

1.1 Studies on analysis of existing mosques

These researches include assessment of single mosque or church cases, comparisons between mosques, and comparisons of mosques to churches or chapels. António and Carina [3] studied the acoustic performance of central mosque of Lisbon, Portugal. They measured the acoustic characteristics such as reverberation time (RT), rapid speech transmission index (RSTI), and background noise (BN). They did measurements for unoccupied situation in male and female prayer halls. The outcomes were analyzed and compared to another studies done for Catholic churches and mosques within volume average; in general, the average RT was 500–1 kHz but was a little higher when compared to the value recommended by the authors. El-khateeb and Ismail [4] studied the speech intelligibility in Sultan Hassan Mosque and Madrasa situated in Cairo, Egypt, by field measurements and ODEON simulation. The parameters were RT and Speech Transmission Index (STI) for occupied and unoccupied cases. They concluded that Sultan Hassan Mosque and Madrasa had high RT and echo at some examined points; however, it did not impact worshippers' understanding of Imam either in Friday speech or daily prayers.

Zühre and Yilmazer [5] investigated the acoustic characteristics of Kocatepe mosque in Ankara, Turkey, and compared them with masjid in the ancient Othman period. Kocatepe had a long RT in low frequencies due to central dome which was the aim of the study. An analysis and computer simulation by ODEON 6.05v were carried out to identify the acoustic features, including the parameters such as RT, early decay time (EDT), clarity (C80), sound definition (D50), lateral fraction (LF), STI, and strength (G). They tested three scenarios: the empty mosque, prayer mode when mosque was one-third full, and fully occupied, for daily and Friday speech. The acoustic performance of Kocatepe mosque was below average when empty but was acceptable when entirely occupied. António and Cândido [6] did an acoustic comparison of Catholic churches and mosques to clarify the main similarities and differences based on architectural and acoustic features. They studied variabilities between the following parameters for unoccupied spaces: RT, C50/C80, and STI/RSTI. Also, they considered the architectural information related to each building such as volume, length, area, height, and width. From measurements on churches (41 buildings in Portugal) and mosques (21 buildings in Saudi Arabia), they concluded that mosques in general had an overall better acoustic performance due to floor surface absorption value. A similar study was also reported from Istanbul, Turkey [7], which compared four mosques and three churches in Turkey. António and José [8] investigated the acoustics of Mekor Haim Synagogue (Jewish worship place), Portugal. The aim of this study was to compare the acoustic behavior of the Synagogue with Catholic churches in Portugal and mosques in Saudi Arabia with comparable volume. They suggested reducing RT only at dome in order to enhance the Synagogue acoustics. David and Paulo [9] evaluated the acoustic performance of a contemporary church in Curitiba, Brazil, to study its compliance

with NBR 12179 Brazilian National Standard, ISO 3382-1 international standard and IEC 60268-16 standard. They measured RT and D50 in accordance with ISO 3382 and ISO 3382-1 and calculated STI by ODEON software. It was found that the overall performance of the church exceeded the recommended values of some standards and was satisfactory for some parameters in a specific standard. An acoustic comparison of modern and ancient mosques has been done by Zerhan and Sevda [10] for a modern mosque and an ancient mosque.

1.2 Studies on architectural features and recommendation of floor plan geometries and materials

Few studies applied solely electronic sound reinforcement systems (SRS) with no modifications on interior design, while in some, both approaches are used. Abdou [11] made a wide analysis of the most common mosque floor plan geometries to measure the effect of the floor plan geometry on acoustic performance, particularly on the spatial distribution patterns of speech intelligibility without SRS. A simulation has been done of sound fields of five common forms of Muslim worship activities and level of occupancy. The study concluded that the square floor plan was the best in terms of acoustics. Another study [12] focused on Mihrab design and its basic acoustic characteristics of traditional vernacular mosques in Malaysia. The aim of this study was to review the acoustic performance of the investigated mosques and also to evaluate the acoustic performance of Mihrabs. The researchers surveyed 37-year-old mosques built within the period 1728–1830 in Malaysia; all these mosques had either square or rectangular floor plan geometry. The Mihrabs of the investigated mosques had circular niche with flat ceiling to rectangular shape with slanting ceiling and semicircular concaved niched forms. They utilized a PC-based acoustics measuring system and analyzer, and data from previous five case studies were analyzed and compared. They concluded that Mosque Mihrabs offered a good feature to confirm the trend of reasonable acoustic performance with a maximum variance of 4.0 dB. Utami [13] studied about domes coupled to rooms in mosques to identify the impact of centralized ceiling domes on acoustic performance of mosque buildings. A computer model was developed to compare the outcomes derived from analytical, numerical, and experimental (scale modeling) methods. Moreover, statistical techniques such as ANOVA and t-tests were utilized to compare the experimental results. The conclusion was based on comparisons and on realization listening tests in order to discover mosque components that produced the major acoustic impact. The analysis could establish criteria for better mosque acoustic performance with domed ceiling. Kayili [14] examined the applied acoustic systems throughout the history in Othman period; the study elaborated domes and cavity resonator technology made of bronze as well. The researcher found a variety of plaster types on internal surfaces of the investigated mosque (Selimiye mosque in Istanbul, Turkey).

A study about the influence of SRS on acoustic performance in churches [15] analyzed the sound field and its influence to speech intelligibility and clarity of music and recitation. The acoustic parameters such as RT, EDT, D50, C80, and STI were measured with the impulse response technique and compared the outcome with and without SRS. It was shown that SRS improved D50 and C80 for sound receivers. Also, for EDT the reverberance sensation decreased by distance reduction between sound receiver and source. The study concluded that SRS could provide slight enhancement in speech and music/recitation perception; however, it did not solve the issue originated by poor acoustic design. A similar work [16] was also reported on acoustics in worship spaces particularly mosques containing existing or newer computer-supported SRS. The main goal of this study was the development

and optimization of control algorithms of such systems using digital signal processing (DSP) controlled electroacoustic devices and computer-based systems to reach required radiation properties. In terms of floor plan geometry, Eldien and Al Qahtani [17] studied the most common two geometries of mosques, which are rectangular and square. They excluded the dome, worshippers, and sound reinforcement system and used the same finishing materials for both shapes for proper and fair simulation. They measured reverberation time (RT), early decay time (EDT), and sound transmission index (STI). This study found that the square floor plan has better overall sound qualities.

1.3 Studies on acoustic parameters and design guidelines

In this section, previous studies on particular architectural parameters/features that affect the acoustics of the mosque/worship spaces' typology and/or specifying acoustic parameter limits specifically to be applied for mosque typology are included. Abdou [18] studied the acoustic characteristics of existing Saudi Arabian mosques, by conducting field measurements (for parameters such as RT and C50) in 21 typical mosques which had diverse sizes and architectural features. The aim was to list down or specify their acoustic performance and to clarify air cooling system, ceiling fans, and sound systems' acoustic effect. BN was measured with and without air conditioning system operation, while STI was evaluated with and without SRS. It was deduced that the acoustic qualities of the investigated mosques deviated from optimum conditions when it was empty, but the acoustic performance improved in the occupied condition. Similar study on measuring STI with and without SRS was also reported by Cunha [15] for a church.

Diocese of Columbus [19] provided acoustic recommendations for the construction and renovation of churches and chapels. The study clarified the most important factors for acoustic design as listed below:

1. Basic requirements for good acoustics in churches
2. Elements of good natural acoustics for worship
3. Physical provisions for sound source isolation
4. Mechanical system noise control
5. Sound reinforcement system acoustics and the design/building process
6. An acoustic checklist for a typical church building process

In addition, it suggested guidelines for an appropriate natural acoustics in the architectural and acoustic design of churches and chapels, which included to provide RT of at least 2–3 s and to minimize the amount of sound-absorbing materials. In all cases, sound-absorbing materials should not be situated nearby the important sources of sound: the assembly, the music ministry, and the presiders and readers. Since all of these sound sources are at the floor level, floors cannot be carpeted in churches, and pews cannot be covered with upholstery or cushions. Additional suggestions included providing sufficient room volume to allow the natural development and support of sound. A volume of 300–400 cubic feet per seat was recommended for churches with seating capacities up to about 800 seats. Larger

churches might require greater volume, but smaller churches should not fall substantially below this range. In providing sufficient room volume for acoustics, height is a more important factor than floor area. It was also suggested to provide properly oriented, hard-surfaced materials around sound sources. All surfaces (including floors, walls, and ceilings) near and around presiders, cantors, readers, musicians, and the assembly must have hard surfaces. The study concluded that the acoustic effort includes the four essential facets of church acoustics: (1) natural/architectural acoustics, (2) sound isolation, (3) mechanical system noise and vibration control, and (4) sound reinforcement system design and specification. The following list of acoustic checkpoints was provided for acoustic consultants:

1. Predesign and programming phases
2. Schematic design phase
3. Design development phase
4. Construction document phase
5. Construction phase
6. Final construction evaluation

Each step of the above checklist has its own requirement that helps any designer to generally manage the acoustic requirements from project designing phase. Besides, the study gave general instructions that could be used for any building without parametric specification or limitations. Francesco et al. [20] provided guidelines for acoustic measurements in churches, with the motive of preserving the architectural features of this group of cultural heritage buildings. A team of three Italian universities was formed to provide technical and operative supports to perform measurements inside different churches. They collected detailed data of acoustic features of most important cultural heritages in order to improve the knowledge of sound propagation, preserve the architectural aspects in case of renovation, and determine the best approaches to improve the acoustic performance in existing buildings. A set of guidelines were proposed to simplify and normalize the choice of source and receiver locations and to suggest suitable hardware for acoustic measurement in churches.

Ismail [21] highlighted that designers do not pay enough attention to the acoustic performance in prayer halls due to projects' time limitation and insufficient basic guidelines for better acoustic performance during the early design stage. He investigated the acoustic performance of contemporary mosques by using computer model based on ray tracing theory. The study considered three most common mosque design topologies, which had different size, shape, and internal surface materials. Diverse acoustic treatments were studied to the geometric nature. The study provided design recommendations and guidelines that could help architects in conceptual design. A case study by Zühre [2] in Dogramacızade Ali Pasa mosque (Ankara, Turkey) focused on the impact of design decisions on acoustic comfort parameters. The selected mosque had a unique design, which was intensively studied at all design phases. Simulations were done by ODEON v10.13, and the outcomes were validated by site measurement in the studied space. The acoustic parameters assessed were RT C50, C80, STI, and sound pressure level (SPL).

1.4 Summary of literature review

In the first category, the studies focused on existing unoccupied mosques such as Lisbon mosque in Portugal and Sultan Hassan Mosque in Egypt. Moreover, these studies compared the acoustic performance between mosques and churches with comparable characteristics and volumes. Besides, some studies were on existing churches to evaluate the acoustic performance. In the second category, which focused on renovation and modification of worship places, the most common mosque floor plan geometries were studied and compared. In addition, these studies addressed the acoustic impact of the architectural elements of mosques or churches, such as Mihrabs, domes, and internal finishing, and the influence of SRS on acoustic performance in churches. The studies in the third category were on virtual or real mosques to develop acoustic design criteria. In general, the floor plan geometry of worship spaces was investigated. In addition, many researches were reported about different shapes and styles of domes and other architectural features in mosques and churches, which have a major effect in room acoustics. Some studies were about acoustic performance of existing Mihrab. However, detailed research on the acoustic performance of well-known Mihrab geometries is still lacking, which is the focus of this chapter.

2. Methodology

The simulated scenario is the daily prayer when the mosque is empty, by following ISO acoustic standards and procedures (building acoustic measurements standards ISO 140 and ISO3382). We have developed a three-dimensional design of a typical mosque inside Imam Abdulrahman Bin Faisal University (IAU) campus of Saudi Arabia and imported into the simulation tool (ODEON). The simulations were performed for 10 Mihrab geometries whose data were collected from previous studies. Mihrab's height and width were fixed. The SPL values were analyzed in order to select the best Mihrab geometry in terms of acoustic performance.

2.1 Mihrab development throughout Islamic history

Islamic architecture developed throughout Islamic empire expansion, the massive Islamic land from Eastern Asia toward Africa and some parts of Europe, has influenced mosque component architecture such as Mihrab, Minarat, and Quba [22]. **Table 1** shows each Islamic period that contributed on mosque architecture and development. Each Islamic period in **Table 1** has a masterpiece mosque

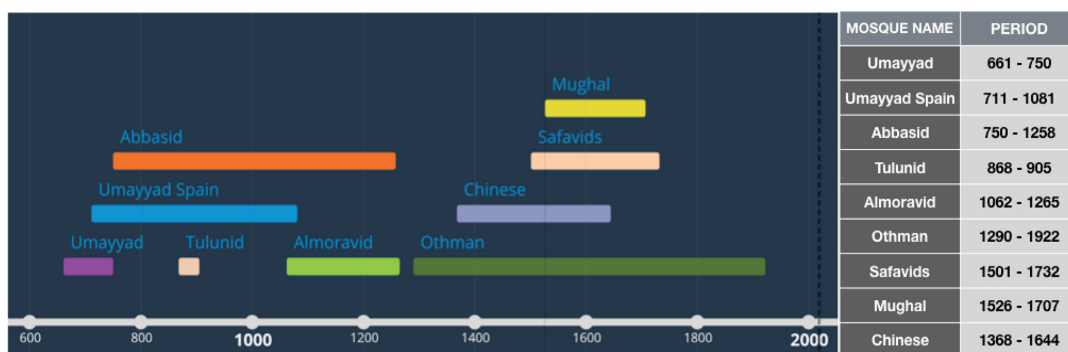


Table 1. Mihrab development throughout Islamic history (historical timeline).



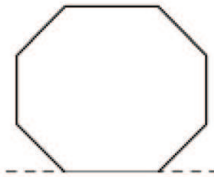





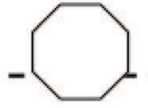




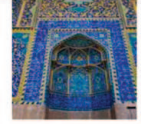






| Period | Nation | Masjid | Mihrab Floor Plan | Mihrab Elevation |
|-----------|-----------------|--------------------------|--|---|
| 661-750 | Umayyad | Great Masjid of Damascus |  |  |
| 711-1031 | Umayyad Spain | Great Masjid of Cordoba |  |  |
| 750-1258 | Abbasid | Abu Dulaf Masjid |  |  |
| 868-905 | Tulunid | Masjid of Ibnu Tulun |  |  |
| 1062-1269 | Almoravid | Great Masjid of Tlemchen |  |  |
| 1290-1922 | Ottoman | Üç Serefeli Masjid |  |  |
| 1501-1732 | Safavids | I-Shah Masjid |  |  |
| 1526-1707 | Mughal | Moti Masjid |  |  |
| 1368-1644 | Chinese Dynasty | Great Masjid of Xi'an |  |  |
| Recent | Saudi Arabia | IAU Masjid (Base Case) |  |  |

Table 2.
 Development of Mihrab shape throughout Islamic history.

(landmark) of the nation describing their architecture and culture. **Table 2** presents each period's famous Mihrab geometry and related information.

2.2 Modeling configurations

The various Mihrab geometries used for the computer simulation are summarized in **Table 2**. The size of the mosque corresponds to a community mosque with prayer hall area of 28×28 m and ceiling height of 4.95 m, as illustrated in **Figure 1**.

One worship scenario is examined in the simulation. The congregation (worshippers) performs the prayer behind the Imam who recites in a standing position facing the Qibla niche using his raised voice. It is natural that persons delivering speech without the aid of electroacoustic sound system tend to raise their voice. The background noise in the mosque is assumed to reach a noise criterion (NC) rating of NC30 (religion spaces). The worshippers are assumed to be listening to the Imam

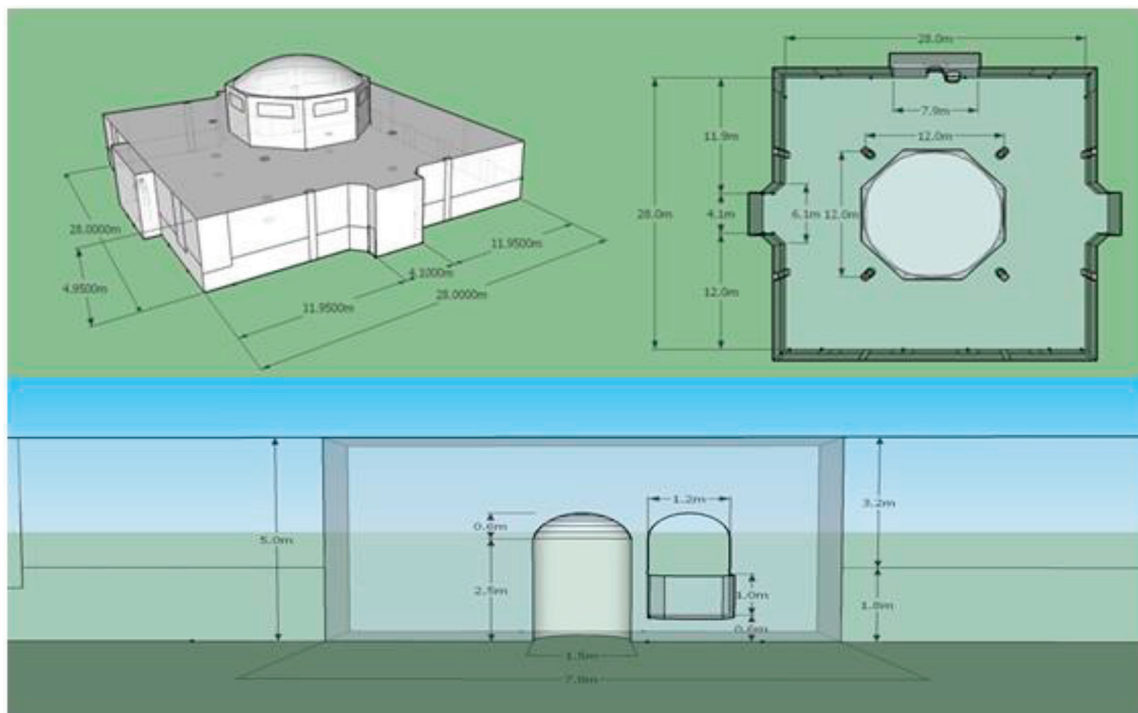


Figure 1.
IAU campus mosque dimensions.

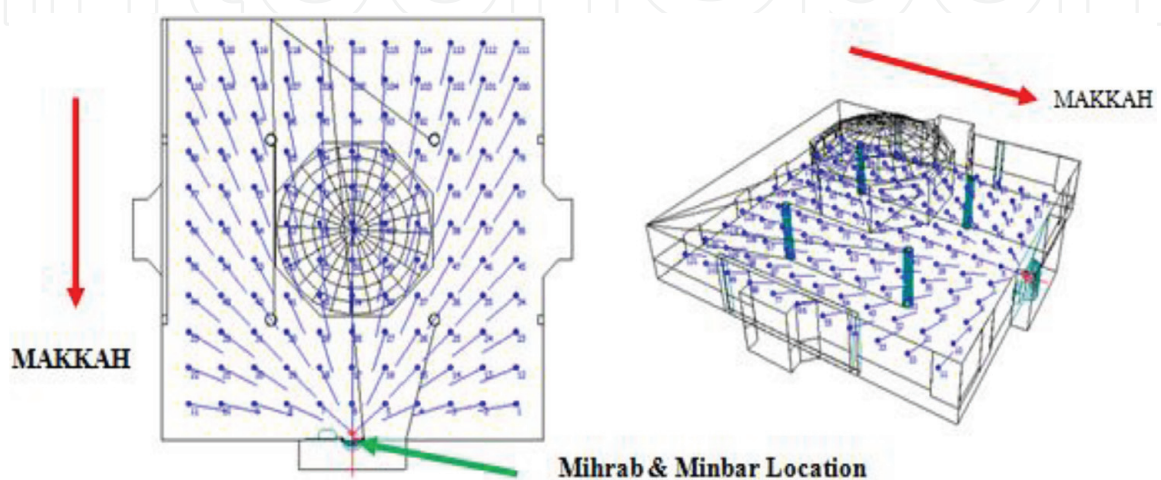


Figure 2.
Sound source and receiver points.

in standing position as is usually the case during the daily prayers. Their ear height was taken to be 1.65 m from the floor. Measurements and simulation were done when the mosque was assumed empty. **Figure 2** demonstrates the positions of sources and receives points for all configurations. These parameters were simulated in 121 different point positions as indicated in **Figure 2**. These points were measured for 10 Mihrab geometries including base case (**Table 2**). The distribution was on a 2.4 m grid. Each receiver point was 1.65 m high.

3. Results and discussion

SPL is the result of the pressure variations in the air achieved by the sound waves. The lowest sound pressure that can be heard by humans is called the hearing threshold, and the highest is known as the pain threshold. The human voice's average (speech) SPL is 50–70 dB. We investigated the average values for the selected Mihrab geometries on the overall floor plan and prayer row wise. Moreover, the analysis for Mihrab geometries was made on 2.4 m grid scale with 121 receiver's points distributed equally on the floor plan. When the SPL value is higher, it is an indication of higher acoustic performance.

Figure 3 presents the SPL contour plan for the Mihrab geometries studied. It presents the SPL performance for 10 Mihrab geometries. Therefore, each Mihrab geometry was investigated separately and, for each prayer row, with respect to the average SPL value. Finally, we summarized the SPL average values for all the prayer rows in order to compare them between the Mihrab geometries.

3.1 Base case Mihrab geometry SPL analysis (IAU)

Figure 4 shows the SPL contour values for the IAU (base case) Mihrab. We can observe that the SPL values decrease with the distance from the sound source. The

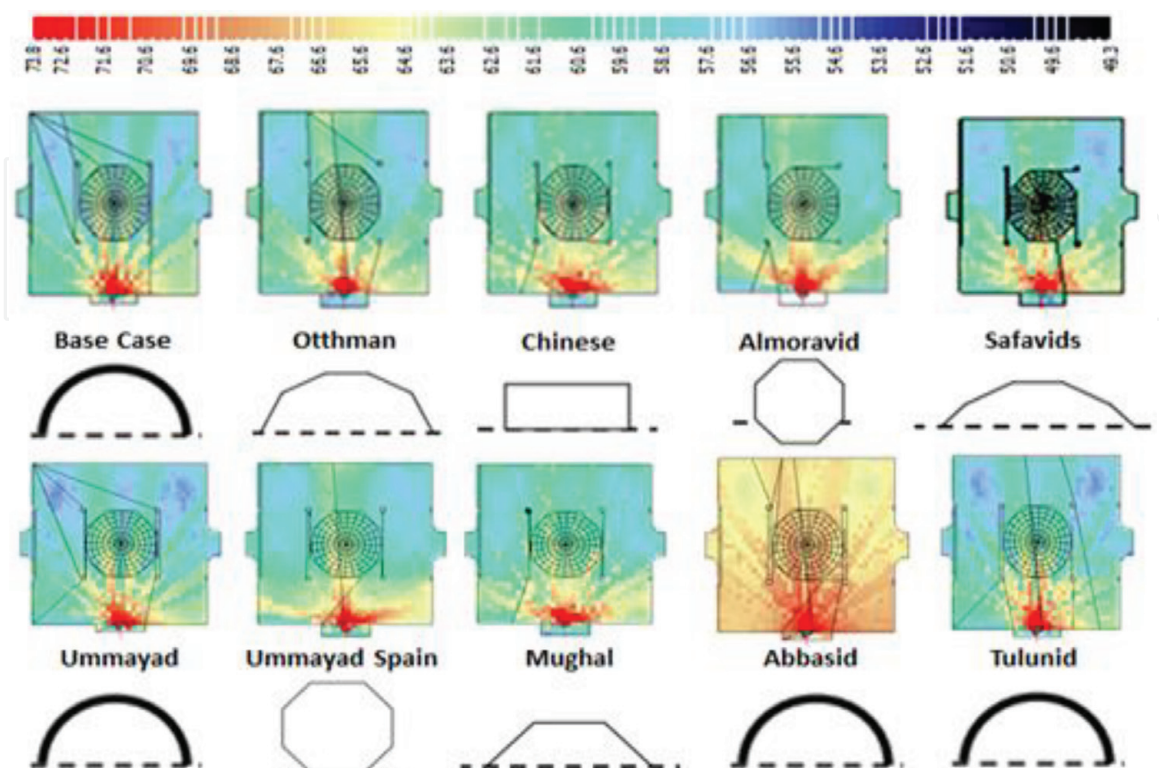


Figure 3.
SPL contour plans for all studied Mihrab geometries.

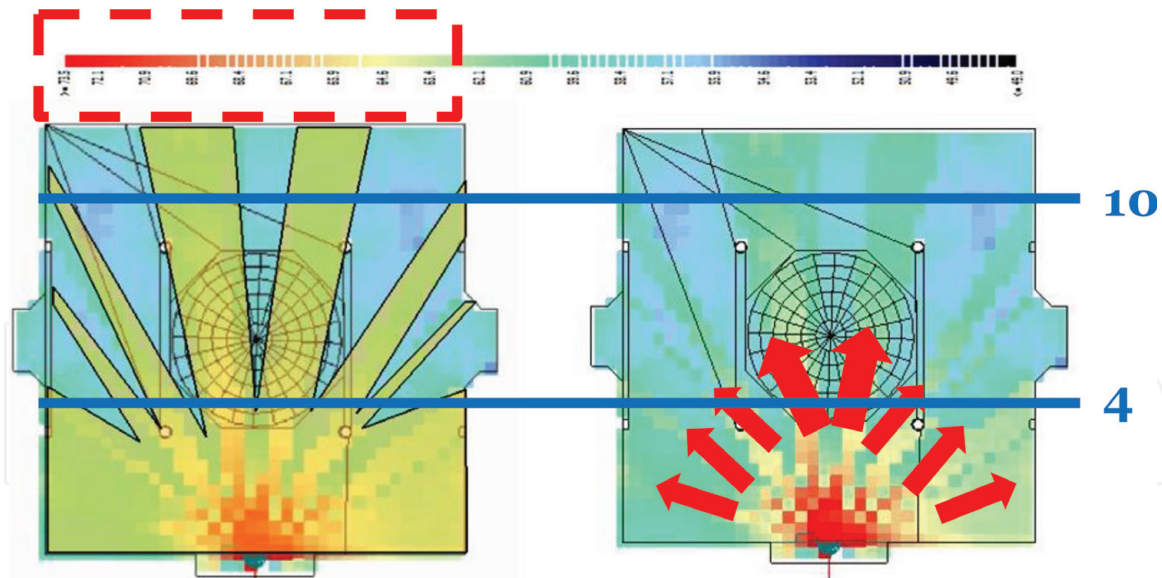


Figure 4. SPL value contour plans for base case mosque Mihrab geometry at 1 kHz.

SPL values range from 73 to 65 dB at 1 kHz. In general, the maximum values are located at the areas near the Mihrab and at the two sides. In general, this case has a noticeable increase of SPL value at the most critical point, which is behind the sound source. In addition, the Minbar (pulpit for the preacher) impact is low, and 35% of mosque area has low dB. Moreover, the yellow-hatched area is about 510 m² which is equivalent to approximately 65% of the floor plan. This Mihrab geometry is more suitable for a rectangular floor plan, once the sound distribution is homogeneous all over the floor plan.

Figure 5 presents SPL average values for prayer rows of the base case Mosque Mihrab geometry. The SPL average values are varying from 70 to 65 dB. The first row has the highest SPL value due to its relative position to the source. The second and third prayer rows have the same average of SPL values. The fourth prayer row has comparatively lesser average value than the fifth prayer row. Moreover, there is a gradual decrease of SPL average values from the fifth to the tenth prayer row. There is a noticeable increase of SPL average value at the last portion of mosque floor plan from lower SPL average value from the tenth prayer row to the

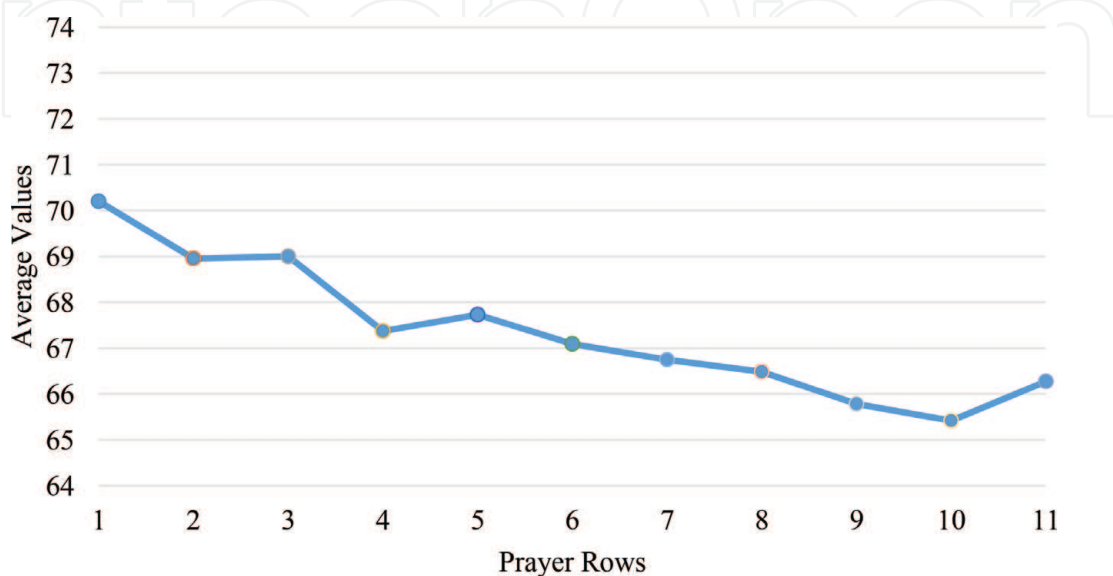


Figure 5. SPL average values for base case Mihrab prayer rows.

eleventh prayer row. The average SPL value of this Mihrab geometry for 121 sound receiving points on the prayer rows is 0.65 dB.

3.2 Othman Mihrab geometry SPL analysis

Figure 6 illustrates SPL values of Othman Mihrab geometry. SPL values from 66 dB to 74 dB are near the sound source and start decreasing as we move away. In general, it is found that the maximum values are located at the middle of the row closest to the sound source. Moreover, the yellow-hatched area (60–74 dB) is about 470 m² which is equivalent to 59% of overall mosque floor plan. This Mihrab geometry is more suitable for rectangular floor plan once the direction of the sound (red arrows) is toward the plan's longer direction.

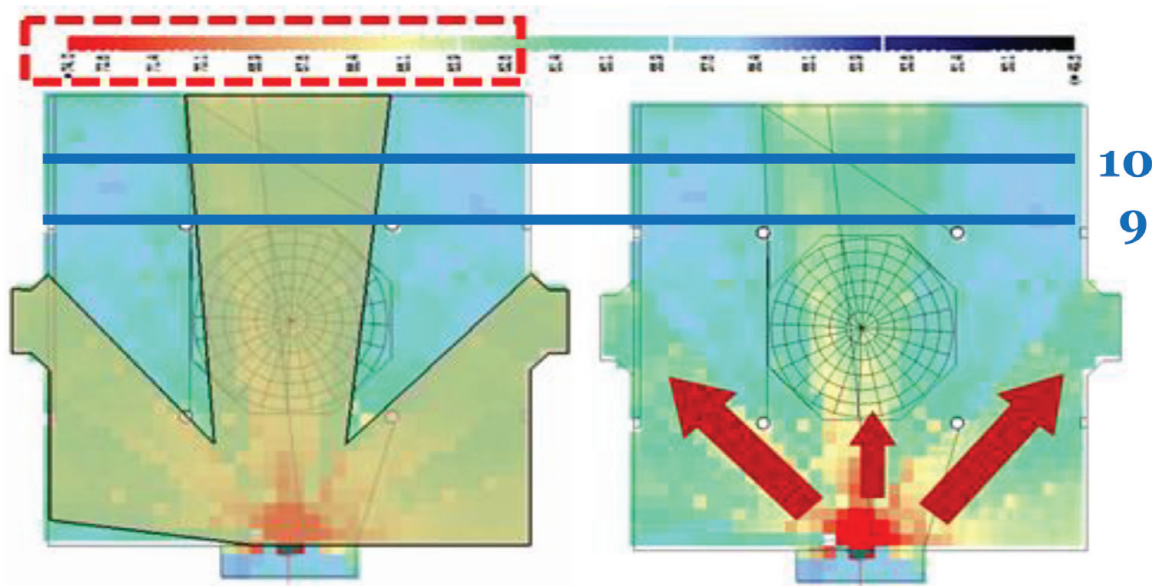


Figure 6.
 SPL contour values for the Othman Mihrab at 1 kHz.

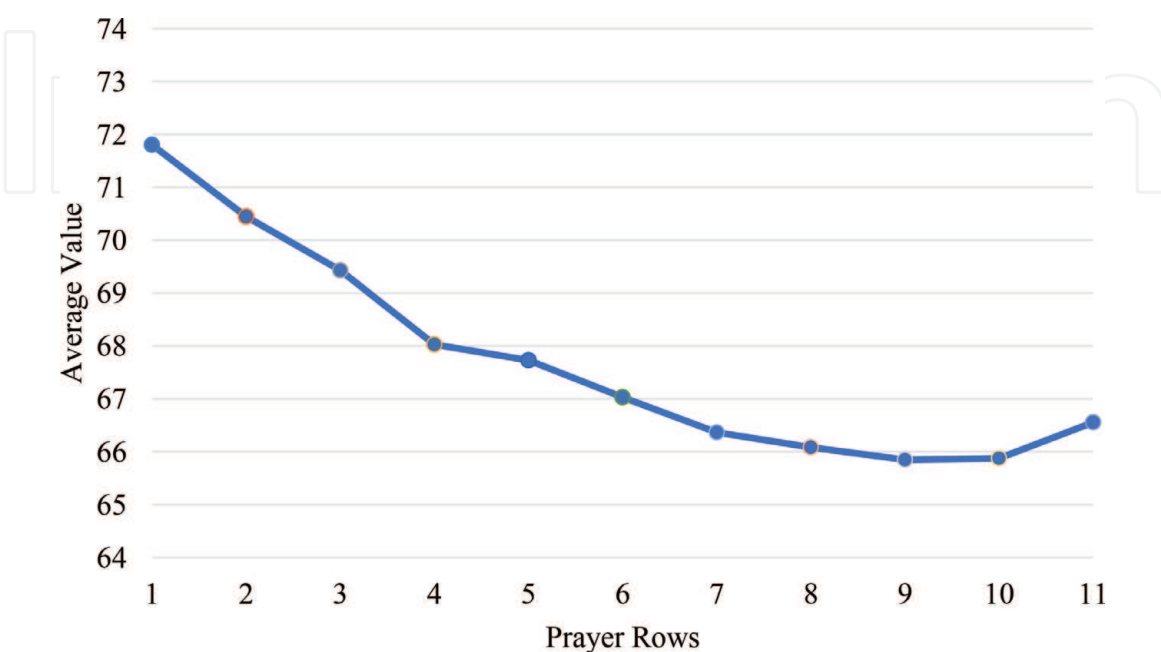


Figure 7.
 SPL average values for Othman Mihrab prayer rows.

Figure 7 presents the SPL average values for prayer rows of Othman Mosque Mihrab geometry. The SPL average values are varying from 71 to 66 dB. The first prayer row has the highest SPL average value due to the sound source position. The SPL average values gradually decrease from the first prayer row to the lowest SPL average values at the ninth and tenth prayer rows. Moreover, the SPL average values are noticeably higher at the last portion which is found at the eleventh prayer row. The average SPL value of this Mihrab geometry for 121 sound receiving points on mosque prayer rows is 0.70 dB.

3.3 Chinese Mihrab geometry SPL analysis

Figure 8 shows the SPL values of Chinese Mihrab geometry. The SPL values are varying from 49 dB to 73 dB on the plan reference to SPL scale. **Figure 8** presents the scattered sound distribution of Chinese Mihrab geometry. The yellow-highlighted area (60 dB–73 dB) covers 62% of mosque floor plan. In general, this Mihrab geometry is a good sound distributor for the square and the rectangular mosques. The sound effect of this Mihrab is approximately the same as the Othman's Mihrab. **Figure 9** presents SPL average values for prayer rows of Chinese Mosque Mihrab geometry. The SPL average values are varying from 72 dB to 66 dB. The first prayer row has the highest SPL average value. The SPL average values are progressively decreasing from the first prayer row toward the tenth prayer row which has the lower SPL average value. The SPL average value steadily increases from the tenth to the last/eleventh prayer row. The average SPL value of this Mihrab geometry for 121 sound receiving points on mosque prayer rows is 0.70 dB.

3.4 Almoravid Mihrab geometry SPL analysis

Figure 10 demonstrates the SPL values of Almoravid Mihrab geometry. The SPL values are varying from 47 to 72 dB on the plan reference to SPL scale. Almoravid Mihrab has an octagonal shape. Almoravid Mihrab geometry has three

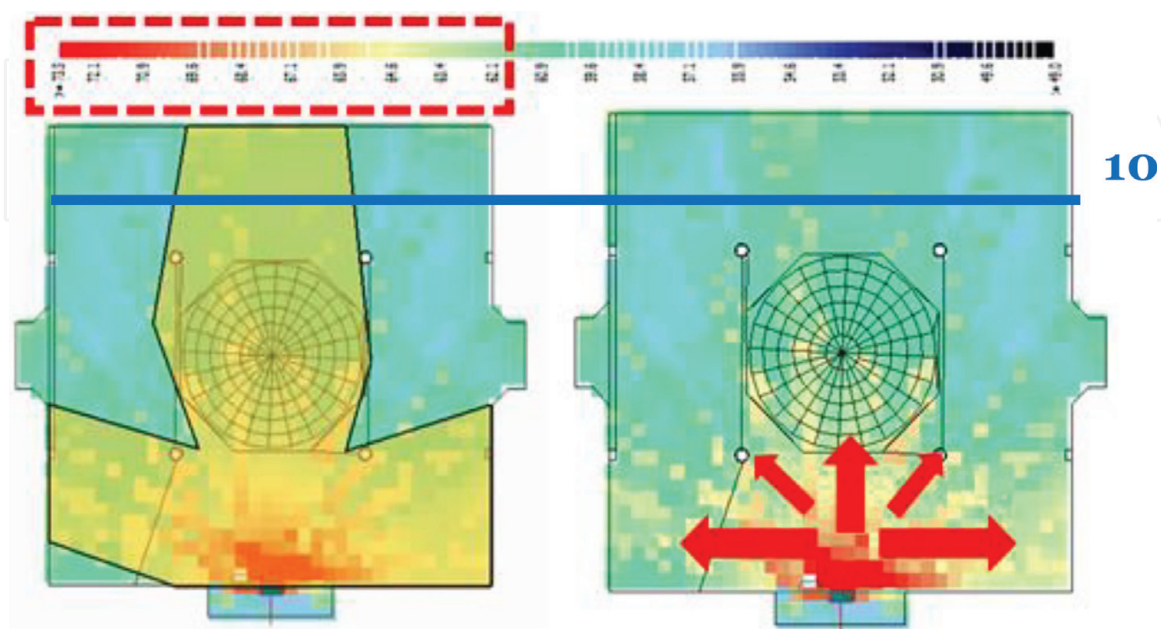


Figure 8.
SPL contour values for the Chinese Mihrab at 1 kHz.

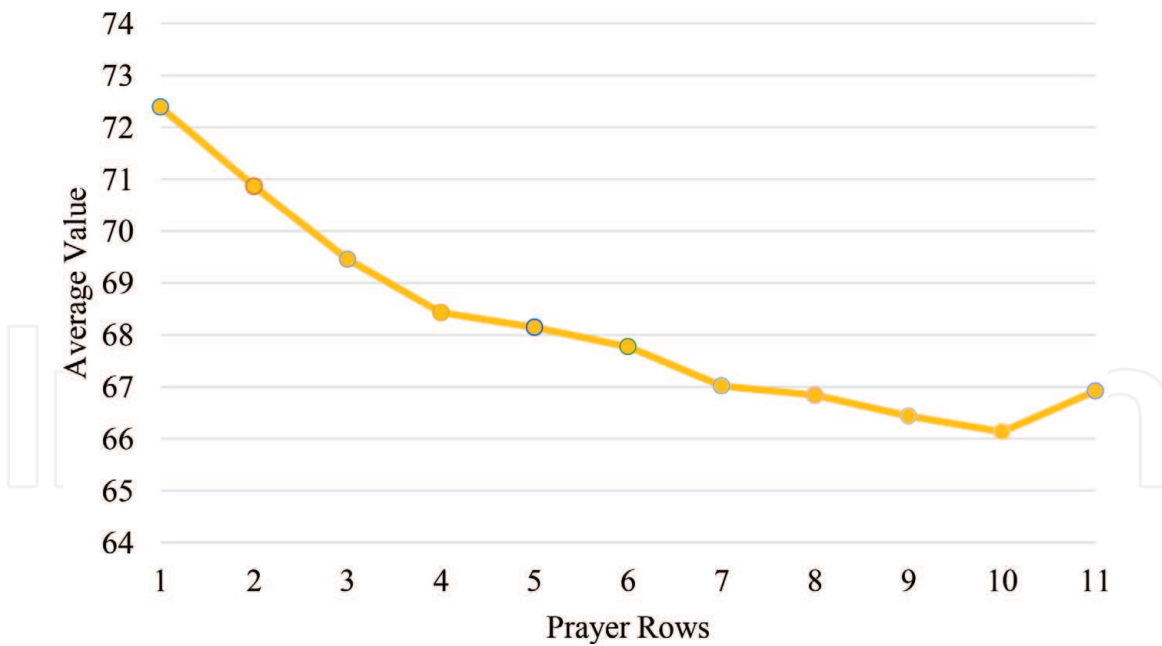


Figure 9.
 SPL average values for Chinese Mihrab prayer rows.

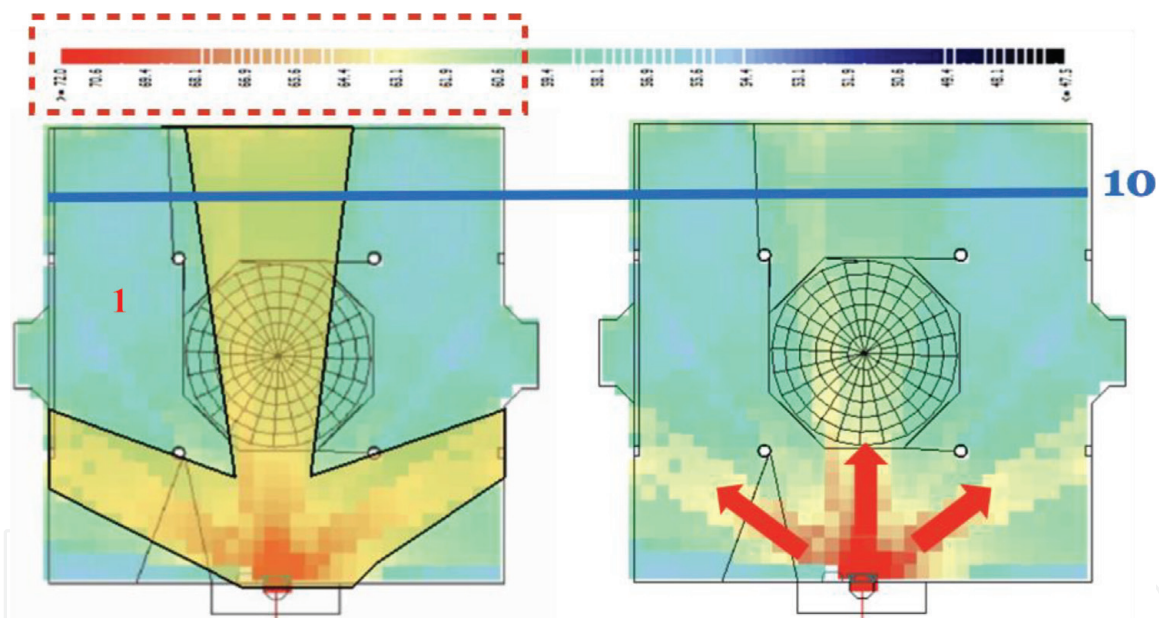


Figure 10.
 SPL contour values for Almoravid Mihrab at 1 kHz.

main sound directions and very lower SPL dB throughout most of the floor plans. The sound effect of this Mihrab appears clearly at the center and the near sides of the mosque. The yellow-hatched (60–72 dB) area is 43% of plan surface. Almoravid Mihrab shape has generally low sound coverage on mosque receiving points.

Figure 11 illustrates SPL average values for prayer rows of Almoravid Mosque Mihrab geometry. The SPL average values are varying from 70.5 to 6.5 dB. The highest SPL average value is found at the first prayer row, and then it is gradually decreasing toward the tenth prayer row. Also, there is a little increase of SPL average value from the tenth to the eleventh prayer row. The average SPL value of this Mihrab geometry for 121 sound receiving points on mosque prayer rows is 0.65 dB.

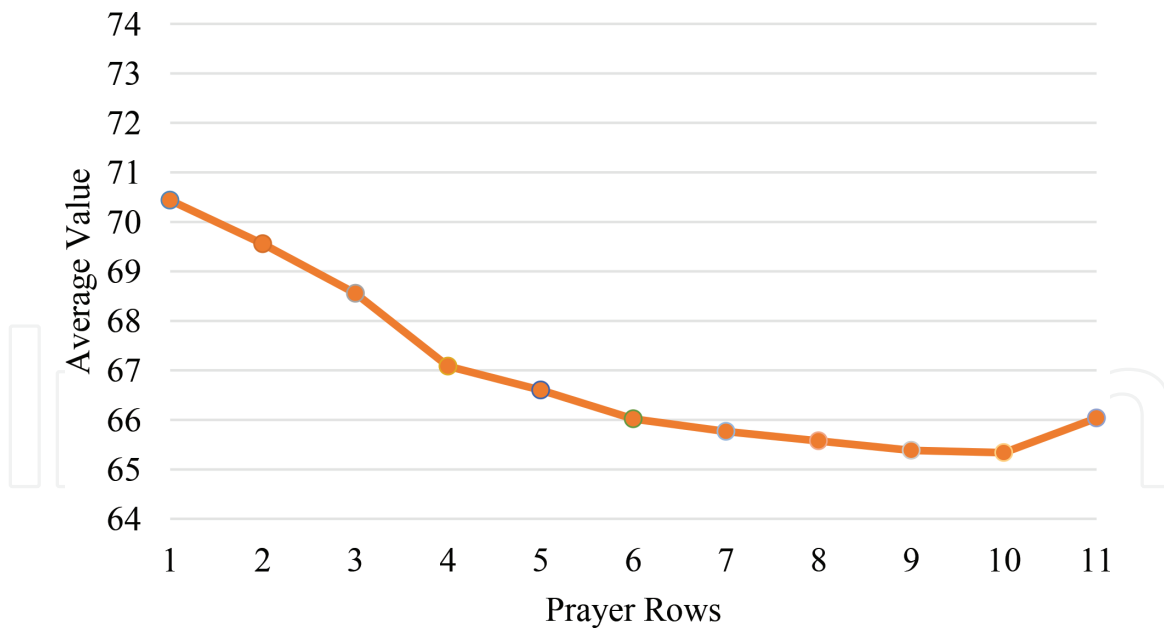


Figure 11.
SPL average values for Almoravid Mihrab prayer rows.

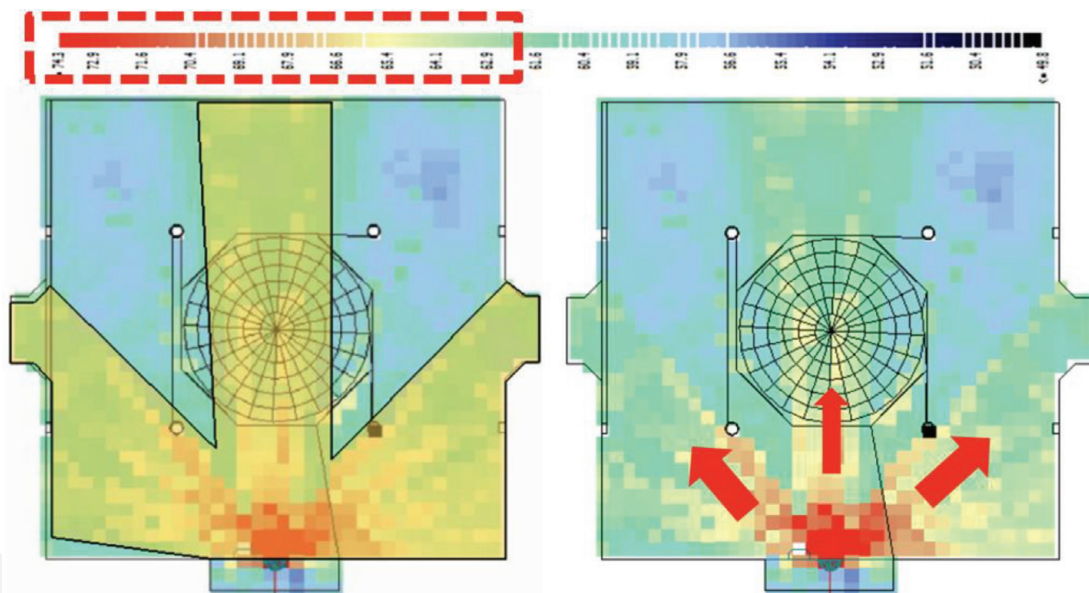


Figure 12.
SPL contour values for Safavid Mihrab at 1 kHz.

3.5 Safavid Mihrab geometry SPL analysis

Figure 12 shows the SPL values of Safavid Mihrab geometry. As shown in **Figure 12**, SPL values are varying from 49 to 77 dB. The highest SPL values are found in the area nearby Imam position (sound source) which is the first three prayer rows in general. The highlighted area covers 58% of the floor plan with good SPL values (60–74 dB). The maximum diffusion effect is located at the center and the first half area of the mosque. For that reason, Safavid Mihrab can have a good acoustic performance for the rectangular floor plan geometry mosques due to the main directions of sound reflection (red arrows).

Figure 13 presents SPL average values for prayer rows of Safavid Mosque Mihrab geometry. The average values vary from 37 to 66 dB. High SPL values are observed at the first prayer row and start decreasing till the tenth prayer row. The lowest average value is found at the tenth prayer row. Moreover, slight SPL average

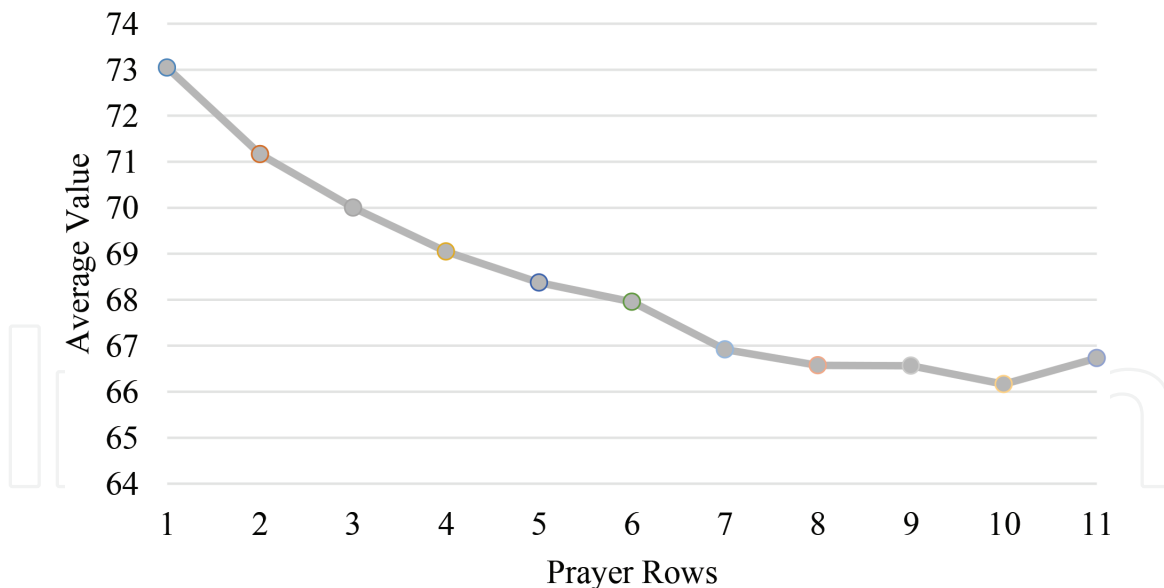


Figure 13.
 SPL average values for Safavid Mihrab prayer rows.

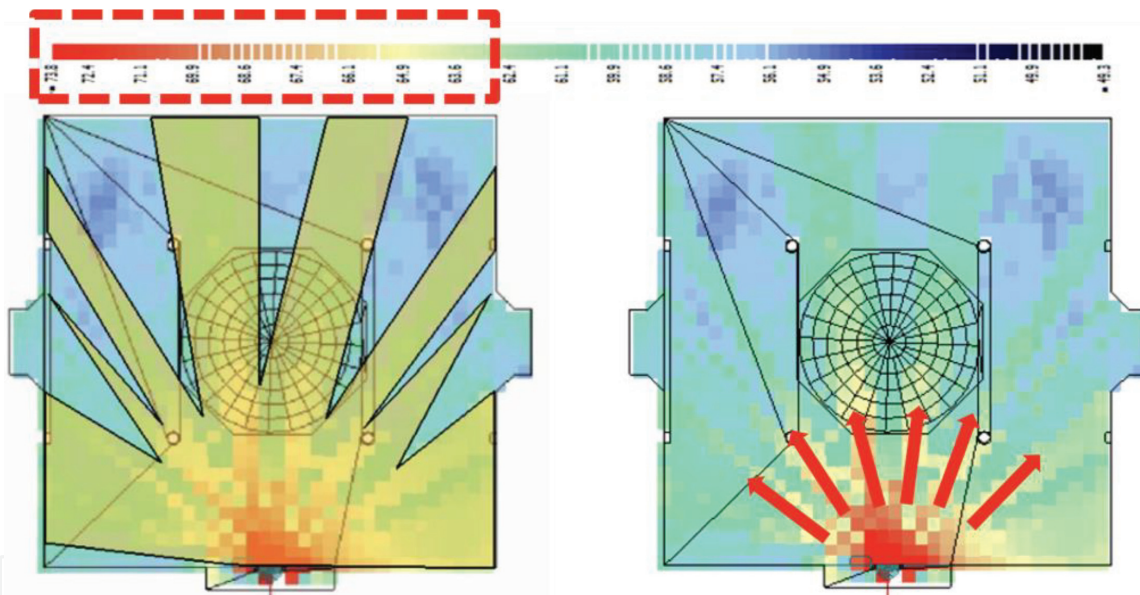


Figure 14.
 SPL contour values for Umayyad Mihrab at 1 kHz.

value increment is noticed from the tenth to the last/eleventh and ninth prayer rows. The average SPL value of this Mihrab geometry for 121 sound receiving points on mosque prayer rows is 0.70 dB.

3.6 Umayyad Mihrab geometry SPL analysis

Figure 14 shows the SPL contours and SPL values for all proposed receiver points obtained by Umayyad Mihrab geometry. This Mihrab has a semicircle form as the IAU Mihrab. The main difference between the two Mihrabs is the architectural decorations and the top end of the Mihrab. For that, the results obtained by Umayyad Mihrab geometry are completely different from that obtained by the IAU Mihrab. Umayyad Mihrab diffuses the sound energy in a semicircle form, where the highest SPL values are found at the first three prayer rows nearby Imam position (sound source). The yellow-hatched area is covering 67% of floor plan area with

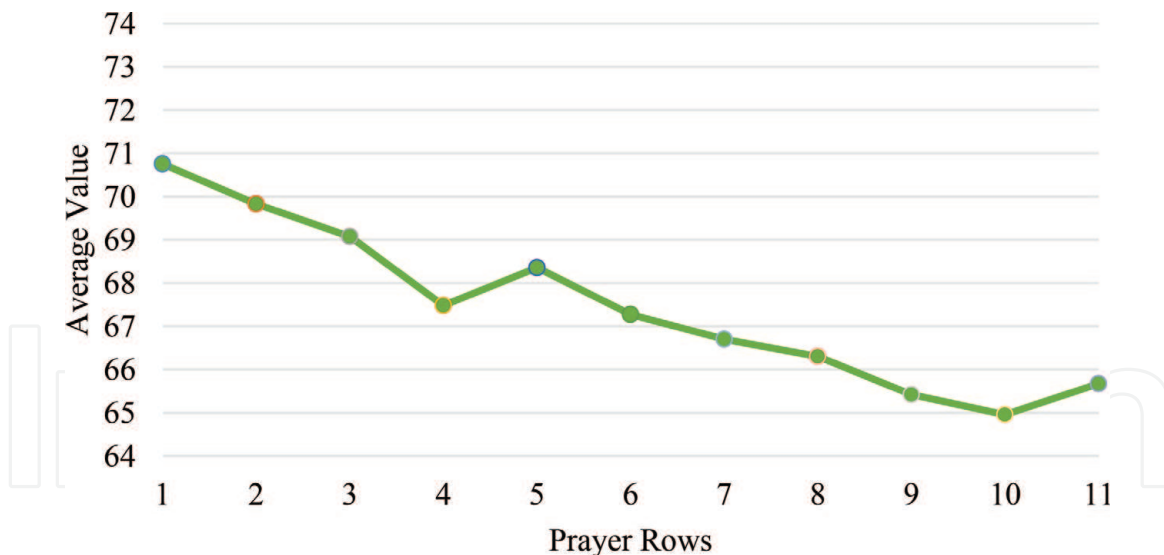


Figure 15.
SPL average values for Umayyad Mihrab prayer rows.

high SPL values ranging from 60 dB to 73 dB. Generally, this shape has scattered sound distribution on the floor geometry; thus, it is suitable for rectangular and square floor plans.

Figure 15 presents SPL average values for prayer rows of Umayyad Mosque Mihrab geometry. The average values vary from 70 to 65 dB. The first prayer row receives the highest SPL average value and then starts decreasing gradually toward the fourth prayer row. Moreover, the SPL average value is recovered at the fifth prayer row which has higher value than the fourth prayer row. The SPL average value progressively falls from the fifth to the tenth prayer row which receives the lowest average values. Another recovery on SPL average value is at the eleventh prayer row which has higher value than the tenth prayer row. The average SPL value of this Mihrab geometry for 121 sound receiving points on mosque prayer rows is 0.65 dB.

3.7 Umayyad Spain Mihrab geometry SPL analysis

Figure 16 depicts the SPL contours and SPL values for all receiver points obtained by Umayyad Spain Mihrab geometry. As Almoravid, Spanish Umayyad Mihrab has an octagonal shape. The top end of this Mihrab is different from that of Almoravid Mihrab. As shown in **Figure 16**, this slight difference caused an increase of sound energy especially on the left side of the mosque. The highest SPL values are found at the first three prayer rows due to the proximity to the sound source as well as the middle portion of each prayer row (behind Imam position). The yellow-hatched area covers 58% of the mosque floor plan with high SPL values that range from 72 to 60 dB. Moreover, this figure shows the three main sound directions of Mihrab geometry, which are good for rectangular floor plan. **Figure 17** presents SPL average values for prayer rows of Umayyad Spain masjid Mihrab geometry. The average values vary from 71 to 65 dB. The highest SPL average value is at the first prayer row and starts decreasing gradually toward the tenth prayer row. Slight increment in SPL average value is found at the last/eleventh prayer row.

3.8 Mughal Mihrab geometry analysis

Figure 18 illustrates the SPL values of Mughal Mihrab geometry. The SPL values are varying from 49 to 73 dB on the plan reference to SPL scale in **Figure 18**. The

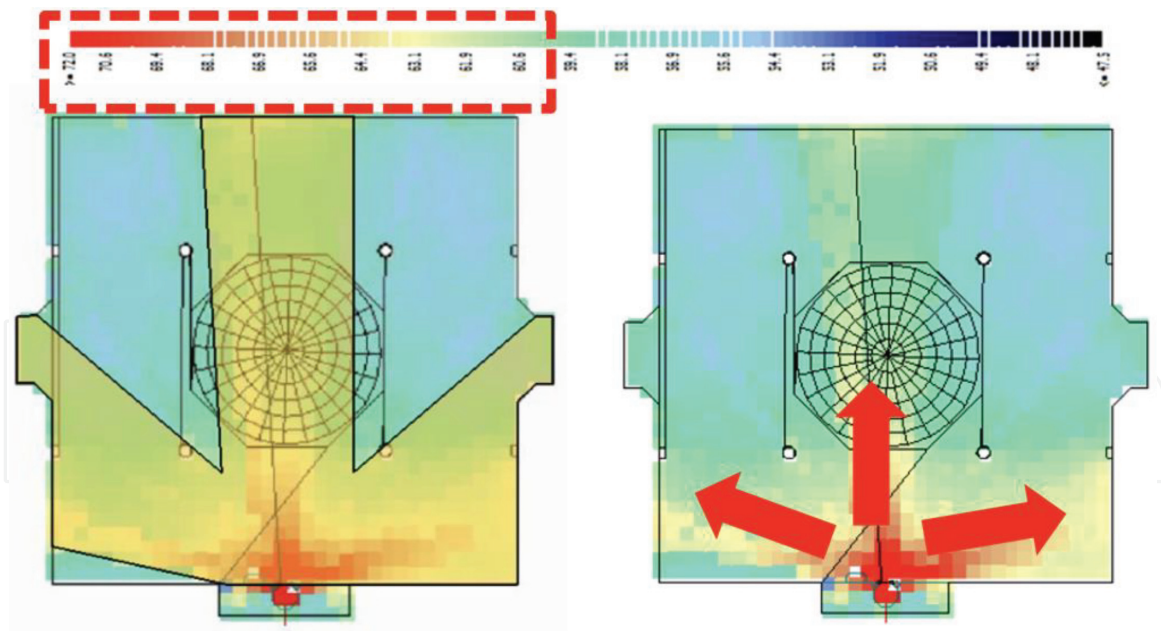


Figure 16.
 SPL contour values for Spanish Umayyad Mihrab at 1 kHz.

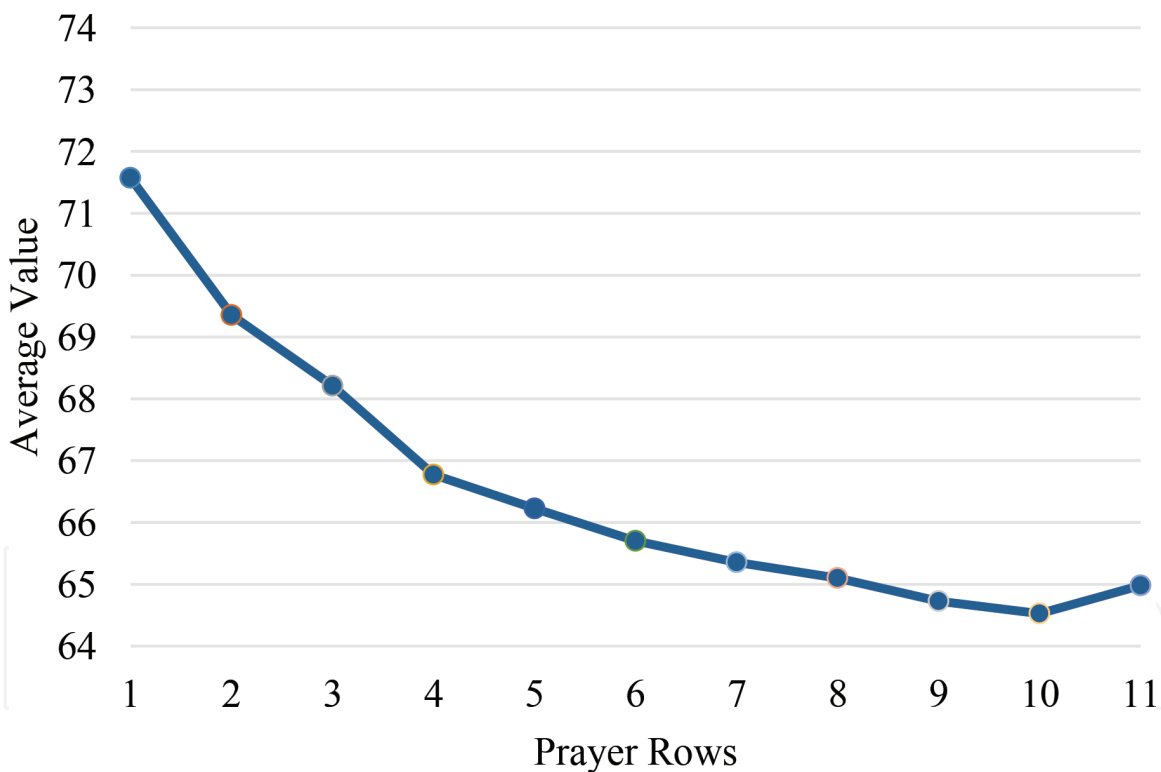


Figure 17.
 SPL average values for Umayyad Spain Mihrab prayer rows.

SPL pattern shows nonsymmetrical sound distribution all over the floor plan. The yellow-highlighted area covers 69% of floor plan with high SPL values that range from 73 to 60 dB. Contrary to previous shapes, this shape covers most of floor plan area with high SPL values, which is suitable for most floor plan geometries. **Figure 19** shows SPL average values for prayer rows of Mughal masjid Mihrab geometry. The average values vary from 72 to 66 dB. Besides, the highest SPL average value is received by the first prayer row and then decreases sharply of average values toward the fourth prayer row. There is a slight decrease of average values from the fourth to the seventh prayer row. The seventh, eighth, and eleventh

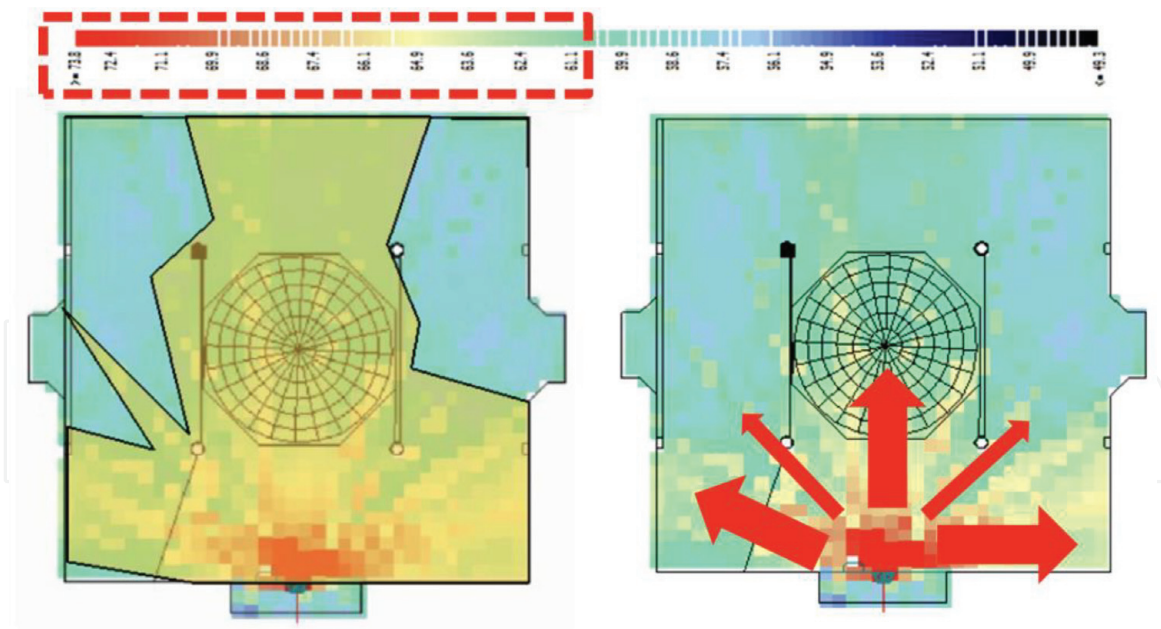


Figure 18.
SPL contour values for Mughal Mihrab at 1 kHz.

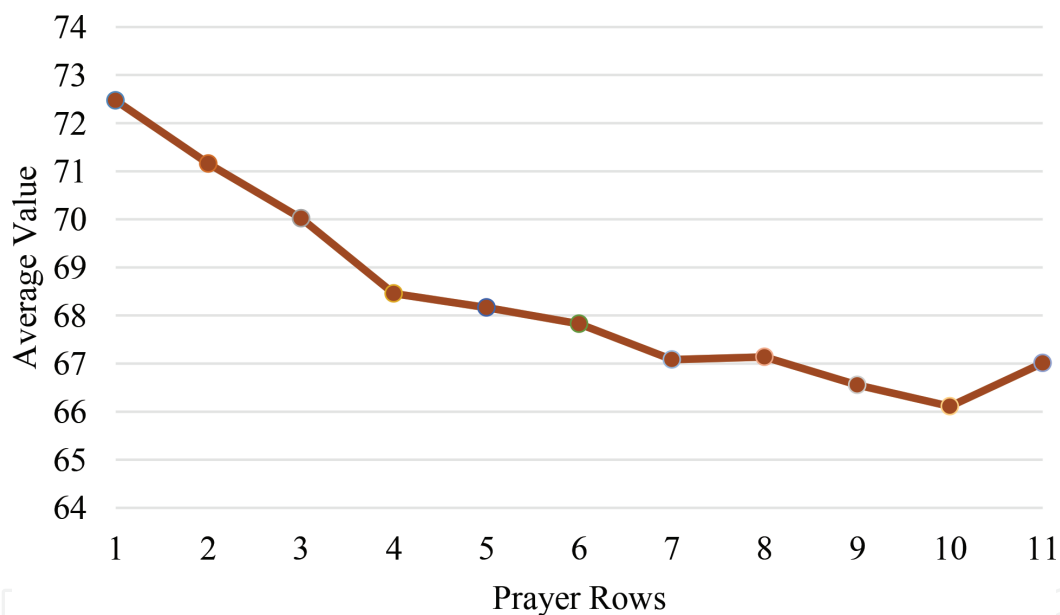


Figure 19.
SPL average values for Mughal Mihrab prayer rows.

prayer rows have the same SPL average values. The lowest average values are found at the tenth prayer row.

3.9 Abbasid Mihrab geometry analysis

Figure 20 shows SPL contour obtained by the Abbasid Mihrab. This Mihrab provides a very high SPL values on all floor area. The SPL values are varying from 49 dB to 73 dB on the plan reference to SPL scale in **Figure 20**. The SPL pattern shows nonsymmetrical sound distribution all over the floor plan. The yellow-highlighted area covers 69% of floor plan with high SPL values that range from 73 to 60 dB. Contrary to previous shapes, this shape covers most of floor plan area with high SPL values, which is suitable for most floor plan geometries.

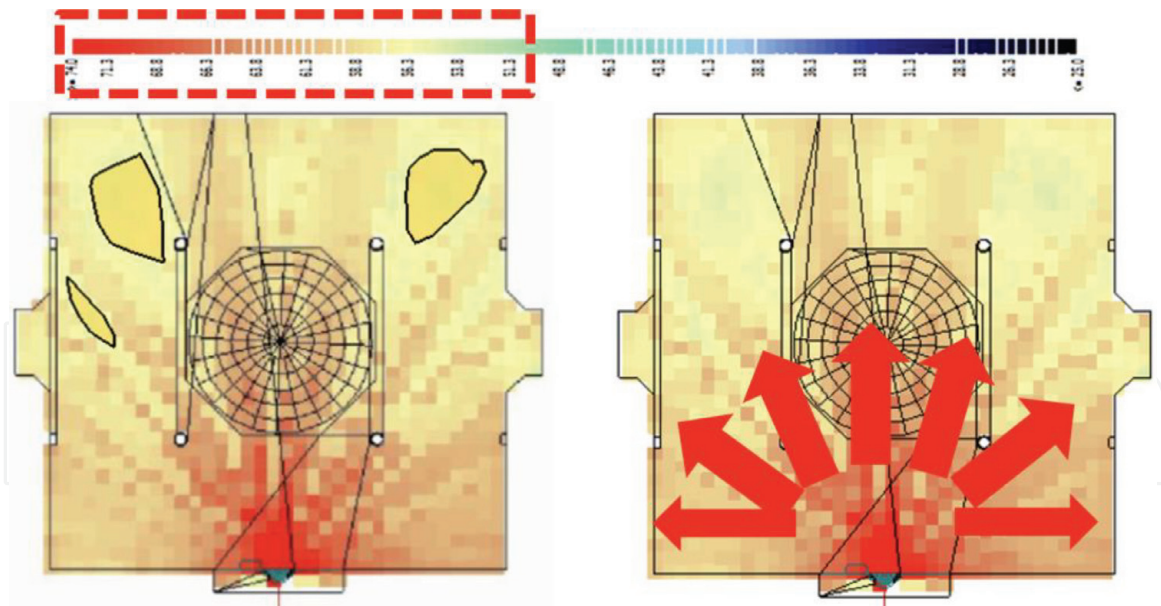


Figure 20.
 SPL contour values for Abbasid Mihrab at 1 kHz.

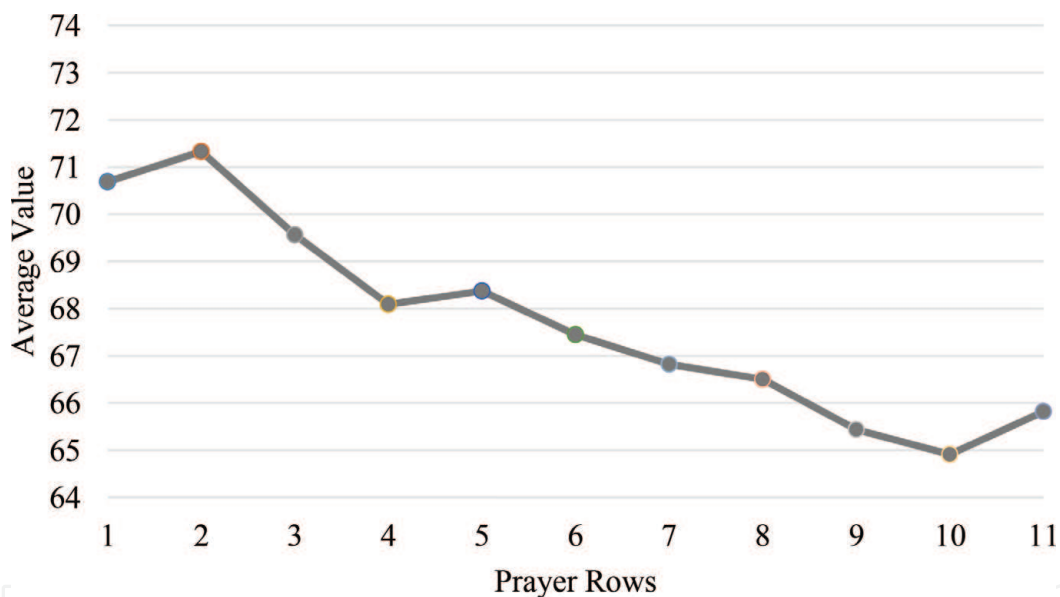


Figure 21.
 SPL average values for Abbasid Mihrab prayer rows.

Figure 21 illustrates SPL average values for prayer rows of Abbasid Mihrab geometry. The average values vary from 71 to 65 dB. High and low levels of SPL values are shown from the first to the fifth row. Highest SPL average value is found at the second prayer row where it is higher than the first prayer row. In addition to that, the lowest SPL average value is found in the tenth prayer row. From the sixth to the tenth prayer rows, SPL average values are gradually decreasing to the lowest SPL average value.

3.10 SPL analysis for Tulunid Mihrab geometry

Figure 22 presents the SPL values of Tulunid Mihrab geometry. The SPL values are varying from 49 to 74 dB on the plan reference to SPL scale. It is observed that

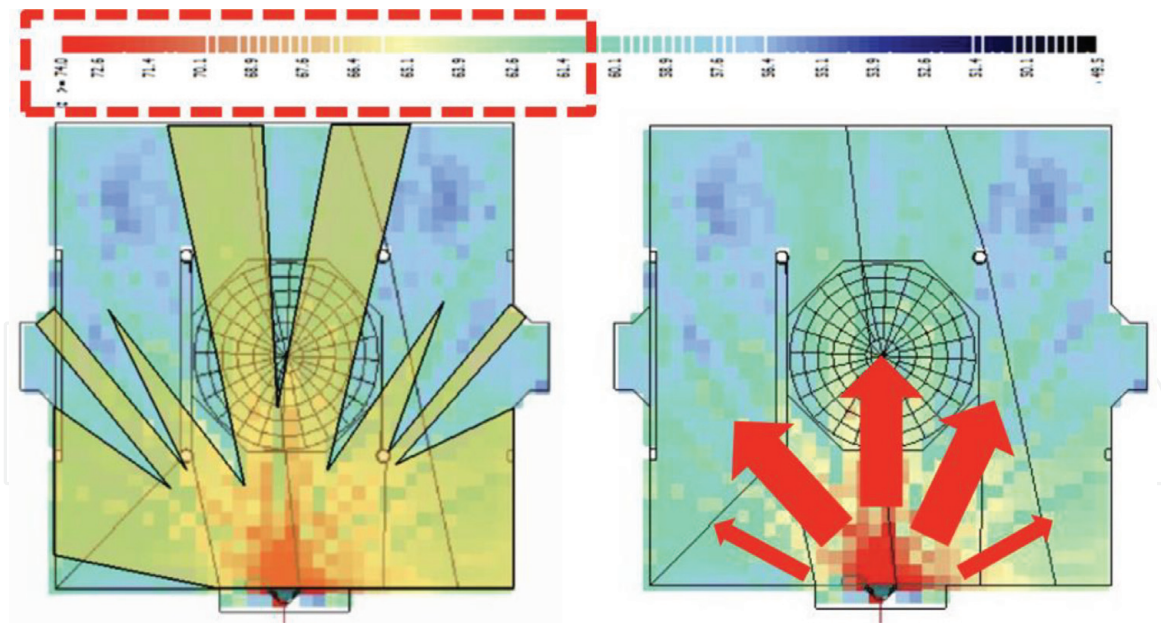


Figure 22.
SPL contour values for Tulunid Mihrab at 1 kHz.

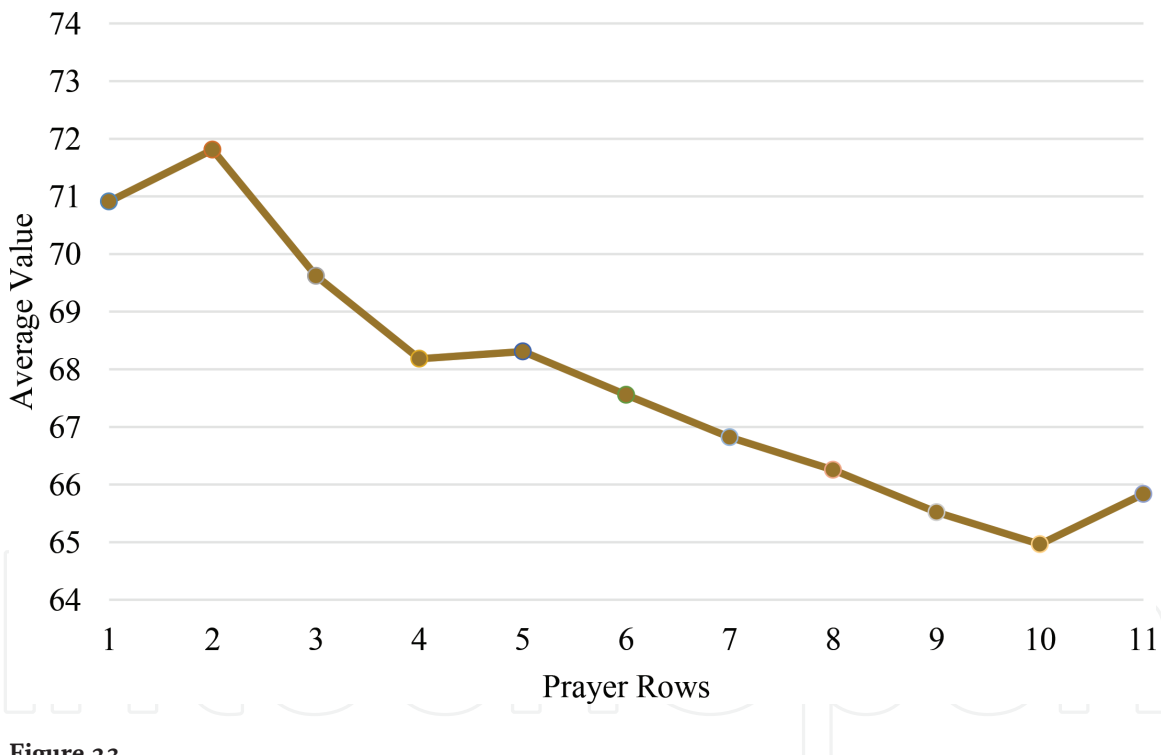


Figure 23.
SPL average values for Tulunid Mihrab prayer rows.

Tulunid Mihrab shape has symmetrical sound distribution and yellow-hatched area covers 57% of Mosque floor plan area with high SPL values that range from 74 to 60 dB. Moreover, Tulunid Mihrab shape is suitable for the square floor plan geometry. **Figure 23** illustrates SPL average values for prayer rows of Tulunid Mosque Mihrab geometry. The average values vary from 72 to 65 dB, and high and low levels of SPL values are shown from the first to the fourth prayer row. Peak of SPL average value is found at the second prayer row where it is higher than the first prayer row. In addition, the lowest SPL average value is found in the tenth prayer row. From the fifth to the tenth prayer row, SPL average values are gradually decreasing to the lowest SPL average value. The average SPL value of this Mihrab geometry for 121 sound receiving points on mosque prayer rows is 0.70 dB.

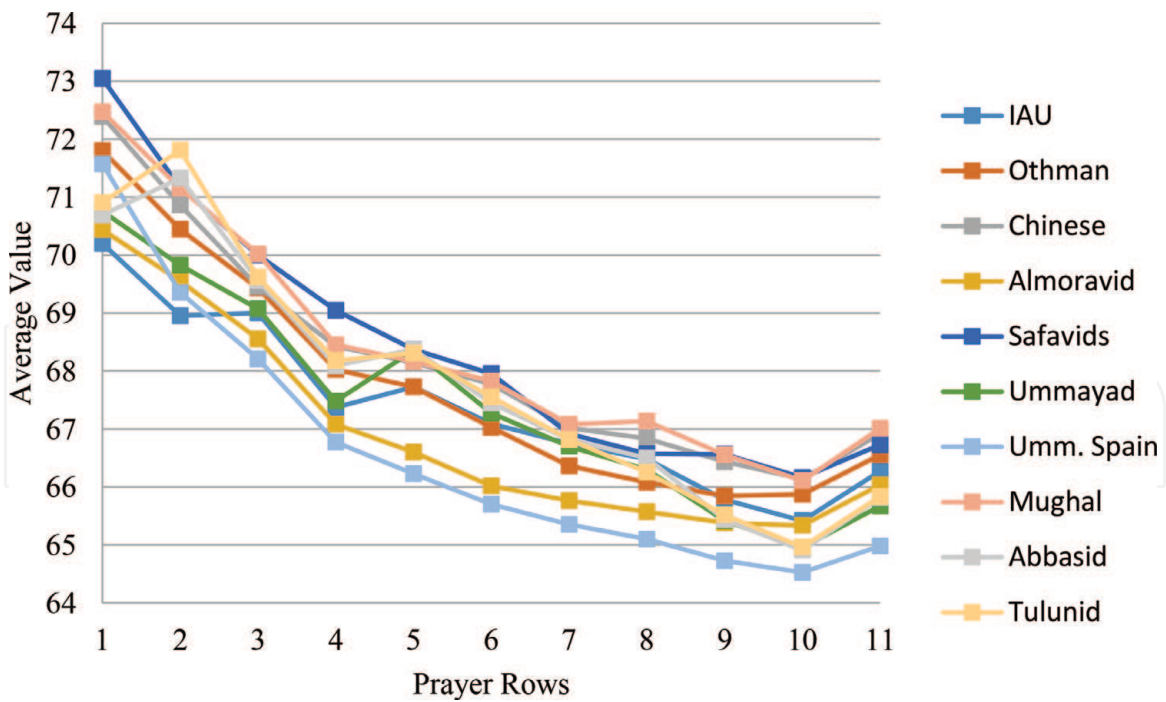


Figure 24.
 SPL prayer rows' average values, for all studied Mihrab.

3.11 Overall evaluation

As shown in **Figure 24**, the SPL average values for the Mihrab geometries are studied. In general, the SPL average values show good (greatest) values at the first prayer row, progressively decrease to the tenth prayer row, and then increase to the eleventh prayer row. Moreover, at the first four prayer rows, the Safavid has the highest average values and base case mosque has the lowest. Safavid and Mughal have high SPL average values at the first three rows as well, and the rest of geometries still receive good SPL average values. Furthermore, from the fourth toward the sixth prayer row, the Safavid still receives the highest average value besides Tulunid, Mughal, and Umayyad Mihrab geometries. Almoravid and Umayyad Spain Mihrab geometries have the lowest SPL average values among other geometries in this area. At the same portion, other geometries have higher SPL average values, which are close to the highest average values. From the sixth to the ninth prayer row, the receiving points decrease when we go far from sound source. Mughal Mihrab geometry has the best SPL average values at these rows as well as Chinese, Safavid, and Abbasid geometries. The worst SPL values at these prayer rows are found for Almoravid and Umayyad Spain Mihrab shapes. From the ninth to the eleventh prayer rows, Safavid and Othman receive the highest SPL average values, while the lowest (worst) values are for Tulunid, Abbasid and Umayyad Spain.

In order to clarify further on the acoustic performance of the studied geometries and to rank them accordingly, they are graded based on the total SPL average

| SPL Average Values Grades | | | | | | | | | | |
|---------------------------|----|----|----|----|----|----|----|----|----|----|
| Grade | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| SPL Value | 85 | 80 | 75 | 70 | 65 | 60 | 55 | 50 | 45 | 40 |

Table 3.
 SPL average value grade key table.











| Prayer Rows | Mihrab Geometries | | | | | | | | | |
|------------------|---|---|---|---|---|--|---|---|---|---|
| | Base Case | Othman | Chinese | Almoravid | Safavids | Umayyad | Umayyad Spain | Mughal | Abbasid | Tulunid |
| |  |  |  |  |  |  |  |  |  |  |
| 1 st | 70 | 70 | 70 | 70 | 75 | 70 | 70 | 70 | 70 | 70 |
| 2 nd | 70 | 70 | 70 | 70 | 70 | 70 | 70 | 70 | 70 | 70 |
| 3 rd | 70 | 70 | 70 | 70 | 70 | 70 | 70 | 70 | 70 | 70 |
| 4 th | 65 | 70 | 70 | 65 | 70 | 70 | 65 | 70 | 70 | 70 |
| 5 th | 70 | 70 | 70 | 65 | 70 | 70 | 65 | 70 | 70 | 70 |
| 6 th | 65 | 65 | 70 | 65 | 70 | 65 | 65 | 70 | 65 | 70 |
| 7 th | 70 | 65 | 65 | 65 | 65 | 65 | 65 | 65 | 65 | 65 |
| 8 th | 65 | 65 | 65 | 65 | 65 | 65 | 65 | 65 | 65 | 65 |
| 9 th | 65 | 65 | 65 | 65 | 65 | 65 | 65 | 65 | 65 | 65 |
| 10 th | 65 | 65 | 65 | 65 | 65 | 65 | 65 | 65 | 65 | 65 |
| 11 th | 65 | 65 | 65 | 65 | 65 | 65 | 65 | 65 | 65 | 65 |
| Total Grade | 50 | 50 | 49 | 52 | 48 | 50 | 52 | 49 | 50 | 49 |
| Rank | 3 rd | 3 rd | 2 nd | 4 th | 1 st | 3 rd | 4 th | 2 nd | 3 rd | 2 nd |

Table 4.
Total SPL average values, grades, and rank of the Mihrab geometries.

values by following the rule presented in **Table 3**. Based on this rule, the SPL average value at each prayer row was assigned the grades which were summed up to obtain the total grade for each geometry. A lower total grade indicates higher SPL average value, which means a good acoustic performance; accordingly, the geometries were ranked by assigning the first rank for the lowest total grade and lower ranks for higher total grades, as tabulated in **Table 4**. It is obvious from **Table 4** that Safavid Mihrab geometry has the highest and best SPL average value, which is the best value for the first prayer row among the study of Mihrab geometries. Chinese, Mughal, and Tulunid Mihrab geometries have the second best performance in the study, and the worst performance is for Almoravid Mihrab geometry with 52 grades.

4. Conclusion

The Mihrab geometry has always been one of the major features in mosque's architecture, which directly affect the sound quality inside the prayer hall. This sound quality has been tested and simulated in a typical mosque within the Abdulrahman Bin Faisal University campus using 10 principal Mihrab shapes as a

variable parameter in correlation with the fixed mosque shape and volume. Out of the 10 geometries studied, the Safavid Mihrab geometry can provide the best acoustic performance inside the mosque, followed by Chinese, Mughal, and Tulunid, while the Almoravid geometry shows the worst performance. Thus, the present study has established that the geometry of the Mihrab, as an Islamic architectural feature, can have a direct positive or negative impact on the sound quality within a prayer hall.

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