



# Road traffic noise pollution and prevalence of ischemic heart disease: modelling potential association and abatement strategies in noise-exposed areas

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**Abstract** In many developing countries with surging vehicular traffic and inadequate traffic management, excessive road traffic noise exposure poses substantial health concerns, linked to increased stress, insomnia and other metabolic disorders. This study aims to assess the linkage between sociodemographic factors, traffic noise levels in residential areas and health effects using a cross-sectional study analyzing respondents' perceptions and reports. Noise levels were measured at 57 locations in Srinagar, India, using noise level meter. Sound PLAN software was employed to generate noise contour maps, enabling the visualization of noise monitoring locations and facilitating the assessment of noise levels along routes in proximity to residential areas. Correlation

analysis showed a strong linear relationship between field-measured and modelled noise ( $r^2=0.88$ ). Further, a questionnaire-based survey was carried out near the sampling points to evaluate the association of ischemic heart disease with traffic noise. Residents exposed to noise levels ( $L_{den} > 60$  dB(A)) were found to have a 2.24 times higher odds ratio. Compared to females, males reported a 16% higher prevalence of the disease. Multi-faceted policy strategies involving noise mapping initiatives, source noise standards, traffic flow urban mobility optimization, smart city initiatives and stringent litigatory measures could significantly reduce its detrimental impact on public health. Finally, this study envisions a region-specific strong regulatory framework for integrating noise pollution mitigation strategies into the public health action plans of developing nations.

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## Introduction

Environmental noise pollution is a critical challenge for the urban population, with road traffic being one of the predominant contributors in major cities (Rodríguez-Molares et al., 2011). Especially traffic noise pollution concerns have become more significant in developing countries like India, where rapid

increase in the number of vehicles, and extension of road networks have surged with urbanization in recent years (Singh et al., 2016). Moreover, the complexities associated with heterogeneous vehicles, congested roads, suboptimal road conditions, incessant honking and a general lack of traffic awareness collectively heighten the challenges in analysing and estimating traffic noise in developing countries (Mahesh, 2021). Road traffic noise is significantly impacted by vehicle factors such as aerodynamics, road geometry, road-tire friction and noise from propulsion, exhaust and honking (Das et al., 2022; Ho et al., 2013; Vijay et al., 2015). Several other traffic parameters, including vehicular volume and speeds, along with road characteristics such as pavement width, gradient and surface roughness, also play a substantial role in influencing traffic noise (Sisman & Unver, 2011).

Road traffic noise pollution is the second most significant environmental stressor in Europe, following air pollution (European Environmental Agency, 2020; WHO, 2018). The World Health Organization (WHO) depicted the association of road traffic noise with several health and physiological disorders in Western Europe, including hearing loss (22,000 disability-adjusted life-years (DALYs)), ischemic heart disease (IHD) (61,000 DALYs), sleeplessness (903,000 DALYs), irritation owing to annoyance (654,000 DALYs) and cognitive impairment in children (45,000 DALYs) (Hahad et al., 2022). Specifically, the pervasive use of honks subtly ingrained in Indian driving behaviour is reported to contribute to potential physiological and psychological factors (Thakre et al., 2020). Moreover, prolonged exposure to noise levels  $> 55$  dB(A) stimulates mental disorders, hormonal alterations and metabolic disruptions from noise-induced stress (Daiber et al., 2020; Lee et al., 2023). Elevated stress hormones (noradrenaline, cortisol), blood sugar and cholesterol levels increase coagulation infraction (Babisch et al., 2014), which further increases the development of hypertension, atherosclerosis and myocardial infarction (MI) (T. Li et al., 2022).

Ischemic heart disease (IHD) has been identified as a serious threat to public health, particularly in individuals suffering from pre-existing conditions such as cardiovascular disease (CVD) (Li et al., 2022). Especially in developing countries like India, the significant lifestyle changes associated with rapid socioeconomic development pose

a considerable factors in multiple cardiovascular diseases (Huffman et al., 2011). For instance, the mortality rate in India attributed to CVD estimated in disability-adjusted life years (DALYs) has nearly doubled from 1990 (14.1%) to 2016 (28.1%) (Sreenivas Kumar & Sinha, 2020). Furthermore, IHD contributed to 7.8% of all DALYs lost in India in 2019, underscoring its substantial impact on individual and societal well-being (Bhattacharjee et al., 2021). As the social impact of IHD is significantly greater in developing countries compared to developed countries (Konstantinides et al., 2014), it is imperative to identify and analyze the potential sources to mitigate and control the association with cardiovascular diseases. Although the previous research has established correlations between road traffic noise and IHD, it was particularly focused on developed countries. However, considering the variable dynamics in the socio-economic status of people along with intricate road and traffic conditions, the studies on understanding the correlations between road traffic noise and the prevalence of IHD in developing countries are very limited (Banerjee et al., 2014; Khosravipour & Khanlari, 2020). Furthermore, to address the challenge, the urgently needed implementation of effective policy interventions targeting noise reduction becomes a critical public health priority.

The primary objective of the current study is to evaluate the association between road traffic noise and the prevalence of IHD. While the traffic noise was estimated through baseline noise mapping using general noise distribution across a selected urban area, a survey-based assessment was used to understand the prevalence of IHD. The study was conducted with the hypothesis that the prevalence of IHD would be higher in locations exposed to traffic noise levels  $L_{den} > 60$  dB(A). Further, the survey data was also used to determine the most vulnerable populations to IHD due to vehicular noise pollution, in terms of sociodemographic characteristics, gender, chronological age and daily lifestyle habits. The study comprises three key components, categorized as (i) field measurement by employing a noise level metre to assess the amount of noise near various roads, (ii) modelling of traffic noise levels using Sound PLAN (TNM 2.5) from various road sites and (iii) a survey study on the sociodemographic features, perception of noise sensitivity, stress and sleep quality of people

living in relatively close proximity to road networks as a result of road traffic noise exposure.

### Methodology

#### Study area

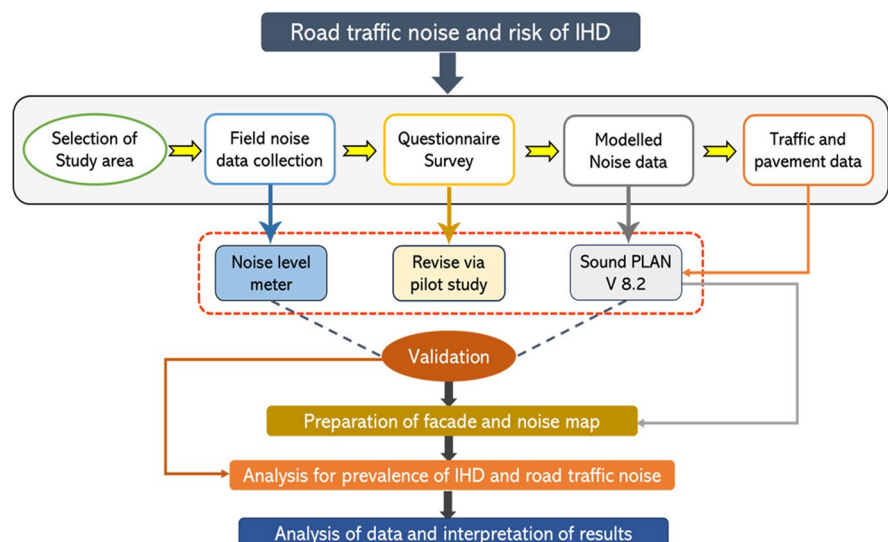
The study has been carried out in Srinagar city, the summer capital of the union territory of Jammu and Kashmir, located in Northern India (33°57'30" to 34°15 0" N latitudes and 74°40'0" to 74 o 57'30"E longitudes). The city is spread over a total area of 341 km<sup>2</sup> and is predominantly characterized by a mix of commercial and residential buildings, complemented by various tourist attractions (Batool et al., 2023; Majid & Mir, 2021). The city has an estimated population of 1,521,229 (as of 2021), and is divided into 61 wards by Srinagar Municipal Corporation (SMC) (Majid & Mir, 2021). The current study which comprises an assessment of noise exposure and a questionnaire survey was carried out in Nowhatta Srinagar, India, the residential core of the city and the heart of the overall urban system. The area is densely populated (30% of city population), congested roads, witnessed huge traffic congestion and experiences high levels of noise because of frequently occurring traffic congestion (Pasha et al., 2020) (Supplementary table, S1). This was coupled with the random and unplanned development in the area with rapid urbanization in the last decade. The selected area typically

represents the traffic conditions of unplanned development of a developing country with rapid urbanization. Figure 1 depicts in brief the research methodology applied in the current study.

#### Noise exposure assessment

While noise assessments are routinely conducted by specialized organizations in developed nations, data on ambient noise levels in developing countries, such as India, is conspicuously absent. To address this gap, a comprehensive survey was undertaken within the urban area of Nowhatta, Srinagar. Field noise levels were recorded at 57 distinct locations encompassing residential areas and roadways using Class 1-Casella CEL-633C noise level metre. These sites were meticulously chosen based on a multi-factor analysis, including traffic volume, land utilization, demographic shifts and urban dynamics (Zambrano-Monserrate & Ruano, 2019). To obtain a comprehensive understanding of typical traffic patterns, a data collection schedule was developed in cooperation with municipal authorities. Their technical assessments provided insights into typical vehicular movement patterns within the study area. The chosen measurement locations were strategically selected to represent areas with the highest potential for noise exposure. These sites were situated near heavily trafficked roads and in close proximity to residential areas, effectively representing the worst-case scenario for both traffic volume and residents exposure.

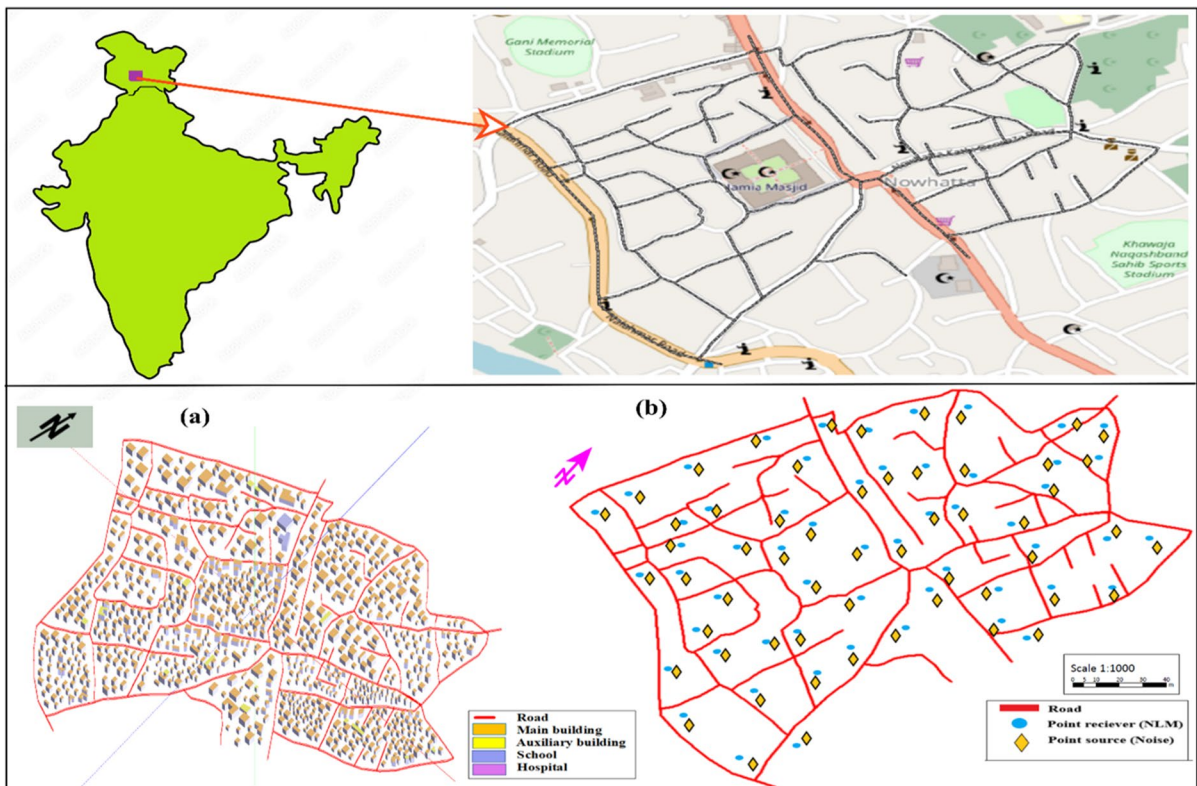
**Fig. 1** A flowchart showing the several stages in the research analysis process



The noise level metre was calibrated using “Class 1-Casella CEL-120/1”, followed by field measurements as per ISO 1996 (ISO 2003, 2007). The noise level metre was installed in an appropriate orientation to measure the sound intensity at  $1.5 \pm 0.1$  m above ground and  $3 \pm 0.2$  m in front of the most exposed façade (International Organization for Standardization, 1993). Similar procedure was implemented at all survey stations throughout the research area. The noise measurements were taken for 24 h from 7:00 am to 10:00 pm and 10:00 pm to 7:00 am. Figure 2 illustrates a visual representation of the noise monitoring sites, which includes point source of traffic noise (yellow), receiver points of the noise level metre (blue) and roads in the research area (red). The Casella software was used to extract the  $L_{den}$  (24 h) values directly from the instrument. The average  $L_{den}$ , which takes into account daytime, evening and nighttime noise levels with penalties of 10 decibels (A) for nighttime and

5 decibels (A) for evening, was chosen as the noise level index (Weihofen et al., 2019).

Further, data on traffic volume counts, which includes assessment of the frequency of traffic movements (heavy vehicles, automobiles and two-wheelers) were also collected during the duration of field noise monitoring. The traffic volume and speed data were collected through a 24-h video graphic survey. A high-definition camera (GoPro Hero 8 CHDX-801) suitable for nighttime recording was mounted at a safe and strategic location near the study site. The video recordings were transferred to a computer for manual vehicle classification and volume count. To determine average traffic speed, a 100-m segment was marked at each pre-selected site, and the time taken by vehicles to traverse this distance was measured from the video footage. The data was subsequently used in Sound PLAN V 8.2 software to simulate noise levels (modelled noise) from the study area along with the graphical representation of noise-impacted areas through noise maps by



**Fig. 2** Sampling locations for road traffic noise level assessments. **a** depicts the study area and three-dimensional visualization residential area; **b** indicates the point receiver, point source 57 main sampling locations

employing traffic noise model (TNM 2.5) (Karantonis et al., 2010). TNM 2.5 inputs comprise geographical coordinates of the study area, road traffic information, classification of the traffic volume, traffic speed, width of lanes, dwelling height and road surface type for the development of noise maps. A façade map was developed to represent the noise levels reaching the exteriors of the residences in the specified area (Fuks et al., 2017). Noise map of the study area was generated using a 5-m grid space and a height of 2 m above ground level. The field size was set to (9×9) m, and an acceptable level of 55 dB(A) was determined below which interpolation was used. Sound PLAN software uses an interpolation technique (inverse distance weighted) to examine the acoustic behaviour of the geographical area. Within traffic noise modelling, a crucial step involves the visual representation of noise levels using a spatial interpolation method. The IDW method stands as one of the most prevalent techniques employed for spatial analysis (Sojib et al., 2021). While IDW is considered most suitable for flat terrain applications (Ameen et al., 2021), it finds primary use in noise mapping, aiming to depict and elucidate the reality of noise pollution within the study area (Ali et al., 2018). By interpolating noise data obtained from noise sources and their corresponding distances, IDW is established as a powerful and reliable tool (Oyedepo et al., 2019). This transformation of available spatial data into a continuous surface by IDW allows for the visualization of areas categorized as relatively noisy, moderately noisy and low noise for the phenomenon under investigation (Akintunde et al., 2022; Esmeray & Eren, 2021).

### Questionnaire survey

The objective of the questionnaire was to collect first-hand information from the residents of the study area. Initially, a pilot study was conducted for the preliminary draft with 150 participants to assess clarity, scale distributions and length of time constraints. Pilot study also ensured correct structure of the questions to eliminate emotional and subjective interpretations. Pilot studies allow researchers to assess the clarity of the questions, as ambiguous or unclear questions might lead to emotional or subjective responses from respondents. By testing the questionnaire on a small sample of participants during the pilot study, researchers identify confusing or unclear questions

and revise them to improve clarity. Since a significant portion of the questions included in the final draft of the questionnaire were obtained from previously published literature related to road traffic noise and the prevalence of ischemic heart disease (Begou et al., 2020; Héritier et al., 2018), the implementation of a pilot study ensured the appropriate phrasing of the questionnaire items, thereby avoiding the potential for subjective and emotional interpretations. Consequently, following the pilot study, the questionnaire was refined to ensure clarity and appropriateness for data collection. It was revealed from the pilot survey that many respondents found it difficult to comprehend the questions in the English language and had to be provided with assistance regarding the meaning of the questions. During the survey, a verbal inquiry was conducted to ascertain the most preferred language for the questionnaire. Urdu emerged as the popular choice among the respondents. The translated Urdu version of the questionnaire was finalized based on the pilot study feedback, ensuring better communication with the sample population. Furthermore, we followed a translation-back-translation procedure to ensure the accuracy of the Urdu version of our document. The original document was translated into Urdu by a professional translator. A separate translator, unfamiliar with the original document, then back-translated the Urdu version into English. We carefully reviewed both the original document and the back-translation to identify any discrepancies and ensure the final Urdu version accurately reflects the intended meaning.

The survey team comprised of three researchers with adequate knowledge of questionnaires and familiarity with the local native language (Urdu). An interviewer-administered house-to-house survey method was employed for collecting the data as it simplifies the interviewer to provide comprehensive explanations to questions and facilitates effective communication with participants by asking multiple questions to investigate the responses provided by the respondents. The data was collected from 22 November 2022 to 28 August 2023 over 39 weeks and 6 days. To reduce the possibility of sampling bias, the survey was conducted on both weekends and weekdays. Participation of the respondents in the survey was entirely voluntary and no monetary remuneration or inducement was given to respondents during the survey. As our research involves the use of human participants, the

authors of the study ensured that all procedures were carried out in compliance with relevant laws, and institutional guidelines, and formal ethical approval and data collection for the survey was obtained and approved by the National Institute of Technology, Srinagar, India (NIT/CIVIL/TEP/22/117–120) (S1 Figure). A word-of-mouth/consent letter to seek the consent of each study participant at the site of question administration. The respondents were given full disclosure about the purpose of the study and given the opportunity to consent to the interview process. For the survey, researchers approached 1730 participants out of which 1670 consented to take part in the survey. The participants were informed of a time frame of 10–20 min (i.e. estimated survey duration obtained from the pilot survey) that would be required to completely answer the questions. Therefore, face-to-face interviews were conducted only for those participants who had agreed to participate in the survey voluntarily and were able to allocate the requested time. However, despite the followed protocol in conducting the survey, if the participant experienced any unforeseen situations to leave the survey mid-way, that partially filled record was eliminated before proceeding for statistical analysis. Out of the 1670 respondents participated in the survey, 47 were removed owing to the lack of acceptable attribute data and an incomplete record. This resulted in 1623 valid samples with a 94% response rate. Supplementary table S2 shows the characteristics of the study sample in comparison to the target population.

### Covariates

A comprehensive questionnaire with four components—sociodemographic variables, noise sensitivity, stress and quality of sleep was used in the present study. The primary aspect of the questionnaire was related to the standard of living, daily routine habits and sociodemographic details, followed by noise sensitivity, sleep quality and self-reported stress levels.

Covariates that could represent potential confounding factors for IHD were taken into consideration in the analysis. The selection of covariates was done based on the availability of data, probable biological significance and the current scientific literature. It helps in determining the impartial immediate impact of the exposure variable (road traffic noise) on the resultant variable (occurrence of IHD). Age, gender,

socioeconomic status, comorbidity and noise sensitivity factors were found to be linked to the state of mental health (Rocha et al., 2012). The socioeconomic status of the respondents was determined by using annual income, level of education and professional status. Age was determined as the difference between the baseline survey date and the official birth date on the identity cards or family registration booklets. The height as well as the weight of each participant was measured using specialized medical equipment and divided the weight in kilograms by the square of the height in metres to calculate body mass index (BMI). Participants reported their annual income within four categories (less than 1 lakh INR, 1–2 lakh INR, 2–3 lakh INR and greater than 3 lakh INR). Marital status (unmarried, married, widowed/divorced) and educational attainment (up to higher secondary, graduation, postgraduate) were also assessed. Professional status was initially categorized into five groups (working outside, working at home, retired, student, unemployed/disabled) and then consolidated into employed (working outside/at home), unemployed (student/unemployed/disabled) and retired. Health characteristics included chronic conditions (defined as having at least one of the listed ailments: diabetes, kidney problems, chronic obstructive pulmonary disease, hypertension). Lifestyle factors assessed were residence duration ( $\leq 10$  years or  $> 10$  years), physical activity level (sedentary or active), smoking status (never, ex-smoker, current smoker), family history of heart disease (yes/no) and bedroom window orientation (facing the road or other side). The questionnaire was expanded to assess the general intake of specific foods (fruits, raw vegetables/salad) alongside reported dietary product consumption frequency. Daily intake of meals and nutrients was determined for each participant, with consumption of specific food items further weighted based on the additional food intake questions. Following established research and WHO guidelines, a daily intake threshold of 400 g was used as the reference point to assess the likelihood of cardiac problems.

In this study, while accounting for all of the necessary mediators and confounders, DAG (directed acyclic graph) was used to evaluate the immediate effect of vehicular noise on IHD (Austin et al., 2019). DAG was developed with the use of the web-based software program called DAGitty. Based on the extensive literature review and hypothesized causative relationship

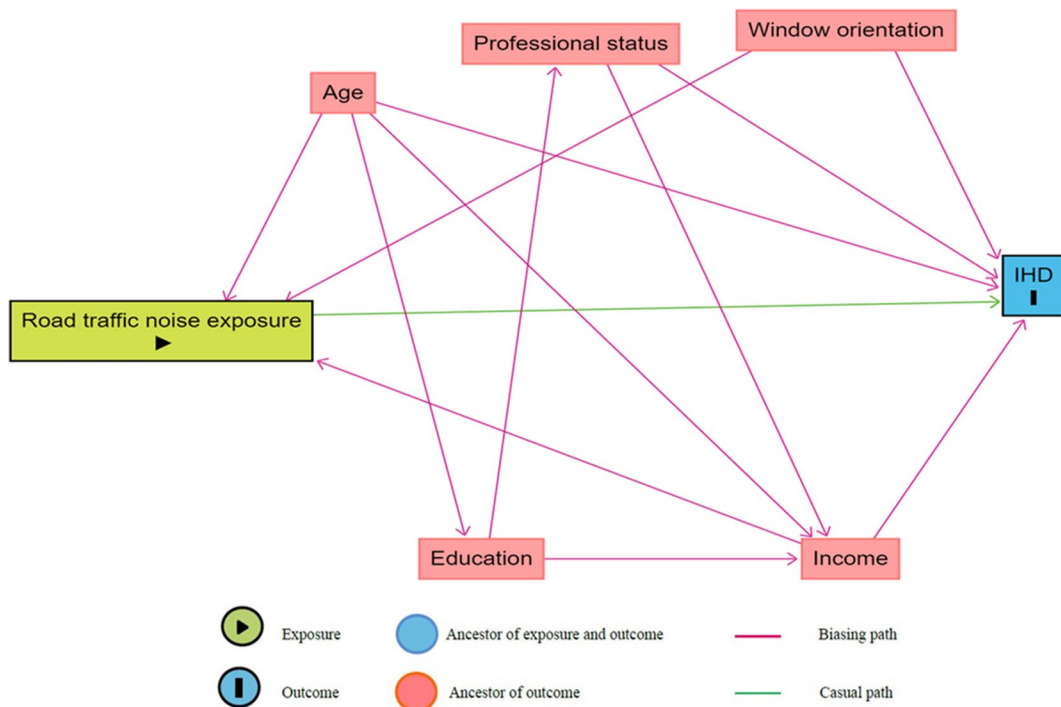
between vehicular noise and IHD, the DAG analyzed model was developed, and the variables needed to construct the model were identified by questionnaire survey. Figure 3 emphasizes the model for identifying an association between vehicular traffic noise and IHD. To determine unbiased direct effects of traffic noise on IHD, DAGitty software analyses the minimal number of variables that need to be adjusted for calculating the influence of exposure on outcome variable. In this study, the minimum variable adopted to develop a model includes “age”, “window orientation”, “education”, “income” and “professional status”. Figure 3 illustrates the DAG for the minimum adjustment set of covariates or mediators based on the perceived causal association.

To analyze the sleep patterns of respondents over the previous month in seven clinically significant domains, the Pittsburgh Sleep Quality Index (PSQI) scale was utilized, which includes “subjective sleep quality”, “sleep latency”, “sleep duration”, “sleep efficiency”, “sleep disturbances”, “use of sleep medication” and “daytime dysfunction”. The respondents assessed themselves on a Likert scale of 0 to 3, with

3 representing the “negative extreme”. The seven components were scored on a scale of 0–1 representing “excellent sleep quality”, 3–5 representing “good sleep quality” and 6–21 suggesting poor sleep quality. The scale is also a valid instrument for assessing sleep quality among the Indian population (Manzar et al., 2015). Bedrooms with windows facing the street or road can be detrimental as they are exposed to vehicular noise, particularly during the night, resulting in fragmentation of sleep structure without the actual perception of the stressor. Although sleep quality was not present in the initial draft, PSQI was added to the final questionnaire after analyzing the responses from the pilot study.

### Assessment of ischemic heart disease

The questions regarding health status assessment adhered to the protocols established in the Japan Public Health Center-based Prospective Study on Cancer and Cardiovascular Diseases (Konishi et al., 2001). The questionnaire investigated cardiovascular diseases (CVDs), encompassing both self-reported



**Fig. 3** Directed acyclic graph (DAG) for the minimum adjustment set of covariates or mediators based on the perceived causal association

diagnoses with a focus on stroke (cerebral infarction or intracerebral haemorrhage) and ischemic heart diseases (IHDs) such as angina pectoris or myocardial infarction (Azuma & Uchiyama, 2017). Questions regarding IHD-related subjective symptoms within the past year addressed chest pain: “Have you experienced abrupt chest pain lasting for more than 10 s?,” disturbances in pulse: “Have you experienced disturbances in pulse or arrhythmia?,” acute impaired tongue movement: “Have you experienced sudden feeling of thickness of the tongue?,” limb paralysis: “Have you experienced crippled feelings or numb hands and feet?” and foot pain or numbness during walking: “Have you experienced intermittent claudication in the legs?” Furthermore, participants were identified as IHD cases based on an affirmative response to the question: “Have you ever been diagnosed with cardiovascular disease like myocardial infarction or angina pectoris by a physician while residing at your current address?” The second stage involved validation of self-reported information about an illness by seeking a photocopy of the most recent prescription of diagnosis from a doctor or licenced healthcare professional. Further, all the obtained copies were independently cross-verified by licenced medical professionals (Gilani & Mir, 2021). Among the 1623 subjects in this study, 106 cases were identified using this criterion. Accordingly, the participants were classified into a case group of 106 subjects and a control group of the remaining 1517 subjects.

### Statistical analysis

To assess the link between road traffic noise components and IHD prevalence in both “quiet” and “noisy” exposure groups, continuous variables were analyzed with appropriate “non-parametric” or “parametric” tests based on data distribution, while categorical variables were analyzed using chi-square ( $\chi^2$ ) tests. Initially, “Shapiro–Wilk” and “Kolmogorov–Smirnov” tests were conducted to determine the normality for continuous variables including age,  $L_{den}$  and BMI. Further, non-parametric statistical evaluations, specifically the Wilcoxon signed rank-sum for scaler and the chi-square for nominal data, were comprehensively analyzed to examine variances within each exposure group.

Logistic regressions were used to compute odds ratios (OR) and 95% confidence intervals (CI) in this

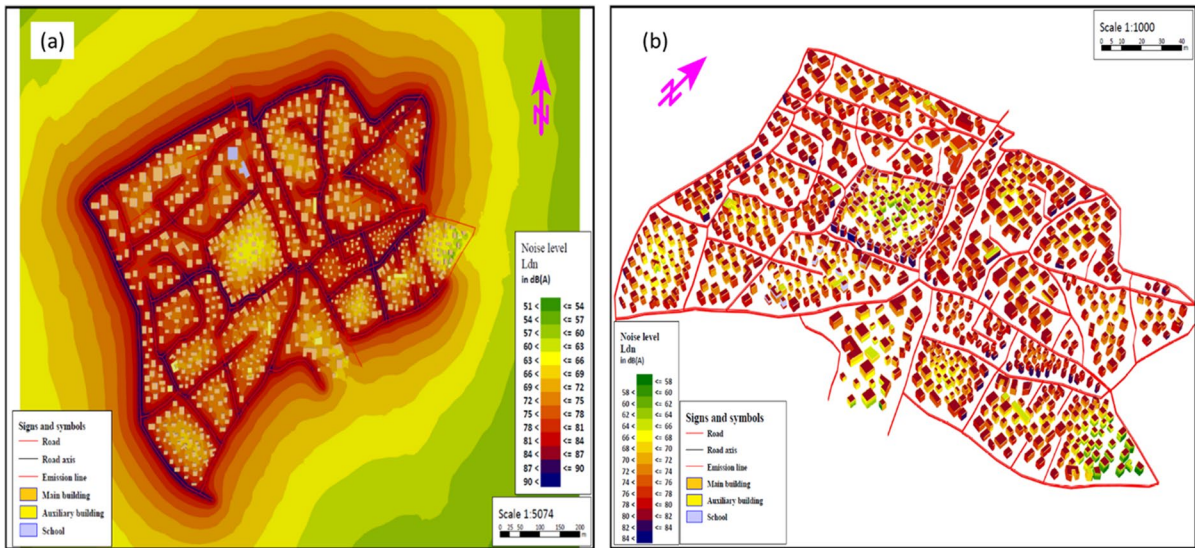
study. The association between the  $L_{den}$  index and the odds of IHD for both genders and noise levels, either as a continuous or categorical variable was assessed through “Univariate logistic regression”, using the baseline level of noise exposure < 60 decibels (A). Odds ratios for the univariate unadjusted model, two partially adjusted models and a fully adjusted model were computed. Age, window orientation was adjusted for the first partially adjusted, while the second partially adjusted model was further adjusted for professional status. The fully adjusted multivariate model was adjusted for all the covariates present in the second partially adjusted model alongside other covariates like income and education. All the statistical tests conducted using a two-tailed hypothesis were considered statistically significant at  $p < 0.05$  level. IBM SPSS 26 software was used for all statistical calculations.

## Results

### Noise assessment and validation of noise levels

Figure S3 provides a visual representation of the residential area encompassed by the study. The figure depicts the spatial distribution of questionnaires administered to respondents within this area. Noise grid map and façade map were developed using Sound PLAN 8.2 software incorporating traffic characteristics, classification of the traffic volume, traffic speed, width of lanes, dwelling height and road surface type determined from field investigations (Fig. 4). These maps generated from the assessment of modelled noise levels were used to study the acoustic environment of the study area through efficient graphical representation. The grid noise map distinguishes between the varying noise levels experienced across different zones within the study area, while the facade map illustrates the impact of varying noise levels on facade structures. Areas with less than 60 decibels (A) of  $L_{den}$  values were classified as “low-noise area”, whereas those with values greater than 60 decibels (A) of  $L_{den}$  were classified as “high-noise area”. The threshold value of 60 decibels (A) was selected for two reasons: first, the median for noise level was 65.1 decibels (A). Secondly, the threshold value for ambient noise quality standards is 55 decibels (A) for residential areas (Farooqi et al.,





**Fig. 4** Acoustic environment of the study area based on road traffic characteristics. **a** Noise grid map with contours of low- and high-noise decibels. **b** Facade map with the acoustics experienced by façade structures

2022; Ministry of Environment and forest, 2000). Moreover, previous studies, analysing the association between road traffic noise and prevalence of cardiovascular in both developed and developing countries, also adopted 60 decibels (A) as their threshold value (Andersson et al., 2020; Dzhambov & Dimitrova, 2016; Gilani & Mir, 2021; Kupcikova et al., 2021). Banerjee et al. (2014) also considered 60 decibels (A) threshold in their study for the association between road traffic noise and prevalence of coronary heart disease, considering the diverse spectrum of road traffic circumstances prevalent in India. Significantly, a study encompassing approximately 4000 participants unveiled a substantial odds ratio of 1.8 for the incidence of myocardial infarction among individuals residing on streets where noise levels exceeded 70 decibels for at least 10 years, compared to those inhabiting areas with levels at or below 60 decibels (Welch et al., 2023). This assertion is supported by a population-based study in Vancouver, Canada, where individuals inhabiting regions characterized by high-noise levels (> 70 decibels) exhibited a 22% higher mortality rate from coronary heart disease than residents of areas with lower noise levels (≤ 58 decibels) (Gan et al., 2012).

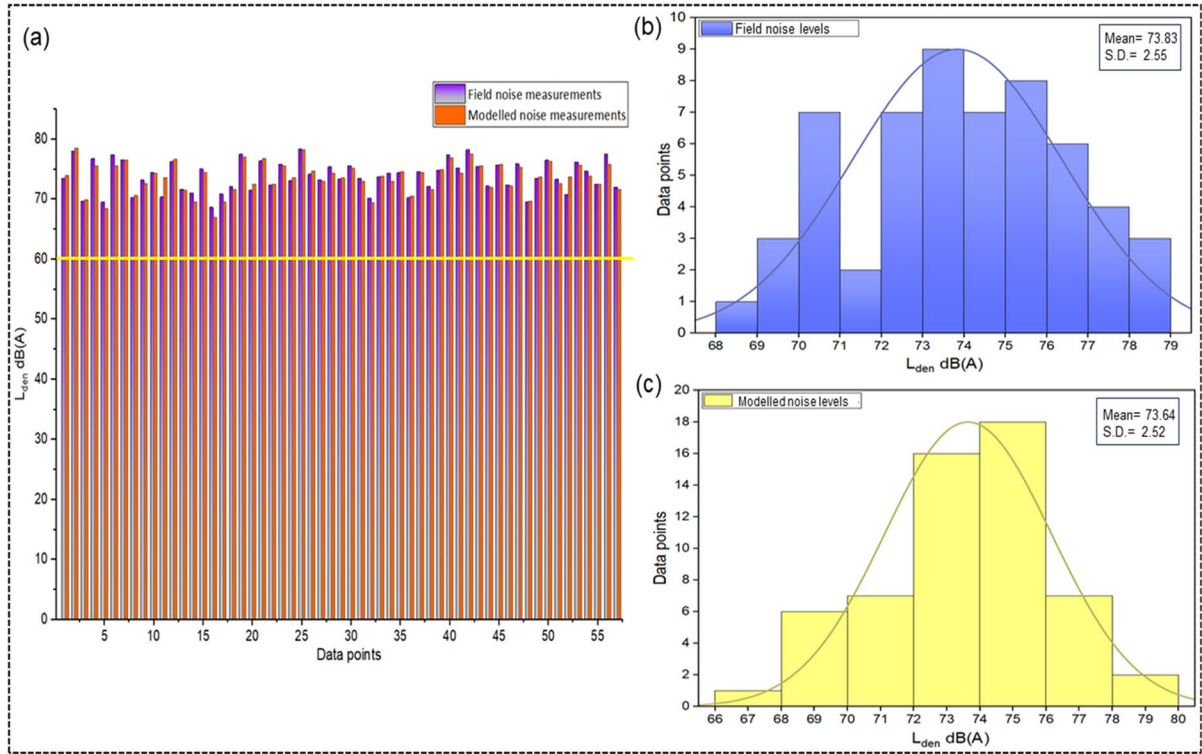
The field noise measurements were carried out at 57 pre-determined locations in the research area from 22 November 2022 to 28 August 2023 (during

the same course of time as the questionnaire survey). The extended timeframe for noise measurements may introduce limitations regarding scheduling flexibility for data collection. However, the proximity of these locations to high-traffic areas ensures that the data collected represents a worst-case scenario for noise exposure within the study region. Figure 5 a depicts a comparison of noise pollution levels acquired through field measurements ( $n=57$ ) and modelling simulations performed using Sound PLAN software. The field data indicates noise levels ( $L_{den}$ ) ranged from a minimum of 68.6 dB(A) to a maximum of 78.3 dB(A) during the study period. To further illustrate the distribution of noise levels, locations were categorized. While 7% of the monitored areas exhibited levels between 65 and 70 dB(A), the majority (57.9%) had noise levels between 70 to 75 dB(A) range. The remaining 35.1% of locations experienced noise levels between 75 and 80 dB(A). Figure 5 b and c provide a visual representation of this distribution using histograms for both field measurements and modelled data. The reading comprehension mean score for the field data (mean ± SD: 73.8 ± 2.55) and for the modelled data (Mean ± SD: 73.6 ± 2.52). To assess normality, the field and modelled noise levels were subjected to Shapiro–Wilk and Kolmogorov–Smirnov tests at a 95% confidence level. The resulting  $p$ -values > 0.05 indicate that neither noise distribution

significantly deviates from normality (Table 1). Furthermore, the measured noise levels were compared to the modelled noise levels employing the paired sample *t*-test.

The test yielded a non-significant outcome ( $p > 0.05$ ), suggesting no significant difference

between measured and modelled noise levels (Table 2). Figure S2 depicts the variation of field noise decibels with modelled noise retrieved from the field instrument (NLM) and noise map of the research area, respectively. Furthermore, linear regression analysis revealed a high correlation



**Fig. 5** Noise pollution calculated at 57 locations. **a** shows the variation of field-measured and modelled noise levels. **b** and **c** illustrate the histograms of the noise levels for field-measured and modelled data, along with statistical summaries

**Table 1** Statistical analysis of field and modelled noise levels through the Shapiro–Wilk and Kolmogorov–Smirnov tests

Variable	Shapiro–Wilk			Kolmogorov–Smirnov		
	Statistic	df	<i>p</i> value	Statistic	df	<i>p</i> value
FMeNL	0.97	57	0.25	0.06	57	0.20
MdNL	0.98	57	0.55	0.08	57	0.20

<sup>1</sup>SD, standard deviation; <sup>2</sup>FMeNL-MdNL, field-measured noise levels-modelled noise levels

**Table 2** *t*-test between field-measured and modelled noise levels

Variable	Mean	Std. error mean	SD <sup>1</sup>	95% CI	<i>t</i> statistic	df	Sig. (2-tailed)
(FMeNL-MdNL) <sup>2</sup>	0.19	0.11	0.88	-0.04 – 0.43	1.65	56	0.10

<sup>1</sup>SD, standard deviation; <sup>2</sup>FMeNL-MdNL, field-measured noise levels-modelled noise levels.

( $r^2=0.88$ ) between the actual noise levels measured in the field and the levels predicted by the TNM 2.5 model. This strong agreement validates the use of TNM 2.5 for generating noise maps in the research area. The model performance efficiency was carried out through statistical metrics, which also depicted low root mean square error (RMSE) (0.81) and high coefficient of correlation ( $r$ ) (0.93) (Supplementary Table S3), depicting high model precision (Mohammed et al., 2021).

## Noise impact analysis

### Baseline characteristics

A total of 1623 participants (874 males and 749 females) aged 18–75 years were selected by stratified random sampling to ensure the gender ratio during the questionnaire survey process. The gender distribution within the sample reflects the national demographics according to the 2011 Indian Population Census (Census, 2011). The method was also followed in other studies as reported in the literature (Azuma & Uchiyama, 2017; Gilani & Mir, 2021). This sampling strategy strengthens the generalizability of the study findings to the target population (Supplementary Table, S2). As for noise exposure, 62% of the interviews were conducted in areas defined as exposed to noise. Table 3 describes the variables considered in the study, stratified by gender, varied between noise levels regarding age and sleep quality ( $p < 0.05$ ). Furthermore, the survey found a substantial age difference for both genders, with younger people living in high noisy regions. The noise levels differed significantly between sexes, with males perceiving slightly higher noise than females. In terms of noise exposure, 38.07% of people were exposed to noise levels  $\leq 60$  dB(A), 12.6% to noise levels of 61–65 dB(A), 16.9% to noise levels of 66–70 dB(A) and 32.2% to noise levels of  $> 75$  dB(A). According to the research findings, there was a 6.53% total reported prevalence of IHD, with 4.20% of cases affecting quiet areas and 7.96% in noisy regions.

### Association between sociodemographic confounders, road traffic noise and IHD

The regression models shown in Table 4, indicate that a 5 dB(A) increase in noise levels corresponds

to a significant increase in the association of IHD, especially when adjusted for different variables. In crude analyses and after further adjustment for sociodemographic variables and potential health hazards for all sample responses, residents residing in  $L_{den} > 60$  dB(A) had stronger associations for the prevalence of IHD compared to individuals in quieter environments. Considering the IHD outcome, associations are significant and have a higher prevalence of the odds ratio in the fully adjusted model (Model III) (OR=2.24, 95% CI, 1.48–4.42). Stratification based on gender; males had a higher odds ratio of IHD than females. Stronger associations were observed for males (OR=2.61, 95% CI, 1.17–6.37) than for females (OR=2.10, 95% CI, 1.16–4.01). For males, compared with the unadjusted model, respondents adjusted for all factors in the fully adjusted model (Model III) had a 16% higher prevalence of IHD. After accounting for all factors, the adjusted odds ratio for IHD development was 50.5% higher in males compared to females, indicating a significant sex difference.

### Stratified analyses

To identify the threshold noise level associated with a statistically significant rise in IHD, stratified analyses were performed, categorizing data into 5-decibel intervals, and calculating the specific cutoff value above which the association becomes significant. While analyzing the prevalence of IHD in our research, we initially employed a baseline noise level of 60 decibels (A) for the general analysis. However, to identify the noise thresholds at which the relationship between road traffic noise and IHD became statistically significant and affects the residents in the research area, we adopted a lower threshold of 50 decibels (A). The figure reveals a clear threshold effect for IHD at 60 dB(A). The noise levels below 60 dB(A) show a non-significant odds ratio ( $p > 0.05$ ), while odds ratio escalates sharply above 60 dB(A). For every 5-decibel increase, the OR becomes a significant and relative increase of approximately 10.71% in the odds ratio when moving from 65 to 70 dB (A).

A significant age-related disparity in IHD was associated with traffic noise. While individuals aged 36–45 years faced a substantial (OR=2.01), it was even higher for those aged 66–75 years (OR=2.21).

**Table 3** Descriptive statistical data of participants on gender-based, stratified by vehicular noise above and below 60-decibels (A) of exposure

Baseline characteristics	Males ( <i>n</i> = 874)			Females ( <i>n</i> = 749)		
	Low-noise area <sup>c</sup> ( <i>n</i> = 362)	High-noise area <sup>d</sup> ( <i>n</i> = 512)	<i>p</i> -value	Low-noise area <sup>c</sup> ( <i>n</i> = 256)	High-noise area <sup>d</sup> ( <i>n</i> = 493)	<i>p</i> -value
$L_{den}$ (mean $\pm$ SD)	52.5 $\pm$ 3.6	70.6 $\pm$ 5.0	< 0.001 <sup>a</sup>	52.2 $\pm$ 3.8	70.3 $\pm$ 5.6	< 0.001 <sup>a</sup>
BMI <sup>e</sup> (mean $\pm$ SD)	24.9 $\pm$ 2.6	25.2 $\pm$ 2.6	0.269 <sup>a</sup>	24.4 $\pm$ 3.8	25.0 $\pm$ 2.4	0.558 <sup>a</sup>
Age <sup>f</sup> (mean $\pm$ SD)	46.1 $\pm$ 15.8	42.2 $\pm$ 14.4	0.003 <sup>a</sup>	44.6 $\pm$ 15.4	39.8 $\pm$ 14.6	0.005 <sup>a</sup>
Residence period			0.243 <sup>b</sup>			0.543 <sup>b</sup>
≤ 10 years	117	185		93	188	
> 10 years	245	327		163	305	
Level of education			0.330 <sup>b</sup>			0.312 <sup>b</sup>
Below high school	117	170		58	177	
Up to higher secondary	131	181		106	173	
Above higher secondary	114	161		92	143	
Chronic disorders <sup>f</sup>			0.745 <sup>b</sup>			0.784 <sup>b</sup>
Yes	71	105		52	96	
No	291	407		204	397	
Smoking <sup>h</sup>			0.195 <sup>b</sup>			
Never	87	112				
Ex-smoker	63	71				
Smoker	212	329				
Family history IHD <sup>g</sup>			0.879 <sup>b</sup>			0.205 <sup>b</sup>
Yes	58	84		65	105	
No	304	428		191	388	
Walking			0.206 <sup>b</sup>			0.664 <sup>b</sup>
No	116	173		83	176	
Yes ≤ 1.5 h/day	139	215		107	198	
Yes > 1.5 h/day	107	124		66	119	
Marital status			0.729 <sup>b</sup>			0.658 <sup>b</sup>
Unmarried	134	192		95	187	
Widowed or divorced	39	47		24	61	
Married	189	273		137	245	
Fruit consumption			0.207 <sup>b</sup>			0.932 <sup>b</sup>
No ≤ 400 g/day	169	217		116	225	
Yes > 400 g/day	193	295		140	268	
Veg. consumption			0.163 <sup>b</sup>			0.350 <sup>b</sup>
No ≤ 400 g/day	47	84		32	74	
Yes > 400 g/day	315	428		224	419	
Bedroom window			0.131 <sup>b</sup>			0.425 <sup>b</sup>
Facing towards road	113	140		89	186	
Facing other side	249	372		167	307	
Sleep quality			< 0.001 <sup>b</sup>			0.027 <sup>b</sup>
Poor	80	186		65	196	
Good	148	196		77	181	
Excellent	134	130		114	116	
Stress			0.279 <sup>b</sup>			0.127 <sup>b</sup>
Low	118	166		66	106	

**Table 3** (continued)

Baseline characteristics	Males (n = 874)			Females (n = 749)		
	Low-noise area <sup>c</sup> (n = 362)	High-noise area <sup>d</sup> (n = 512)	p-value	Low-noise area <sup>c</sup> (n = 256)	High-noise area <sup>d</sup> (n = 493)	p-value
Medium	132	164		103	186	
High	112	182		87	201	
Sensitivity			0.237 <sup>b</sup>			0.141 <sup>b</sup>
Low	91	104		75	118	
Moderate	146	217		97	221	
High	125	191		84	154	
Annual income			0.429 <sup>b</sup>			0.126 <sup>b</sup>
Less than 1 lakh	82	134		70	163	
1–2 lakh	45	74		36	60	
2–3 lakh	127	163		99	155	
Greater than 3 lakhs	108	141		51	115	
Professional status			0.727 <sup>b</sup>			0.218 <sup>b</sup>
Employed	147	201		121	219	
Unemployed	151	227		108	236	
Retired	64	84		27	38	
Physical activity			0.873 <sup>b</sup>			0.443 <sup>b</sup>
Sedentary	195	273		141	257	
Active	167	239		115	236	
Prevalence of IHD						
Yes	17	42	0.042	09	38	0.025
No	345	470		247	455	

<sup>a</sup>Wilcoxon signed sum test of the difference between high- and low-exposure groups

<sup>b</sup>Chi-square test for the difference between high- and low-exposure groups

<sup>c</sup>L<sub>den</sub> ≤ 60 dB(A)

<sup>d</sup>L<sub>den</sub> > 60 dB(A)

<sup>e</sup>Body mass index (kg/m<sup>2</sup>)

<sup>f</sup>Other chronic disorders like kidney ailments, diabetes, COPD, hypertension

<sup>g</sup>Family members having a history of ischemic heart diseases before 60 years of age

<sup>h</sup>Women were not found to be smoking

<sup>l</sup>Age: reported in years

SD, standard deviation

The age group in the middle, 56–65, had the highest odds ratio, almost one and half times higher for the younger age group, highlighting the increasing vulnerability with age. So, the importance of developing targeted noise reduction techniques to protect people from the detrimental effects of road noise pollution is prominent. Further, participants also demonstrated a positive association between noise sensitivity and the magnitude of observed effects. Compared to individuals with low and medium noise sensitivity, individuals with high-noise sensitivity had higher chances

of experiencing the odds ratio of the association of road traffic noise and IHD. High-noise sensitivity was associated with an increase in developing IHD (OR = 3.18, 95% CI, 1.95–5.17).

A statistically significant association was observed between self-reported stress levels and IHD due to vehicular noise. Participants experiencing “moderate stress” and “high stress” exhibited odds ratios of 1.76 (95% CI, 0.28–3.72) and 2.28 (95% CI, 1.85–5.76), respectively, compared to the “low stress” baseline group. Further highlights the impact of sleep quality

**Table 4** Hierarchical logistic regression for the prevalence of IHD stratified for both males and females with odds ratio determined for each 5 decibels (A) increase in the level of noise

Road traffic noise level	Area type	IHD <sup>1</sup> Prevalence percentage	Univariate unadjusted model	Partially multivariate adjusted Model (I) <sup>2</sup>	Partially multivariate adjusted Model (II) <sup>3</sup>	Fully adjusted multivariate model Model (III) <sup>4</sup>
Continuous per 5 dB(A) Increment			Odds ratio (95% CI)			
			P value			
All sample	L <sub>den</sub> ≤ 60 dB(A)	4.20	1	1	1	1
	L <sub>den</sub> > 60 dB(A)	7.96	1.97 (1.18–3.77)	2.01 (1.18–3.90)	2.13 (1.27–4.37)	2.24 (1.48–4.42)
			0.012	0.004	0.001	<i>P</i> < 0.001
Males	L <sub>den</sub> ≤ 60 dB(A)	4.69	1	1	1	1
	L <sub>den</sub> > 60 dB(A)	8.20	2.45 (1.03–6.42)	2.50 (1.08–5.63)	2.54 (1.12–5.74)	2.61 (1.17–6.37)
			0.031	0.013	0.008	0.001
Females	L <sub>den</sub> ≤ 60 dB(A)	3.51	1	1	1	1
	L <sub>den</sub> > 60 dB(A)	7.70	1.93 (1.10–3.57)	1.98 (1.10–2.69)	2.03 (1.15–3.96)	2.10 (1.16–4.01)
			0.023	0.003	0.001	<i>P</i> < 0.001

<sup>1</sup>IHD, Ischemic heart disease

<sup>2</sup>Partially multivariate-adjusted model (I): age, window orientation

<sup>3</sup>Partially multivariate-adjusted model (II): age, window orientation, professional status

<sup>4</sup>Fully adjusted multivariate model (III): age, window orientation, professional status, income, education

on IHD. Respondents reporting “poor sleep” faced a 3.14 times increased odds ratio (95% CI, 1.89–6.04) compared to those with “excellent sleep”, while “good sleep” was associated with a smaller but significant association (OR = 2.13, 95% CI, 1.01–3.97).

Both stress and poor sleep quality emerged as significant independent factors for IHD, with a substantial increase observed for individuals experiencing either or both conditions. All the effect modifications based on age group, noise sensitivity, stress and sleep quality along with their significance values are shown in supplementary table S4. Adjusted subgroup analysis for potential effect modifiers of the association of IHD and road traffic noise exposure is shown in Fig. 6 with the overall *p*-value equal to 0.038.

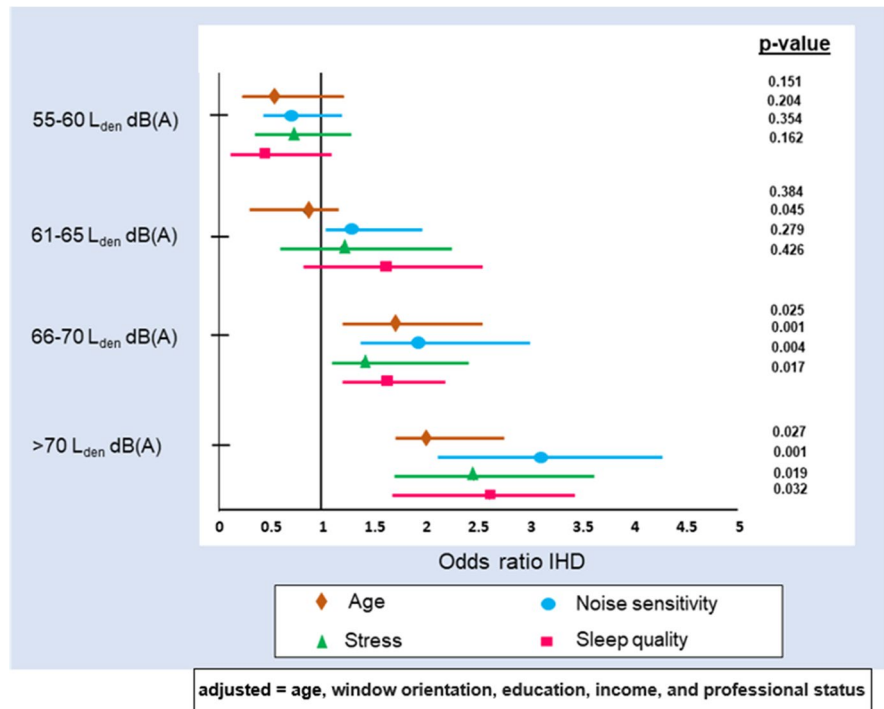
## Discussion

### Noise impact analysis

The study investigated the association between road traffic noise exposure and the prevalence of IHD in residents of traffic-exposed areas in Srinagar, India.

Our findings revealed that sound pressure levels (SPL) in most parts of the study area exceeded the thresholds prescribed by the Central Pollution Control Board of India (CPCB) and the World Health Organization (WHO) (CPCB, 2021; WHO, 2018), highlighting the widespread prevalence of potentially harmful noise pollution in these areas. Especially, the areas color-coded in darkest shades of blue and purple in noise maps (which corresponds to 75–80 decibels), depict noise levels significantly higher than the recommended acoustic comfort levels for residential areas, exposing the residents to noise pollution and its adverse health effects. Similar observations were reported by Zytoon (2016), which demonstrated noise levels in Saudi Arabian residential areas as higher than the thresholds recommended by their national environmental noise regulations. Considering the heterogeneous traffic and living conditions of developing countries, the study emphasizes the need for effective identification of the traffic noise-exposed areas as a primary step for implementing targeted environmental noise control measures as a public health measure. Noise mapping as depicted in this study can be an effective tool for simplified visualization of noise

**Fig. 6** Subgroup analysis for potential effect modifiers of the association between ischemic heart disease and road traffic noise exposure ( $L_{den}$ )



dispersion in a specific area through color-coded scales, enabling comprehensive spatial analysis and facilitating urban planning and management strategies to tackle noise pollution effectively. The successful application of air quality indices, providing valuable information to authorities and the public on anticipated air pollution impacts, serves as a compelling example for guiding remedial actions at various levels (Reis et al., 2018).

As for the effects of traffic noise on health, a significant positive association was observed between exposure to traffic noise and the prevalence of IHD among the participants residing in traffic-exposed areas. This suggests a dose-dependent relationship, where higher noise levels correspond to an increased association of IHD. The results of this study reveal a significant increase in IHD for adults exposed to noise levels exceeding 60 dB(A), suggesting a critical noise threshold for cardiovascular health. Our findings are in line with similar findings from previous studies that examined the traffic noise levels in Thessaloniki, Greece (Begou & Kassomenos, 2021). As reported in that study, noise levels were low in countryside areas, whereas suburban areas near Thessaloniki exhibited high-traffic noise levels during both daytime and nighttime hours. Consequently, 28% of

the population was exposed to potentially harmful noise levels (60–69 dB), which has been linked to an increased odds ratio of IHD. The elevated acoustic environment in India, potentially exceeding that of Western nations, necessitates consideration of the potential long-term and short-term health consequences of environmental noise exposure. The repercussions are mediated through disturbing influence on sleep, and annoyance reactions. These disruptions elicit cognitive and emotional responses that, in turn, trigger physiological alterations within the autonomic and endocrine systems (Hahad et al., 2022). Elevated levels of stress hormones, such as catecholamines and cortisol (Daiber et al., 2020; Thacher et al., 2022), lead to alterations in lipid and glucose metabolism and dysregulation of blood pressure. These metabolic and physiological modulations increase the association factors such as myocardial infarction, cardiac arrest, coronary artery disease, heart arrhythmia, ischemic stroke and pulmonary hypertension (Zaman et al., 2022).

The study demonstrated a statistically significant gender difference, with men having a higher prevalence of the investigated outcome compared to women. The observed difference could be influenced by several factors, including social determinants

of health, environmental exposures and individual lifestyle choices (Gan et al., 2012; Hao et al., 2022; Lacombe et al., 2019; Vienneau et al., 2015). The other potential explanation for the observed difference could be variations in noise exposure and stress levels between different work environments for males as compared to females. Especially, since females in low-income countries or developing nations are primarily homemakers (Choudhury & Kumar, 2022; Unnikrishnan et al., 2020), and they are not subjected to higher noise levels. Although the residential building may be exposed to road noise, having better control over limiting exposure can reduce IHD. It is plausible to hypothesize, based on the present findings, that the observed correlation between gender disparity and adverse health consequences in the context of various other environmental exposures. This observation invites exploration of its potential generalizability across developing countries, with South Asia serving as a particularly illustrative example due to its gender disparity to various environmental threats and environmental challenges. In addition to different perceptions of both genders towards road noise exposure, the pathophysiological impact of noise can also be a plausible reason for males experiencing a higher prevalence than females (Münzel et al., 2014).

Furthermore, the confluence of rapid urbanization, lifestyle modifications and rural-to-urban population shifts intensifies the impact of noise pollution in environments already challenged by high ambient levels (Gupta et al., 2018; Morillas et al., 2018). Deficient housing, limited insulation and pre-existing high ambient noise levels, especially in developing nations, create conditions where substantial populations are continuously exposed to extreme noise levels, often exceeding those found in congested urban centres in Europe and America (Münzel et al., 2017). Studies on cardiovascular disease (CVD) outcomes revealed potential associations between noise exposure and adverse health effects. Short-term noise exposure in Serbia has been associated with slight increase in blood pressure in children, while long-term exposure in India has been linked to an increased prevalence of coronary artery disease (CAD) in adults (Chen et al., 2023). In our research, subgroup evaluation revealed an association between higher levels of stress, sleep problems and exposure to vehicular noise with an increase in association of IHD

(Christensen et al., 2015). A higher concentration of adrenaline hormone, an increase in oxidative stress and noise-induced psychological stress contribute to high blood pressure, along with endothelial dysfunction and higher prevalence of coronary ailments such as “rapid heart rate”, “myocardial infarction”, “ischemic heart disease”, “stroke” and “cardiac failure” (Zaman et al., 2022). The study identified a potential link between rapid noise pollution particularly from vehicles at night, and an increased association of IHD due to disrupted sleep patterns and changes in hormone levels like leptin and ghrelin. The phenomena may result in increased calorie consumption and decreased energy expenditure, potentially leading to obesity and an increase in BMI, both of which are known factors for IHD (Getahun et al., 2021; Madsen et al., 2019; Song et al., 2020). In addition, age-related cardiovascular disorders such as IHD, hypertension and myocardial infarction increase the ailments because of the increasing degeneration of the heart and vascular system (Christoffersen et al., 2014; Rodgers et al., 2019). Traffic noise frequently causes anxiety and annoyance among individuals who are sensitive to noise, and in response, body reacts by releasing stress hormones to maintain homeostasis to increased annoyance levels. As a result, these hormones contribute to the increase of IHD development.

The existing evidence suggests a potential association between road traffic noise and ischemic heart disease (IHD) among residents living in areas with high-noise exposure. However, it is crucial to highlight that this relationship may vary depending on various factors, and further research is needed to better understand the nature and potential causality of this association. Developing nations can benefit from the existing research conducted by European countries and, more importantly, international organizations like the WHO, European Environmental Agency (EEA), United Nations Environmental Programme (UNEP), United States Environmental Protection Agency (EPA) and the International Civil Aviation Organization (ICAO) (Bouzir et al., 2023; Schwela, 2023). While these organizations frequently base their recommendations on developed countries, their frameworks and data can provide a significant basis for developing nations to build on. Indeed, active involvement by developing countries in these discussions is not only beneficial



but also essential, as their distinctive lifestyle characteristics and environmental situations can enrich the discussions and lead to more comprehensive and adaptive solutions.

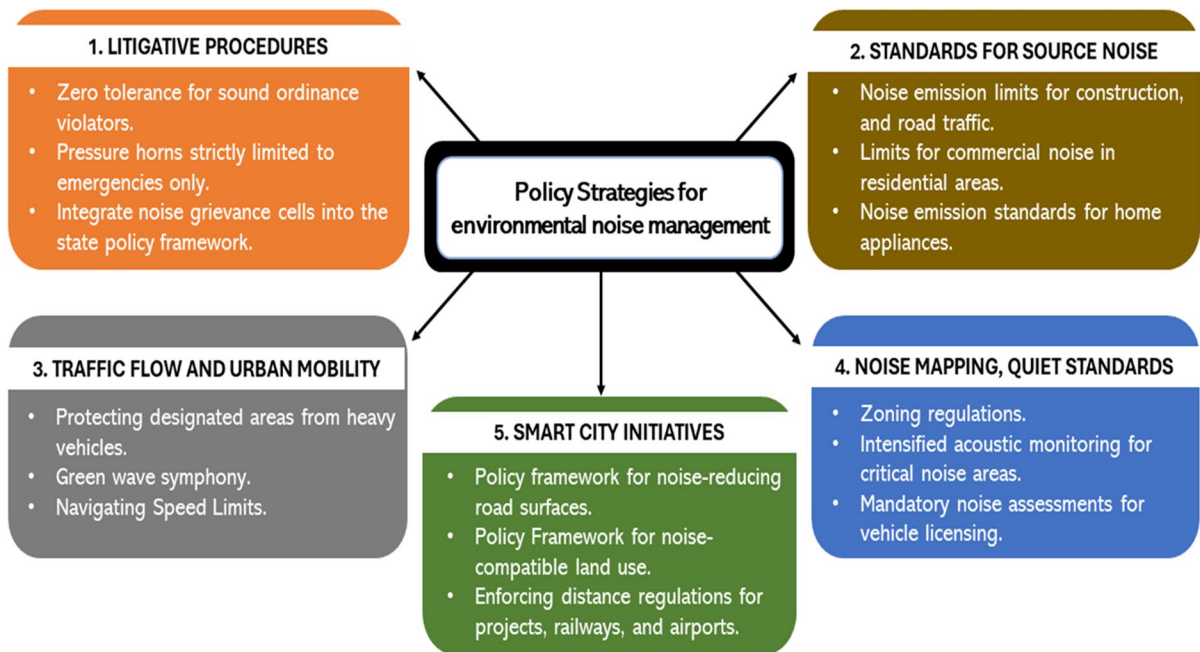
**Policy measures for environmental noise management**

This section outlines a set of high-potential policy interventions, focusing on the strategic integration of noise pollution into the national public health agenda and subsequently exploring legal frameworks that state and local governments can leverage to address and mitigate the critical issue in developing countries. For instance, the European Union through Environmental Noise Directive 2002/49/EC in 2002 has initiated a comprehensive and long-term program aimed at achieving a significant decline in noise pollution levels (Huh & Shin, 2018). Similarly, the Australian government has proactively adopted a multi-faceted approach to traffic noise management, implementing a range of legislative and regulatory measures, including the establishment of stringent vehicle noise emission limits (Burgess & Macpherson, 2016). So, the development of a comprehensive and action-oriented policy framework with effective environmental noise

management (ENM) strategies is necessary (Schwela, 2023). Figure 7 depicts various policy strategies for ENM in developing countries.

The policy framework should have a multi-faceted approach inculcating the principles of noise-conscious urban planning, developing detailed noise maps, targeting noise reduction projects and strengthening enforcement. Strategic Noise Mapping (SNM), a widely adopted tool in Hong Kong, China, plays a pivotal role in estimating the impact of noise on residents and informing future urban development projects (Lee et al., 2022; Xue et al., 2021). This approach, apart from supporting the formulation of effective noise control policies, also facilitates the analysis of noise suitability for construction projects and encourages comprehensive public participation in noise mitigation efforts. The efficacy of SNM in mitigating noise pollution and improving public well-being was illustrated by a significant decrease in the number of individuals affected by excessive traffic noise in Hong Kong, from 1.14 million (17.3%) in 2002 to 960,000 (13.6%) by 2010 (Wu et al., 2019).

Elevating unplanned urban development, as often observed in developing countries, necessitates the integration of human acoustic comfort as a critical element of urban planning and



**Fig. 7** Policy strategies for environmental noise management

traffic management. For example, the German model of urban development strategically prioritizes pedestrian and residential well-being over vehicular flow through targeted interventions of speed restrictions (Borowska-Stefańska et al., 2023; Brink et al., 2022). Further, zoning policies can effectively reduce noise exposure by establishing a safe distance between noise sources and residential buildings (De Roo, 2017; Farooqi et al., 2021), offering the most effective technique for minimizing noise exposure for residents. Notably, the establishment of “traffic calming zones” in residential areas where children play, coupled with the enforcement of stricter speed limits in densely populated areas, has proven to be an effective approach to mitigating noise (Tranter, 2018). Moreover, prioritizing scientifically supported strategies like source reduction remains the most cost-effective approach for safeguarding public health (Bello et al., 2019).

Strategically deploying noise barriers in acoustically challenging areas can prove effective, especially when retrofitting existing buildings is impractical (Yuan et al., 2019). Notably, establishing green spaces emerges as an economically and environmentally sustainable choice. Beyond its aesthetic and psychological benefits, vegetation is reported to enhance building acoustics by reducing traffic noise by 9–11 dB(A) (Mishra et al., 2021; Ow & Ghosh, 2017). A comprehensive analysis covering 978 European cities and 49 greater cities across 31 countries quantified the positive health impacts of urban green spaces. The findings underscored that populations residing in areas with extensive green space coverage experienced a significant 20% reduction in all-cause mortality per 100,000 inhabitants. This corresponded to a notable 2.3% decrease in total natural-cause deaths, presenting a potential gain of 245 years of life lost per 100,000 inhabitants (Barboza et al., 2021).

Additionally, implementing noise-proofing measures for roads and transportation infrastructure, along with embracing eco-friendly transport alternatives such as buses, metros, cycling and walking, represent effective source reduction strategies. Furthermore, for developing countries limited by financial constraints in noise mitigation, leveraging locally sourced sustainable materials such as bamboo, coconut fibres, cigarette butts and recycled rubber as cost-effective alternatives (Schiavi et al., 2006; Vanapalli et al., 2023) can be a sustainable strategy.

However, comprehensive research is necessary to assess their long-term viability and cost-effectiveness. These materials, along with alternative asphalt technologies like thin layers and double-layered porous asphalt, exhibit significant noise absorption potential (Teti et al., 2020). Although noise-reducing asphalt (providing a 3–6 dB(A) reduction) and adherence to speed limits (with a 1 dB(A) reduction per 10 km/h decrease) offer moderate decibel reductions, prioritizing a greener environment through sustainable transportation and emissions reduction yields more substantial, long-lasting benefits (Münzel et al., 2021).

Finally, the efficacy of ENM strategies relies on a robust regulatory framework that incorporates stringent emission and health-based standards, enforced rigorously by empowered authorities. To address this, developing countries should embrace and diligently enforce comprehensive environmental procedures, including mandatory Environmental Impact Assessments (EIAs) before the initiation of any development project. Establishing and reinforcing a strong legal framework, integrating specific noise grievance mechanisms into state policy frameworks and directly regulating noise sources through emission limits can collectively serve as a potent strategy for mitigating population-wide noise exposure. The United States serves as a notable example of successful regulatory implementation, where annual air transport noise exposure exceeding 65 dBA  $L_{DN}$  has shown a significant 90% decline since 1981, impacting a mere 0.015% of the population in 2007, compared to 4% in 1981 (Hammer et al., 2014).

National health policies and ordinances in developing countries require revisions to combat noise pollution through strengthened ambient noise standards, building codes mandating improved sound insulation and noise limits for construction and domestic appliances (Garg, 2022). It is critical to identify and mitigate “noisy hot spots” that exceed recommended  $L_{Aeq,24h}$  values (WHO, 2018). Epidemiological studies investigating the link between traffic noise and cardiovascular disease (CVD) employ a range of noise index selection methods. According to studies employing average noise level metrics such as  $L_{den}$ ,  $L_{eq,day}$  and  $L_{eq,night}$ , total noise exposure is an important factor when assessing the impact of traffic noise on CVD outcomes (Begou et al., 2020). However, several studies use event-based indices such as the Intermittency Ratio (IR) to establish associations (Brink et al., 2019;

Héritier et al., 2017). The IR can be estimated using traffic and geometric data for any transportation noise source and time period, or directly from acoustic measurements (Brambilla et al., 2019). While  $L_{Aeq}$  and  $L_{den}$  provide valuable details regarding average noise levels, employing the intermittency ratio alongside these indicators can provide a more comprehensive understanding of the noise environment, particularly in settings with frequent noise peaks such as honking (Gilani & Mir, 2021). Future urban development must prioritize noise barriers around vulnerable areas and designated silence zones, while socio-acoustic surveys and health impact studies will raise public awareness and inform effective noise pollution control strategies (Szopińska et al., 2022). Importantly, the concept of revised standards, building codes and control mechanisms are effectively correlated with the Government of India's "smart cities" idea, reflecting the EU's zero-pollution action plan and eventually fostering better public well-being (Fermeglia & Pedrosa, 2022; Garg & Maji, 2016).

#### Limitations of the study and scope for future research

While this study suggests an association between road traffic noise pollution and IHD, it is important to recognize the limitations in establishing causality. Further research is necessary to explore the potential role of road traffic noise as a contributing factor to IHD development. This study relies on self-reported data for sleep quality and stress levels. While self-reporting can offer valuable insights, it may be subject to biases related to how people remember and report their experiences. The measure of psychological distress in this study combined assessments of anxiety and depressive symptoms, preventing independent evaluations of their specific relationships with the examined components. Therefore, we were unable to determine the distinct effects of anxiety and depression on self-reported psychological distress. Moreover, the amount of traffic noise that entered the residential interiors was not taken into consideration, which might have caused the exposure levels to be overestimated.

The present findings invite further investigation into the potential generalizability of the observed association between gender disparities and adverse health consequences beyond the environmental exposures of noise pollution. This could involve investigating about the interplay between gender disparities and diverse

environmental stressors to exacerbate health, paving the way for future research in this direction. Such research holds the potential way for more targeted and effective policy interventions aimed at mitigating the environmental burdens on public health and promoting environmental justice. Furthermore, future research could employ more probability-based sampling procedures with a larger sample size to strengthen the findings of the current study. A recent advancement in noise exposure assessment involves the implementation of a new descriptor to quantify the eventfulness, or intermittency, of transportation noise. This metric, termed the Intermittency Ratio (IR), incorporates both the frequency and intensity of discrete noise events occurring over a defined time period. The IR can be derived directly from acoustic measurements or estimated using traffic and geometric data, offering applicability to various transportation noise sources and timeframes. In addition, investigating the impact of diverse diseases like hypertension, stroke, diabetes, breast cancer, anxiety and mental health prevalent among individuals living in noise-prone areas could be a potential avenue for further exploration.

#### Conclusion

Road traffic noise is a significant public health threat in India, with strong links to physiological health implications. This study investigates the link between road traffic noise and IHD in India, a developing nation with diverse traffic patterns and living conditions. Our cross-sectional analysis reveals a significant association between high-noise exposure ( $L_{den} > 60$  dB(A)) and IHD prevalence. Particularly, males and individuals aged 56–65 years exhibited a stronger association. Highlighting the multi-faceted health impacts of noise pollution, the study emphasizes the need for noise reduction strategies as a public health priority in developing economies. A comprehensive policy framework encompassing legal regulations, stricter noise standards, optimized traffic management, noise mapping and smart city initiatives adapted to regional complexities is recommended. Future research should explore multiparameter models integrating noise pollution with other stressors for a more holistic understanding of their combined health impacts.

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**Author contribution** MYP: questionnaire sampling, field noise analysis, noise modelling, data collection, data analysis, methodology, conceptualization, writing—original draft preparation; MSM: resources, reviewing, editing and supervision; KRV: reviewing and editing; BM: resources, reviewing, editing, and supervision.

**Data availability** The datasets generated during this study are not currently available to the public due to ethical considerations pertaining to their ongoing utilization in another research project. However, access may be granted upon reasonable request to the corresponding authors.

## Declarations

**Ethics approval** Ethical approval to conduct the study was granted by the University Council of Ethics, National Institute of Technology, Srinagar prior to research work commencing. There was no minimal risk of discomfort or harm to participants. All principles outlined in the 1964 Helsinki Declaration and its later amendments were followed.

**Consent to participate** A word-of-mouth/consent letter to seek the concern of each study participants at the site of question administration.

**Consent to publish** The authors confirm that this manuscript has not been previously published or is not under consideration by other journals. The authors also guarantee that this manuscript is original and is their own work. All authors have reviewed and agreed to the final version of the submitted manuscript for publication.

**Competing interests** The authors declare no competing interests.

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