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Impact of low-frequency noise on a residential zone due to commercial HVAC systems

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ABSTRACT

Low frequency noise (LFN) is a serious growing global challenge for the urban environment where noise itself is an undervalued pollutant. The commercial establishments are equipped with multiple HVAC (Heating Ventilation and Air Conditioning) units responsible for the generation of LFN. To assess the impact of LFN, the noise was monitored using A and C-weighting sound level meters at HVAC outlets as well as in and around the residential premises. The noise due to HVAC units is found to be highly intensive in the lower frequency zones (<250Hz), affecting psychological and physiological health of living beings in the residential zones. A substantial 39.4 dB sound pressure level discrepancy between A and C-weighting inside the residential premises underscores the pronounced predominance of low-frequency noise. Noise monitoring using A-weighting failed to highlight the significant impact of lower frequency octave bands. The C-weighting noise monitoring revealed a substantial contribution of lower frequency octave bands (8Hz–250Hz) with 48.2 dB(C), in the overall equivalent noise level of 48.6(C), primarily attributed to HVAC units. The study suggests monitoring and assessment of the LFN, its mitigation and control strategies and its impact on the noise environment, especially on a residential zone.

1. Introduction

"Noise" is becoming one of the burgeoning pollutants in the environment, especially in the urban scenario. The growing urbanization has recently shed light on one of the major pollutants which is noise pollution. Environmental noise is one of the variables that contribute to the deterioration in people's standard of living especially in urban scenarios [1]. The LFN emission sources generally consist of vehicular traffic, airplanes, mechanical machines requiring rotation mechanisms, Heating Ventilation and Air Conditioning (HVAC) units, etc. Due to urbanization, the mixed land use pattern in the urban areas is arising that compels the inclusion of commercial establishments in the residential zone. Nowadays, commercial establishments are equipped with Heating Ventilation and Air Conditioning units (HVAC) units consisting machinery with high rpm like compressors of air conditioning units, fans, servers, etc. [2]. The human ear is capable of hearing frequencies ranging from 20 Hz to 20,000 Hz. The human ear is most susceptible to frequencies between 1500 and 4000 Hz, which encompass typical speech [3–5]. Low-frequency noise (LFN) is a growing concern in today's world, with the maximum frequency ranging up to 250 Hz [6]. These types of machinery introduce the LFN which is quite tedious to control and mitigate. Due to the low-frequency sound by the HVAC units, the distance travelled by the sound wave is quite greater as compared to high-frequency noise waves. HVAC units appear to be severely impacted by high frequency sound (over 3 kHz) and low frequency

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sound (under 100–200 Hz) [7]. The noise due to HVAC can reach up to 80 dB in the lower frequency zones (22–44Hz), which is sufficient to cause surface vibrations. Assessment of the noise environment in the interior of a small office rendered high sound level exceeding 75 dB in the lower frequency zone ranging from 8Hz to 63Hz [8]. LFN noise in the range of 30–80 Hz is more likely to be an issue in terms of annoyance [9]. A rumbling sound was observed in the lower frequency zones by the HVAC system due to the high rpm fans and ducting vibrations [10]. The LFN is also observed in the occupational environments range of 20–200Hz which adversely affects the efficiency of the workers [11]. In terms of the change in the subjective perception of loudness, an increase of 5 dB at 20 Hz is similar to an increase of 10 dB at 1 kHz [12]. Leventhall and Kyriakides (1976) [13] observed traffic noise peaks in the octave band of 63Hz. The LFN have also been shown to be a growing problem for marine animals, having an impact on their call behaviour and their capacity for nourishment [14]. In addition, as environmental noise masks the vocalization at lower frequencies, bird species alter their vocalization toward a higher frequency range [15].

The majority of rules and laws are formulated in relation to “A” weighting, which does not account for lower frequency disturbances. LFN’s in the environment remain neglected as A weighting is inefficient to trace the LFN since it resembles to only higher frequencies response of the human ear. The difference between the A and C weighting sound pressure levels can be utilized to assess the presence of LFN. According to the literature, a minimum difference of 15 dB is required between C and A sound pressure levels to assured the presence of LFN. A sound having a larger dB(C)-dB(A) difference between two levels may be less grating than a sound with a smaller difference [6]. Hence, a single-numbered common noise equivalent level (Leq) index could not accurately represent a subjective assessment of the LFN scenario [16,17]. It implies that a single A-weighted sound pressure level cannot serve as a valid indication that may be used to determine whether or not a disturbance is present due to the presence of LFN. The assessments used for low-frequency constituents and their implications for health effects have garnered less focus than those for high frequencies, despite the fact that low frequencies are deemed more aggravating [18,19].

LFN has serious consequences with regard to human health. LFN can be felt greatly as compared to being heard, since human hearing capacity lacks in the LFN zone. LFN quickly become uncomfortable and loud once they are audible. Even with low intensity, the LFN can cause annoyance and irritation to a greater extent. Individuals’ judgments of threshold and loudness vary more at low frequencies than at high ones which leads to non-auditory health effects [20]. Residents are at high risk of being adapted to the ambiance having LFN since the constant exposure will increase their sensitivity to LFN. Health status is a multifaceted concept that includes a wide range of factors such as lifestyle, genetics, and environment [21]. Generally, LFN is known for causing sleeping distress as the high-frequency noises get filtered due to the walls of establishments and closed windows whereas the characteristics of LFN are not much affected [22]. LFN are a common source of cognitive impairment, psychological anguish, anxiety, increased social conflict, uneasiness and emotional instability [23–25]. Noise and its health effects must be regarded as quality-of-life measures in the development of sustainable cities as an essential parameter. Since noise is already considered to be a silent killer itself, the LFN aspect is highly reticent. The primary objective of this research study is to evaluate the impact of low frequency noise (LFN) generated by HVAC units installed in a commercial establishment, in periphery of residential premises. Monitoring was carried out using noise level meters employing both A and C-weightings. For assessment of frequency spectrum, 1/1 and 1/3 octave band analysis were carried out with the support of multiple noise metrics.

2. Study area

The study area is located in the city of Nagpur, Maharashtra, India. Nagpur bears sweltering weather (42–45 °C) in the months of April–June, while in winter, the temperature of the city floats around 12–27 °C. The commercial and residential establishments reside around a road traffic junction as shown in Fig. 1. The residential premises having the issue of LFN, is surrounded majorly by a commercial establishment residing commercial activities like banks, telecom services, offices, etc. which also consists of computer servers and their supporting equipment. For cooling purposes, multiple air-cooling units are installed around the commercial

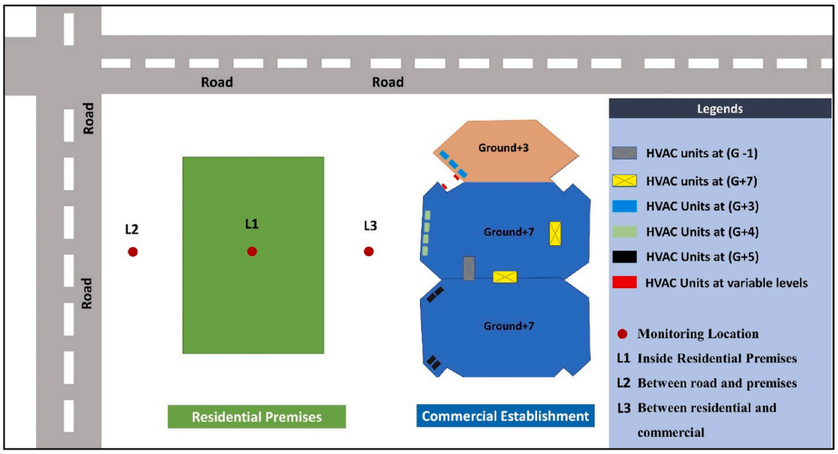

Fig. 1. Study area.

establishment and the direction of these multiple cooling units is towards the residential premises. The unit's mechanism is such that it rotates around a single axis with high number of revolutions per minute (rpm). Due to the high rpm (revolution per minute), the generated noise consists of a varied frequency spectrum [26]. The monitoring is conducted for 3 locations around the residential premises namely L1, L2, and L3. L1 location is situated inside the residential premises whereas L2 and L3 cover the front side and backyard of the premises respectively. The location L1, L2 and L3 are receptors of noise.

3. Materials and methods

For quantitative assessment of the low frequency noise due to commercial establishments and its impact on the residential premises, the methodology adopted in the present research has been elaborated in two sections. Section I details the monitoring session adopted with the description of sound level meters implied for the monitoring. Section II deals with the data analysis of the monitored data using multiple noise matrices with diverse consideration of frequency spectrum analysis. Also, the technical details regarding the frequency spectrum undertaken for the analysis and the weighing's preferred for the monitoring of noise level in the premises is also elaborated.

3.1. Data collection

Multiple noise meters at locations L1, L2 and L3 were installed around the residential establishment to capture the noise environment in the periphery as shown in Fig. 1. Also, noise levels were monitored inside the residential premises for holistic assessment. For receptors, the monitoring was conducted for 24 h, for daytime, the session was considered from 06:00 h to 22:00 h and for the nighttime, the session was 22:00 h to 06:00 h as specified in Noise Pollution Rules (Noise pollution (regulation and control) Rules, 2000). For monitoring the noise level of the sources i.e. HVAC, the monitoring was conducted in small sessions in the night to capture the specific noise only with minimum disturbance in the ambiance. In order to account for the constant fluctuations in the noise levels, the noise measurements are performed using Type I calibrated sound level meters. The Class-I sound level meter Sound Advisor Model 831C by Larsen Davis meeting the international standards IEC 61672–1:2013, ANSI S1.4-2014, was used for monitoring the noise levels. The noise levels are generally measured under three weightings namely A, C and Z [27,28]. The "A" weighting modifies sound pressure level data to reflect the human ear's sensitivity. The C weighting sound level against low frequencies measures the noise level uniformly over the whole frequency range. The Z weighting is the flat response that adapts no correction factors and presents true sound nature as shown in Fig. 2. The weightings A, C, and Z are represented as dB(A), dB(C) and dB(Z). Since the sound spectrum is distributed in a broader range from 20Hz to 20000Hz, different weightings are employed to capture the noise characteristics depending on the sources.

3.2. Data analysis

Noise metrics like L_{eq}, L_{max}, L_{min}, were also derived which are effective for the elaborated distribution of the noise environment [29–31]. L_{max} is described as the maximum Sound Pressure Level (SPL) while L_{min} is described as the minimum Sound Pressure Level (SPL) measured during the monitoring period. L_{max} and L_{min} denote the variation in sound pressure level over time. The equivalent continuous sound level (L_{eq}) was determined for the judgment of the noise scenario in the vicinity [32]. A-weighting is used to measure the noise levels as it mimics the human ear performance and responses. C weighting is utilized majorly to capture the lower frequency noises efficiently which A weighting fails to confiscate. A and C weighting noise measurements are represented by dB(A) and dB(C) respectively [33]. To reduce interference from sound reflections on the noise instruments, all of the noise meters were kept at least 3 m away from a boundary wall or other objects. To simulate the height of a human ear from the ground, the noise meter was kept at a

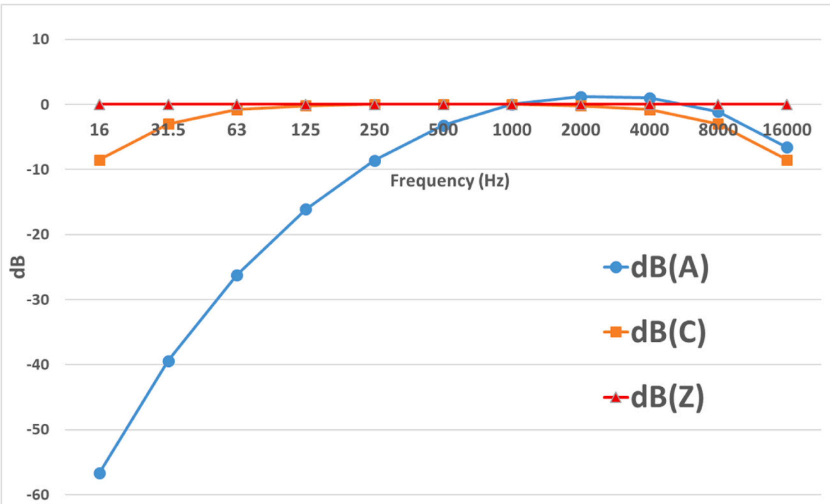

Fig. 2. Correction factors for different types of weighting.

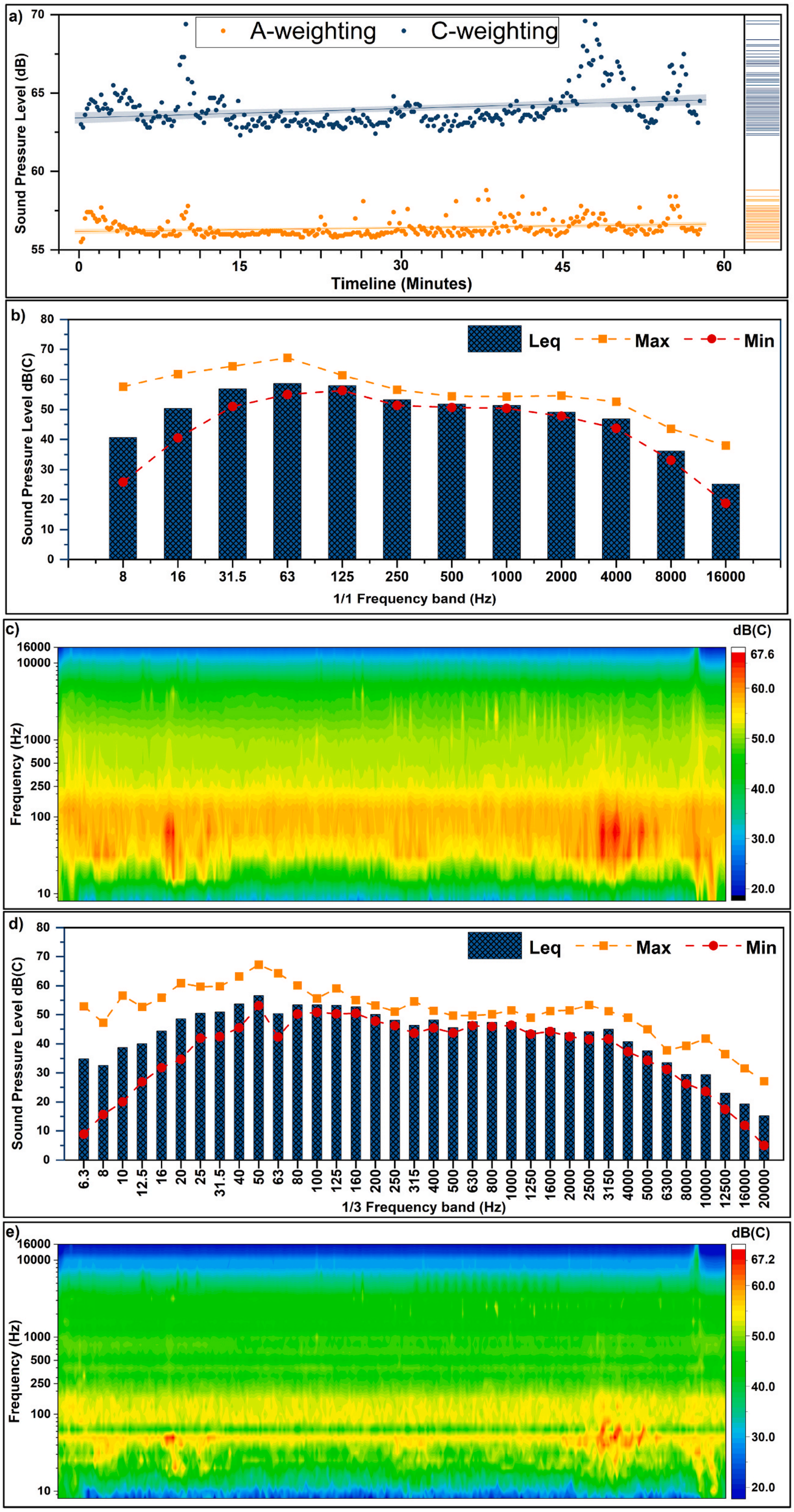

Fig. 3. Noise level and frequency spectrum analysis of HVAC unit noise a) Sound pressure level for A-C weighting b) Noise metrics in dB(C) as per 1/1 octave c) Spatial distribution of noise in dB(C) as per 1/1 octave d) Noise metrics in dB(C) as per 1/3 octave e) Spatial distribution of noise in dB(C) as per 1/3 octave.

height of 1.5 m [34]. To lessen the noise caused by wind flow, wind balls were fastened to the instrument's microphone. The A-weighting is not able to assess the LFN efficiently since the correction factors are quite high in the lower frequency zones [35]. Since C-weighting covers the lower frequency zones more efficiently hence higher noise-generating sources consisting of bass noise or LFN of high intensities are monitored through the respective weighting. The difference can be observed in the correction factors for A and C weighting with respect to the Z weighting. More correction factors are applied to the A-weighting in the lower frequency bands (16–250 Hz) as compared to the C-weighting. As compared to the Z weighting, the A weighting endure a massive correction of −56.7 dB, −39.4 dB, −26.2 dB and −16.1 dB for the octave band of 16Hz, 31.5Hz, 63Hz and 125Hz respectively. Whereas, the C-weighting endure a minor correction of −8.5 dB, −3 dB, −0.8 dB and −0.2 dB for the respective bands [27,28]. Between 1 Hz & 20 Hz the slope is approximately 12 dB per octave. The cut-off below 1 Hz has a slope of −24 dB per octave, and above 20 Hz the slope is −24 dB per octave. Hence, for proper assessment of the LFN, weighting "C" is preferred over "A" and "G" weighting. The correction factors for different types of weightings (A,C and Z) are depicted in Fig. 2.

For minute noise level assessment, the spectrum is analyzed with the help of 1/1 octave band or 1/3 octave band. The 1/1 octave band divides the acoustic range into 11-octave bands. The octave band is defined by its central frequency which covers the range from $f_n/2^{1/2}$ (low) to $2^{1/2}f_n$ (high) (f_n being the central frequency). The fractional bandwidth percentage per octave band is 70.7 % for 1/1 octave band as given in **Eq. (1)**.

$$\text{Percentage Bandwidth (BW)} = 100\left[\left(f_n^{high} - f_n^{low}\right) \Big/ f_n^{central}\right] = 70.7\% \tag{1}$$

In the same way, 1/3 octave band divides the acoustic range into 31 octave bands. The octave band is defined by its central frequency which covers the range from $f_n/2^{1/6}$ (low) to $2^{1/6}f_n$ (high) (f_n being the central frequency). The fractional bandwidth percentage per octave band is 23.2 % for 1/3 octave band as given in **Eq. (2)**.

$$\text{Percentage Bandwidth (BW)} = 100\left[\left(f_n^{high} - f_n^{low}\right) \Big/ f_n^{central}\right] = 23.2\% \tag{2}$$

4. Results and discussion

Based on the noise monitoring in A and C weightings at commercial and adjacent residential zones, noise levels are analyzed as per noise matrices and 1/1 and 1/3 frequency octave bands to assess the impacts of HVAC units on the noise environment.

4.1. Noise and frequency analysis of HVAC units

The major noise sources due to a commercial establishment in the vicinity of residential premises are identified as HVAC units. The noise levels are observed under "A" and "C" weightings and the frequency spectrum is elaborated for C-weighting only since the objective of the research study was focused on LFN.

a) HVAC

HVAC units are known for generating LFN due to their high rpm. The noise level was monitored at a distance of 3 m from the air conditioning unit in both A and C weightings. The SPL ranged between 55.5 - 58.8 dB(A) and 62.3–69.6 dB(C) for "A" and "C" weightings respectively as shown in Fig. 3(a). The maximum difference observed in the SPL level for A and C weightings was 12.7 dB. The frequency spectrum analysis of HVAC units under A-weighting does not convey any specific information. Therefore, the monitoring was conducted with C-weighting. As per 1/1 octave band analysis, the octave band of 63.5Hz dominated the SPL with L_{max} 67.2 dB(C) whereas the lowest SPL i.e. L_{min} was rendered by the octave band of 16 KHz with 18.7 dB(C), as presented in Fig. 3(b).

The noise of HVAC units was highly fluctuating in the lower frequency's octave band with differences (L_{max}-L_{min}) ranging from 5.1 to 31.8 dB(C) whereas the differences (L_{max}-L_{min}) in the higher frequencies zone ranged between 3.7 and 19.3 dB(C). The spatial spectral distribution as observed in Fig. 3(c), represents the dominance of the lower frequencies of noise for the HVAC units. To further investigate the octave band, the noise was analyzed with the help of 1/3 octave band spectrum. As compared to the 1/1 octave band, the 1/3 band analysis rendered the highest L_{eq} of 56.6 dB(C) for 50 Hz octave band while the lowest L_{eq} was observed for the band of 20 KHz, as shown in Fig. 3(d). The highest SPL was observed for the band 50Hz and the lowest intensity was rendered by the 20 KHz band. Also, the maximum fluctuation was observed for the band of 6.3Hz with an SPL difference of 44 dB(C) (L_{max}-L_{min}). By spatial distribution it can be observed that the HVAC unit noise is dominant in the lower frequency zones (6.3Hz–250Hz) as seen by the red and yellowish shade as shown in Fig. 3(e). The lower frequency bands (<250Hz) are found to be highly fluctuating which was not perceived under A-weighting scenario. It was observed that the fluctuation reduces as the noise approached the higher frequencies noise (>250Hz). A 44 dB(C) fluctuation in the octave band of 6.3Hz (L_{max}-L_{min}) is sufficient to cause annoyance and irritation. This analysis of the HVAC noise using C-weighting proves to be quite advantageous as A-weighting does not render the dominance of lower frequency noise.

4.2. Noise and frequency analysis at noise receptors

The impact of low-frequency noise due to different sources are observed in location namely L1, L2 and L3 i.e. around the residential premise and inside the premise. The noise levels are monitored under A and C weighting with frequency spectrum analysis of the noise rendered by C weighting.

a) Inside the residential premise (Location L1)

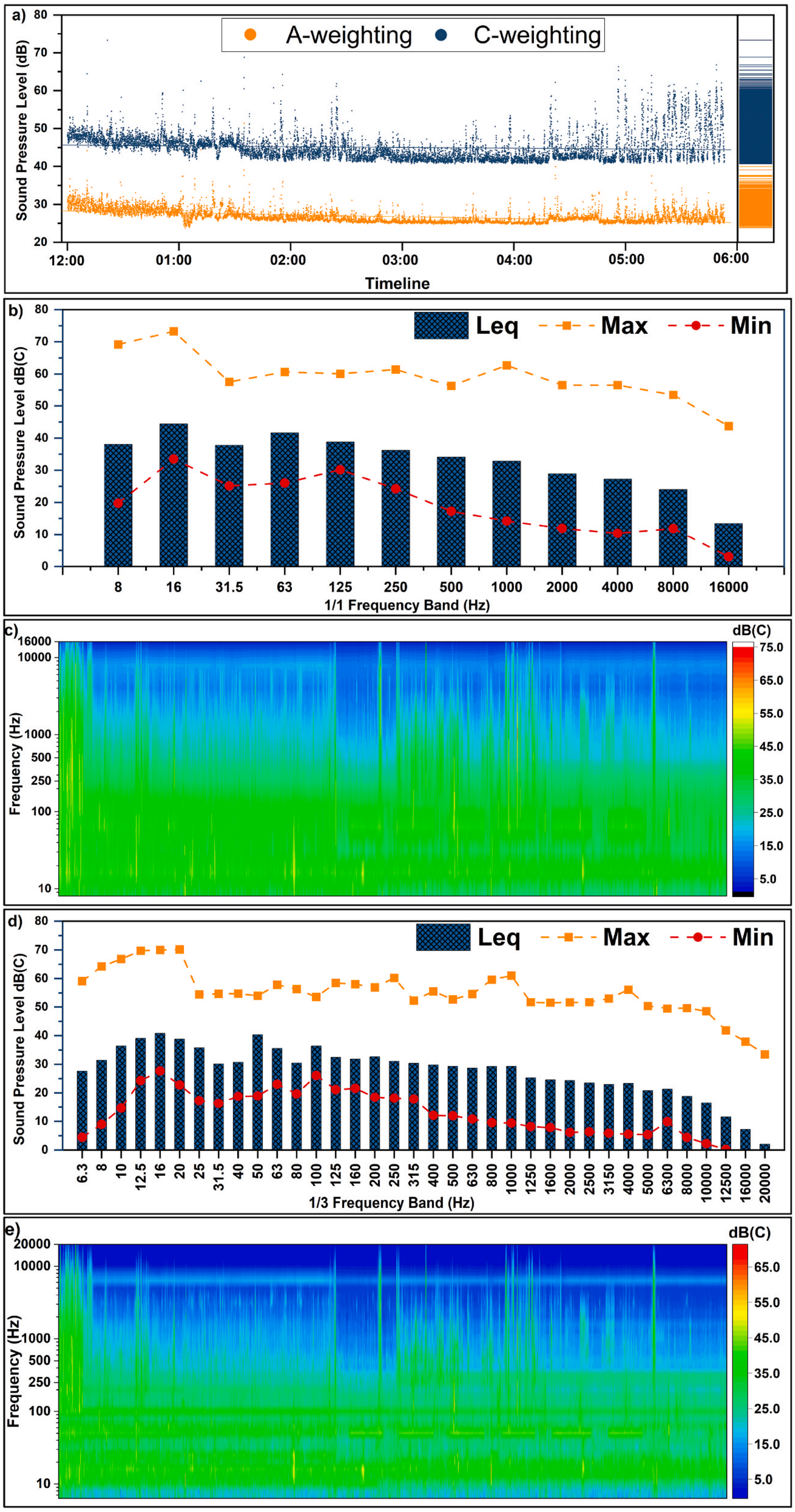

Fig. 4. Noise level and frequency spectrum analysis for inside the residential premises a) Sound pressure level for A-C weighting b) Noise metrics in dB(C) as per 1/1 octave c) Spatial distribution of noise in dB(C) as per 1/1 octave d) Noise metrics in dB(C) as per 1/3 octave e) Spatial distribution of noise in dB(C) as per 1/3 octave.

To arrest the LFN in the residential premises noise monitoring was carried out during night time as the background noise is quite lower in the respective session. The sound pressure level (SPL) inside the residential premises was found to be highly fluctuating between 23.8 and 51.4 dB(A) and 40.6–73.3 dB(C). Surprisingly, the highest difference between the A and C weighted SPL was observed to be 39.4 dB while the lowest difference was 15.9 dB as shown in Fig. 4(a). As per 1/1 octave band, the lowest fluctuation (L_{max}-L_{min}) of 29.9 dB(C) was observed for the octave band of 125Hz while the 8Hz band rendered fluctuation of 49.4 dB(C). The highest L_{eq} of 44.4 dB(C) was observed for the band of 16Hz. Also, the band of 63.5Hz showcased a high L_{eq} of 41.6 dB(C) as shown in Fig. 4(b). The spatial distribution of noise levels showed a high difference between the low and high frequency zones, as observed under 1/1 octave band analysis [Fig. 4(c)]. The noise spectrum when elaborated with the help of a 1/3 octave band showed that the L_{eq} for the lower frequency octave bands (<250Hz) ranged between 27.6 and 40.8 dB(C) whereas for the higher frequency octave bands (250Hz-16KHz) the L_{eq} ranged from 7.2 to 30.3 dB(C). The octave band of 8Hz fluctuated highly with a maximum SPL of 64.2 dB(C) and the lowest SPL observed to be 9.0 dB(C) as shown in Fig. 4(d). The SPL fluctuation in the lower frequency zone (L_{max}-L_{min}) can be observed between 27.5 and 55.2 dB(C) whereas for the higher frequency zone octave bands the SPL ranged between 34.5 and 51.6 dB (C). The spatial distribution of noise level -with varying bands observed under 1/3 octave band analysis is presented in Fig. 4(e). In 1/1 octave band analysis, it can be observed that SPL is fluctuating very densely, therefore the feeling of irritation and annoyance is quite obvious for the resident. This heavy fluctuation in the noise level may give rise to sleep disturbances. The variation in the lower frequency zone is quite significant as compared to the octave band of higher frequencies, substantial health effects are expected to arise due to varying low-frequency noises.

To confirm the presence of LFN, the sound pressure level (SPL) was observed minutely. The full closure of the residential premises was attempted i.e. restricting any activities that might fluctuate the noise level around the instrument. As observed in Fig. 5, the activities were restricted around the instrument and a sudden drop in the SPL for weighting A can be observed at Point I**.** But at the same time, the C-weighting SPL did not suffer the same amount of reduction. Multiple peaks can be observed for C-weighting SPL at points “II” and “III” in Fig. 5, where the A-weighting SPL was quite normal. Also, by Z weighting SPL it can be confirmed that the sound pressure in the residential premises remains the same which is an indication of presence of LFN.

b) Between road and residential premises (L2)

A major part of the noise is contributed due to running traffic including honking around the respective monitoring location. The noise level in between road and residential premises (L2) is presented in Fig. 6(a). The contribution of all noise sources like traffic, honking, HVAC units, etc. has increased the noise intensity at the lower as well as higher frequency zones. The highest difference between the A and C weighting SPL was observed to be 19.6 dB and lowest difference was found to be 2.7 dB as shown in Fig. 6(a). The L_{max} for A and C weighing SPL are 71.1 dB(A) and 78.3(C) respectively. Due to mixed noise from the LFN sources as described above with exposure to the traffic noise, the noise level is heavily fluctuating.

Under the 1/1 octave band analysis, the highest L_{eq} of the 63.5 Hz band was observed to be 67 dB(C) while the lowest at 16 KHz band with an intensity of 16.1 dB(C). The highest SPL (L_{max}) for the octave band of 63.5 Hz is observed at 76.9 dB(C) with the lowest SPL (L_{min}) of 7.2 dB(C) for the 16 KHz band as shown in Fig. 6(b). A high L_{min} value for the octave band of 63.5Hz and 125Hz with SPL 54.6(C) and 54.9 dB(C) respectively, conveys the dominance of the lower frequency octave band. Due to the traffic noise, the spatial representation is highly distributed in the overall frequency spectrum as observed in Fig. 6(c).

In the 1/3 octave analysis SPL level of the 50Hz octave band with 76.2 dB(C) was observed to be the highest among other octave bands, as shown in Fig. 6(d). The L_{eq} was observed to be highest for the octave band of 80Hz with 65.8 dB(C). The fluctuation in the SPL level was highest in the lower frequency zone (<250Hz) where the difference between L_{max} and L_{min} was found to be 14.5–47.6 dB(C). The spatial noise distribution under 1/3 octave band analysis is presented in Fig. 6(e). Even with a combination of noise sources, the lower frequency zones are quite high for the area around the resident premises.

c) Between residential and commercial establishment (L3)

The outlets of HVAC units are faced toward the residential premises (L3) and multiple units of HVAC are installed at different heights with respect to the residence height. The SPL for the A weighting fluctuated between 45.2 and 65.2 dB(A) whereas the SPL ranged between 56.5 and 80.5 dB(C) for C-weighting as shown in Fig. 7(a). In 1/1 octave band analyses, the maximum SPL was observed for the band of 31.5Hz with 79.2 dB(C). The L_{min} value for the octave band of 63.5 and 125Hz band was observed to be 49.8 and 48.3 dB(C), displaying the impact of LFN in the ambience. The maximum L_{max}-L_{min} difference was observed for the 8Hz octave

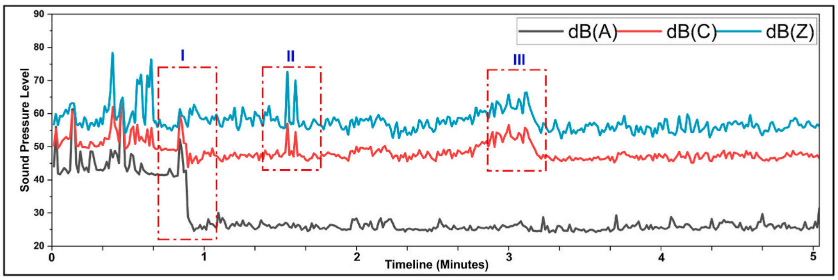

Fig. 5. Minute observations indicating the effect of LFN inside the residential premises.

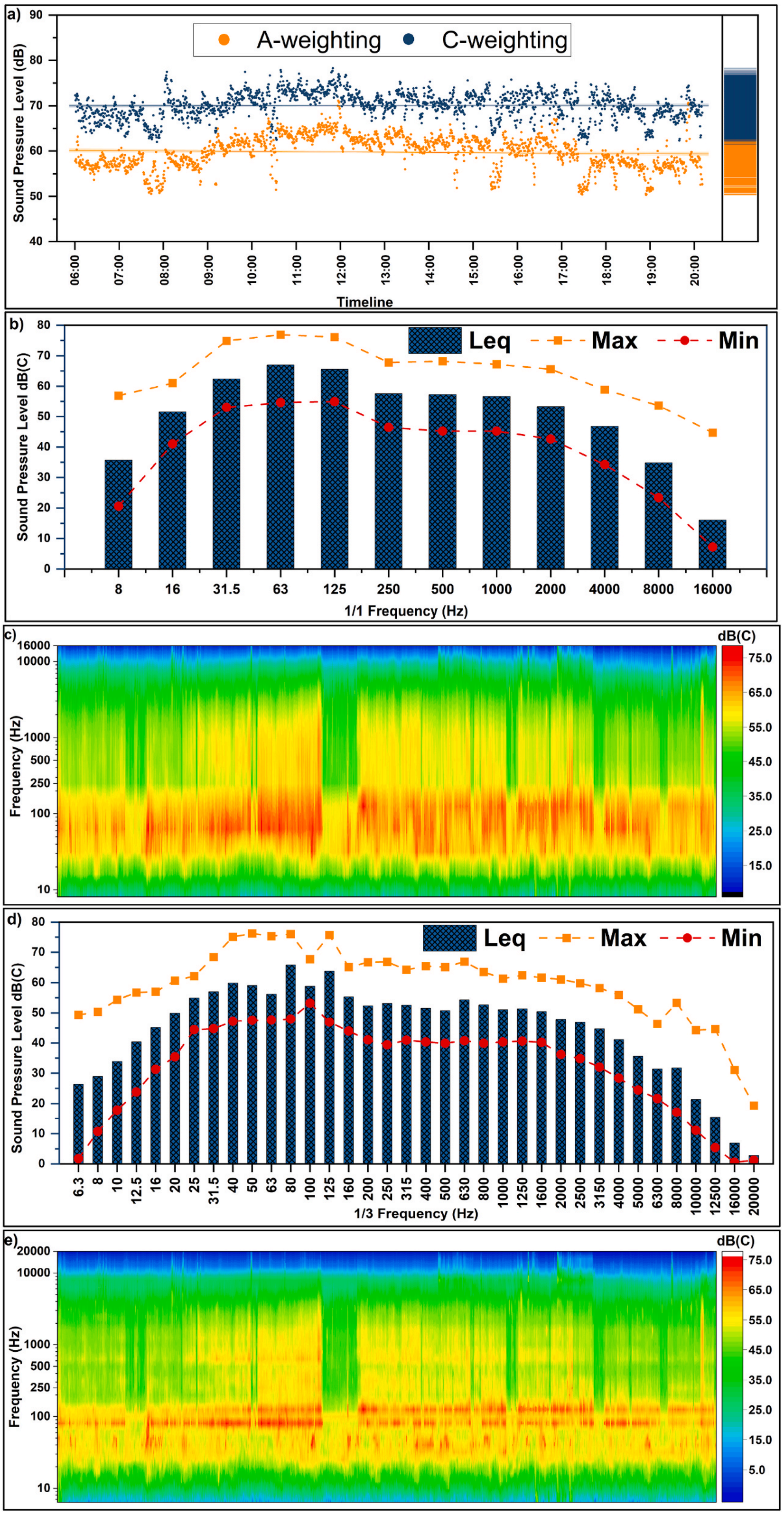

Fig. 6. Noise level and frequency spectrum analysis at infront of residential premises a) Sound pressure level for A-C weighting b) Noise metrics in dB(C) as per 1/1 octave c) Spatial distribution of noise in dB(C) as per 1/1 octave d) Noise metrics in dB(C) as per 1/3 octave e) Spatial distribution of noise in dB(C) as per 1/3 octave.

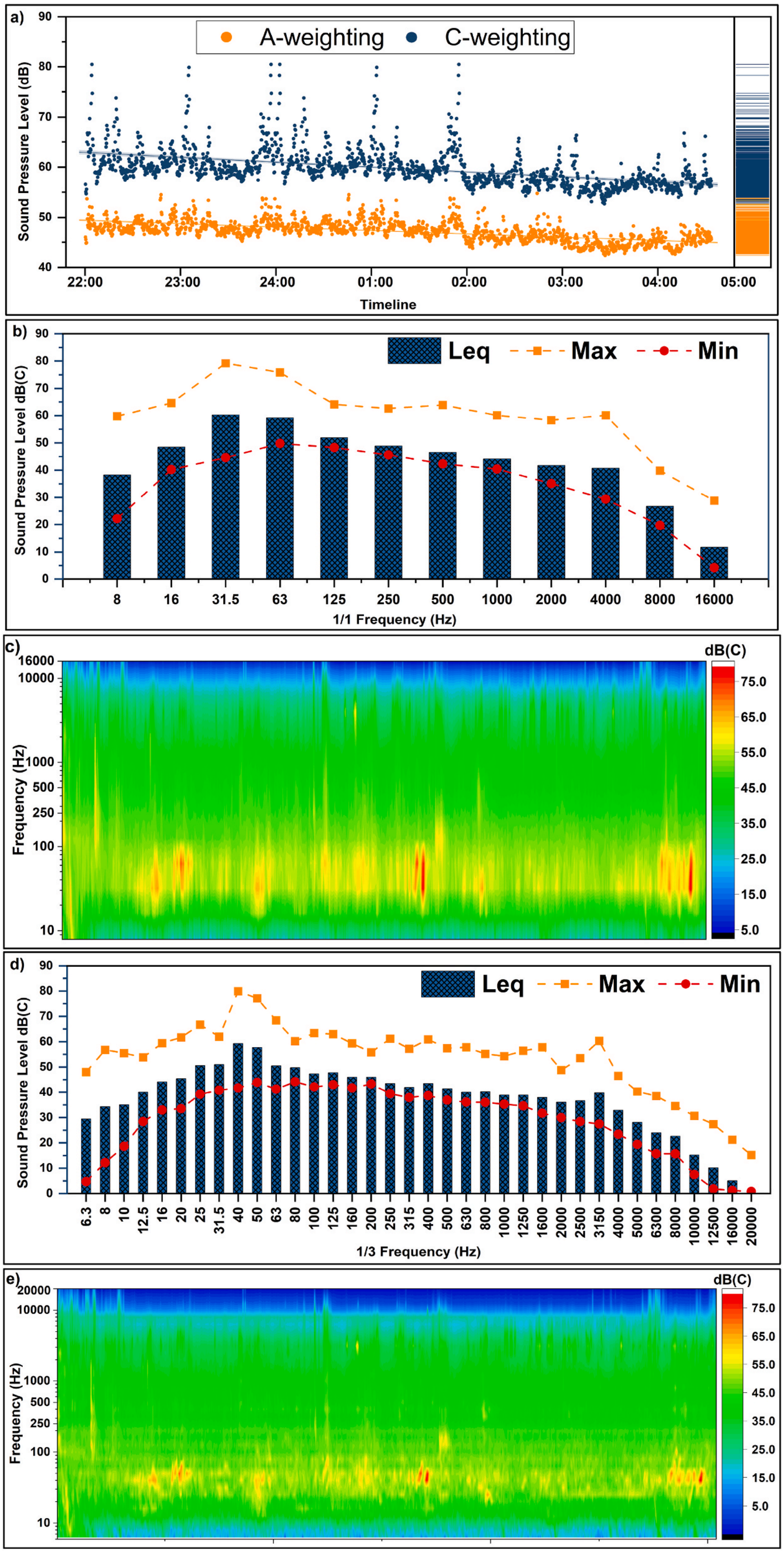

Fig. 7. Noise level and frequency spectrum analysis for location between residential and commercial establishment a) Sound pressure level for A-C weighting b) Noise metrics in dB(C) as per 1/1 octave c) Spatial distribution of noise in dB(C) as per 1/1 octave d) Noise metrics in dB(C) as per 1/3 octave e) Spatial distribution of noise in dB(C) as per 1/3 octave.

band with 37.6 dB(C). The highest L_{eq} was rendered by the octave band of 31.5Hz with 60.3 dB(C) as shown in Fig. 7(b). The spatial distribution of the noise level presents the difference between the lower and higher frequency zones, as depicted in Fig. 7(c). To further enhance the band characterization, the noise levels was observed with 1/3 octave bands. The highest SPL was observed for the octave band of 40Hz with 79.9 dB(C). The highest L_{eq} was observed for the octave band of 40Hz with 59.3 dB(C) while the L_{eq} of the 50Hz octave band was quite high at 57.7 dB(C) as shown in Fig. 7(d). It was also noted that the minimum SPL (L_{min}) of the octave bands 50, 80, 125 and 200Hz were quite high with the 43.9, 44.2, 43, 43.3 dB(C) respectively, ensuring the heavy dominance of the lower frequency bands. The fluctuating spatial distribution noise of the noise level under 1/3 octave band analysis is presented in Fig. 7(e).

4.3. Frequency spectrum analysis

The residential premises are exposed to LFNs resulting from the commercial establishment accommodating multiple HVAC units. The isolated field monitoring of HVAC outlets has rendered the dominance of LFN which is dispersing all around the residential. The noise frequency pattern of A and C weightings under 1/1 and 1/3 octave bands as shown in Fig. 8. The noise levels are almost identical after the range of 250Hz, but differs by a larger margin for frequency range lower than 250Hz, especially for the bands of 16Hz,

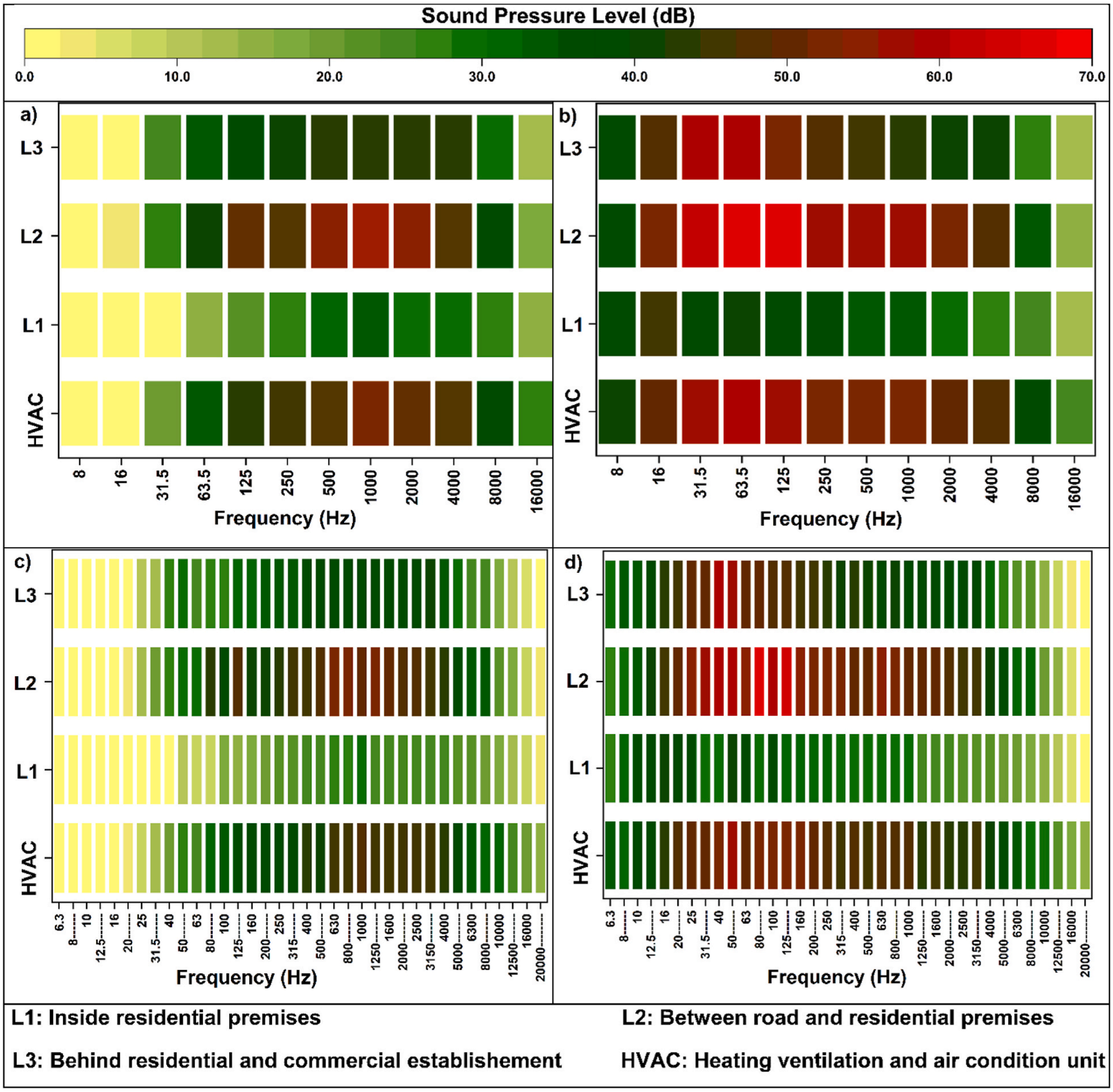

Fig. 8. Comparison of the noise frequency spectrum at different locations (a) 1/1 octave band with A-weighting (b) 1/1 octave band with C-weighting (c) 1/3 octave band with A-weighting (d) 1/3 octave band with C-weighting.

31.5Hz, 63Hz and 125Hz. The noise levels are observed to be highest for the monitoring location L2, since the respective location also includes the noise due to movement of vehicles, as the location lies between road and residential premises, away from the commercial establishments. The noise levels inside the residential premises (L1) are also quite high, hence sufficient in causing disturbance in the sleep and giving rise to many psychological and physiological health effects among the residents. It can be observed that A-weighting fails to encompass the lower frequency noise octave zones. The comparison of noise frequency spectrum of 1/1 octave bands, as shown in Fig. 8(a) and (b), clarifies the importance of C-weighting noise monitoring over the A-weighting. The 1/3 octave band analysis with A [Fig. 8(c)] and C-weighting [Fig. 8(d)] renders a smaller frequency range distribution for the sound, which specifies the dynamic characteristics of the noise. The fluctuating bands in the lower frequency zones can be observed clearly in Fig. 8(d). The simultaneous peak values of noise level observed with both A and C-weighting is the resultant of influence of traffic noise on the L2 location. The 1/3 octave band further provides insight on the specific frequency bands fluctuations due to presence of low frequency noise in which A-weighting fails to encompass. All the locations are rendering a higher intensity of LFN in the vicinity as well as inside the residence. The A and C-weightings L_{eq} distribution for low and high frequency noise (HFN) also showcases the impact of LFN as presented in Table 1. In case of HVAV unit A-weighted L_{eq}, the contribution of LFN (8Hz–250Hz) is 46.7 dB(C) whereas the HFN L_{eq} (250Hz-20KHz) is observed to be 56.1 dB(C). The overall L_{eq} is observed to be 56.5 dB(A) for the entire frequency range of 8Hz-20KHz. Likewise, for the location L1, L2 and L3, the impact of HFN is comparatively higher than LFN. For HVAC units noise level, C-weighted for the LFN (8Hz–250Hz) is 63.4 dB(C) whereas the HFN (250Hz-20KHz) is observed to be 56.3 dB(C). Surprisingly, the overall L_{eq} for the whole range (8Hz-20KHz) is 64.1 dB(C), which conveys the excessive dominance of LFN. In case of A-weighted L_{eq}, the impact of HFN is deemed to be higher as compared to LFN. A clear difference can be observed for the L_{eq} levels for A and C-weighting for each location. The contribution of lower frequency zones L_{eq} is quite high as compared to high frequency zones, which compels the utilization of C-weighting for the monitoring the low frequency noise.

5. Conclusion

Across the world, low-frequency noise is a growing compelling nuisance but still an underrated aspect of noise pollution. Using A-weighting and C-weighting noise monitoring, the frequency distribution patterns were analyzed focusing the impact of low frequency noise (LFN) generated by the HVAC system in a commercial facility on residential premises. Noise monitoring using A-weighting failed to highlight the significance of lower frequency octave bands, where L_{eq} distribution revealed the dominance of HFN with 37.3 dB(A), in the overall L_{eq} level of 38 dB(A). Within the residential premises, a substantial difference of 39.4 dB was observed in the noise level between A and C-weighting underscores the pronounced predominance of low-frequency noise, highlighting its significant impact. Therefore, the utilization of C-weighting revealed that a significant portion of the overall noise level of 48.6(C), is being dominated by the lower frequency octave bands (8Hz–250Hz) with L_{eq} of 48.2 dB(C), primarily attributed to HVAC units. The observed L_{eq} level of 65.8 dB(C) for the 80Hz octave band, monitored between the road and residential premises, reflects the combined influence of HVAC units and traffic noise, affecting the residents. The noise level of LFN in the residence ambiance may cause irritation, and annoyance at the primary level but can lead to psychological and physiological health effects if remain unattended.

The permissible noise level limits all over the world as well as in Indian scenarios are defined with respect to A-weighting noise monitoring. However, it fails to elucidate LFN and therefore the LFN goes unnoticed. The research currently is too limited for the lower frequency spectrum which implies the insufficient precautionary mitigation and preventive measures. The present research study recommends monitoring and assessment of the LFN, its mitigation and control strategies and its impact on the noise environment, especially on a residential zone. International recognition of the LFN as an emerging pollutant will further provides an opportunity to carry out competent research and development in terms of monitoring, mapping, mitigation and management of noise levels with C-weighting.

Ethics approval and consent to participation

Not applicable.

Consent for publication

Not applicable.

Table 1
A and C-weightings distribution for low and high frequency noise (HFN).

Locations	Noise level in A-weighting dB(A)			Noise level in C-weighting dB(C)		
	20Hz–250Hz (LFN)	250Hz-20KHz (HFN)	20Hz-20KHz (Overall L_{eq})	20Hz–250Hz (LFN)	250Hz-20KHz (HFN)	20Hz-20KHz (Overall L_{eq})
HVAC	46.7	56.1	56.5	63.7	54.3	64.1
L1	29.1	37.3	38.0	48.2	37.8	48.6
L2	52.7	60.3	61.0	70.4	60.9	70.9
L3	42.4	49.4	50.2	63.4	49.9	63.6

Availability of data and materials

The datasets used and/or analyzed during the current study is available from the corresponding author on reasonable request.

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Chaitanya Thakre: Data curation, Formal analysis, Visualization, Writing – original draft. **Ritesh Vijay:** Conceptualization, Methodology, Project administration, Supervision, Visualization, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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