Environ Monit Assess (2025) 197:187
https://doi.org/10.1007/s10661-025-13642-1

RESEARCH

# Indoor air quality and human health risk assessment in selected high-altitude villages of Gilgit-Baltistan, Pakistan

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Received: 17 April 2024 / Accepted: 14 January 2025


**Abstract** This research marks the inaugural endeavor in Gilgit-Baltistan (GB) to identify the primary sources of household energy and indoor air pollutants (IAPs) during the winter and additionally, to evaluate the health impacts associated with IAPs within specific high-altitude communities in Gilgit-Baltistan, Pakistan. Using the convenience sampling method, 20 households were continuously monitored to assess IAPs based on standards time-weighted average. The study found that 90% of the population relied primarily on animal dung as their main energy source, with wood, agricultural residues, electricity, and gas as other sources. The average levels of $PM_{2.5}$ were five times greater, and CO levels were three times higher than the National Environmental Quality Standards (NEQS). Among the samples examined, 65% of homes were found to have inadequate ventilation and did not comply with ASHRAE standards for living rooms. Households using animal dung and wood as fuel showed elevated $PM_{2.5}$ and CO levels. Health data indicated increased winter illness, with high rates of respiratory and cardiovascular issues such as morning cough (17%), eye irritation (15%), bronchitis (14%), wheezing (13%), chest tightness (12%), heart disease (11%), morning phlegm (10%), and shortness of breath (8%). The findings indicate that socioeconomic and geographic factors play a significant role in choosing solid fuels. Recommendations include raising awareness of stove maintenance and the harmful impacts of IAPs and proper ventilation, promoting cleaner fuels, and upgrading heating systems. The government should provide health screenings and subsidies for cleaner energy such as hydropower, LPG, and solar power, reducing reliance on dung and wood, and improving health in high-altitude communities.

**Keywords** Air pollution · Indoor air quality · Health effects · Household energy · High-altitude villages

**Supplementary Information** The online version contains supplementary material available at https://doi.org/10.1007/s10661-025-13642-1.

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## Introduction

The high-altitude villages of Gilgit-Baltistan, Pakistan, are known for their unique geographic and

Published online: 24 January 2025

climatic conditions. However, the region's isolation and dependence on traditional energy sources raise concerns about indoor air quality (IAQ) and its potential impact on human health. Household air pollution contributes to nearly 5% of the total global burden of disease, resulting in some 4 million premature deaths annually from respiratory and cardiovascular diseases (World Health Organization, 2014). Globally, 80–90% of the population spends most of their time indoors, resulting in prolonged exposure to high levels of indoor air pollution (IAP) (Ali et al., 2021). Both macroenvironmental and microenvironmental factors influence indoor air pollutant levels. Macroenvironmental determinants encompass socioeconomic status, geographic location, and demographic attributes, while microenvironmental determinants pertain to housing features such as the type of fuel used, the cooking and heating systems, and the existence and kind of windows (Rumchev et al., 2017). A review of epidemiological studies on the health impacts of indoor air pollution found that children under the age of five face a higher risk of pneumonia and other severe infectious diseases due to exposure to polluted indoor air (World Health Organization, 2017). Women, experience indoor pollution three times more than men and are at an increased risk of chronic bronchitis, obstructive pulmonary disease, and emphysema (Bruce et al., 2006). Numerous studies conducted globally have determined that IAP may lead to chronic health effects. Prolonged exposure to polluted indoor air from an early age can cause lung damage and negatively impact productivity later in life. According to a World Health Organization estimate, poor indoor air quality is responsible for 4.1% of total deaths worldwide each year, affecting primarily children and mothers (Ritchie & Roser, 2014).

Based on the progress indicators created by the World Bank, 62.84% of Pakistan's population lives in rural areas. The average household size is seven members, with high fertility rates, low literacy levels, and elevated infant mortality rates (Ali et al., 2019). IAP is linked to various health issues in adults, including chronic bronchitis, low birth weight, cataracts, lung cancer, and potentially cardiovascular disease (Khan et al., 2005). Particulate matter ($PM_{2.5}$), carbon monoxide (CO), and carbon dioxide ($CO_2$) are epidemiologically significant indicators and are frequently used as critical factors for evaluating IAP. In developing countries such as Pakistan, these IAPs are produced mainly by burning solid fuels on traditional stoves for cooking and heating (Us Saqib et al., 2019).

Energy plays a vital role in meeting mankind's basic needs, such as lighting, cooking, and heating. Energy is being primarily ignored worldwide as a prerequisite for good health. Due to a lack of access to primary energy sources to meet daily demands, more than one-half of the global population (Li et al., 2020) and approximately 95% of rural households in low- and middle-income countries (LMICs) rely on solid fuels and biomass fuels (wood, agricultural residue, animal dung) when compared with urban households, i.e., 5% (Puzzolo et al., 2016). These fuels are among the topmost environmental factors causing fatal diseases and are ranked fourth among the causes of overall excess deaths after waterborne diseases, malnutrition, and unsafe sexual activities (Martin et al., 2013). Around 2.8 billion people put their daily lives at risk by using solid fuels (World Health Organization, 2014) (which is "The world's single greatest environmental health risk"(Bruce et al., 2006)). These fuels are used for heating and cooking on traditional stoves or open fires. This process generates high levels of lethal pollutants, including CO and PM, organic compounds, and free radicals, and poses a significant threat to human health globally. Among the people affected by IAP, women and young children are significantly affected: women are primarily responsible for cooking and heating, and children spend most of their time indoors (Duflo et al., 2008).

In GB, many populations living at high altitudes are highly dependent on natural resources and traditional energy sources, i.e., solid fuels (including wood, coal, and animal dung), due to the inaccessibility and nonavailability of modern energy sources in mountainous terrain. During prolonged winters, i.e., from October to March, quantities of wood, agricultural residue, and animal dung are used for cooking and heating. Communities at higher elevations use solid fuels for domestic purposes (i.e., cooking and heating) throughout the year. A limited number of studies have been conducted on the impacts of indoor air quality and its effects on human health in Pakistan. This study was the first to be conducted in GB and will provide data for future studies. Exposure to certain indoor air pollutants including $PM_{2.5}$, CO, and $CO_2$ as ventilation indicators, especially during winter, poses severe environmental health threats for communities and the region's overall environment (Us Saqib et al., 2019).

This study aims to highlight an overlooked public health issue and serves as a foundational investigation in Gilgit-Baltistan (GB). The objectives of the study are three fold: to identify the sources of household energy in high-altitude areas, to measure indoor air pollutant levels in selected villages during the winter season, and to assess the health impacts of indoor air pollutants on the chosen communities.

## Methodology

### Study area

The study was conducted in four selected high-altitude villages of Gilgit-Baltistan, i.e., Chilum and Sherquli in Astore district and Ghashoshal and Holshal in the Hoper Valley district Nagar (see map of the study area in Fig. 1). Chilum and Sherquli are located at average altitudes of 3378 m (35°02′08″ N and 75°06′14″ E) and 3568 m (35°02′02″ N and 37°07′41″ E), respectively. Ghashoshal and Holshal are located at average altitudes of 2816 m (36°13′02″ N and 74°45′47″ E) and 2788 m (36°13′02″ N and 74°45′47″ E), respectively. These tiny villages are located at GB's highest and last settlement areas inhabited by a limited number of people with

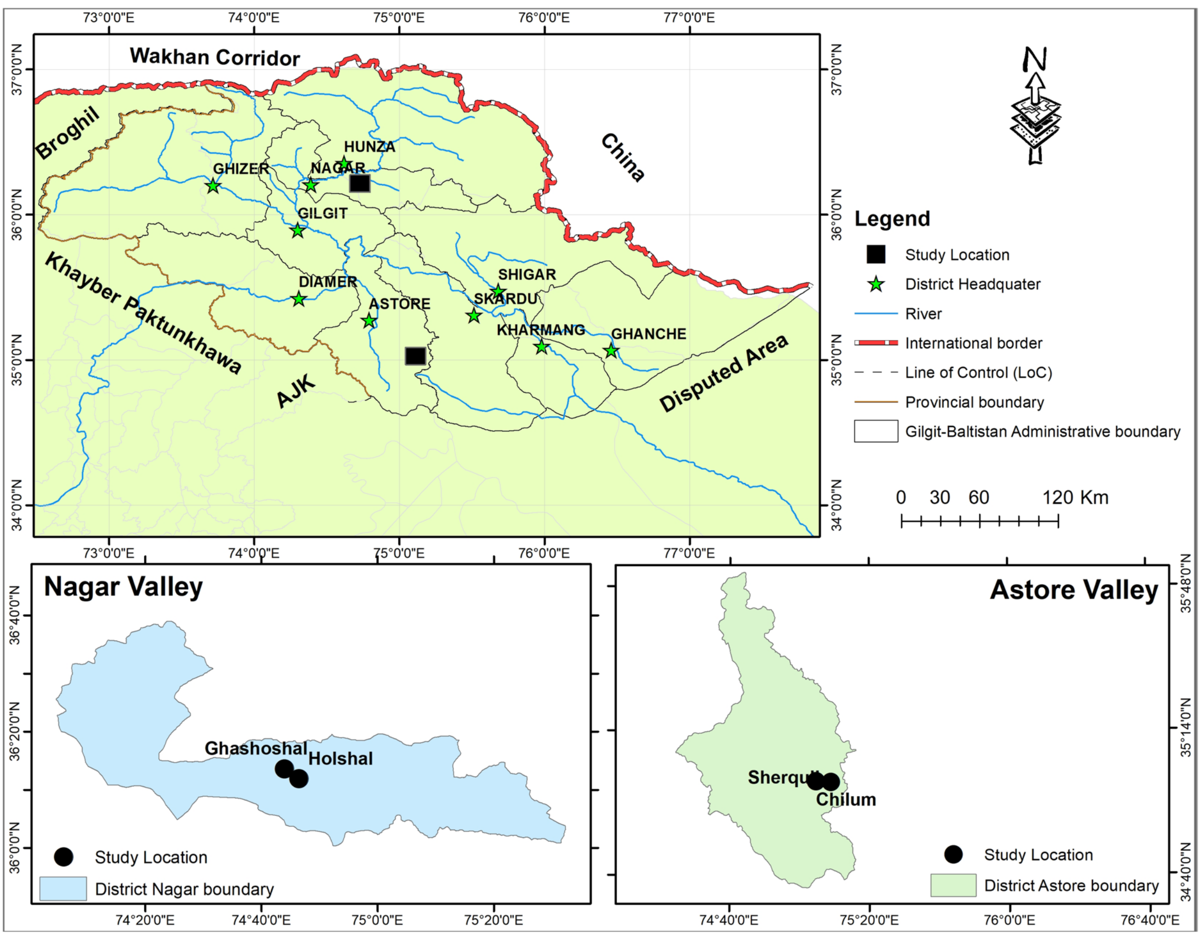


**Fig. 1** Map of the study area

prolonged winters, i.e., October–May. These areas are typically high-elevation ecosystems characterized by low atmospheric pressure, cold, humid, low oxygen and $CO_2$ levels, intense insolation, and rapid radiation (Nawaz et al., 2009). Most of these areas are covered by snow within a year; therefore, they are vulnerable to changing climatic patterns, which affect their built environment, lives, livelihood, and economy (Nawaz et al., 2009). Their houses are built of traditional congested construction style (Fig. 2) with local soil-made roof tiles and single-entry doors, no ventilation or windows in most houses, and no separate kitchen rooms using similar types of mixed solid biomass fuel for cooking (Khan & Jan, 2018).

## Research design

The total number of households in these villages ranged between 10 and 25. The data were collected from those willing to participate voluntarily and the available residents, as most of the population migrated toward warm regions during winter.

Twenty (20) samples, i.e., five (05) samples from each selected village, were collected using convenience sampling; data were collected based on the family's consent. The data collection involved observations, questionnaire-based health, housing surveys, and the installation of monitoring equipment. Ventilation conditions were determined using TELAiRE (Data Logger); $CO_2$ concentrations were recorded both indoors and outdoors. The indoor-outdoor $CO_2$ differential was calculated and interpreted as an indicator of ventilation condition. A total of 20 questionnaires were completed by respondents from the same houses where air quality was monitored. The questionnaire included questions about gender, demographics, source of income, and health status. Smokers and individuals with pre-existing respiratory conditions were excluded from our study. Health data over the previous year were also collected from respective healthcare centers, i.e., Basic Healthcare Units (BHU) and People's Primary Healthcare Initiative (PPHI), to determine the seasonal prevalence of acute respiratory infections (ARIs). Monthly reports from the First Aid Post (FAP)/PPHI Center in Chilum and Astore, and the BHU PPHI Center in Hoper, Nagar, were collected from the previous year, i.e., October 2018 to September 2019; these data were used to verify disease data acquired through questionnaires and to compare the occurrence of disease in the summer and winter seasons. Direct or indirect data on respiratory, cardiovascular, and eye diseases due to IAP were extracted from each monthly report.

## Monitoring equipment

Three criteria indoor air pollutants, namely, $PM_{2.5}$, CO, and $CO_2$, for ventilation assessment (World Health Organization, 2021), and temperature and humidity were monitored on-site during October and November 2019. $PM_{2.5}$, temp, and RH were monitored continuously for 24 h, CO was monitored for 8 h as per the timed-weighted averages (Ministry of Climate Change Pakistan, n.d.) recommended by National Environmental Quality Standards of Pakistan (NEQS), and $CO_2$ concentration recommended

**Fig. 2** Traditional close construction practices

for ventilation conditions is monitored according to American Society of Heating Refrigerating and Air Conditioning Engineers (ASHRAE) standards. NEQS standard limits for $PM_{2.5}$ is 35 μg/m$^3$ and CO is 5 mg/m$^3$ (Ministry of Climate Change Pakistan, n.d.) whereas ASHRAE Standards recommends indoor $CO_2$ concentration below 1000 ppm as a guideline for acceptable indoor air quality and specifies an upper limit of 60% RH (ASHRAE, 2013). Portable environmental monitoring equipment was used to obtain data on the selected environmental parameters. For $PM_{2.5}$, the TSI DustTrak Aerosol Monitor was used to collect data in μg/m$^3$ (Cheng et al., 2008). To monitor $CO_2$ in ppm, TELAiRE (Data Logger) was used (Stankevica & Lesinskis, 2012). CO levels were measured and recorded using Testo 317–3, the CO Monitor (Sung et al., 2019). HOBO Data Logger was used to log real-time temperature and relative humidity data (Stankevica & Lesinskis, 2012). To record accurate locations, i.e., latitude and longitude, as well as elevation of the sampled sites in our study area, the global positioning system (GPS) was used. Monitoring equipment was placed in the central living area/kitchen, where family members spent most of the time during winter. Equipment was installed 1 m from doors, windows, and cooking /heating sources and 5 feet from the ground level inside the house to measure the exposure level of the $PM_{2.5}$ concentration, which better represents health risks due to indoor particulate pollution (Balakrishnan et al., 2004).

## Health risk assessment

A health risk assessment related to air pollution estimates the health impacts expected from exposure to air pollutants. According to the USEPA methods, the three main methods for determining the intake dose include oral ingestion, inhalation, and dermal contact and are used to assess the health risk assessment of ambient air pollution (Beheary et al., 2018; Dong et al., 2018). In our study, the inhalation method was used to assess the health risks focusing specifically on the exposure that occurs through breathing air.

$$ADD_{inh} = \frac{C \times IRing \times F \times EF \times ED}{PEF \times BW \times AT} \quad (1)$$

where $ADD_{inh}$ is the absorbed dose of exposure to air pollutants via inhalation, whereas $C$ is the concentration of pollutant in air, $IR_{ing}$ is the inhalation rate, $F$ is the fraction of time spent, EF is the exposure frequency, ED is the exposure duration, PEF is the particle emission factor, BW is body weight, and AT is the averaging time (MohseniBandpi et al., 2018).

### Chronic daily intake (CDI)

Health risks from indoor air quality through inhalation were assessed for children and adults separately by deriving the following formulas from USEPA-developed methods (MohseniBandpi et al., 2018).

Air pollutants enter the human body through different pathways during inhalation, skin contact, and oral ingestion. In comparison to oral intake, all the other paths are considered insignificant. The $C_{inh}$ (mg/(kg/day) of air pollutants through inhalation is calculated by Eq. (2).

$$C\text{inh} = \frac{\text{Cp} \times \text{In}}{\text{Bw}} \quad (2)$$

where Cp is the concentration of pollutants in the air. In (m$^3$/day) is the daily average inhalation rate (assumed to be 7.6 m$^3$/day for children and 20 m$^3$/day for adults) (USEPA), and Bw (kg) is the average body weight (assumed to be 72 kg for adults and 32.7 kg for children) (Kaewrat et al., 2021).

### Health risk index (HRI)

The health risk index (HRI) was used to assess health risks from exposure to the IAP. The level of risk was categorized by HRI values as follows: an HRI value less than 1 indicates no risk, and a value greater than 1 shows high risk and is considered to predict negative impacts. The HRI was calculated using Eq. (3) to estimate chronic health risks.

$$\text{HRI} = \frac{C\text{inh}}{\text{Rf}} \quad (3)$$

where Rf is the reference dose (in this study, the NEQS for ambient air quality was considered the reference dose).

### Reference standards

The National Environmental Quality Standards of Pakistan (ambient air quality standards) were used as reference standards for $PM_{2.5}$ concentrations for 24 h per time-weighted average and for CO concentrations for 8 h (Ministry of Climate Change Pakistan, n.d.). The American Society of Heating Refrigerating and Air Conditioning Engineers (ASHRAE) standards were used to assess the $CO_2$ concentration as there are no WHO or NEQS standards for $CO_2$ concentration. To determine ventilation conditions, a ventilation calculator, provided with the TELAiRE Data Logger, was used.

### Statistical analysis

All the collected data were analyzed using Statistical Package for the Social Sciences (SPSS) Statistics 20.0 and Microsoft Excel. Descriptive statistics were determined with the help of Excel and SPSS statistical software. We applied Levene's test of equity of variance to check the data distribution for statistical analyses of the collected data. This test showed that our data were not normally distributed, so we applied for a nonparametric test, i.e., the Mann–Whitney. The Mann–Whitney *U* test was used to determine the significant variation among districts, whereas the Kruskal–Wallis *H* test was applied to identify significant variation among villages for the parameters measured for 24 h of continuous monitoring, i.e., $PM_{2.5}$, temperature, and RH. The least significant difference (LSD) post hoc test was applied to determine the significance of differences among all four selected villages, i.e., Sherquli, Chilum, Ghasoshal, and Holshal. The analysis of variance (ANOVA) was used to determine the significance of differences in $CO_2$ and CO among the villages and districts.

## Results

### Household energy sources and socioeconomic conditions

Overall, it was observed that a combination of solid fuels (i.e., animal dung, wood/woody shrubs, use of agricultural remains, gas, and electricity) are utilized for both heating and cooking purposes. Table 1 shows that animal dung (90%) and wood (85%) were used as primary energy sources for cooking and heating throughout the year. In contrast, electricity and gas were used as secondary sources in summer. The primary energy source for 90% of the population in the study area was animal dung, followed by > wood > agricultural remains > electricity, and > gas. Table 1 shows the number of sampled houses using different energy sources in the study area.

The study sample included 11 male and 9 female participants, with 73.33% of the illiterate occupants, 19.33% had a primary education, and only 7.33% had a secondary education, indicating a low literacy rate among the population. According to the analysis, 64% of the households earn less than 90.00 USD/month with annual fuel expenditure ranging from 150.00 to 300.00 USD in winter, decreasing to 70.00–115.00 USD in summer. On average, each household spends 200.00 USD annually on household energy. During winter, 85% of the population spent 16–18 h indoors whereas this dropped to 15% in summer. Most solid fuels were burned in traditional stoves; 80% used Bukhari stoves, and 20% used open-chamber stoves. Additionally, 60% of the sampled houses had only one room aside from the kitchen, serving multiple purposes, including as a living area throughout the year, while 40% had more than two rooms. Furthermore, 70% of the houses did not have a separate kitchen; as a result, the family members spent most of

**Table 1** Household usage of different energy sources over the year

| Energy sources | Sherquli | Chilum | Holshal | Ghasoshal | Total ($n = 20$) | Percentage (%) |
|---|---|---|---|---|---|---|
| Animal dung | 5 | 4 | 4 | 5 | 18 | 90 |
| Wood | 4 | 5 | 4 | 4 | 17 | 85 |
| Agricultural remains | 2 | 2 | 2 | 2 | 8 | 40 |
| Gas | 0 | 1 | 2 | 2 | 5 | 5 |
| Electricity | 1 | 0 | 3 | 2 | 6 | 0 |

their time in a single shared space, particularly during winter, to stay warm and only 30% had a separate kitchen.

Level of selected indoor air pollutants

*Particulate matter ($PM_{2.5}$)*

Descriptive statistics of all parameters at each sampled site are mentioned in Table 2. The Mann–Whitney *U* test was applied to determine the significant variations in $PM_{2.5}$ concentration, temperature, and RH among the districts for 24-h continuous monitoring. The test results revealed a significant difference ($p < 0.05$) in $PM_{2.5}$ concentration between the Astore and Nagar districts. The Kruskal–Wallis *H* test was applied to identify significant variation among villages for 24 h of continuous monitoring of $PM_{2.5}$, temperature, and RH. The Kruskal–Wallis test showed that there was significant variation in $PM_{2.5}$ ($p < 0.05$), temperature, and RH ($p < 0.001$) among the four villages. To further verify the Kruskal–Wallis test results, an LSD post hoc test was applied to determine the significant differences among all the selected villages, i.e., Sherquli, Chilum, Ghasoshal, and Holshal. This test revealed significant differences between the Sherquli-Holshal, Chilum-Holshal, Chilum-Ghasoshal, and Holshal-Ghasoshal for $PM_{2.5}$.

This study characterizes the concentrations of major indoor pollutants in ambient air where open or inefficient combustion occurs. It was difficult to examine pollutants by nature with a single fuel type, as all the sampled houses use different fuel sources simultaneously. The standard limit of $PM_{2.5}$ concentration set by NEQS for ambient air is 35 μg/m$^3$ for 24 h of continuous monitoring. The mean concentrations of $PM_{2.5}$ recorded were 162 μg/m$^3$, 172 μg/m$^3$, 61 μg/m$^3$, and 114 μg/m$^3$ for Sherquli, Chilum, Holshal, and Ghasoshal, respectively. Among the samples, 20% from the Nagar district and 10% from the Astore district were within the limits set by the NEQS, whereas 30% and 40% of the samples from the Nagar and Astore districts, respectively, exceeded the NEQS limits. Figure 3 shows the lowest average value of 22 μg/m$^3$ was recorded in Chilum (i.e., S2), where the primary energy

**Table 2** Descriptive statistics of all measured parameters

| Dependent variable ($n = 20$) | Villages | Mean | Standard error | Minimum | Maximum | Confidence level (95.0%) |
|---|---|---|---|---|---|---|
| $PM_{2.5}$ | Holshal | 60.92 | 10.40 | 3.85 | 154.52 | 21.52 |
| | Ghasoshal | 114.19 | 27.57 | 6.43 | 505.10 | 57.03 |
| | Sherquli | 161.86 | 41.61 | 5.32 | 677.14 | 86.07 |
| | Chilum | 172.04 | 40.91 | 5.03 | 647.44 | 84.63 |
| CO | Holshal | 8.40 | 1.43 | 2.60 | 14.20 | 3.38 |
| | Ghasoshal | 9.73 | 1.21 | 4.80 | 14.40 | 2.85 |
| | Sherquli | 10.65 | 1.86 | 4.40 | 18.20 | 4.39 |
| | Chilum | 11.63 | 1.87 | 4.00 | 19.60 | 4.43 |
| $CO_2$ | Holshal | 1080.60 | 106.65 | 809.00 | 1372.00 | 296.10 |
| | Ghasoshal | 1248.80 | 135.29 | 950.00 | 1650.00 | 375.62 |
| | Sherquli | 1215.40 | 60.74 | 984.00 | 1342.00 | 168.65 |
| | Chilum | 1278.60 | 80.45 | 1000.00 | 1450.00 | 223.35 |
| Temperature | Holshal | 17.48 | 0.98 | 13.81 | 19.14 | 2.72 |
| | Ghasoshal | 18.02 | 1.01 | 15.13 | 20.68 | 2.80 |
| | Sherquli | 15.24 | 1.31 | 11.50 | 18.47 | 3.63 |
| | Chilum | 12.24 | 1.61 | 7.52 | 16.49 | 4.48 |
| RH | Holshal | 44.13 | 2.26 | 38.14 | 50.21 | 6.28 |
| | Ghasoshal | 43.14 | 1.20 | 39.61 | 46.55 | 3.34 |
| | Sherquli | 55.03 | 5.67 | 43.77 | 69.95 | 15.73 |
| | Chilum | 52.41 | 5.80 | 39.03 | 68.39 | 16.11 |

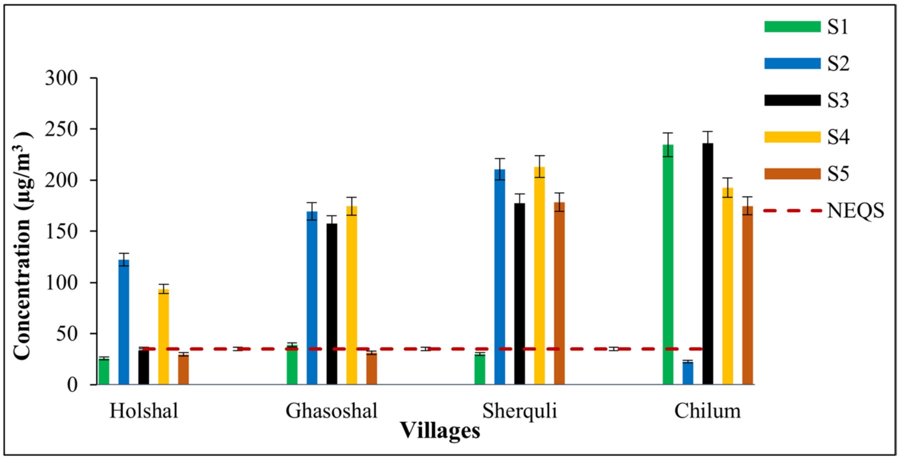


**Fig. 3** Average concentration of $PM_{2.5}$ for 24 h at each sampled site

sources in the sampled house were gas and wood, with a separate kitchen and proper ventilation. The highest concentration of $PM_{2.5}$ (i.e., 236 μg/m$^3$) was measured in sample S3 from Chilum, where integrated solid fuels were the primary energy sources. A higher level of $PM_{2.5}$ was recorded in the Astore district than in the Nagar district (Fig. 3).

The recorded concentration of $PM_{2.5}$ during cooking time represents active smoking within homes; an apparent increase in concentration can be observed during cooking hours, i.e., from 8 to 12 p.m. and 7 to 11 a.m.; the level then decreases once the occupants go to sleep at night and for work during the daytime (Fig. 4). This monitoring was carried out to reflect better the exposure of women and children who spend most of their time indoors.

Carbon monoxide (CO)

ANOVA was used to determine the significant differences in $CO_2$ and CO concentrations among the villages and regions. The statistical test showed a significant difference in CO concentrations in districts (i.e., Astore and Nagar), while the difference in $CO_2$ concentration was nonsignificant among villages and districts. The CO concentration was continuously monitored for 8 h and compared with the NEQS limits, i.e., 5 mg/m$^3$ for 8 h average. The mean concentrations of CO recorded were 11 mg/m$^3$, 12 mg/m$^3$, 8 mg/m$^3$, and 10 mg/m$^3$ for Sherquli, Chilum, Holshal, and Ghasoshal, respectively. Among the samples collected, only 5% were within the limits, 10% were slightly above the limits, and 85% were significantly above the NEQS, as depicted in Fig. 5. The lowest

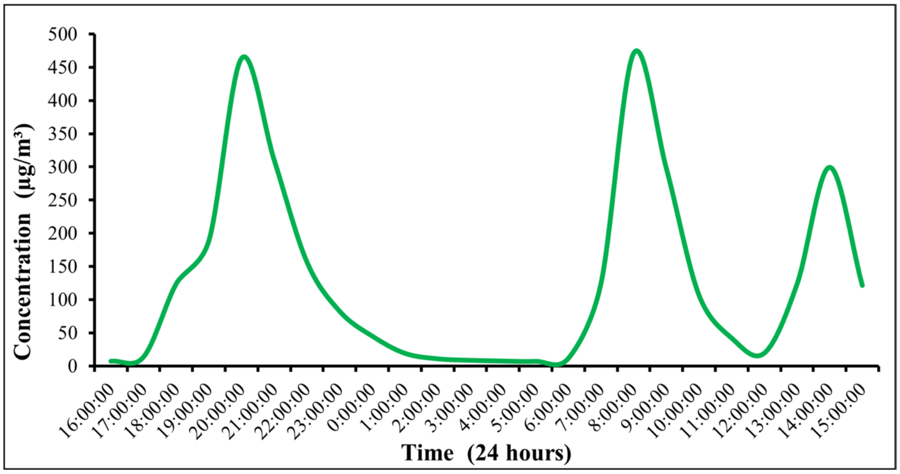


**Fig. 4** Average concentration of $PM_{2.5}$ (μg/m$^3$) for 24 h at all the sampled sites

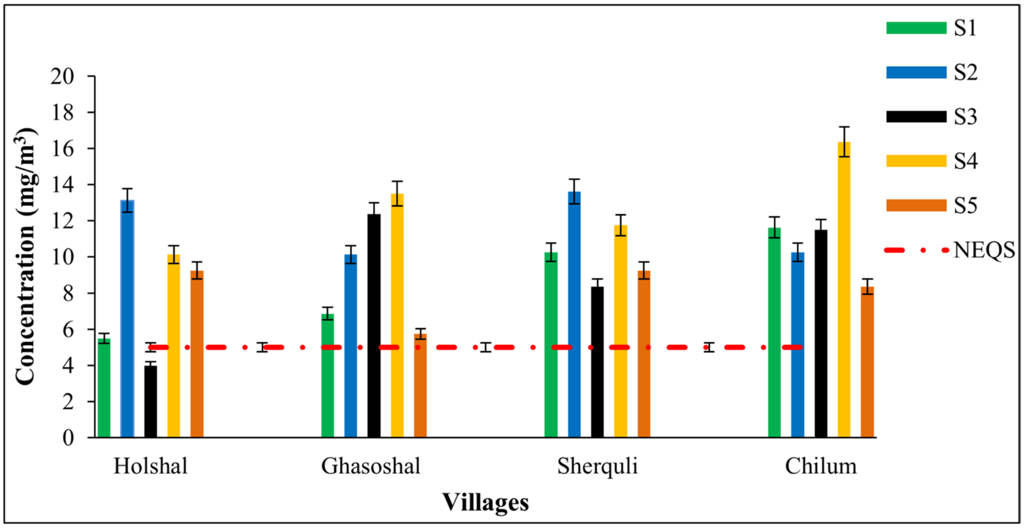


**Fig. 5** The concentration of CO (mg/m$^3$) at each sampled site

value of 4 mg/m$^3$ was recorded in Holshal (i.e., S3), whereas the highest value of 16 mg/m$^3$ was recorded in Chilum (i.e., S4). A district-wise comparison of CO concentration showed that Astore had the highest average concentration compared to Nagar.

The concentration of CO during cooking hours was also recorded. Figure 6 illustrates the 8-h average concentration of CO as per the timed-weighted average recommended by the NEQS; the peak values represent active smoking within homes.

A clear increase in concentration is identified during cooking, i.e., from 8 to 12 p.m., and then again during breakfast time, i.e., from 7 to 11 a.m.; the level then decreases once the occupants sleep at night and for work during the daytime.

Carbon dioxide ($CO_2$)

Overall, the average concentration of $CO_2$ was 1206 ppm, and the average concentrations of $CO_2$ recorded for each village were 1215 ppm, 1279 ppm, 1081 ppm, and 1249 ppm for Sherquli, Chilum, Holshal, and Ghasoshal, respectively. A comparison of $CO_2$ concentrations in the selected districts revealed in

**Fig. 6** Eight (8) h of average CO concentration (mg/m$^3$) at all the sampled sites

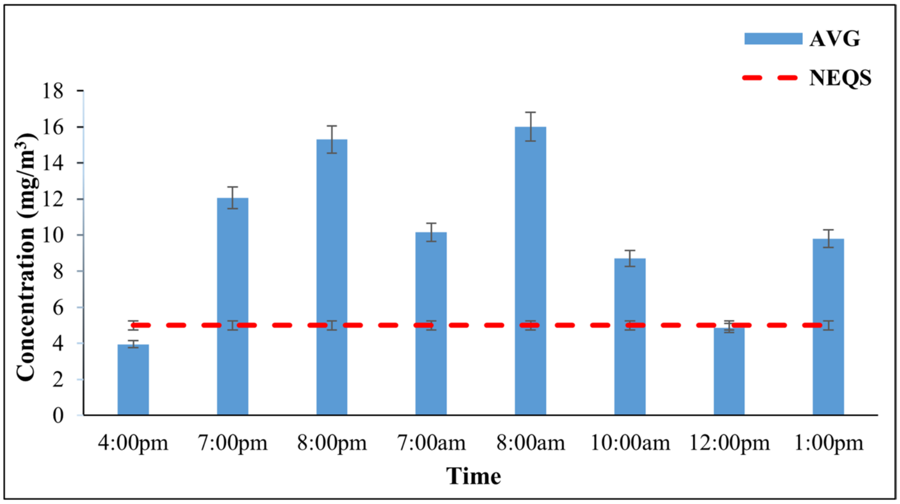

Fig. 7 that Astore has the highest average concentration compared to Nagar. Among all the samples, the minimum $CO_2$ concentration was 809 ppm measured at S1 in Holshal, and the maximum, 1650 ppm, was recorded at S3 in Ghasoshal village.

Ventilation for acceptable indoor air quality

The ASHRAE standard 62.2–2013, "Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings," was used to compare the ventilation conditions in our study area. According to these standards, ventilation in the living room must include 30 cubic feet per minute (CFM)/person and 15 CFM/person for kitchen/indoor cooking areas to dilute indoor air contaminants with less contaminated outdoor air. The ASHRAE Standard 62.2 recommends an indoor $CO_2$ level below 1000 ppm, and for outdoors, it typically ranges from 300 to 400 ppm (Mancini et al., 2020). The concentrations of $CO_2$ inside and outside the houses were measured in parts per million (ppm) to determine the ventilation rate. Indoor-outdoor $CO_2$ differential was compared with the ventilation conditions (CFM/person) provided with the equipment. A small differential indicates better over-ventilation, and a larger differential indicates under-ventilation.

It was observed that most people use a standard room for cooking and living, so 20 CFM/person is considered proper/adequate ventilation, and more than 30 CFM/person is considered over-ventilation. Of the total sampled houses, 65% were under-ventilated, 20% had adequate ventilation, and only 15% were over-ventilated according to ASHRAE standards. Among the under-ventilated samples, 40% were measured in the Astore district and 25% in Nagar.

Temperature

The average temperature increased continuously for 24 h due to heating activities by the residents at that time of day. An average temperature of 15.75 °C was recorded, and an increase in indoor temperature occurred during cooking time, i.e., at night for dinner from 6:00 to 8:00 p.m., in the morning for breakfast from around 5:30 to 8:00 a.m., and then a slight increase in temperature at noon for lunch from 12:30 to 1:30 p.m. was recorded.

The real-time indoor temperature was monitored at each location for 24 h. The overall lowest temperature was observed in the Nagar district as compared to the Astore district due to differences in sampling dates: i.e., in the Astore district, sampling was performed from 13 to 25 Oct., whereas in the Nagar district, sampling was carried out from 4 to 14 Nov. The results indicate an overall average temperature of 15.75 °C between 13.87 and 18.56 °C. The lowest temperature (7.52°C) was recorded at S1 of Chilum, whereas the highest (20.68 °C) was at S1 of Ghasoshal (Fig. 8).

Relative humidity (RH)

According to ASHRAE Standard 55—2017, "Thermal environmental conditions for human occupancy" recommended 60% of the threshold as the upper limit for the relative humidity to maintain thermal

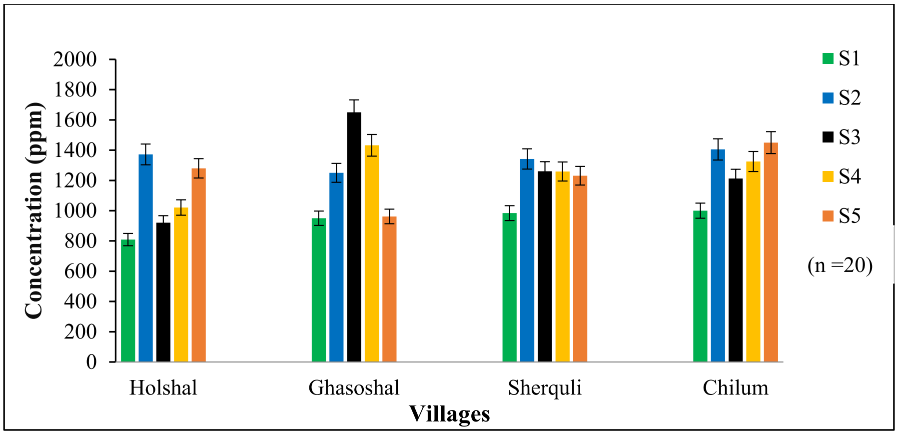


**Fig. 7** Concentration of $CO_2$ (ppm) at each sampled site

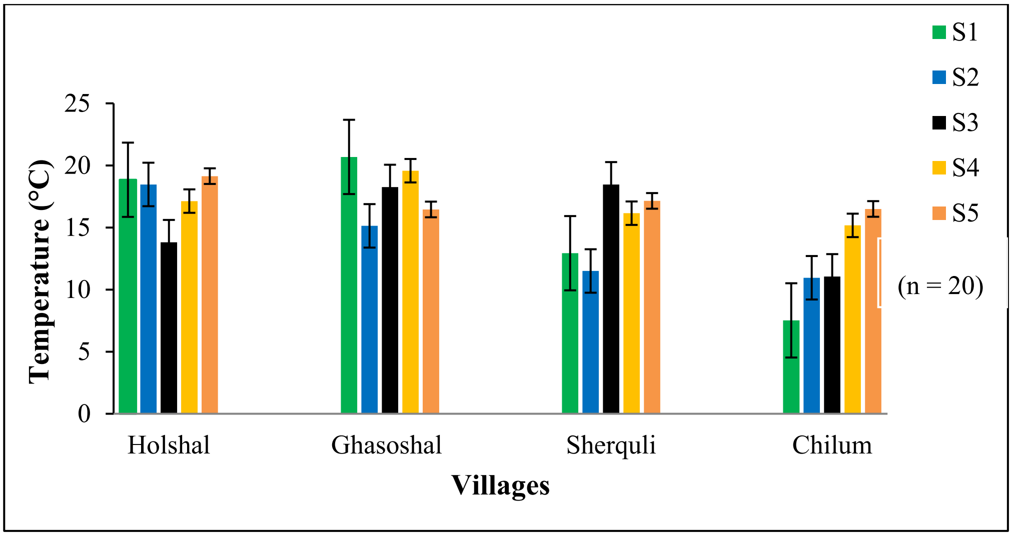


**Fig. 8** Average temperature at each sampled site

comfort (ASHRAE, 2017). Mancini et al. (2020) also highlighted that indoor humidity levels should be maintained between 30 and 65% for optimum comfort. The percentage (%) of indoor relative humidity (RH) was recorded at each location for 24 h using HOBO Data Logger. The overall highest relative humidity was detected in the Nagar district compared to the Astore district (Fig. 9).

The results indicated that the overall average RH for 24 h was 49%, between 38 and 70%. The lowest RH (38%) was recorded at S1 in Holshal, whereas the highest recorded RH was at S1 in Sherquli.

The Mann–Whitney test was applied to test for significant differences in temperature and RH among the districts (Astore and Nagar), which showed a highly significant difference of $p < 0.001$. The Kruskal–Wallis test was applied to determine the significant difference between villages, revealing highly significant differences among the selected villages. The LSD post hoc test was used to test for significant variation among the villages, as presented in Table 3. Temperature and RH exhibited highly significant variations among the various villages except for Holshal-Ghasoshal.

**Fig. 9** Average relative humidity at each sampled site

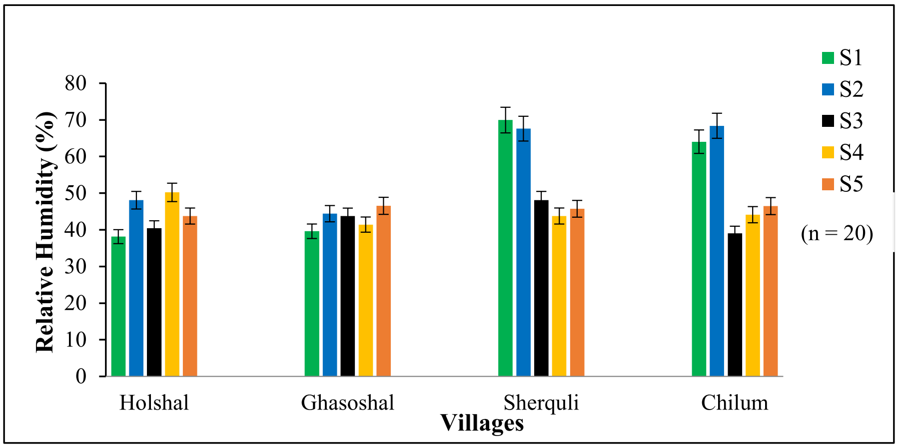

**Table 3** LSD post hoc for all the selected villages

| Villages | $PM_{2.5}$ | Temp | RH |
|---|---|---|---|
| Sherquli-Chilum | $10.2^{ns}$ | 2.9* | 2.9* |
| Sherquli-Holshal | 100.9* | 2.9* | 10.9* |
| Sherquli-Ghasoshal | $47.8^{ns}$ | 2.8* | 11.9* |
| Chilum-Holshal | 111.1* | 5.8* | 7.9* |
| Chilum-Ghasoshal | 57.8* | 5.7* | 8.9* |
| Holshal-Ghasoshal | 53.3* | $0.10^{ns}$ | $1.0^{ns}$ |

*The mean difference is significant at the $p<0.05$ level $^{ns}$Non-significant variation, respectively ($n$ = 20)-significant variation, respectively ($n=20$)

## Health effects of selected indoor air pollutants

### *Based on the questionnaire*

Almost all the respondents reported having at least one respiratory disease when using a high amount of solid fuel for heating and cooking. The prevalence of disease in the selected area and respondents' responses based on completed questionnaires depict the percentage of prevailing diseases due to indoor air pollutants. The occurrence of diseases was on the order of morning cough (17%) > eye irritation (15%) > bronchitis (14%) > wheezy (13%) > chest tightness (12%) > heart disease (11%) and morning phlegm (10%) > shortness of breath (8%), respectively.

### *Based on FAP and BHU/PPHI Center data*

According to data from the FAP Chilum, Astor, and BHU/PPHI Hoper, Nagar; acute respiratory infections (ARIs) (i.e., 37% and 33%, respectively) were among the most prevalent diseases during winter, followed by pneumonia under 5 years (i.e., 13% and 18%, respectively) and fever (i.e., 27% and 13%, respectively). Asthma, heart disease, and pneumonia above 5 years of age were also registered in patients aged 50 years and older. Eye irritation was enumerated in patients of all ages.

## Health risk assessment

### *Chronic daily intake (CDI)*

The chronic daily intake (CDI) of pollutants was detected in the order of CO > $PM_{2.5}$ through inhalation. The highest CDI value of $PM_{2.5}$ was detected at Chilum, which was 47.78 mg/(kg.day). The mean CDI values of CO ranged between 2.333 and 2.958 mg/(kg.day) in adults and 1.952 to 2.701 mg/(kg.day) in children. The mean CDI value of $PM_{2.5}$ ranged from 16.923 to 44.961 mg/(kg.day) in adults and 14.159 to 39.984 mg/(kg.day) in children. The highest CDI values of CO in adults and children were detected in Chilum (Table 4).

### Health risk index (HRI)

Among the samples tested, the HRI for $PM_{2.5}$ showed health risk for both adults and children in District Astore, i.e., Sherquli and Chilum, while in District Nagar, i.e., Holshal and Ghasoshal, no health risk was found for $PM_{2.5}$ or CO (Table 4).

# Discussion

## Household-energy sources and socioeconomic conditions

During our study, it was observed that most of the sampled households depend mainly on solid fuels as major energy sources, i.e., animal dung, wood,

**Table 4** Average chronic daily Intake in mg/(kg.day) and health risk index

| Parameter | Individuals | Sherquli | | Chilum | | Holshal | | Ghasoshal | |
|---|---|---|---|---|---|---|---|---|---|
| | | $n=5$ | | $n=5$ | | $n=5$ | | $n=5$ | |
| | | CDI | HRI | CDI | HRI | CDI | HRI | CDI | HRI |
| $PM_{2.5}$ | Adults | 44.9 | 1.28 | 47.78 | 1.36 | 16.9 | 0.48 | 31.72 | 0.90 |
| | Children | 37.6 | 1.07 | 39.98 | 1.14 | 14.16 | 0.40 | 26.54 | 0.76 |
| CO | Adults | 2.96 | 0.59 | 3.23 | 0.64 | 2.33 | 0.47 | 2.70 | 0.54 |
| | Children | 2.47 | 0.49 | 2.70 | 0.54 | 1.95 | 0.39 | 2.26 | 0.45 |

and agricultural remains, because the communities in GB do not have access to modern energy sources, i.e., gas, solar power, and electricity due to low economic conditions, and the geographical terrain of the area coupled with prolonged winter seasons. Plastic bottles, shopping bags, old clothes, and shoes were also used for burning along with solid fuels in open chambers or traditional stoves (Fig. 10b), resulting in increased concentration of IAP. Approximately 85% of the sampled population spends time indoors during winter; women and children spend more indoors than adult males during both seasons. Women are primarily involved in solid fuel–related activities, from collecting, drying, and storing wood and animal dung to burning fuels for cooking. Consistent with the results of Abedullah et al. (2020), rural women are highly vulnerable and mostly greatly affected by the harmful effects of hazardous pollutants as they are majorly involved in cooking. Nasir et al. (2015) conducted a study in Pakistan to assess the role of poverty associated with fuel choice and exposure to IAP. Their results showed that poverty is the primary factor, coupled with the geographical setting of the area and location of the house, level of income, usage of stove type, household size, house construction patterns, and access to basic facilities, significantly contributing to the choice of fuel. Source control, management, and new technologies, such as improved stoves, are important to ensure a safe indoor environment, and for that, the government needs to promote and encourage the production of cleaner/modern energy sources. A study conducted by Taghizadeh et al. (2023) also suggested potential mitigation solutions, such as the promotion of renewable alternative fuels and the introduction of innovative technologies, are essential for source control and significantly reducing air pollution emissions.

It was observed that the construction of houses in high-altitude villages follows traditional design practices aimed at conserving energy over an extended period. These designs prioritize insulation and heat retention to withstand cold weather, resulting in reduced ventilation, which can impact indoor air quality and occupant health. Figure 10a shows that the *Bukhari* is a traditional wood-burning space heater system widely used across GB for heating and cooking purposes. The existing design and construction practices of houses in GB, the poor design and manufacturing process of *Bukhari*, and its flawed installation inside the building contribute from moderate respiratory problems to annual deaths from CO poisoning and ARIs in aged individuals and newborns. In Pakistan, the use of solid fuels has resulted in more than 50,000 fatalities due to acute lower respiratory infections, along with nearly 19,000 deaths each year from chronic obstructive pulmonary disease (Hasan, 2007).

Energy sources depend on purchasing power as they are directly linked to income and education. In our study area, most families were less educated, had incomes less than 90.00 USD/month, used conventional and open chamber stoves, had no separate kitchens with inadequate ventilation, and spent more time indoors. In contrast, few families with higher


**Fig. 10** Traditional stove (Bukhari) using animal dung and wood from Hoper, Nagar (**a**); open-chamber stove using wood from Astore (**b**)

income levels have more access to gas and electricity. Harsh climatic conditions such as prolonged winters at high-altitude villages; lack of access to energy sources such as liquefied petroleum gas (LPG), electricity, biogas, and fossil fuel; and geographical and socioeconomic conditions compel the locals to consume traditional energy sources (i.e., wood, agricultural residue, and animal dung). Similar results were found in a cross-sectional study conducted by Yadama et al. (2012) in India; according to this study, the type of fuel and stove used in a household depends directly on the socioeconomic privilege of that household. Their results indicated that households with less income were exposed to higher concentrations of indoor air pollutants; additionally, high-income levels and education correlate with proper ventilation inside houses. Our results parallel the results of a study conducted by Ouerghi and Heaps (1993) in Pakistan; the Household Energy Strategy Study (HESS) reported that houses are inadequately ventilated and mostly kept closed in the northern part of the country to conserve heat due to prolonged winters compared to those in the southern part. In the northern region, 38% of the houses were small and improperly ventilated, and single rooms with no separate kitchens led to increased concentrations of IAP and its adverse effects on human health. Households depend entirely on solid fuels due to their low income, but at middle-income levels, people use both solid fuels and non-solid fuels depending upon their expenses, whereas, with the rise in income level, people start using non-solid fuels, which are cleaner and more efficient for cooking and heating purposes (Rehfuess & World Health Organization, 2006).

Level of selected indoor air pollutants

This study characterizes the concentrations of $PM_{2.5}$, CO, and $CO_2$ in indoor air where open or inefficient combustion occurs. Examining the pollutants by nature with a single fuel type was difficult, as all the sampled houses used different sources simultaneously.

Particulate matter ($PM_{2.5}$)

Our results showed that the average concentration of $PM_{2.5}$ at Chilum (172 μg/m$^3$) was five times higher than the NEQS level (35 μg/m$^3$) during cooking, i.e., at breakfast, lunch, and dinner, and $PM_{2.5}$ levels significantly decreased immediately after peak cooking hours, as shown in Fig. 4.

This might be because household members open doors to go out for work during the day and for sleep/rest at night, indicating a positive relationship between higher concentrations of $PM_{2.5}$ and total time spent cooking. Its concentration is higher among integrated solid fuel users than among gas and electricity users and non-maintenance of conventional stoves. A similar relationship was reported in a study conducted in Rehri Goth, a semirural settlement area southeast of Karachi, by Siddiqui et al. (2009); according to them, there is a positive relationship between cooking time, increasing $PM_{2.5}$ concentration in wood users and time spent by occupants in the kitchen during wood burning. The concentration of $PM_{2.5}$ in 75% of our samples was found beyond the NEQS standards. Our study results are similar to those of another study conducted by Sainnokhoi et al. (2022) in Magnolia during the winter of 2018. Their study found that indoor concentrations of $PM_{2.5}$ in all sampled households significantly exceeded WHO limits (10 μg/m$^3$). Our study comparison with colder regions seems to be more relevant due to home heating practices, type of fuel used, and meteorological conditions.

Carbon monoxide (CO)

The indoor concentration of CO was three times higher than the NEQS level (5 mg/m$^3$). Its level was high throughout the monitored time, but CO levels significantly increased during cooking hours, i.e., breakfast, lunch, and dinner (Fig. 6). Approximately 95% of the samples were found beyond the NEQS for CO, according to an 8-h average. Emissions of CO vary when a cooking pot is removed and when the stove lid is opened to add more fuel to it. Our results showed that almost every type of fuel used emits CO due to incomplete combustion of fuel, but its concentration is always high when animal dung and wood are burned or when integrated fuel is used, as most households burn fuels in pits on the ground and in metal or earth stoves which are poorly functioning. The combustion of fuels is incomplete in such stoves, generating significant emissions and high indoor pollution levels. Even instantaneous measurements of CO were found far beyond the NEQS in a study conducted in villages of Sindh, according to this study, the average CO levels in kitchens using improved stoves were significantly lower than those kitchens using traditional tree-stone stoves (Khushk et al., 2005). CO levels were measured instantaneously during cooking hours in the kitchen, and the mean value reported was 28.5 ppm in wood users when compared with our average concentration of 10.1 ppm. The conclusion of the present study and earlier work reported from rural Guatemala in 2000 demonstrated that the type of fuel used, cooking stove type, and different housing characteristics were closely related to CO and $PM_{2.5}$ concentrations (Naeher et al., 2000). There is no direct comparison of CO and $PM_{2.5}$ concentrations among our study and other studies carried out in different areas of the country as all the studies have different stove types for burning and cooking techniques due to dissimilarities in monitoring equipment and sampling duration and techniques, topography, weather conditions, and construction patterns subject to weather conditions.

Carbon dioxide ($CO_2$) and ventilation

A commonly used indicator of proper ventilation is the level of $CO_2$ present in space. Carbon dioxide is a normal by-product of respiration, combustion, and other processes. Our study reported that 65% of the sampled houses showed high levels of $CO_2$ indoors, indicating inadequate or under-ventilation conditions compared to the ASHRAE Standards for $CO_2$ (below 1000 ppm). It was observed that 85% of the occupants spent 16–18 h indoors due to freezing temperatures outside. The concentration of $CO_2$, which is the by-product of the respiration and combustion process, remains high inside as the houses are kept closed, and the available windows or doors are not opened. In our study area, most houses were built with single entry doors and a window or two, kept closed all the time, and packed with plastic sheets during winter as energy-saving practices. Therefore, there was not enough fresh air inside to dilute contaminated air with less contaminated outdoor air, indicating elevated levels of $CO_2$ and indicating that additional ventilation is needed.

Traditionally, construction practices involving inadequate ventilation for energy conservation measures are among the leading causes of poor indoor air quality. Improved ventilation and air circulation conditions are significant factors in enhancing IAQ (Niza et al., 2024). Designing interventions through proper ventilation strategies can reduce the concentration of pollutants produced through indoor activities such as cooking and heating and decrease the health risks to residents. According to a study, natural ventilation is based mainly on the frequency of door opening and relative window positioning (Tsang et al., 2023). Although the most significant way to reduce such indoor pollutants is source control, in areas where people do not have any other better energy alternatives, ventilation can play an essential role in maintaining acceptable indoor air quality levels.

Temperature

Room temperature and humidity are the main determinants of thermal comfort. Indoor temperature and relative humidity were measured continuously for 24 h in the selected houses. Temperature is one of the basic IAQ measurements that directly impacts perceived comfort and, in turn, concentration, and productivity (Madaniyazi & Xerxes, 2021). According to ASHRAE Standard 55–2017, the recommended temperature ranges are perceived as "comfortable" and include 22.8 to 26.1 °C in the summer and 20.0 to 23.6 °C in the winter (Mancini et al., 2020; Sá et al., 2017). The average room temperature in all the selected houses was 15.75 °C, which is far below the recommended level. The temperature increases significantly during cooking hours, as shown in the graph, and decreases once cooking activity or burning stops.

Relative humidity

An average of 48.58% of the RH was observed in the study area. There is an inverse relationship between temperature and relative humidity. The relative humidity level was minimal during heating and cooking hours when the temperature peaked. Usually, the RH and temperature vary from season to season, region to region, and climate to climate. However, the ASHRAE Standards 55–2017, for relative humidity, ranges from 30 to 65% (Mancini et al., 2020; Sá et al., 2017). High RH levels above 65% can provide a medium for mold, bacteria, and fungal growth, as these organisms thrive in highly humid conditions. However, low RH levels (below 30%) cause eye irritation, mucus and skin dryness, and stuffy nose and provide a medium for virus survival, leading to the spread of many viral infections, especially in the winter season (Baughman et al., 1996).

Health effects of selected indoor air pollutants

It was observed through health data analysis that acute respiratory infections (ARIs), cough, eye irritation, chest tightness, asthma, and heart disease were the most prevalent diseases during the winter, possibly due to high levels of indoor air pollutants. These diseases depend on individuals' sensitivity, exposure time to the IAP, type of fuel used for household purposes, and indoor ventilation conditions. This result is similar to that of Niza et al. (2024) who showed that respiratory symptoms depend on individuals' susceptibility to and response to indoor conditions. Traditional and poor-quality fuel types emit more IAPs, negatively impacting human health compared to modern energy sources (Baumgartner et al., 2019). Exposure to higher concentrations of indoor air pollutants for extended periods can cause chest tightness, shortness of breath, coughing, headache, and throat irritation in healthy people (Slezakova et al., 2012). Among the various pollutants, PM and CO negatively impact human health and contribute to ARIs and cardiovascular diseases. The health effects of carbon monoxide are generally thought to be related to the level of carboxyhemoglobin in the blood (Tiwary & Williams, 2018).

Air pollution and asthma are linked; asthma is a condition that causes swelling of airways and the production of more mucus, causing difficulty breathing. Repeated exposure to higher levels of air pollutants can cause severe respiratory infections such as colds, pneumonia, or bronchitis and increase asthma-related hospitalization rates (Ioannis et al., 2020).

The HRI and CDI of the selected indoor pollutants through inhalation were derived from the USEPA methods for HRI and CDI. Previous studies have shown that exposure to environmental pollutants through injection is strongly related to the environment. The HRI values of CO in our research indicated a low hazard, while the $PM_{2.5}$ concentration in the district of Astore was above one and considered to have negative impacts. This shows that individuals have more significant adverse health effects from exposure to $PM_{2.5}$ than individuals in District Nagar. This might also explain the higher incidences of ARIs in Astore. Our results resemble those of other studies, such as those of Kaewrat et al., (2021) which indicated that young children have greater adverse effects from exposure to IAP than others. De Oliveira et al. (2012) also conducted a study to assess the risk of $PM_{2.5}$ to children and adolescents from biomass burning, and the results indicated that the health risk of $PM_{2.5}$ in children was 12% higher than that in adolescents. The health risks of IAPs also depend on body weight, individual activities associated with inhalation, and exposure time and duration. Several studies have been conducted on the HRI and CDI of these IAPs using this derived formula for inhalation.

## Conclusion and recommendations

This study aims to draw attention to an often-overlooked public health issue and will provide a foundational investigation in Gilgit-Baltistan (GB). Indoor air pollution during winter poses a significant public health risk in high-altitude mountainous regions, particularly in GB. The study underscores the importance of addressing this hazard to improve health outcomes for residents in these communities. Fuel types, open fires, and inefficient stoves are the main contributors to indoor air pollution in Gilgit-Baltistan (GB). Inadequate ventilation was identified in 65% of homes, failing to meet ASHRAE standards, which further exacerbates IAP due to traditional energy-saving methods. Furthermore, a household's economic status significantly influences the choice of cleaner energy sources. Communities in these areas of GB primarily rely on a combination of wood, animal dung, and agricultural residues as their main energy sources due to low socioeconomic conditions and education levels. The predominant reliance on solid fuels such as wood, animal dung, and agricultural residues, which are neither efficient nor clean, accounts for 90% of household energy in Gilgit-Baltistan (GB). Consequently, high levels of indoor air pollution (IAP) and personal exposure are noted due to poor ventilation associated with cooking and heating using conventional fuels in inefficient stoves. During the winter season, acute respiratory infections (ARIs) were particularly prevalent, with rates ranging from 33 to 35%, making them the most common illnesses observed.

Our study's analysis of health data, environmental monitoring, and questionnaire surveys indicates a clear association between the high prevalence of acute respiratory infections (ARIs) and poor indoor air quality. The findings suggest that inadequate ventilation during winter is a significant factor contributing to respiratory health issues. The health impacts of indoor air pollution are complex and multifaceted; addressing one issue might not necessarily resolve the root cause. Multiple factors may play a role in the overall problem, all of which must be considered in a comprehensive approach to improving indoor air quality and public health.

This study indicates the urgent need to address the high levels of exposure to indoor air pollutants and the associated burden of diseases as a top priority to safeguard public health. The baseline data provided by this study will serve as a crucial foundation for implementing interventions aimed at promoting fuel-efficient and environmentally friendly alternatives for energy use. Moreover, it will aid in the development of appropriate strategies, policies, and mitigation measures to mitigate health risks stemming from poor indoor air quality. By taking proactive steps based on the findings of this study, significant progress can be made in protecting the health and well-being of individuals in Gilgit-Baltistan and similar regions facing similar challenges.

It is pertinent to raise awareness through community awareness programs focused on the proper stove maintenance (including traditional Bukhari stoves), the health impacts of IAPs, and the benefits of adequate ventilation.

Additionally, targeted measures should be implemented to address source pollution by promoting the use of cleaner fuels and upgrading existing heating systems by installing well-maintained, energy-efficient stoves, which can significantly reduce emissions and improve air quality.

Government involvement is essential in establishing regular health screenings for respiratory and cardiovascular diseases in high-altitude communities in Gilgit-Baltistan, providing necessary medical assistance, especially during the winter, and promoting access to cleaner energy options such as hydropower, LPG, or solar energy by providing subsidies. The government needs to create comprehensive building guidelines for high-altitude areas to withstand the harsh environmental conditions and prioritize health and safety. These initiatives could significantly reduce dependence on animal dung and wood, contributing to better health outcomes and environmental sustainability.

**Acknowledgements** We extend our heartfelt gratitude to the Director and Deputy Director (R&D) GB-EPA for their insightful guidance and motivation in conducting this study. We truly appreciate their invaluable contribution.

**Author contribution** All the authors contributed equally to the preparation of this article. Samreen Liaqat designed and conducted the research study and prepared the article. Syed Waqar Hussain assisted in the data collection and analysis. Khadim Hussain facilitated our selection of the study areas, coordinated with local communities, and co-supervised. Farida Begum assisted in statistical analysis and visualized and supervised the research study overall.

**Funding** This study was financially and technically supported by the Gilgit-Baltistan Environmental Protection Agency.

**Data availability** No datasets were generated or analysed during the current study.

**Declarations**

**Ethical approval** All the authors have read, understood, and complied as applicable with the statement on "Ethical responsibilities of Authors" as found in the Instructions for Authors.

**Conflicting of interest** The authors declare no competing interests.

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