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ORIGINAL RESEARCH ARTICLE

Acoustic pollution in the urban area of the municipality of Kaçanik (2023–2024)

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Abstract

In modern times, technological development, new tools, and the replacement of outdated equipment have brought numerous benefits, but they also carry negative aspects. Acoustic pollution originates from multiple sources, including road, rail, and air transport; agricultural and industrial equipment; generators, air conditioning devices, and lighting systems (particularly in commercial establishments); automotive workshop tools; and the uncontrolled high music volume in gastronomic venues. These sources represent some of the acoustic pollutants affecting the urban area of the Municipality of Kaçanik. This study systematically assesses noise levels in the urban area of the Municipality of Kaçanik (Kosovo) during January and December 2023, and August and September 2024. Noise sources included loud music and other activities within gastronomic establishments, as well as external influences from road and rail traffic. Indoor noise measurements were conducted at four selected hospitality establishments using a Lutron SL-4012 sound level meter. The recorded noise levels ranged from 55.6 to 99.9 dB(A), while the mean values across the four locations and monitoring periods ranged from 66.80 to 88.02 dB(A). These findings indicate that indoor environments of gastronomic establishments are associated with elevated noise levels, highlighting the importance of monitoring acoustic conditions in such settings. These findings underscore the need for improved noise monitoring and management and provide preliminary spatial evidence on the distribution of the investigated measurement locations in Kaçanik. The study serves as a reference for local authorities to enhance monitoring and enforce existing legislation.

Keywords: Acoustic pollution; Noise; Decibel; Measurement; Indoor environments; Urban area

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1. Introduction

Exposure to high noise levels adversely affects both mental and physical health. Noise pollution is an emerging issue in cities around the world.[1] According to the World Health Organization (WHO), environmental noise is a critical environmental health risk in Europe and, unlike several other environmental stressors, exposure to noise remains a

considerable public health concern.[2] It is now known that environmental noise harms human health and interferes with people's activities.[3]

In 2002, the European Union adopted an Environmental Noise Directive (EU Directive 2002/49/EC) establishing a common framework for the assessment and management of environmental noise.[4]

The European Noise Directive has not only been applied to European countries, but has also been used as a reference by non-European countries.[5-8] Recent research on leisure noise has focused on the effects of noise on people participating directly in leisure activities and on workers.[9-14]

However, data on acoustic pollution remain limited for the municipalities of Kosovo. This study focuses on the first urban zone of the Municipality of Kaçanik, as it concentrates a substantial proportion of the city's population, commercial facilities, and the majority of public facilities, including schools, family medical centers, and administrative buildings. Residents and visitors in urban areas may be exposed to multiple sources of environmental noise, including road traffic, commercial activities, and noise generated within gastronomic establishments. Vulnerable populations, including children and the elderly, are particularly affected by high noise levels, which have been associated with stress, anxiety, depression, and adverse effects on cognitive performance in children.

The economic implications of noise pollution are considerable, with substantial costs associated with healthcare and productivity losses, as well as negative effects on community cohesion and quality of life.[15] Prolonged exposure to noise-induced stress results in chronic inflammation and oxidative stress.[16]

Given the lack of data on noisy environments in Kosovo—particularly in smaller towns like Kaçanik—this research aims to assess indoor noise levels in several hospitality establishments within the urban area of Kaçanik. Four locations in the town's central area were selected for the study; noise measurements were taken, and the recorded values were compared against permissible legal limits. Measurements were conducted at different times and months of the year to evaluate variations in noise levels across these periods. Thus, the study provides data on indoor noise levels in hospitality venues and shows that exposure to high noise levels can occur even in relatively small towns like Kaçanik.

Consequently, the research questions in this study were: (i) What noise levels were observed in the selected restaurants in the urban area of Kaçanik, and how do the recorded noise levels compare with the relevant permissible limits? (ii) Do noise levels vary significantly across the four monitoring periods within each investigated location?

2. Materials and methods

2.1. Study area

The Municipality of Kaçanik is located in the southeastern part of Kosovo. It borders the municipalities of Ferizaj to the north, Viti to the northeast, Shtërpcë to the west, and Hani i Elezit to the south, covering an area of 211.4 km^2. The first urban zone is in the western part of Kaçanik's cadastral area, covering 38.68 ha (386,795.02 m^2) and housing a substantial portion of the urban population. The average annual temperature is 10.2 °C, with July being the warmest month (average 20.6 °C) and January the coldest month (average −1.4 °C). Road traffic influences the urban area, particularly along the highway and the national road, which are potential sources of environmental noise. These roads pass through or are near residential areas, increasing the relevance of environmental noise assessment in the municipality. According to the latest census in 2024, the Municipality of Kaçanik had a population of 27,716 inhabitants.[17]

Noise measurements were conducted at four selected hospitality venues on "Ismail Raka" Boulevard as shown in Figure 1: Location 1 (42°13′43″N, 21°15′26″E), Location 2 (42°13′46″N, 21°15′25″E), Location 3 (42°13′44″N, 21°15′25″E), and Location 4 (42°14′03″N, 21°15′22″E). The four investigated establishments were chosen in the central urban area of Kaçanik as an initial assessment of indoor noise conditions in gastronomic venues in a commercially active part of town. The selection was purposive rather than random, and only four establishments were sampled; therefore, the findings should not be taken to be representative of all gastronomic establishments in Kaçanik or of the municipality as a whole but rather site-specific baseline evidence for the locations and monitoring periods studied here. A larger and more geographically diverse sample of establishments would be required to assess broader representativeness of indoor noise conditions across the municipality.

2.2. Noise measurement procedure

The measurements were carried out between 16:00 and 20:00 during the monitoring periods of January and December 2023, as well as August and September 2024. At each location, noise was monitored over an 18-minute interval during each monitoring session. Four repeated three-minute measurements were performed, separated by two-minute pauses. Minimum and maximum noise levels were recorded during the measurements, and the values obtained from these repeated readings were used to

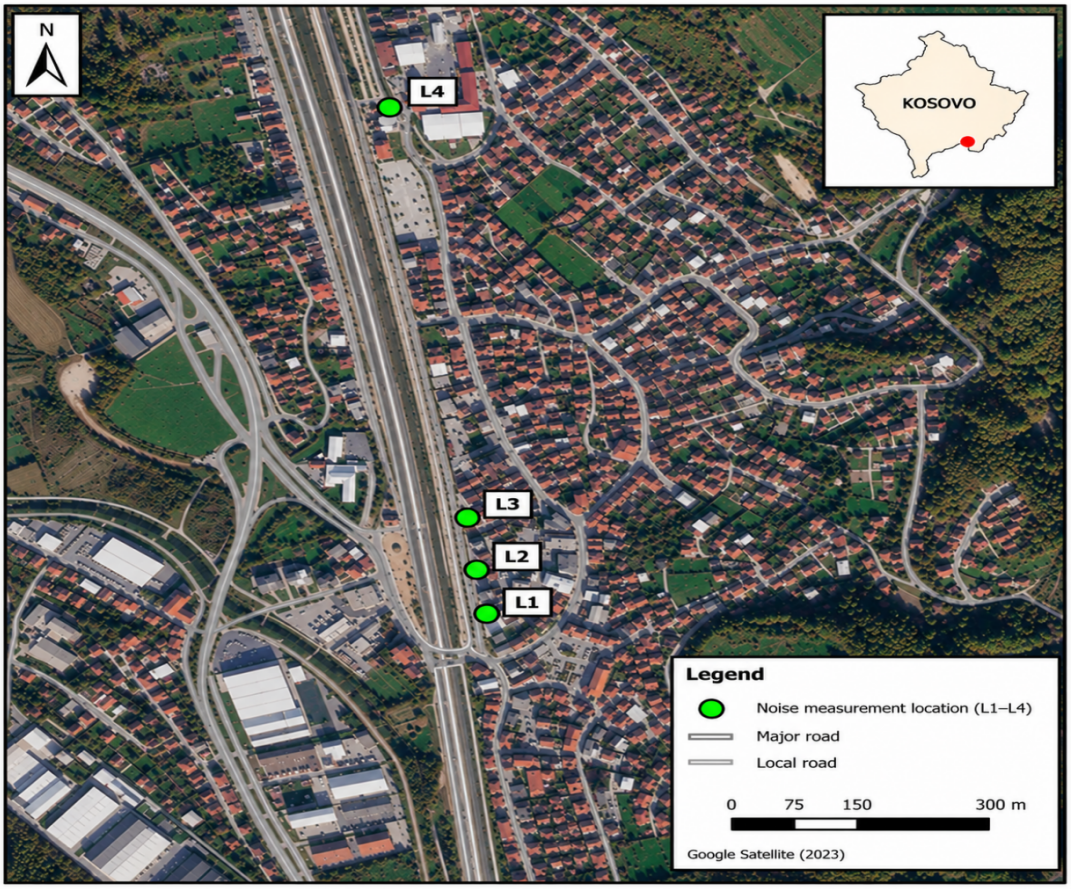


Figure 1. Location of the four noise measurement sites (L1–L4) in the urban area of Kaçanik

calculate the average value for each monitoring station.

2.3. Measurement equipment and quality control

All measurements were expressed in dB(A) using A-weighting, which reflects the sensitivity of human hearing to different frequencies. Measurements were taken using a Lutron SL-4012 (Lutron Electronic Enterprise Co., Ltd., Taiwan) sound level meter. The instrument complies with IEC 61672 Class 2 specifications and was calibrated at 94 dB. Measurements were conducted on six separate days within each monitoring month.

2.4. Data processing and statistical analysis

The recorded noise level data were organized according to location and measurement period. For each recorded minimum–maximum noise level pair, an arithmetic midpoint was calculated as $(L_{min} + L_{max})/2$. Differences in the distributions of daily midpoint values across the four monitoring periods were assessed separately for each location using the Kruskal–Wallis test. The measured noise values were compared against the limits set by applicable regulations, specifically Regulation No. 5307/2010 on Environmental Protection in the Municipality of Kaçanik. Specifically, Articles 27 and 28 establish noise limits of 55 dB during daytime and 45 dB during evening or nighttime hours for loud music in the circumstances specified by Regulation No. 5307/2010.[18]

3. Results

The measurement results obtained in this study indicate that noise levels in the indoor areas of gastronomic establishments in the urban area of the Municipality of Kaçanik are relatively high and, in some cases, exceed the recommended values for indoor environments. The descriptive statistics presented in Tables 1–4 show that mean noise levels in the analyzed locations ranged from 66.80 dB(A) to 88.02 dB(A), while the maximum recorded value was 99.9 dB(A). These findings suggest that, in certain instances, noise levels in these spaces can be substantial and potentially disturbing for users of the premises.

According to the WHO's recommendations, indoor noise levels in spaces where social activities take place should be approximately 55–65 dB(A) to ensure acoustic comfort and prevent adverse health effects.[2] Compared to these reference values, the results of this study indicate that, in most locations, the average noise levels exceeded the recommended limits.

This situation may affect interpersonal communication and the well-being of clients and staff who spend extended periods in these environments. Data analysis by location reveals that Location 3 consistently exhibited the highest noise levels compared to other sites. Spira-Cohen *et al.* have reported similar findings in their study examining noise levels in restaurants and bars.[19]

The results vary and are presented in Tables 1–4. In addition to differences observed between measurements on different days, noticeable variations were also measured between seasons. Measurements conducted during the summer period showed higher values compared to those taken during the winter period.

The January 2023 measurement results presented in Table 1 and Figure 2 indicate that noise levels at all four locations are significantly higher than the permissible evening limit of 45 dB(A), according to municipal regulations.[18] Recorded values exceeded the limit in all measured locations. At Location 1, noise levels ranged from 55.6 dB(A) to 75.7 dB(A). Even the minimum values were approximately 10 dB above the allowable limit, while the maximum values exceeded it by up to 30 dB(A), indicating a persistent presence of music and indoor activity.

In December 2023, noise levels at Location 1 ranged from 65.4 dB(A) to 83.0 dB(A), indicating substantial variation across the monitoring sessions (Table 2). At Location 2, recorded noise levels ranged from 63.7 to 88.0 dB(A), indicating considerable variability during the December monitoring period. Music and social activities may have contributed to these levels; however, their individual effects were not measured separately.

Location 3 recorded the highest mean noise level in December 2023 (88.02 ± 3.29 dB[A]), with individual readings ranging from 76.9 to 99.1 dB(A). At Location 4, recorded values ranged from 68.1 to 98.0 dB(A), with a mean of 80.63 ± 7.92 dB(A). Figure 3 illustrates the average indoor noise levels measured across the four locations in December 2023. These findings indicate elevated and variable indoor noise levels across the investigated establishments.

In August 2024, noise levels at Location 1 ranged from 56.7 to 78.8 dB(A), showing variability across the six monitoring sessions (Table 3). At Location 2, recorded

Table 1. Indoor noise measurements in January 2023

Measurement day	Location 1	Midpoint	Location 2	Midpoint	Location 3	Midpoint	Location 4	Midpoint	Unit of measurement
1	65.2–74.8	70.00	68.4–82.2	75.30	84.5–95.1	89.80	74.9–85.9	80.40	dB(A)
2	55.6–61.1	58.35	81.2–93.9	87.55	74.9–82.0	78.45	74.8–86.4	80.60	dB(A)
3	58.9–61.9	60.40	71.9–78.1	75.00	75.9–82.9	79.40	75.2–86.5	80.85	dB(A)
4	66.8–70.9	68.85	71.2–73.8	72.50	78.1–83.3	80.70	77.1–84.4	80.75	dB(A)
5	67.9–75.7	71.80	68.9–82.0	75.45	84.5–93.1	88.80	74.7–85.9	80.30	dB(A)
6	68.8–74.0	71.40	74.1–82.4	78.25	87.1–94.9	91.00	71.4–77.1	74.25	dB(A)
n	6		6		6		6		
Mean ± SD	66.80 ± 5.88		77.34 ± 5.32		84.69 ± 5.76		79.53 ± 2.59		dB(A)
95% CI	60.63–72.97		71.75–82.93		78.65–90.73		76.80–82.25		dB(A)

Abbreviations: CI: Confidence interval; *n*: Number of measurements; SD: Standard deviation.

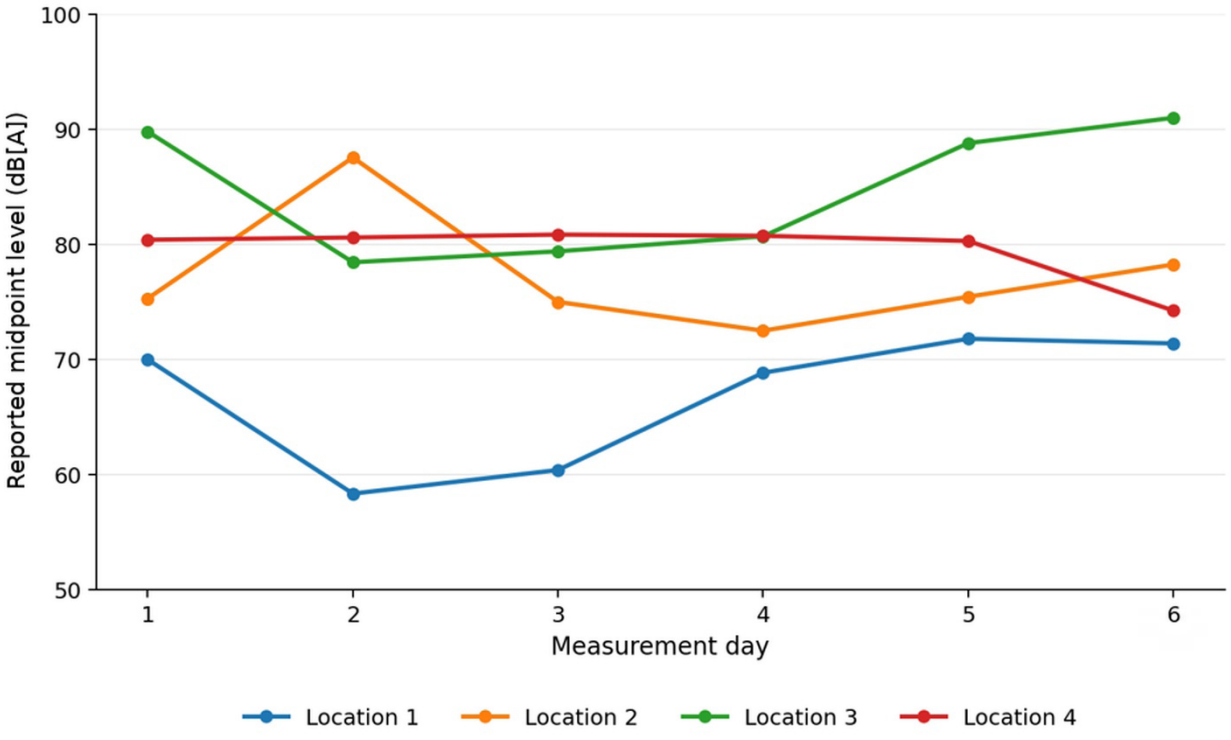


Figure 2. Indoor noise measurements in January 2023

Table 2. Indoor noise measurements in December 2023

Measurement day	Location 1	Midpoint	Location 2	Midpoint	Location 3	Midpoint	Location 4	Midpoint	Unit of measurement
1	69.3–79.9	74.60	70.5–79.1	74.80	86.1–94.9	90.50	79.2–84.8	82.00	dB(A)
2	66.6–83.0	74.80	64.6–71.9	68.25	76.9–98.7	87.80	81.5–82.9	82.20	dB(A)
3	65.4–80.2	72.80	74.7–81.1	77.90	83.1–95.9	89.50	85.1–98.0	91.55	dB(A)
4	67.1–77.8	72.45	79.2–88.0	83.60	82.8–99.1	90.95	84.8–85.6	85.20	dB(A)
5	68.2–71.8	70.00	72.7–81.4	77.05	79.9–84.0	81.95	68.6–73.9	71.25	dB(A)
6	69.2–72.4	70.80	63.7–78.1	70.90	85.9–89.0	87.45	68.1–75.1	71.60	dB(A)
n	6		6		6		6		
Mean ± SD	72.58 ± 1.94		75.42 ± 5.44		88.02 ± 3.29		80.63 ± 7.92		dB(A)
95% CI	70.53–74.62		69.71–81.13		84.57–91.48		72.32–88.95		dB(A)

Abbreviations: CI: Confidence interval; *n*: Number of measurements; SD: Standard deviation.

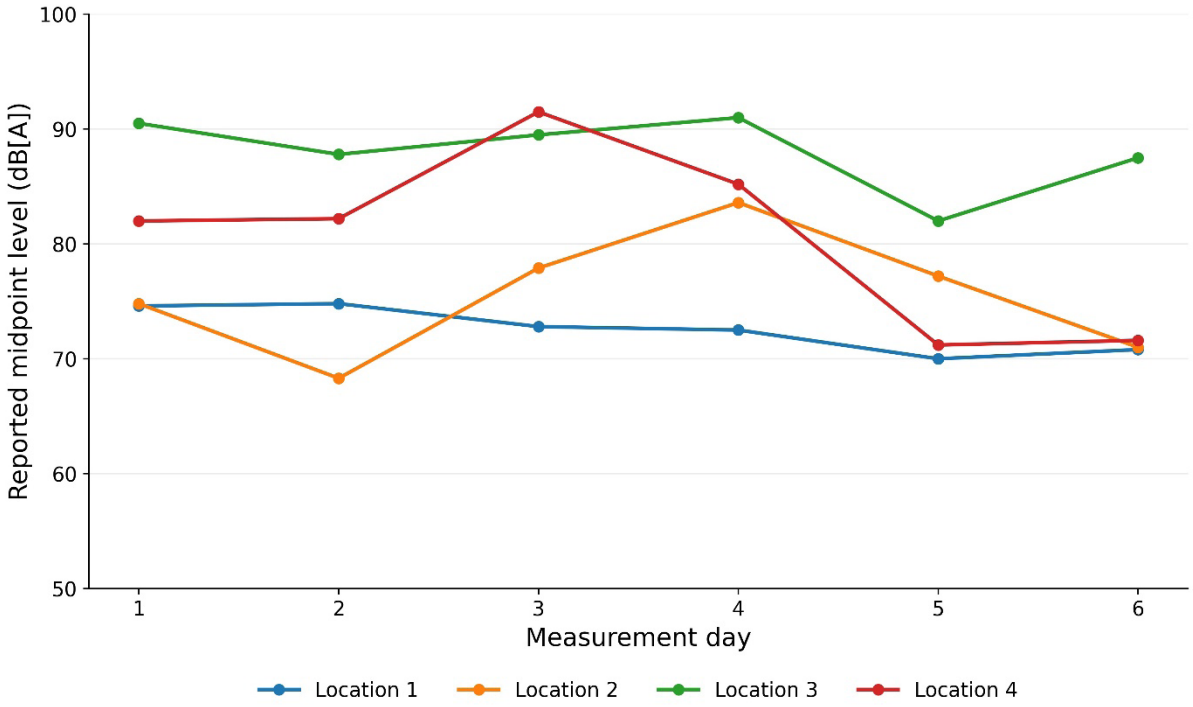


Figure 3. Indoor noise measurements at four locations in December 2023

noise levels ranged from 67.4 to 94.4 dB(A), with a mean of 77.93 ± 5.02 dB(A), indicating substantial variability across the six monitoring sessions. At Location 3, recorded noise levels ranged from 73.8 to 96.8 dB(A), with a mean of 85.41 ± 6.35 dB(A), representing the highest mean level among the four investigated locations in August 2024. At Location 4, recorded values ranged from 73.3 to 88.3 dB(A), with a mean of 80.99 ± 2.29 dB(A). Figure 4 illustrates the average indoor noise levels measured across the four locations in August 2024.

In September 2024, noise levels at Location 1 ranged from 64.0 to 85.3 dB(A) (Table 4). Even the minimum values were approximately 19 dB(A) above the permissible limit, while maximum levels reached up to 40 dB(A) above the limit, indicating persistent acoustic pollution. At Location 2, noise levels varied from 62.8 to 92.1 dB(A), with exceedances of approximately 47 dB(A). At Location 3, measured values ranged from 76.1 to 99.2 dB(A), indicating large exceedances up to 55 dB(A) of the permissible limit, reflecting high exposure to acoustic pollution. Noise levels at Location 4 ranged from 65.4 to 99.9 dB(A), with recorded values exceeding the regulatory limit by up to approximately 54 dB(A). Figure 5 illustrates the average indoor noise levels measured across the four locations in September 2024.

Green and Anthony[20] investigated occupational noise exposure among employees at six restaurants in a college town in the United States using National Institute for Occupational Safety and Health measurement criteria; they reported eight-hour time-weighted average noise exposures ranging from 69 to 90 dB(A), with an overall mean of 80 ± 4 dB(A). Approximately 8% of the assessed exposures exceeded the National Institute for Occupational Safety and Health-recommended occupational exposure limit of 85 dB(A). These findings highlight the relevance of noise exposure in gastronomic establishments. However, direct numerical comparisons with the present study should be interpreted cautiously, as Green and Anthony[20] assess personal occupational exposure over work shifts, whereas the present investigation reports arithmetic midpoints of minimum and maximum indoor sound levels recorded during shorter monitoring sessions.

A comparison of noise levels across the four periods showed that temporal variations differed depending on the location (Figure 6). Statistically significant differences between measurement periods were observed at Location 1 (Kruskal–Wallis: $H[3] = 10.21$, $p = 0.017$), whereas the other locations did not show significant differences (Table 5).

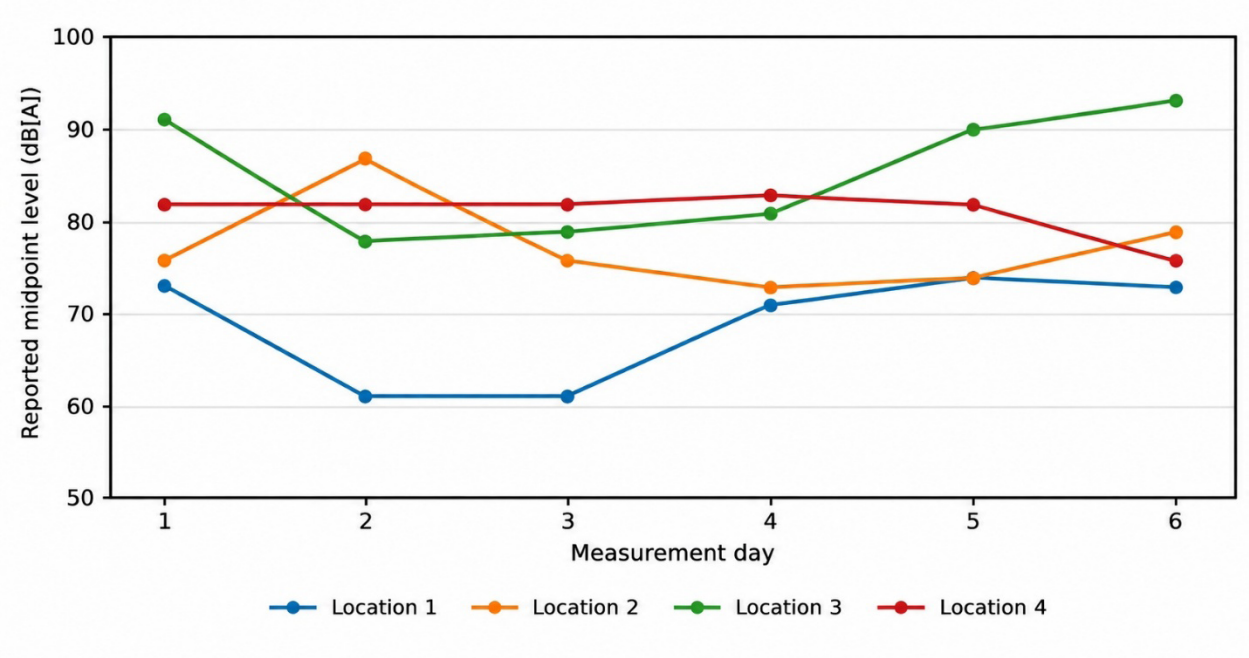


Figure 4. Indoor noise measurements at four locations in August 2024

Table 3. Indoor noise measurements in August 2024

Measurement day	Location 1	Midpoint	Location 2	Midpoint	Location 3	Midpoint	Location 4	Midpoint	Unit
1	67.8–78.8	73.30	68.8–83.2	76.00	85.5–96.3	90.90	75.7–87.5	81.60	dB(A)
2	56.7–65.2	60.95	80.2–94.4	87.30	73.8–83.1	78.45	75.7–87.5	81.60	dB(A)
3	57.9–63.9	60.90	72.7–80.0	76.35	74.8–84.3	79.55	76.1–87.2	81.65	dB(A)
4	67.5–73.9	70.70	72.7–74.7	73.70	77.9–84.5	81.20	79.0–86.3	82.65	dB(A)
5	69.9–78.0	73.95	67.4–81.8	74.60	83.9–95.5	89.70	75.8–88.3	82.05	dB(A)
6	69.5–76.5	73.00	75.0–84.3	79.65	88.5–96.8	92.65	73.3–79.5	76.40	dB(A)
n	6		6		6		6		
Mean ± SD	68.80 ± 6.20		77.93 ± 5.02		85.41 ± 6.35		80.99 ± 2.29		dB(A)
95% CI	62.30–75.30		72.67–83.20		78.75–92.07		78.59–83.39		dB(A)

Abbreviations: CI: Confidence interval; *n*: Number of measurements; SD: Standard deviation.

The results from Kaçanik can also be interpreted in relation to noise measurements conducted elsewhere in Western Balkan cities. In Tirana, Albania, Laze[21] measured logarithmic average noise levels of 61.0–80.5 dB(A) at five urban crossroads and a maximum A-weighted, Fast time-weighted sound pressure level of 99 dB(A) during the measurement period (although these are mainly road-traffic noise measurements and not comparable with indoor measurements in gastronomic establishments in Kaçanik). The upper range is similar to those higher values

Table 4. Indoor noise measurements in September 2024

Measurement day	Location 1	Midpoint	Location 2	Midpoint	Location 3	Midpoint	Location 4	Midpoint	Unit of measurement
1.	68.5–81.8	75.15	72.5–81.2	76.85	85.3–96.2	90.75	78.4–85.9	82.15	dB(A)
2.	68.2–85.3	76.75	63.5–73.5	68.50	76.1–99.2	87.65	81.5–82.9	82.20	dB(A)
3.	64.0–82.6	73.30	73.2–85.2	79.20	81.5–97.8	89.65	84.5–99.9	92.20	dB(A)
4.	65.5–78.5	72.00	78.1–92.1	85.10	77.8–98.8	88.3	83.5–91.6	87.55	dB(A)
5.	67.6–78.9	73.25	71.5–83.9	77.70	77.5–83.0	80.25	65.4–75.3	70.35	dB(A)
6.	70.1–77.2	73.65	62.8–80.2	71.50	86.8–92.5	89.65	71.1–77.7	74.40	dB(A)
n	6		6		6		6		
Mean ± SD	74.02 ± 1.68		76.48 ± 5.86		87.71 ± 3.82		81.48 ± 8.08		dB(A)
95% CI	72.26–75.78		70.32–82.63		83.70–91.71		72.99–89.96		dB(A)

Abbreviations: CI: Confidence interval; *n*: Number of measurements; SD: Standard deviation.

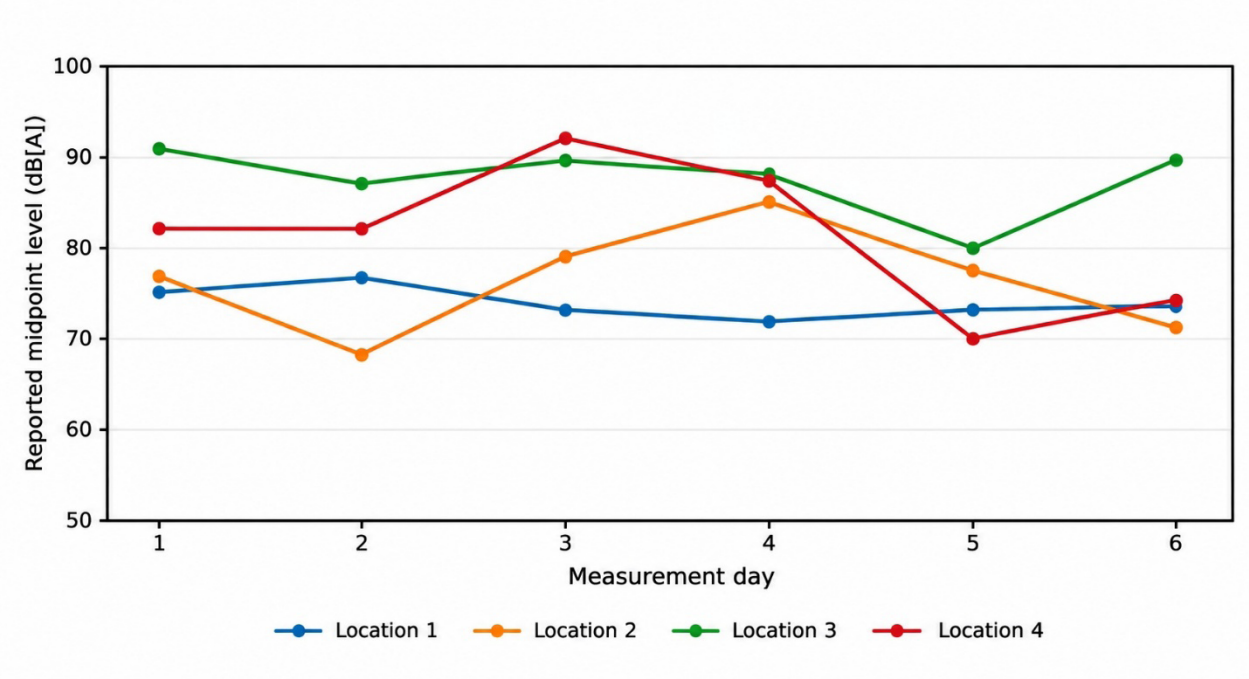


Figure 5. Indoor noise measurements at four locations in September 2024

observed in the present study, suggesting that peak sound levels may occur even when dominant noise sources and measurement environment differ.

Regional evidence from Skopje, North Macedonia, also shows that people are exposed to high levels of urban noise. Ristovska *et al.*[22] reported an average daytime level of 62 ± 6.45 dB(A) and a nighttime level of 56 ± 6.52 dB(A). Evidence from Belgrade, Serbia, showed similarly high exposure to urban noise, reporting mean equivalent noise levels during daytime (77.2 ± 4.6 dB[A]) and nighttime (69.8 ± 3.8 dB[A]) at noisy streets but substantially lower levels in quieter urban areas.[23]

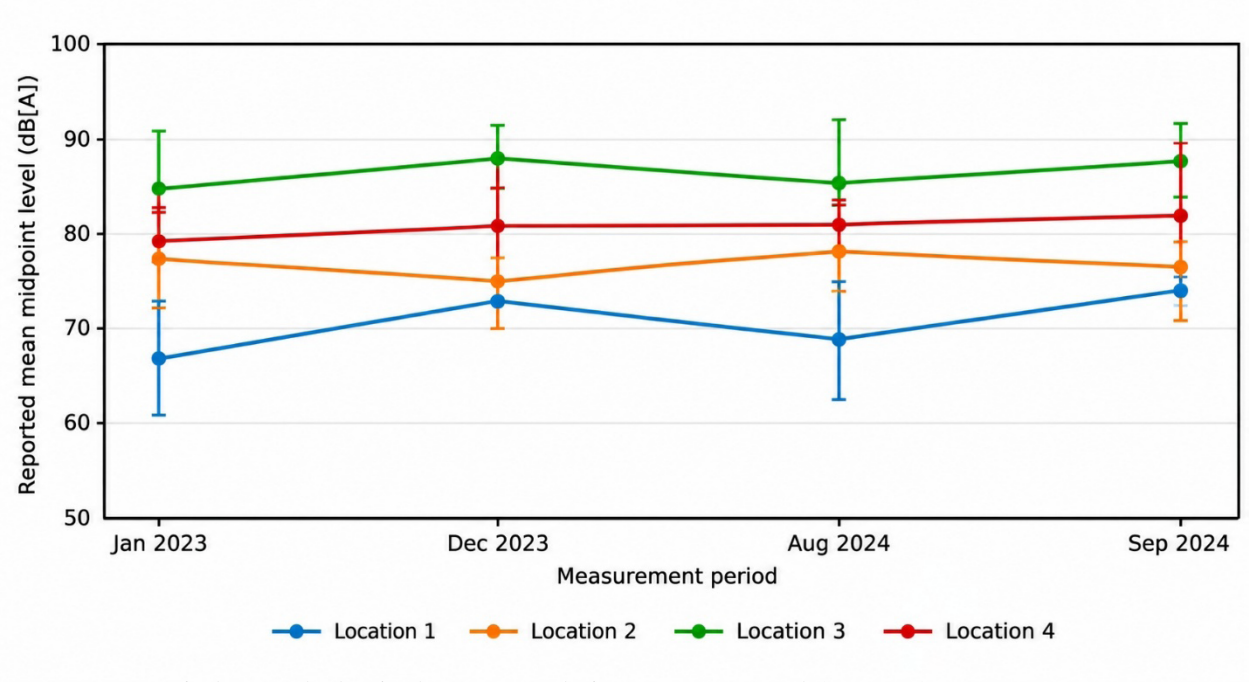


Figure 6. Comparison of indoor noise levels at four locations across the four measurement periods (mean ± SD)
Abbreviation: SD: Standard deviation.

Table 5. Comparison of noise levels among measurement periods at each investigated location

Location	January 2023 Mean ± SD (dB[A])	December 2023 Mean ± SD (dB[A])	August 2024 Mean ± SD (dB[A])	September 2024 Mean ± SD (dB[A])	Kruskal–Wallis, $H(3)$	p-value
Location 1	66.80 ± 5.88	72.58 ± 1.94	68.80 ± 6.20	74.02 ± 1.68	**10.21**	**0.017***
Location 2	77.34 ± 5.32	75.42 ± 5.44	77.93 ± 5.02	76.48 ± 5.86	0.48	0.923
Location 3	84.69 ± 5.76	88.02 ± 3.29	85.41 ± 6.35	87.71 ± 3.82	0.61	0.894
Location 4	79.53 ± 2.59	80.63 ± 7.92	80.99 ± 2.29	81.48 ± 8.08	3.08	0.379

Notes: Values are presented as mean ± SD. Differences among the four measurement periods were evaluated using the Kruskal–Wallis test. *$p < 0.05$ was considered statistically significant. Bold values indicate statistically significant differences between measurement periods.
Abbreviation: SD: Standard deviation.

Collectively, these regional studies show that high noise levels are a common feature of urban environments in the Western Balkans. Kaçanik findings provide another perspective on this regional evidence because they reflect indoor gastronomic environments in a smaller urban area (rather than outdoor traffic-noise exposure in larger cities) and the relatively high levels at some investigated locations (especially Locations 3 and 4). Therefore, these findings warrant consideration regarding urban acoustic exposure. However, direct numerical comparisons should be interpreted with caution because the studies differ in measurement indicators, duration, and timing, acoustic environments, and dominant noise sources. In this regional context, the present study adds measurement-based evidence from a smaller Western Balkan urban area and data on indoor gastronomic environments, which appear less represented in the available regional literature. Several contextual factors may have affected the recorded indoor noise levels. The investigated establishments are located along an important urban road used by vehicles and frequented by residents, students, and workers; therefore, customer conversations, occupancy levels, music played

inside the establishments, and nearby road traffic might have influenced acoustic conditions during monitoring. Additionally, room dimensions, interior materials, furnishing, and sound absorption characteristics could have affected noise propagation and reverberation in individual premises. Customer numbers, music volume, traffic intensity, and room acoustic properties were not measured independently. Consequently, their potential contribution should be interpreted as plausible explanations rather than statistically determined determinants of the recorded noise levels.

In their study, García-Rivero *et al.*[24] reported exceedances of the allowed values. Their instrumental measurements show that sound pressure levels exceeded the values established in current environmental regulations for commercial zones, with records reaching significantly high peaks during hours of heavier vehicular traffic. Concurrently, survey data revealed that most participants perceive noise as a factor that affects life quality, identifying motorized transport and informal commercial activity as the main disturbance sources. The findings indicated that equivalent noise levels consistently exceeded environmental quality standards for commercial zones, reaching maximum values above 90 dB(A). Vehicular traffic and informal commercial activity were the main noise sources, and most respondents perceived noise as intense and disturbing, especially during the evening–nighttime period.

Noise exposure has been associated with a range of auditory and non-auditory health effects.[25] According to the WHO, prolonged exposure to noise levels over 55 dB(A) can cause speech interference and cognitive distraction, hindering children's learning directly. Long-term exposure to environmental noise has been associated with stress, hypertension, and cardiovascular effects. The WHO has reported that noise pollution is a strong risk determinant of several conditions that affect physical and mental health, such as hypertension and hearing impairment. Chronic noise exposure has also been associated with adverse psychological effects, including anxiety and irritability.[26] In the European Union, noise pollution issues have often been given similar concern ratings as those for global warming.[27] Noise exposure is the most severe in urbanized areas.[28,29] Several researchers have indicated that higher exposure to recreational noise would increase the risk of hearing impairment.[13,30-33] Dalton *et al.*[32] investigated the correlation between noisy leisure activities and hearing impairment, concluding that, among participants suffering from hearing loss, individuals engaged in activities with noise levels exceeding 90 dB(A) significantly outnumbered those in quieter environments.

4. Conclusion

In Kosovo, there is limited data regarding acoustic pollution, particularly from noise and loud music in gastronomic establishments, and few comparable studies have been identified. Our findings serve as an alert to both local and central authorities, indicating that relatively high noise levels were recorded in the investigated gastronomic venues. The results reveal high values and elevated noise levels during the investigated measurement periods of permissible noise levels, largely due to the lack of institutional monitoring that could prevent such occurrences. Since no similar measurements exist in other municipalities, this study is useful as baseline data for future research. However, because only four establishments from the central urban area of Kaçanik were investigated, the results cannot be generalized to all gastronomic establishments in the municipality. Future studies should use a larger and more diverse sample of locations, as well as additional measurements of factors influencing indoor noise levels. We concluded that noise pollution from gastronomic establishments is considerably high, in violation of municipal regulations, and requires concrete institutional action. Mitigation measures should include installing noise monitoring devices in gastronomic venues, supervising continuously, and enforcing fines for non-compliance according to existing legislation. This is particularly important given the documented auditory and non-auditory health effects associated with prolonged noise exposure.

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Conflict of interest

The authors declare that they have no competing interests.

Author contributions

Conceptualization: Rushan Ceka, Ornela Çuçi
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Investigation: Rushan Ceka, Iliriana Demaj, Abidin Zenku
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Writing–original draft: Rushan Ceka, Ornela Çuçi, Iliriana Demaj, Neritan Turkeshi
Writing–review & editing: Rushan Ceka, Ornela Çuçi

Availability of data

The datasets generated and analyzed during the current study are available from the corresponding author upon

reasonable request.

AI tools statement

ChatGPT (OpenAI, GPT-6) was used during the manuscript revision process exclusively to assist with minor language editing, grammatical corrections, and graphical modifications to the original figures, including the removal of graph titles, correction of axis labels, and improvement of visual presentation in accordance with the editor's recommendations. All original data, measurements, and statistical analyses were conducted by the authors. The authors reviewed the AI-assisted revisions and take full responsibility for the accuracy, scientific content, and integrity of the final manuscript.

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