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Estimation of Emerging Indoor Air Pollutants and Associated Health Effects on Humans in the Capital City of Central India

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Abstract

Indoor air pollution is a major public health concern, particularly in low- and middle-income countries, contributing substantially to pollution-related mortality. Exposure to indoor pollutants is associated with adverse health effects mediated through oxidative stress. This study assessed seasonal and spatial variations in indoor air quality across residential, commercial, and industrial areas of Bhopal City, India. Thirty households were randomly selected from three localities: Kolar (residential), Bairagarh (commercial), and Govindpura (industrial). Indoor air quality was monitored during winter, rainy, and summer seasons using a DustTrak aerosol monitor to measure total particulate matter (PM), PM1, PM2.5, PM4, PM10, and TVOCs. Questionnaire-based surveys collected socio-demographic details, housing conditions, and morbidity data. A total of 270 samples were analyzed. Residential areas showed higher PM1, PM2.5, PM4 and PM10 concentrations across most seasons. Total PM peaked in residential areas during rainy and summer seasons, while industrial areas recorded higher levels in summer. TVOCs were elevated in residential areas during summer and in commercial and industrial areas during the rainy season. Morbidity prevalence was highest in industrial areas. Of 270 samples, 258 were classified as unhealthy. Residential areas contributed higher indoor pollutant loads compared to commercial and industrial areas. These findings emphasize the need for targeted policies and regulatory frameworks to control indoor air pollution in residential environments and promote healthier living conditions.

Introduction

Air pollution stands as one of the most severe global environmental health crises, with the World Health Organization (WHO) attributing approximately seven million premature deaths annually to ambient and indoor exposures. Nearly half of these fatalities are directly tied to household air pollution (HAP), disproportionately impacting low- and middle-income countries where solid fuel combustion remains prevalent. In India, household and ambient air pollution account for approximately 6% and 3% of the total national disease burden, respectively, driving over 1.6 million premature deaths annually. While the International Organization for Standardization (ISO) and ambient regulatory bodies have instituted rigid outdoor frameworks, indoor environments lack enforceable legal standards despite occupants spending up to 90% of their time inside. Respirable suspended particulate matter fractions PM10, PM2.5, and PM1.0 and sub-micron 10 μm (PM10) and total volatile organic compounds (TVOCs) are highly critical indoor toxins due to their capacity to bypass upper respiratory defenses and trigger systemic oxidative stress pathways. While existing literature broadly addresses rural household solid fuel combustion, limited empirical data tracks urban indoor pollutant profiles under common household practices like burning mosquito coils, incense sticks, and dhoop within rapidly developing Indian cities. Indoor dynamics are modulated by complex interactions between microclimatic factors, ventilation properties, land-use zoning, and direct ambient outdoor pollutant infiltration. Epidemiological and toxicological work increasingly associates fine particulate matter not only with classic respiratory and cardiovascular pathologies, but also with neurodegenerative disorders, adverse pregnancy outcomes, and emerging sensory dysfunctions like auditory impairment. Consequently, systematic evaluations are necessary to understand how specific land-use activities alter the microenvironments where humans reside.

The novelty of this investigation is threefold: It establishes a simultaneous spatial-seasonal matrix tracking five separate size-fractionated particulate matters (Total PM, PM10, PM4, PM2.5, and PM1), alongside TVOCs within an urban environment. It bridges microclimatic variation with direct socio-demographic and multi-system morbidity surveys across three distinct land-use zones (residential, commercial, and industrial) in a major Central Indian urban hub. It explicitly captures and isolates the micro environmental impacts of sub-micron particle fractions PM1 which are rarely represented in domestic Indian air quality monitoring portfolios. Accordingly, this study was designed to quantify fine indoor air toxicants across selected zones of Bhopal, India, and evaluate their relationships with self-reported human morbidities

Materials and methods

Study Design and Setting

A cross-sectional observational study was conducted to continuously monitor indoor air toxicant concentrations over a 24-hour period in households located in Bhopal. Monitoring was carried out during three distinct seasons—winter, summer, and rainy season—across residential, commercial, and industrial land-use settings of the city. The study primarily included households using liquefied petroleum gas (LPG) for cooking and reporting common indoor pollution sources such as incense stick burning, candles, mosquito coils, air fresheners, tobacco consumption, and use of plastic utensils. A total of 30 households were randomly selected from each locality Bhopal City - residential (Kolar), commercial (Bairagarh), and industrial (Govindpura). Indoor air quality parameters, including particulate matter fractions (PM1, PM2.5, PM4, and PM10), total volatile organic compounds (TVOCs), temperature, and relative humidity, were measured using real-time monitoring instruments across three seasons [18]. Household occupants were randomly enrolled. Individuals presenting with respiratory symptoms, skin allergies, or cardiovascular and other medical health condition complaints were included in the study [19].

Data Collection

A structured questionnaire-based survey was administered to collect information on socio-demographic characteristics, household environmental conditions, lifestyle factors, and self-reported morbidities. Indoor air toxicant monitoring was conducted concurrently using portable real-time environmental monitoring systems installed within the selected households **(S1 & S2)**

Indoor Air Monitoring

Continuous indoor air quality monitoring was performed for 24 hours in each household using portable environmental monitoring device DUST TRAK™ DRX (Model 8533) and multiple gas analyzer

(Advancsdsense Directsence Tox) Pollutant measurements were recorded during winter, summer, and rainy seasons to assess seasonal variations in indoor air toxicant concentrations.

Data Management and Statistical Analysis

Data obtained from structured questionnaires and real-time indoor air monitoring systems were entered into an electronic database and subjected to comprehensive data cleaning procedures. Each household was assigned a unique identification code to facilitate accurate linkage of survey responses and environmental measurements. To ensure data quality and reliability, 20% of the entries were randomly verified by a statistician. Statistical analyses were performed using IBM SPSS Statistics.

Descriptive statistics were calculated for continuous variables and included frequencies, minimum and maximum values, means, medians, and standard deviations. Categorical variables were summarized using frequencies and percentages.

Associations between health outcomes and indoor air pollution parameters were evaluated using Pearson's chi-square test for independent categorical variables. Student's *t*-test was applied for comparisons between two groups, while one-way analysis of variance (ANOVA) was used for comparisons involving more than two groups. Pearson's and Spearman's correlation coefficients were used to determine relationships between continuous and non-normally distributed variables, respectively. All statistical tests were two-tailed, and a *p*-value of less than 0.05 was considered statistically significant [20, 21].

Results

Indoor Air Quality Classification and Characteristics

A total of 270 indoor air quality observations were collected from 30 households across three localities during the winter, summer, and rainy seasons. Based on the classification criteria, 258 samples were categorized as unhealthy, while only 12 samples met healthy indoor air quality standards. As no universally accepted reference values for indoor air pollutants are available, the median concentrations of the measured toxicants across seasons and study localities in Bhopal were used as cut-off values to classify pollutant levels into high and low contamination categories (Table 1). Indoor air quality assessment included measurements of particulate matter fractions PM1, PM2.5, PM4, and PM10), total particulate matter (Total PM), total volatile organic compounds (TVOCs), temperature, and relative humidity using real-time monitoring instruments. The seasonal and locality-wise distribution of these indoor air quality parameters is presented. (Table 2 & Figure 1)

Seasonal and Spatial Variations in Particulate Matter

Elevated concentrations of Total PM were observed across all study areas. The industrial area consistently showed the lowest contribution of PM1 compared with residential and commercial

localities. Residential areas recorded the highest PM1 concentrations during the rainy and winter seasons, whereas the highest PM1 levels during summer were observed in commercial areas. Similar seasonal trends were observed for PM2.5 and PM4, with comparatively higher concentrations in residential and commercial localities. PM10 concentrations remained consistently highest in residential areas across all seasons.

The higher particulate matter concentrations observed in residential settings may be attributed to indoor household activities such as cooking, burning of incense sticks and mosquito coils, use of air fresheners, tobacco smoking, and inadequate ventilation.[2,4,22–24] Reduced ventilation during winter and rainy seasons may further enhance the accumulation of finer particulate fractions indoors.[26,27] Elevated particulate concentrations in commercial areas during summer may be associated with greater occupancy, increased human activity, and enhanced infiltration of outdoor pollutants.[28,29]

Total Particulate Matter and TVOC Distribution

Total PM Concentrations were comparatively higher in residential areas during rainy and summer seasons; however, the highest overall Total PM concentrations were observed in industrial areas during the summer season. This finding may reflect the influence of ambient industrial emissions and resuspension of particulate matter under elevated temperature conditions.[30,31]

TVOC concentrations did not vary substantially across localities during winter; however, elevated levels were observed during summer in residential areas and during the rainy season in commercial and industrial areas. Increased volatilization of household chemicals, cleaning products, and personal care items during warmer and humid conditions may explain these seasonal patterns. [30]

Microclimatic Parameters

Relative humidity was lowest in residential areas and highest in commercial areas, while temperatures were comparatively higher in industrial areas during the rainy season, highlighting the role of microclimatic conditions in shaping indoor pollutant dynamics. [29]

Socio-Demographic Characteristics of Study Participants

Socio-demographic characteristics of study participants (n=270) from industrial, commercial, and residential areas (n=90 each) are presented in (Table 3). The three groups were comparable with respect to age, sex, marital status, education, and occupation; however, significant differences were observed regarding addiction and smoking habits. [26, 27]

Morbidity Profile among Study Participants

Morbidity prevalence was highest in industrial areas, followed by residential and commercial areas. Major symptoms reported among study participants included headache, abdominal pain, hearing loss, redness of the eyes, rhinitis, vomiting, and watery eyes (Figure 2). The most frequently reported

symptoms were headache (180 cases), abdominal pain (107 cases), and hearing loss (59 cases), followed by redness of eyes (36 cases), rhinitis (36 cases), vomiting (36 cases), and watery eyes (36 cases) among the 270 observations (Table 4).

Exposure to particulate matter and VOCs has been associated with respiratory irritation, mucosal symptoms, and neurological complaints including headache.[2,30] Respiratory morbidities were more common in industrial and residential areas during winter, whereas cardiovascular morbidities were higher in industrial areas during summer. Gastrointestinal morbidities demonstrated a similar seasonal distribution during summer. Ophthalmic morbidities were higher in residential areas during summer and in industrial areas during the rainy season.

Association between Indoor Environmental Parameters and Reported Health Conditions

A significant correlation was observed between hearing loss and all particulate matter fractions as well as TVOCs across all three seasons (Tables 5–11). Present the associations between indoor environmental exposure parameters (PM1, PM2.5, PM4, PM10, TVOC, temperature, and relative humidity) and self-reported health conditions among study participants. For particulate matter exposures, no significant associations were observed between PM1, PM2.5, PM4, or PM10 categories and respiratory disorders, heart diseases, gastrointestinal disorders, ophthalmic disorders, central nervous system disorders, endocrine disorders, headache, anaemia, or menstrual disorders (all $p > 0.05$). However, hearing loss showed a consistent and statistically significant association with particulate matter exposure. The prevalence of hearing loss was significantly higher among participants in the low PM1 group (36.7%) than in the high PM1 group (17.2%) ($\chi^2=9.145$, $p=0.002$). Similar findings were observed for PM2.5 (38.0% vs. 16.7%; $\chi^2=10.941$, $p=0.001$), PM4 (38.0% vs. 16.7%; $\chi^2=10.941$, $p=0.001$), and PM10 (34.0% vs. 17.7%; $\chi^2=6.410$, $p=0.011$).

Regarding volatile organic compounds, most health outcomes were not significantly associated with TVOC exposure levels. Nevertheless, hearing loss was significantly more prevalent among participants exposed to higher TVOC concentrations (28.2%) compared with those in the low TVOC group (11.4%) ($\chi^2=7.829$, $p=0.005$). Temperature demonstrated significant associations with two health outcomes. Participants in the high-temperature group reported a greater prevalence of endocrine disorders (20.2% vs. 9.7%; $\chi^2=3.987$, $p=0.046$) and headache (72.7% vs. 54.2%; $\chi^2=8.064$, $p=0.005$) compared with those in the low-temperature group. Menstrual disorders showed a borderline association with temperature (28.4% vs. 16.7%; $\chi^2=3.794$, $p=0.051$), although the relationship did not reach statistical significance.

Table 12 indicates that no statistically significant associations were identified between relative humidity categories and any of the assessed health conditions, including respiratory disorders, cardiovascular diseases, gastrointestinal disorders, ophthalmic disorders, central nervous system disorders, endocrine disorders, headache, hearing loss, anaemia, or menstrual disorders (all $p > 0.05$). Overall, hearing loss emerged as the health outcome most consistently associated with indoor air quality parameters, showing significant relationships with particulate matter fractions (PM1, PM2.5, PM4, and PM10) and TVOC concentrations. In contrast, elevated indoor temperature was associated with increased

prevalence of endocrine disorders and headache, whereas relative humidity was not significantly associated with any reported health condition.[32,33,34]

The observed associations between indoor environmental parameters and health outcomes are consistent with previous studies and global reports indicating that particulate matter, VOC exposure, and thermal conditions are linked with respiratory, cardiovascular, neurological symptoms, and general morbidity.[35,36,37,38,39,40]

This study assessed associations between indoor air quality parameters and self-reported health symptoms using chi-square tests. Participants were categorized into low and high exposure groups based on measured pollutant levels. The analysis identifies statistically significant differences in symptom prevalence between exposure categories. However, due to the cross-sectional design and reliance on self-reported health outcomes, the findings indicate associations rather than causal relationships between indoor air pollutants and health symptoms.[41,42,43,44]

Public Health Implications

Overall, the findings demonstrate substantial spatial and seasonal variability in indoor air quality across different land-use settings in Bhopal. The predominance of unhealthy indoor air quality conditions and the observed associations with multiple morbidities underscore the urgent need for improved indoor air management strategies. Enhanced household ventilation, reduction in indoor combustion-related practices, public awareness programs, and development of location-specific indoor air quality guidelines are recommended to mitigate associated health risks.

Conclusion

The findings of this study demonstrate that indoor air pollution in Bhopal's residential, commercial, and industrial areas is a significant and pervasive public health concern, driven mainly by elevated levels of PM1, PM2.5, PM4, and TVOCs. Seasonal trends and location differences were clearly associated with specific morbidity patterns, emphasizing the importance of tailored preventive strategies. The evidence strongly calls for the establishment of indoor air quality guidelines and sustained public health interventions to mitigate exposure risks. Future studies should aim at longitudinal assessments and intervention-based models to generate actionable strategies for reducing the health burden related to indoor air pollutants.

Declarations

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Contributions

Sindhuprava Rana: Conceptualization, Investigation, writing-original draft, writing—review and editing. Ruma Galgalekar: Validation, Conceptualization, Writing – review & editing, Conceptualization. Dharma Raj: Writing – review & editing. RajNarayan R. Tiwari: Writing – review & editing, Investigation, Conceptualization.

Funding Information

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Ethics declarations

Ethics approval

The study protocol was approved by the Institutional Ethics Committee of the ICMR–National Institute for Research in Environmental Health ICMR-NATIONAL INSTITUTE FOR RESEARCH IN ENVIRONMENTAL HEALTH, BHOPAL (ICMR-NIREH), Bhopal (Approval No. NIREH/BPL/IEC-2017/2018-19/182), in accordance with the principles of the Declaration of Helsinki and applicable ethical guidelines and regulations

Consent to participate

Informed consent was obtained from all participants included in the study. In cases involving infants, written informed consent was obtained from their parents or legal guardians.

Consent to publish statement

Not applicable

Conflicts of interests

The authors declare no conflict of interest.

Clinical Trial

Not applicable

Data Availability Statement

The datasets generated and analyzed during the current study are available from the corresponding author on reasonable request.

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Tables

Tables 1 to 12 are available in the Supplementary Files section.

Figures

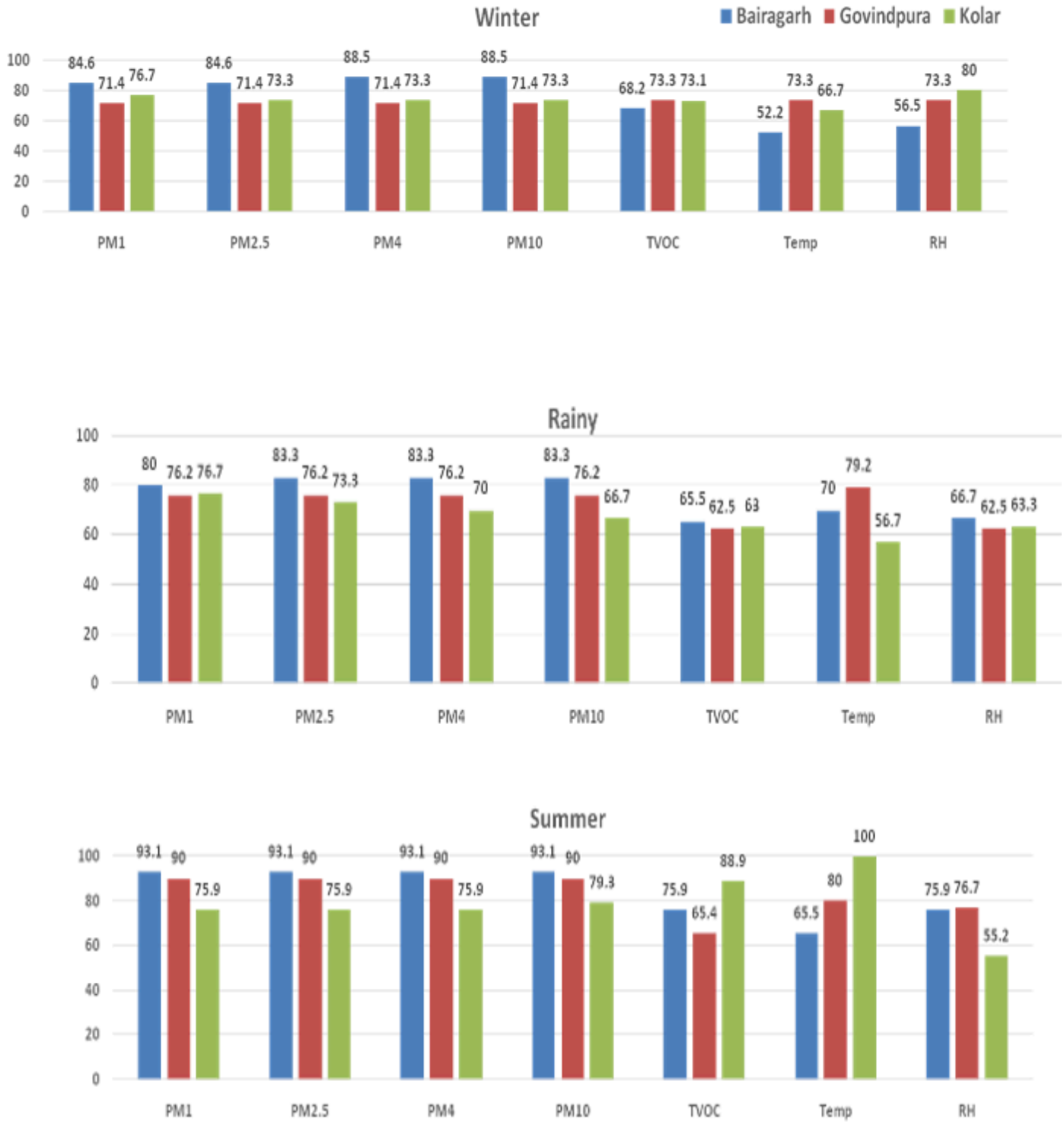


Figure 1

Graphical representation of Seasonal and location wise distribution of each Toxicant level

*The table-2 and graph-1 shows percentage of houses affected by indoor air toxicants in 3 seasons at Commercial (C), Industrial (I) and Residential (R) Areas of Bhopal. Total PM Values were found highest in commercial are followed by Industrial area in summer season. TVOCs levels showed no significant fluctuations in winter and rainy season in the study site whereas high concentration were found in summer in residential and commercial areas.

System-wise morbidity trends:

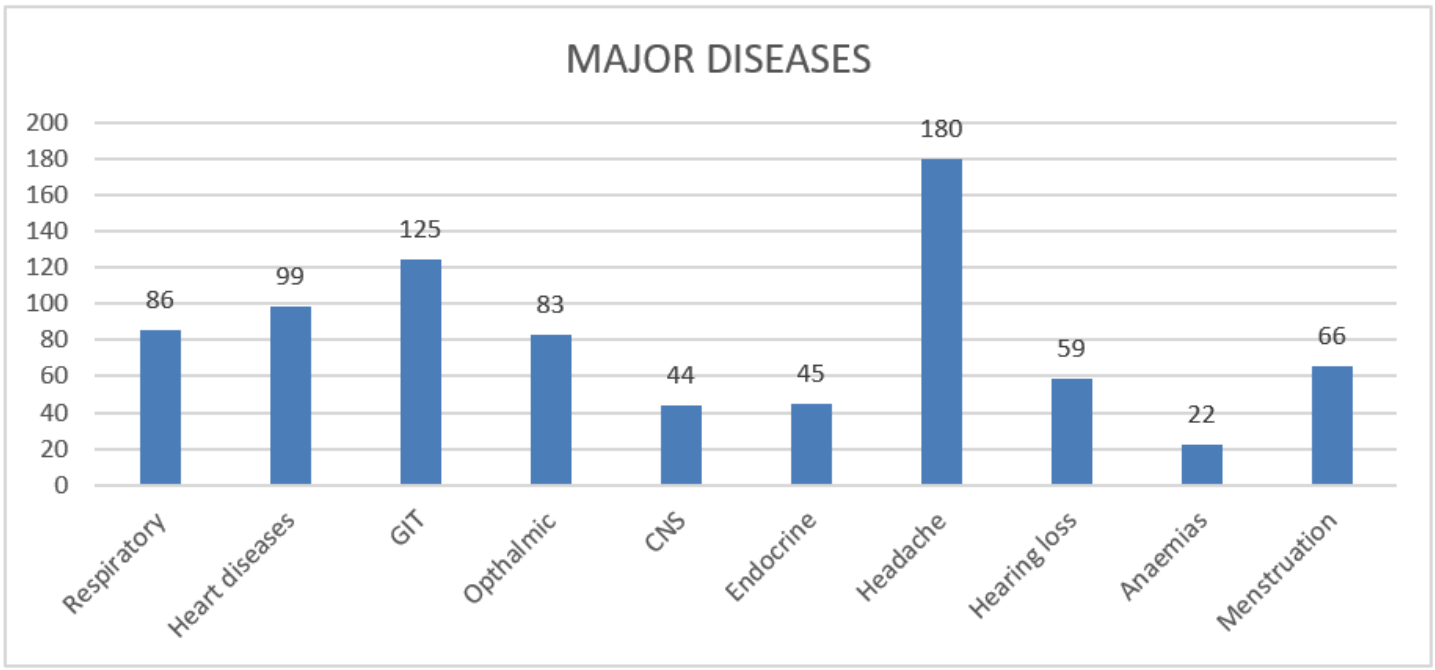


Figure 2

Annual distribution of morbidities in total households:

*More than one symptom was present in many subjects. Total 28 symptoms were categorized into 6 systems (Respiratory, Heart disease, GIT, Ophthalmic, CNS, & endocrine) along with major symptoms (Headache, Hearing loss, Anaemia& Menstruation).

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- Tables.docx
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- S2.docx