

Perception-based Assessment of Health Risk Due to Urban Noise Pollution

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Urban noise pollution, driven by high population density and rapid development, poses significant risks to public health and quality of life. However, studies examining noise perception and health impacts based on age and socioeconomic gradient across diverse urban populations in India remain limited. This study aimed to assess the health risks of urban noise exposure among Mumbai residents using a comprehensive questionnaire. Data were collected from 844 participants spanning varied age groups (adolescent children to older adults) and socio-economic statuses. The survey captured socio-demographic details, noise exposure sources, and up to seventeen auditory and non-auditory health effects. Vehicular traffic and construction emerged as the main noise sources. The findings clearly show age-based differences in health impacts. Headaches and sleep issues were common across all ages, with adults and older adults more affected due to longer exposure and stress. Children showed high rates of headaches, annoyance, and distraction but less anxiety, while adults reported more stress and mental fatigue. Behavioural issues, like poor concentration and communication, were highest in children and working-age adults. Adults faced the greatest risk of temporary hearing loss and tinnitus, though children also showed early signs of auditory vulnerability. Socio-economic disparities were pronounced, with children in lower-income groups experiencing more severe symptoms, while adults in higher-income groups reported the highest overall burden. The study is unique in integrating age, socio-economic, and source-specific data to record noise-induced health risks in an Indian metro context. The findings provide valuable, quantifiable insights essential for evidence-based policy interventions to safeguard urban health and wellbeing.

Keywords: Age-specific health effects, Noise-induced health effects, Questionnaire-based survey, Socioeconomic status, Urban health

Introduction

Noise pollution, often described as “unwanted sound,” remains a persistent issue disrupting the natural balance of our body and causing multiple health problems.¹ Recognised as a major environmental pollutant, it leads to communication difficulties and severe health effects, making it a pressing public health concern. First quantified in 1972 as the “third pollution” after air and water pollution,² organisations like WHO, ILO, NIOSH, and ACGIH have highlighted traffic noise as highly harmful in urban areas, labelling it a serious threat to human well-being. Arising from urbanisation, industries, economic growth, and motorised transport, noise pollution impacts hearing and causes cardiovascular issues, hypertension, reduced efficiency, and annoyance, especially with prolonged or intense exposure.^{1,3,4}

Environmental noise is a common urban stressor, yet its link with social deprivation remains under-researched. Economically disadvantaged people often have limited housing options, leading them to live in poor conditions near multiple environmental hazards such as heavy traffic roads, industrial zones, or toxic waste sites.⁵ However, higher-income groups can also face significant environmental stressors. For instance, in Rome, affluent individuals lived in high-traffic areas.⁶ Studies in Germany,⁷ Hong Kong,⁸ and Minnesota⁹ showed greater noise exposure among the disadvantaged, while research in France found mixed patterns.^{10,11} Overall, global evidence is scarce and inconsistent, and such studies are lacking in the Indian context.

Studies on age-specific health effects of noise exposure show that noise impacts auditory, cognitive, and physiological health differently across age groups. In older adults, chronic noise exposure increases dementia risk; a systematic review found

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that every 25 dB rise in noise elevates Alzheimer's and dementia risk by 17%.⁽¹²⁾ Repeated loud noise exposure accelerates presbycusis (age-related hearing loss), and young people exposed to high noise levels may develop premature presbycusis.¹³ Even without clinical hearing loss and aging, noise affects the auditory system, as evidenced by subtle changes in Auditory Brainstem Responses (ABRs) and Otoacoustic Emissions (OAEs).¹⁴ The American Academy of Pediatrics highlights that noise-induced hearing loss in children may cause social isolation and hinder learning. Finnish research indicates that young females exposed to occupational noise are prone to depressive symptoms.¹⁵ Additionally, a Korean study found that long-term occupational noise exposure can reduce kidney function in females under 60, suggesting noise-induced stress and inflammation as possible mechanisms.¹⁶ These findings highlight the need for age-focused noise health assessments.

Advancements in medical and other fields have increased life expectancy, but this also brings challenges such as declining quality of life, altered disease perceptions, and worsening cognitive and mental health, often influenced by environmental factors. As perceived noise significantly impacts health and well-being, understanding how people perceive noise pollution is essential for improving their health perceptions, overall well-being, and satisfaction with their environment.¹⁷⁻¹⁹ Noise pollution can be assessed using instruments for objective data and through subjective personal reports; both are vital for a comprehensive understanding.¹⁷ Questionnaires are increasingly used to study quality of life and perceptions in environmental health, requiring a structured design and clear guidelines for meaningful insights.²⁰

In this study, a comprehensive questionnaire was developed to assess the health impacts of noise pollution on individuals across diverse age groups and socio-economic strata. It aims to gather data on physical, psychological, behavioral, and auditory effects experienced due to urban noise exposure. The primary objective is to evaluate subjective perceptions of noise as a stressor among people with varying socio-economic and demographic backgrounds in the Indian context, ultimately guiding the formulation of effective noise pollution control strategies.

Materials and Methods

Study Area

The study has been conducted in Mumbai city, the capital city of Maharashtra state and the financial

capital of India. Mumbai City district is a district of Maharashtra in Konkan Division, India. It extends from Colaba in the south to Mahim and Sion in the north. The city has an area of 157 km² (61 sq mi) with the population count of 30,85,411⁽²¹⁾ Mumbai is a coastal city located at latitude 19°02'11.11" North, longitude 72°51'34.09" East in Western part of India along Arabian sea. The study area and survey locations are presented in Fig. 1.

Study Design and Ethical Issue

The present cross-sectional study involved creating both an online and offline questionnaire to gather data from individuals exposed to noise pollution in Mumbai. A self-administered health survey questionnaire was developed to assess participants' views on noise-related health issues. The survey adhered to all ethical considerations concerning human subjects. The consent form for participants explicitly noted that the data would be used exclusively for research purposes. Participants were not offered any incentives for taking part in the survey.

Questionnaire Development

A systematic approach was used to design the questionnaire, aligning questions with research objectives. Available in Marathi, Hindi, and English, it comprised three sections: socio-demographic details, noise pollution exposure, and noise-related health impacts (Fig. 2). It aimed to collect demographic data, identify urban noise sources, and assess perceived health effects, anticipating age and socio-economic gradient-based differences in perceptions. Questions covered types and main sources of noise at home and workplace, peak noisy times, vehicles causing noise, honking issues, and earphone use. The health section addressed awareness and experiences of 17 noise-related problems, including physical, psychological, behavioral, and auditory effects.

Data Collection and Sampling

Surveys were conducted both online and offline between August 2022 and December 2023. The online survey, created on Google Forms, was shared via social media and email with Mumbai residents, while the offline survey targeted shopkeepers, students, traffic police, and others exposed to noise. For holistic assessment of health effects due to noise pollution, participants from various area categories uniformly distributed across Mumbai city and from different socio-economic status were approached for questionnaire based survey. Participants had to be

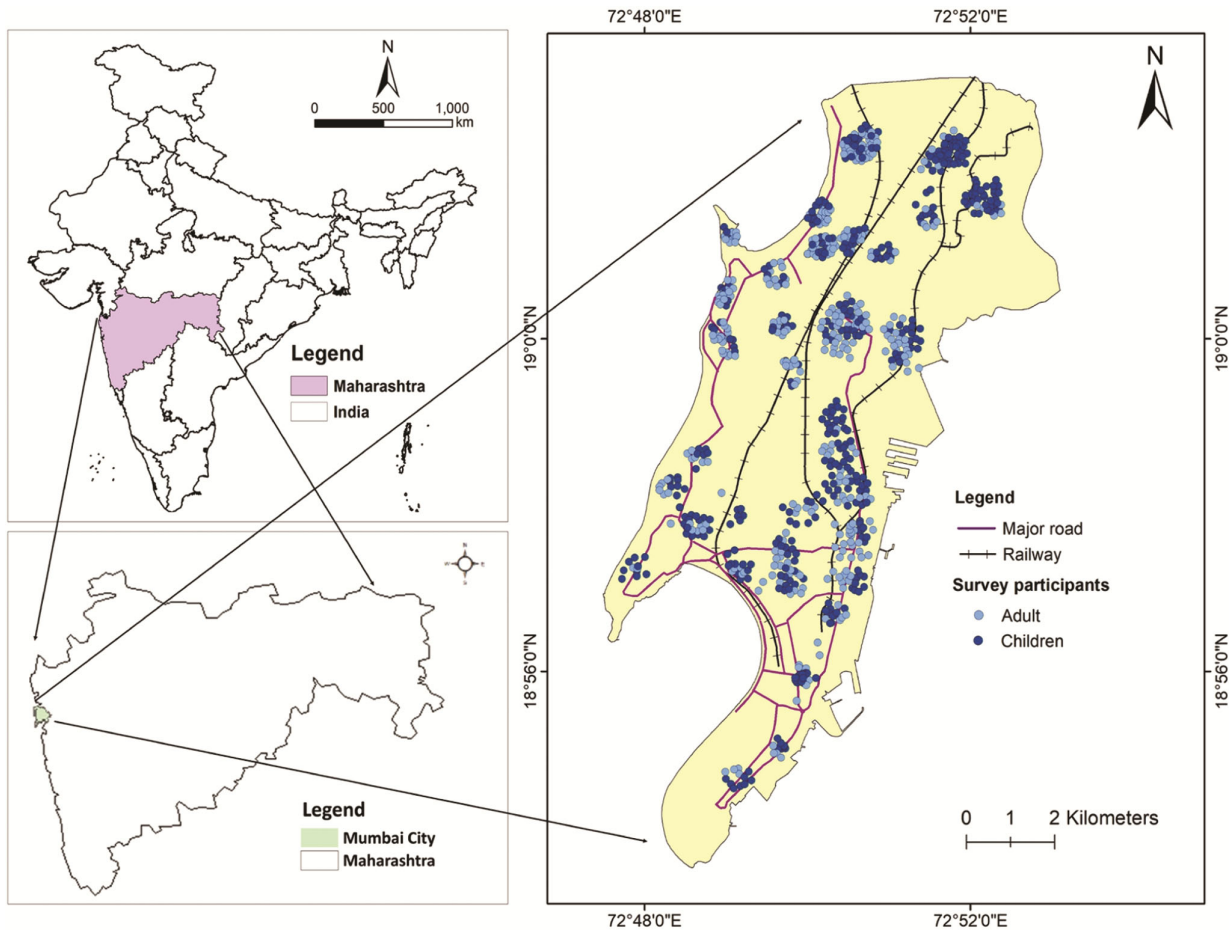


Fig. 1 — Study area and survey locations in Mumbai city

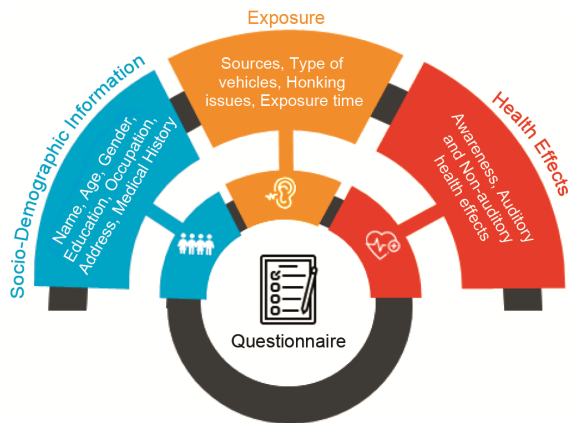


Fig. 2 — Overview of questionnaire for perception-based health survey of urban populations exposed to noise pollution

11 years or older, living in Mumbai during the survey, and have internet access (preferably to participate in online survey). A total of 844 responses were collected, much exceeding the minimum required sample size of 385 (95% CI).²² Parental consent was taken for minor participants (age below 18 years).

Statistical Data Analysis

Descriptive statistics (frequencies and percentages) were computed to summarize survey responses and compare patterns across age groups, socio-economic categories, and health effects. Also, the chi square (χ^2) test of independence was used to analyze the relationship between the various health effects and socio-economic status i.e. people living in different housing types—hutments (slums), chawls (shared housing units), and apartments. Each health effect was recorded as a binary response in the form of (Yes/No). The chi square test evaluated the significant relationship between the various health effects and the socio-economic groups. Statistical significance was determined at a threshold value of $p < 0.05$.

Results and Discussion

The questionnaire-based survey was conducted to assess the effects of urban noise pollution on the population with 844 respondents completing the questionnaire.

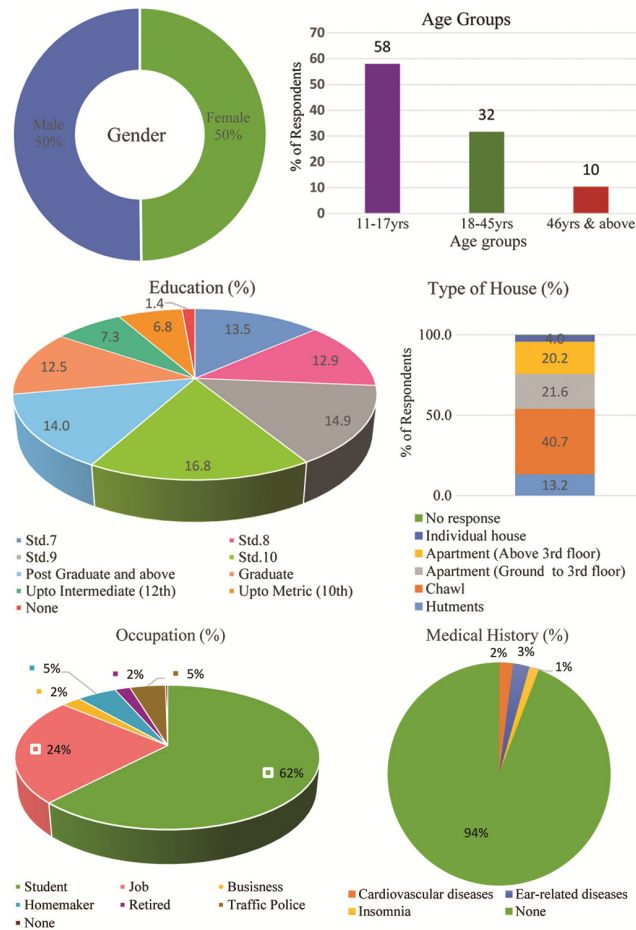


Fig. 3 — Socio-demographic profile of survey respondents

Socio-demographic Profile

The socio-demographic profile of the respondents, as outlined in Fig. 3, provides a comprehensive overview of the age, gender, residence type, occupation, education level, and medical history of the surveyed population. Respondents were grouped into three age categories: 11–17 years (58%, n = 490), 18–45 years (32%, n = 270), and 46 years and above (10%, n = 84). This shows a predominantly younger population, with nearly 90% below 45 years. Gender distribution was equal, with 50% males and 50% females, ensuring balanced representation of perceptions. Educational backgrounds varied widely. Only 1.4% had no formal education, indicating an overall well-educated sample.

Housing in Mumbai city is very expensive, and housing types reflect socio-economic diversity in Mumbai. Regarding housing, respondents were distributed across various types of accommodation. The largest group (40.7%) lived in chawls (low-income housing), 21.6% lived in apartments on the

ground to third floors, 20.2% in flats above the third floor, 13.2% in hutments (slum housing), and 4% in individual houses. This demonstrates significant variation in living conditions, with many from low-income backgrounds. In terms of occupation, students comprised the largest group (62%), followed by employed individuals (24%). Homemakers and retired persons each constituted 5%, while traffic police and businesspersons each formed 2%. Only 0.3% of respondents reported no occupation. Regarding medical history, the majority (94%, n = 793) reported no significant health conditions. However, 2% had cardiovascular diseases, 3% had ear-related problems, and 1% reported insomnia. Respondents with such medical histories were excluded from further analysis to focus on general health impacts of noise pollution.

Overall, the data highlights a youthful, gender-balanced, diverse sample with varied educational backgrounds, occupations, and housing conditions, providing a comprehensive understanding of the urban population’s socio-demographic context relevant to noise pollution exposure and health outcomes.

Awareness about Noise Pollution and its Health Effects

Public awareness of noise’s health impacts is crucial for mitigation, enabling individuals to adopt preventive measures.³ The study assessed urban awareness levels. Most participants (97%) knew about noise pollution, but only 38% were aware of related government rules. While 83% knew noise affects health, only 52% linked traffic noise to hearing disability. Half of the participants felt at health risk from urban traffic noise (Table 1). These findings suggest that a majority of individuals are aware of the risks of noise, contradicting the idea of widespread ignorance about noise pollution.

Noise Sources and Exposure

This study assessed noise exposure among different age groups and socio-economic backgrounds at home and school/workplace (Fig. 4). Traffic was the most reported noise source, especially at school/work. Construction noise ranked second, affecting both settings equally due to ongoing infrastructure projects in Mumbai. Neighborhood noise was the third most reported, mainly at home. Commercial and industrial noise had minimal reporting. Few respondents experienced no significant noise, with slightly more indicating quieter school/workplace environments.

Table 1 — Awareness of noise pollution and its health effects among survey participants

Sr. No.	Questions to Participants	Response	Children (n)	Adults (n)	Total (N)	(%)
1.	Do you know what noise pollution is?	Yes	444	325	769	97
		No	16	8	24	3
2.	Are you aware about Noise Pollution (Regulation and Control) Rules 2000, given by Govt of India?	Yes	162	142	304	38
		No	298	121	419	53
		No response	0	70	70	9
3.	Do you know that prolong exposure to noise pollution can have an impact on the human health & its well-being?	Yes	414	243	657	83
		No	46	18	64	8
		No response	0	72	72	9
4.	Do you think that exposure to loud traffic noise can cause a disability in hearing?	Yes	214	199	413	52
		No	61	28	89	11
		Sometimes	185	106	291	37
5.	Did you feel your health is on a risk because of the urban noise pollution?	Yes	243	153	396	50
		No	101	54	155	20
		Sometimes	116	123	239	30
		No Response	0	3	3	0

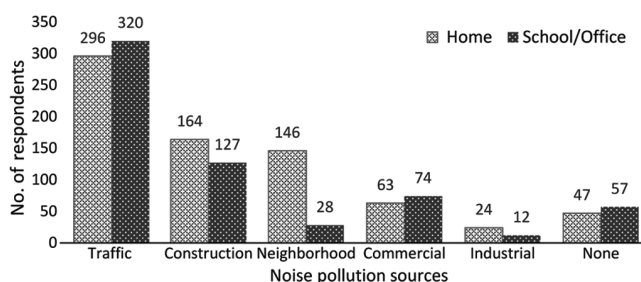


Fig. 4 — Noise pollution sources encountered by survey participants (Age: 11–89 yrs) in their premises

Noise-induced Health Effects

In terms of personal health risk perception, half of the respondents (50%, n = 396) felt their health was at risk due to urban noise pollution (Table 1), indicating substantial concern and general awareness. Another 30% (n = 239) sometimes felt at risk, suggesting that perceived health impacts vary with exposure intensity or duration. Meanwhile, 20% (n = 155) did not view noise as a health risk. The questionnaire-based health perception survey was aimed at the assessment of noise-induced health effects into four categories – physical effects, psychological effects, behavioural effects and auditory effects. Out of 844 participants, 51 with cardiovascular, ear diseases, or insomnia were excluded, leaving 793 respondents comprising 460 children (11–17 years), 251 adults (18–45 years) and 82 older adults (46 years and above), whose age-wise and socio-economic based health effect prevalence was visualised using heatmaps (Figs 5–8). The colour intensity indicates the percentage of respondents experiencing each effect, with darker shades representing higher frequencies.

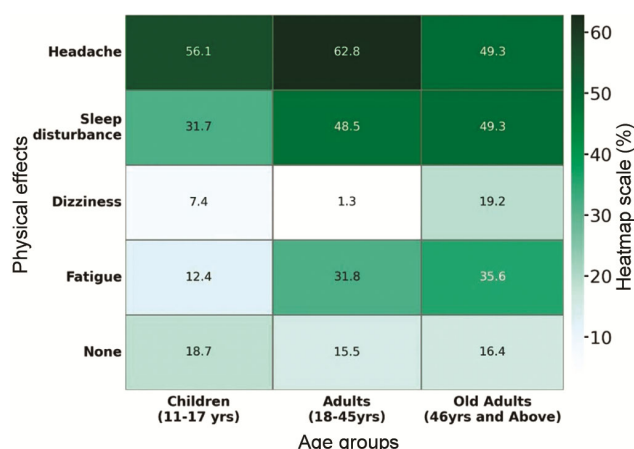


Fig. 5 — Heatmap of physical effects perceived by respondents of all age groups

Physical Effects

The heatmap (Fig. 5) shows percentage prevalence of physical effects of noise pollution across three age groups. Headache is most common effect reported across all age groups; highest in adults (62.8%), followed by children (56.1%) and older adults (49.3%). It is associated with stress responses, blood vessel constriction, and increased muscle tension due to noise exposure. Younger individuals are more susceptible to noise-induced stress responses, as elevated noise levels activate the Hypothalamic-Pituitary-Adrenal (HPA) axis, triggering physiological stress responses that contribute to headaches and general malaise.²³ Sleep disturbance is reported by nearly half of adults (48.5%) and older adults (49.3%) while it is less in children (31.7%). Noise pollution disrupts sleep architecture by increasing arousals, leading to fragmented and poor-

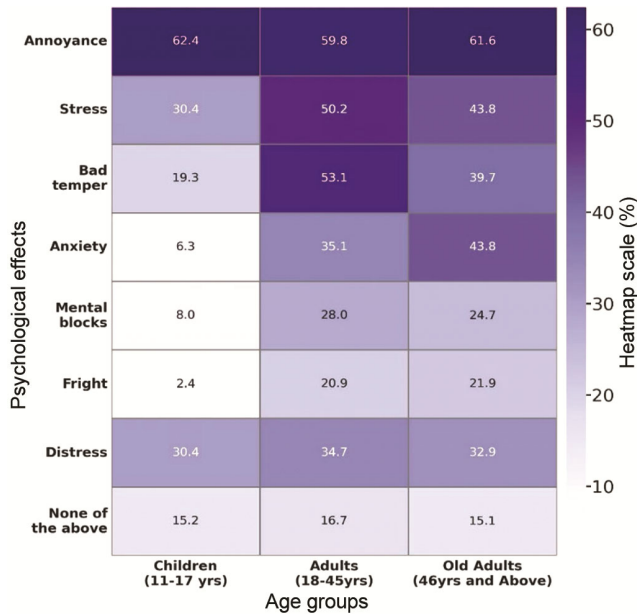


Fig. 6 — Heatmap of psychological effects perceived by respondents of all age groups

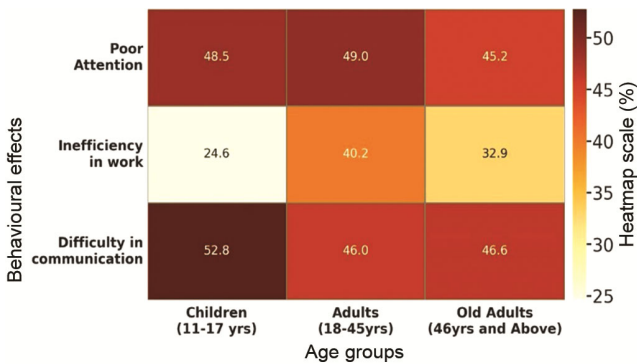


Fig. 7 — Heatmap of behavioural effects perceived by respondents of all age groups

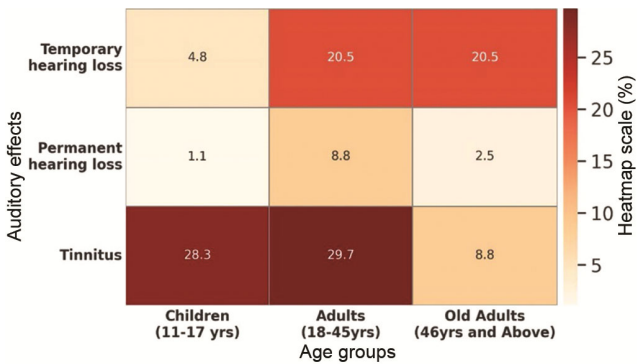


Fig. 8 — Heatmap of auditory effects perceived by respondents of all age groups

quality sleep, which is particularly harmful for cardiovascular and metabolic health leading to hypertension, diabetes, and heart disease.²⁴

Dizziness is reported to be highest in older adults (19.2%), while low in children (7.4%) and minimal in adults (1.3%). Dizziness may be linked to vestibular disturbances caused by chronic noise exposure, as suggested by research on occupational noise effects.²⁵ In older adults, noise-induced dizziness or vertigo, may be linked to inner ear dysfunction, cochlear damage, or vestibular disturbance.²⁶ Fatigue is a well-documented consequence of prolonged exposure to urban noise.²⁷ Chronic exposure to noise leads to sustained stress hormone release, which disrupts rest and recovery, causing physical and mental exhaustion.²⁸ It is observed more commonly in adults (31.8%) and older adults (35.6%) compared to children (12.4%). Lowest proportion of participants (15–19%) reported no physical effects, indicating most individuals are affected physically by noise exposure. Younger individuals may have higher resilience or different noise exposure patterns compared to adults and elderly individuals.²⁹

These results suggest that noise pollution causes significant physical health effects in all age groups, with headache and sleep disturbance being the notable ones. Adults and older adults are more affected, likely due to longer exposure periods and higher sensitivity to noise-related sleep loss and stress.

Psychological Effects

Noise pollution is widely recognized as a psychological stressor, influencing emotional and cognitive well-being.³⁰ The heatmap (Fig. 6) provides a visual representation of the prevalence of psychological effects—annoyance, stress, irritation, anxiety, mental blocks, fright and distress— across different age groups based on the responses of 793 participants.

Annoyance is the most reported effect across all age groups with 62.4% individuals being affected in 11–17 years’ age group, followed by 59.8% of adults in the 18–45 years’ age group and 61.6% old adults in 46+ years’ age group (Fig. 6). This is consistent with literature indicating that noise is a chronic environmental stressor leading to annoyance, which may mediate other psychological and physiological health outcomes,³¹ adolescents being more vulnerable due to ongoing neurological and psychological development.²⁹

Chronic exposure to environmental noise activates the Hypothalamic-Pituitary-Adrenal (HPA) axis, increasing stress hormone release.³² Stress shows higher prevalence in adults (50.2%), followed by

older adults (43.8%) and children (30.4%). Bad temper (irritability or aggression) is significantly reported by adults (53.1%) and older adults (39.7%), with minimal impact on children (19.3%). This aligns with findings suggesting adults perceive noise as interfering with occupational and social functioning, increasing aggression.³³

Noise exposure is associated with increased anxiety due to perceived uncontrollability and unpredictability.³⁴ Anxiety is higher in older adults (43.8%) compared to adults (35.1%) and children (6.3%). Mental blocks, indicating cognitive interference or reduced focus, are more prominent in adults (28.0%) and older adults (24.7%) than in children (8.0%). Cognitive impairment from noise is well documented, particularly affecting attention and working memory.²⁹ Fright (startle responses or fear) is low across groups, slightly higher in adults and older adults (~21%) compared to children (2.4%). Distress is similarly distributed across all age groups (~30–35%), suggesting that noise is associated with emotional discomfort regardless of age. Individuals reporting none of the psychological effects are minimal, indicating most individuals report at least one psychological effect from noise exposure.

These findings underscore the age-related vulnerability differences in psychological responses to noise pollution. Children experience annoyance and distress more but less cognitive and emotional effects like anxiety or irritation (bad temper), potentially due to less occupational stress. Adults show heightened stress, irritation, and mental blocks, reflecting occupational and social pressures. Older adults exhibit higher annoyance, stress and anxiety, suggesting that noise exacerbates age-related emotional regulation challenges.

Behavioral Effects

Chronic noise exposure has been linked to reduced concentration, cognitive fatigue, and decreased academic/work performance, especially in younger individuals who are still developing adaptive coping mechanisms, particularly among children and adolescents who require quiet environments for learning.³⁵ Behavioral effects such as poor attention, inefficiency in work, and difficulty in communication are commonly reported consequences of prolonged exposure to noise pollution. The heatmap (Fig. 7) shows that the highest reported behavioural effects observed in the 11–17 years age group was difficulty in communication in 52.8% individuals, followed by poor attention in 48.5% individuals and work

inefficiency in 24.6% individuals. This aligns with research showing that high noise levels in educational environments impair speech perception, reading ability, and memory retention, negatively impacting academic performance.³⁶ Chronic noise exposure may also be associated with frustration, reduced social interactions, and increased stress levels in students.

The age group of 18–45 years is predominantly affected with poor attention, inefficiency in work and difficulty in communication among 49%, 40.2% and 46% individuals, respectively. This suggests that noise in workplaces and urban settings contributes to reduced productivity and cognitive fatigue.³⁷ The individuals in age group of 46+ years also reported behavioural effects moderately with poor attention (45.2%), work inefficiency (32.9%), and difficulty in communication (46.6%). Possible reasons include age-related cognitive sensitivity to noise which makes this group vulnerable to subtle effects. The lower values compared to children and adults may indicate that old adults have developed coping mechanisms or that their environments allow for some control over noise exposure.

In brief, children (11–17 years) experience the highest levels of behavioural disruption, particularly in attention and communication. Working-age adults (18–45 years) are significantly affected, with noise impairing concentration, workplace efficiency and communication. Older adults (46+ years) report moderate behavioural effects due to age-related cognitive sensitivity to noise or coping mechanisms.

Auditory Effects

Prolonged exposure to high noise levels can cause temporary or permanent hearing loss and tinnitus.³¹ The heatmap (Fig. 8) visually represents the prevalence of these effects among different age groups. Temporary hearing loss (Temporary Threshold Shift, TTS) occurs due to exposure to high-intensity noise (e.g., traffic, industrial noise, loud music), leading to reversible damage in hair cell function within the cochlea. In Fig. 8, children show minimal temporary hearing loss, likely due to lower exposure duration and intensity or temporary threshold shifts that recover over time³⁸, but vulnerability remains due to recreational noise (headphones, fireworks). Adults and older adults show a higher prevalence due to occupational exposures and cumulative noise doses.

Permanent Noise-Induced Hearing Loss (NIHL) results from irreversible damage to cochlear hair cells,

often due to prolonged occupational or environmental noise exposure exceeding safe limits (>85 dB). Working-age adults (age: 18–45 years) show the highest prevalence, reflecting occupational and recreational exposure. Older adults show lower prevalence here, possibly due to underreporting or overshadowing by age-related hearing loss (presbycusis).

Tinnitus is the perception of ringing or buzzing in the ears without an external stimulus, often linked to noise-induced cochlear or auditory pathway damage.³⁹ Prevalence is highest in adults (29.7%) and children (28.3%), suggesting that early-life exposure to loud noise is causing auditory disturbances even in adolescence. This aligns with studies showing that excessive exposure to loud music, recreational noise (e.g., headphones, concerts), and urban environmental noise contributes to tinnitus in young individuals.⁴⁰ Older adults show lower tinnitus prevalence here, possibly due to adaptation, reduced reporting, or masking by other age-related hearing changes.⁴¹

In brief, adults in age group 18–45 years are at the highest risk for temporary hearing loss and tinnitus, reflecting occupational and recreational exposure. Children show concerning tinnitus prevalence, implying early auditory system vulnerability with potential impacts on learning, concentration, and mental health. Older adults have lower tinnitus reporting but remain susceptible to noise-induced auditory damage combined with age-related hearing decline.

Potential Health Risks based on Socio-economic Status Gradients

Housing type serves as a key indicator of socio-economic status, particularly in a megacity like Mumbai, where housing options vary widely and reflect economic disparities and social stratification. Individuals residing in apartments are classified as upper-middle class, those in chawls (shared housing units with communal spaces) as middle class, and those in hutments (slums) as part of the low-income group. Apartments, typically found in high-rise buildings, are home to middle- to upper-middle-income individuals, including professionals, salaried employees, and small business owners. In contrast, a significant portion of Mumbai’s population resides in slums and chawls, where overcrowding, inadequate infrastructure and poor housing conditions are common. These areas are primarily inhabited by lower- and middle-income groups, including daily

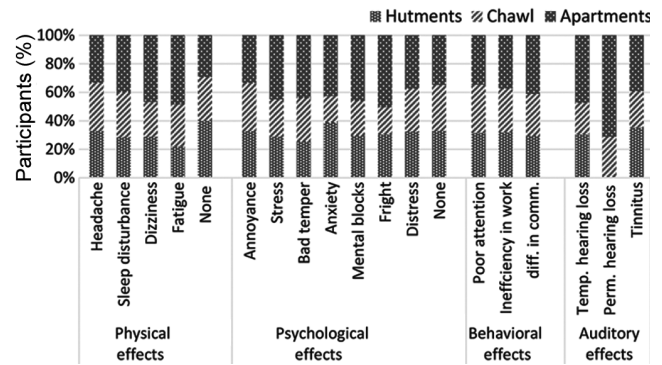


Fig. 9 — Noise-induced health effects perceived by survey participants across different socio-economic groups

wage laborers, domestic workers, and migrant workers. Given that noise exposure varies with housing type, occupation, and other factors, the study assesses the prevalence of noise-induced health effects across these socio-economic groups as illustrated in Fig. 9.

The graph (Fig. 9) presents the distribution of perceived physical, psychological, behavioral, and auditory health effects due to environmental noise exposure among residents of hutments, chawls, and apartments. These residential types broadly reflect gradients in housing quality, environmental buffering, and socio-economic vulnerability. Among physical health effects, headache emerged as the most frequently reported effect and appeared comparable across hutments (57% participants), chawls (57.9% participants), and apartments (57.3% participants). Other physical health effects were also prevalent among apartment dwellers while lower in chawl and hutment dwellers.

Psychological effects except annoyance and distress, display a clearer residential gradient. Apartment residents consistently reported higher prevalence of stress (37.7%), bad temper (39.9%), anxiety (26.4%), mental blocks (21.8%) and fright (15.4%) compared to hutment and chawl residents. This suggest that perceived noise exposure and psychological response are not solely determined by housing quality. On the other hand, noise annoyance and distress are strongly mediated by contextual and perceptual factors, including predictability of noise, personal sensitivity, and co-existing urban stressors, rather than sound pressure levels alone^{42,43} which supports the comparable prevalence of annoyance (60.7–62.2%) and distress (28.5–35.5%) among residents of all housing types.

Behavioral impacts such as poor attention and inefficiency in work were comparable across residents of all housing types whereas difficulty in communication was prevalent among apartment residents (74.9%). Though the effects are evident across all residential categories, there is slightly higher prevalence in apartments which highlights that chronic environmental noise can impair cognitive functioning and daily performance regardless of residential form.

Auditory effects show a distinct pattern. Tinnitus is more prevalent among the survey participants, highest being reported by 45.7% apartment residents followed by 41.1% hutment residents while permanent hearing loss is reported at low levels across all residential types. This suggests that environmental (non-occupational) noise primarily contributes to reversible auditory symptoms, with cumulative exposure posing long-term risk. Recent studies indicate that repeated exposure to environmental noise can induce hidden hearing loss and tinnitus without immediate audiometric threshold shifts, potentially explaining the low prevalence of reported permanent hearing loss despite widespread symptoms.⁴⁴ Under-reporting or lack of audiological assessment may further mask true long-term auditory damage.

Association between Socio-economic Status (SES) and Noise-induced Health Effects

Chi-square tests of independence were performed to examine the association between socio-economic status based on residential categories (hutments,

chawls, and apartments) and health effects across physical, psychological, behavioral, and auditory domains. In the physical category, significant association was observed for sleep disturbance and fatigue ($\chi^2 = 18.437$, $df = 2$, $p < 0.001$) as shown in Table 2, conveying influence of socio-economic status of residents on the noise-induced health effects. Whereas, headache was reported almost equally by participants living in hutments, chawls, and apartments hence showed no significant association with the SES. Under psychological effects, stress, anxiety, bad temper, mental block, and fright shows statistically significant associations with the SES. In contrast, annoyance and distress were not significantly associated with SES as shown in Table 2. Communication difficulty was faced differently by each socio-economic group as conveyed by the strong association ($\chi^2 = 38.189$, $df = 2$, $p < 0.001$) across all health effects, while, poor attention and inefficiency in work were observed to be non-significant. Under auditory health outcomes, all categories of health effects show significant association with the SES of the residents. Auditory health outcomes showed significant associations for temporary hearing problems, permanent hearing problems, and tinnitus, indicating a clear socio-economic influence on auditory health.

The findings suggest that even though perception of noise-induced health effects is prevalent among apartment residents (Fig. 9), majority of the health effects showed significant association with socio-

Table 2 — Chi-square (χ^2) analysis of the association between socio-economic status and health effects

Domain	Health effects	χ^2	df	p-value	Significance
Physical	Headache	0.037	2	0.982	No
	Sleep disturbance	9.709	2	<0.005	Yes
	Dizziness	13.667	2	0.001	Yes
	Fatigue	18.437	2	<0.001	Yes
	Annoyance	0.077	2	0.962	No
	Stress	22.021	2	<0.001	Yes
Psychological	Bad temper	17.299	2	<0.001	Yes
	Anxiety	25.354	2	<0.001	Yes
	Mental block	13.73	2	0.001	Yes
	Fright	16.514	2	<0.001	Yes
	Distress	3.987	2	0.136	No
Behavioural	Poor concentration	0.656	2	0.72	No
	Inefficiency in work	2.78	2	0.249	No
	Difficulty in communication	38.189	2	<0.001	Yes
Auditory	Temporary hearing loss	12.313	2	<0.005	Yes
	Permanent hearing loss	12.544	2	<0.005	Yes
	Tinnitus	18.819	2	<0.001	Yes

Table 3 — Categories of respondents based on the number of perceived noise-induced health effects

Number of health effects reported	Impact of noise pollution on exposed population
0	No impact
1 to 4	Low impact
5 to 9	Moderate impact
10 to 13	High impact
14 to 17	Severe impact

economic status of the participants (Table 2). Contrary to the expectation that lower-quality housing would always show the highest burden, the prevalence of health effects among apartment residents suggests that environmental noise exposure is not confined to informal or low-income housing, but also affects apartment residents, likely due to urban density, traffic proximity, and inadequate façade insulation.

Impact of Noise Pollution on Exposed Urban Population

To understand the overall extent of noise exposure impact on the exposed population, all the respondents were categorized as per the number of health effects perceived by them. Respondents who perceived no health effects were grouped as unaffected (no impact) individuals. Those who reported 1–4 health effects, were grouped as low impact individuals, 5–9 health effects as moderately impacted, 10–13 health effects as highly impacted and respondents who reported 14–17 health effects were categorized as severely impacted individuals (Table 3).

Out of the total survey respondents (n = 793), 7% encountered no impact, 45% encountered low impact, 35% were moderately impacted, 8% were highly impacted and 5% were severely impacted due to urban noise pollution exposure (Fig. 10a). Among adolescents, 54% were categorized as low impact and 37% as moderately impacted. A very small proportion of adolescents (3%) were highly impacted and no adolescents were classified as severely impacted. Six percent of adolescents reported no impact (Fig. 10b). For adults, 33% individuals perceived low impact and 32% individuals were moderately impacted of noise exposure (Fig. 10c). Adults were found to be more affected compared to adolescents (3% highly impacted and 0% severely impacted) with 15% of adults highly impacted and 11% severely impacted due to noise pollution exposure.

Mitigation Measures

In the questionnaire, respondents were asked about the most effective mitigation measures with respect to

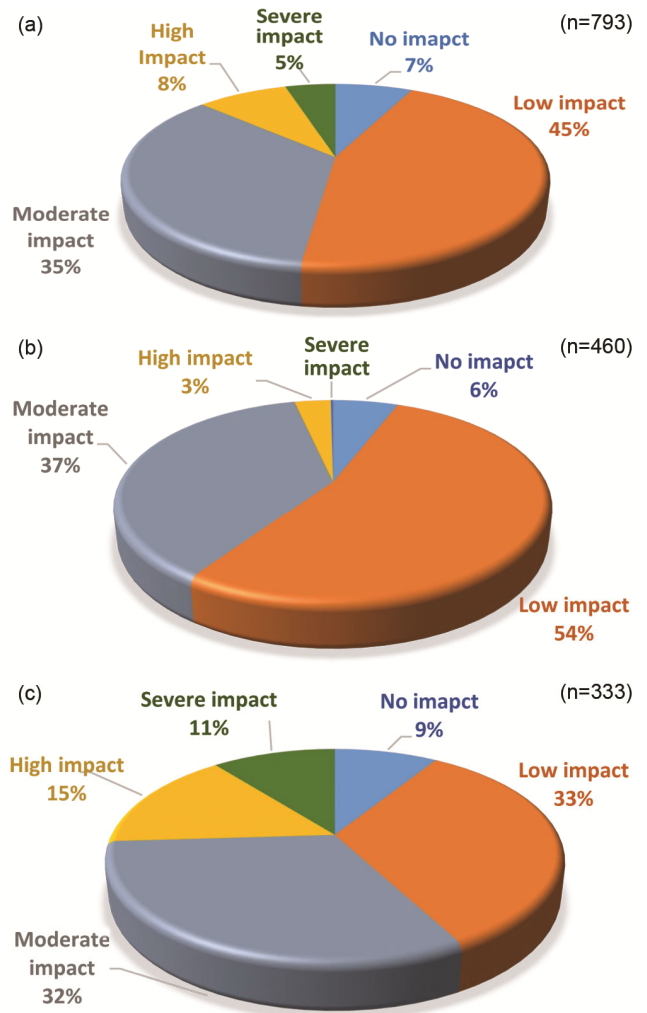


Fig. 10 — Impact of noise pollution on exposed population: (a) Total survey respondents, (b) Adolescents and (c) Adults

the sources and noise environment in their surroundings. Many of the respondents suggested more than one mitigation measure.

The various mitigation measures suggested by respondents, along with the frequency of responses for each measure are presented in Fig. 11. The measures reflect a range of strategies aimed at reducing traffic congestion, noise pollution, and improving urban transport efficiency. Survey respondents most frequently recommended better traffic management (453 respondents) as the primary noise mitigation strategy, emphasizing smoother traffic flow and reduced congestion to lower vehicular noise.⁴⁵ Strict noise regulations (448 respondents) and judicious use of honks (391 respondents) were also strongly supported, highlighting enforcement needs. Environmental measures such as plantation or noise barriers combined with innovative materials⁴⁶ (276

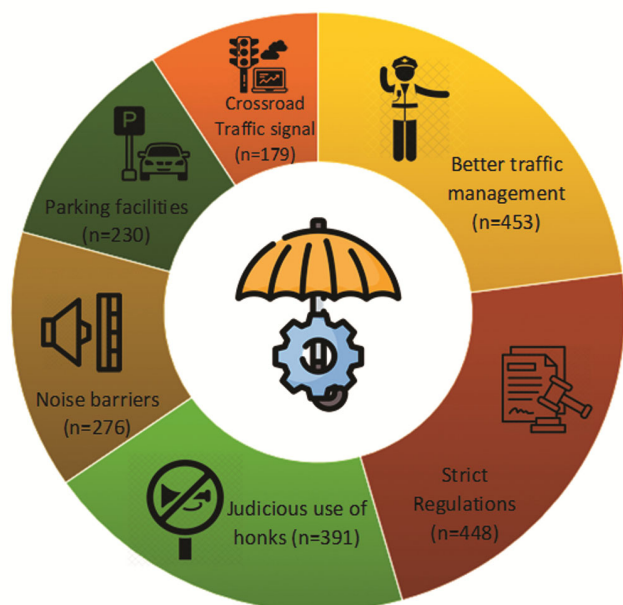


Fig. 11 — Mitigation measures to control urban noise pollution suggested by survey respondents

respondents), along with improved parking facilities (230) and cross-road traffic signals (179), were suggested to further minimize traffic-related noise.⁴⁷

Conclusions and Recommendations

The study revealed that a predominantly young urban population with varied occupational, educational, and residential backgrounds experiences noise exposure differently by age and socio-economic context, with adults showing the greatest overall health burden, followed by children and older adults. Overall assessment shows adults are more affected compared to children with 15% adults highly impacted and 11% severely impacted due to noise pollution exposure. The aligned analysis underscores that urban noise exposure exerts multidimensional health effects across the lifespan, with residential type shaping severity but not exclusivity of risk. Socio-economic conditions significantly shape health responses to environmental exposure, with pronounced effects observed in physical, psychological and auditory domains.

However, the study is limited by its reliance on self-reported data, lack of objective noise measurements, and cross-sectional design, which restrict causal interpretation and generalizability beyond the study area. Based on these findings, future efforts should prioritize integrating objective and longitudinal assessments, expanding research across multiple cities, and

implementing targeted urban planning, regulatory, and public health interventions to protect high-risk groups such as children and vulnerable socio-economic groups. The study's findings underscore the need for designing quieter residential and educational zones, inform policymakers to strengthen noise regulation enforcement by developing targeted, evidence-based strategies to mitigate noise pollution and improve urban health and wellbeing in metropolitan cities.

Statements and Declarations:

Conflict of interest: On behalf of all authors, the corresponding author states that there is no conflict of interest.

Compliance with Ethical Standards:

- Ethical approval from “Institutional Ethics Committee for Research on Human Subjects, CSIR-NEERI, Nagpur” was granted vide Ref. No. Eth.Com./001/IEC/06/2022.
- Informed Consent: Informed consent was obtained from all participants involved in the study before their inclusion.

Clinical trial number: Not applicable.

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