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Abstract

Background: Household air pollution is an important source of exposure to fine particulate matter ($PM_{2.5}$), particularly in households that rely on solid fuels and traditional cooking technologies. However, direct measurements of household $PM_{2.5}$ concentrations and their temporal and seasonal variability remain limited in Ethiopia. This study assessed household kitchen $PM_{2.5}$ concentrations and examined differences between rural and urban households, seasonal variation, and factors associated with $PM_{2.5}$ concentration in Eastern Ethiopia.

Methods: A community-based comparative cross-sectional study was conducted among households in selected rural and urban kebeles under the Haramaya University Health and Demographic Surveillance System. A total of 923 households (573 rural and 350 urban) were included. Kitchen $PM_{2.5}$ concentrations were measured continuously using 20 PurpleAir II-Secure Digital (SD) optical sensors for three to five consecutive days per household between January 2023 and December 2024. Twenty-four-hour mean $PM_{2.5}$ concentrations were calculated from minute-level measurements. Seasonal variation was assessed using repeated measurements from 96 kitchens (60 rural and 36 urban) monitored during both wet and dry seasons. Independent and paired t-tests were used to compare rural–urban and seasonal concentrations, respectively. Kernel regression was used to assess factors associated with household $PM_{2.5}$ concentrations.

Results: The mean 24-hour $PM_{2.5}$ concentration was substantially higher in rural kitchens than in urban kitchens (473 ± 255 μg/m³ versus 80 ± 92 μg/m³), with an observed mean difference of 393 μg/m³ (95% CI: 370–416; $p < 0.0001$). All rural households used unclean fuels and open-fire stoves, whereas 58.3% of urban households used electricity as their primary cooking fuel. Among the 96 kitchens monitored in both seasons, rural mean $PM_{2.5}$ concentration increased from 343 μg/m³ during the dry season to 732 μg/m³ during the wet season, corresponding to a mean within-kitchen difference of 388 μg/m³ (95% CI: 348–430; $p < 0.0001$). In urban kitchens, mean concentrations increased from 47 to 105 μg/m³, with a mean difference of 59 μg/m³ (95% CI: 39–78; $p < 0.0001$). In the adjusted kernel regression model, rural residence was the strongest factor associated with $PM_{2.5}$ concentration (estimate = 383.21 μg/m³; 95% CI: 357.52–406.65; $p < 0.001$). Rich households had lower concentrations than very poor households (estimate = −7.80 μg/m³; 95% CI: −14.62 to −0.84; $p = 0.031$), while lack of ventilation was associated with higher concentrations (estimate = 4.81 μg/m³; 95% CI: 0.30–9.46; $p = 0.040$). Clean-fuel use was associated with lower $PM_{2.5}$ concentrations (estimate = −4.12 μg/m³; 95% CI: −6.48 to −2.07; $p < 0.001$).

Conclusion: Household kitchen $PM_{2.5}$ concentrations were very high, particularly among rural households relying on unclean fuels and open-fire cooking. Concentrations also varied substantially by season, with markedly higher levels during the wet season in both rural and urban kitchens. Rural residence showed the strongest association with $PM_{2.5}$ concentration, while wealth, ventilation, and fuel type showed smaller independent associations. The findings highlight the importance of expanding access to clean cooking energy and appropriate cooking technologies and of considering seasonal and temporal variability when assessing household $PM_{2.5}$ concentration. Future research should incorporate longer monitoring periods, personal exposure assessment, and validation against reference or gravimetric instruments.

Keywords: household air pollution; $PM_{2.5}$ concentration; biomass fuel; seasonal variation; PurpleAir; Ethiopia

Introduction

Household air pollution (HAP) refers to contaminants generated indoors, primarily from cooking and heating with biomass fuels in inefficient stoves. It is a major environmental health concern, particularly in low- and middle-income countries where households continue to rely heavily on polluting fuels and technologies. Globally, approximately 2.1 billion people still lack access to clean cooking, with the burden disproportionately affecting rural populations and households in sub-Saharan Africa **[1**; **2]**. In Ethiopia, dependence on traditional cooking fuels remains particularly widespread, with approximately 92.9% of rural households relying on traditional fuels for cooking **(2**; **3]**. Combustion of biomass and other polluting fuels generates a complex mixture of particulate and gaseous pollutants, including particulate matter with an aerodynamic diameter of ≤2.5 μm ($PM_{2.5}$), PM_{10}, carbon monoxide (CO), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and various organic compounds **[4]**. Among these pollutants, $PM_{2.5}$ is of particular concern because its small particle size allows it to penetrate deeply into the respiratory tract and reach the lower airways and potentially the systemic circulation.

Exposure to particulate air pollution has been associated with a broad range of adverse health outcomes, including respiratory and cardiovascular diseases and premature mortality **[5, 6]**. Particulate matter has also been classified by the International Agency for Research on Cancer (IARC) as carcinogenic to humans (Group 1), underscoring the importance of particulate pollution as a public health concern **[5]**. Globally, air pollution contributed substantially to the burden of premature mortality, with an estimated 7.8 million deaths attributed to air pollution in 2021 **[6]**. In household environments, the magnitude of particulate exposure can be particularly high during cooking with biomass fuels, making household $PM_{2.5}$ an important indicator of exposure to combustion-related air pollution.

Household $PM_{2.5}$ concentrations are influenced by several interrelated factors, including the type and characteristics of cooking fuel and stove, cooking frequency and duration, fuel characteristics, kitchen configuration, ventilation, and household structure. Previous research has demonstrated substantial variation in particulate emissions and exposure according to fuel type, combustion conditions, and household characteristics **[7- 9]**. Therefore, classification of households solely according to the type of cooking fuel may not adequately characterize actual household particulate exposure. Direct measurement of $PM_{2.5}$ within household environments can provide a more objective assessment of exposure and can capture variations that may not be apparent from reported fuel use alone.

In Ethiopia, several studies have documented high levels of household particulate pollution associated with the use of biomass and other polluting cooking fuels. Reported household $PM_{2.5}$ concentrations in different Ethiopian settings have exceeded both the World Health Organization guideline level of 15 μg/m³ and the Ethiopian daily standard of 37.5 μg/m³ **[10- 13]**. These findings indicate that household particulate pollution remains an important environmental exposure in Ethiopia. However, household $PM_{2.5}$ concentrations may differ substantially between locations because of differences in fuel use, cooking practices, kitchen characteristics, and access to cleaner cooking technologies. Evidence describing these variations in Eastern Ethiopia remains limited.

Eastern Ethiopia provides an important setting for examining household $PM_{2.5}$ because cooking practices, fuel availability, dietary traditions, kitchen arrangements, and access to clean cooking energy may differ between rural and urban households. Rural households predominantly rely on biomass fuels, whereas urban households may use a mixture of biomass and cleaner cooking-energy sources. These differences may contribute to variation in $PM_{2.5}$ concentrations between rural and urban settings. In addition, seasonal conditions may influence household $PM_{2.5}$ concentrations through changes in fuel characteristics, ventilation practices, and cooking activities. Repeated measurements from the same households across

seasons provide an opportunity to assess seasonal variation while accounting for relatively stable household characteristics.

Despite the substantial contribution of household air pollution to environmental exposure, evidence remains limited regarding directly measured $PM_{2.5}$ concentrations among rural biomass-dependent households compared with urban mixed cooking fuels users in Eastern Ethiopia. There is limited evidence simultaneously examining rural–urban differences and seasonal variation using paired measurements from the same households. Characterizing these patterns may provide a more comprehensive understanding of household particulate pollution and the factors contributing to variation in $PM_{2.5}$ concentrations.

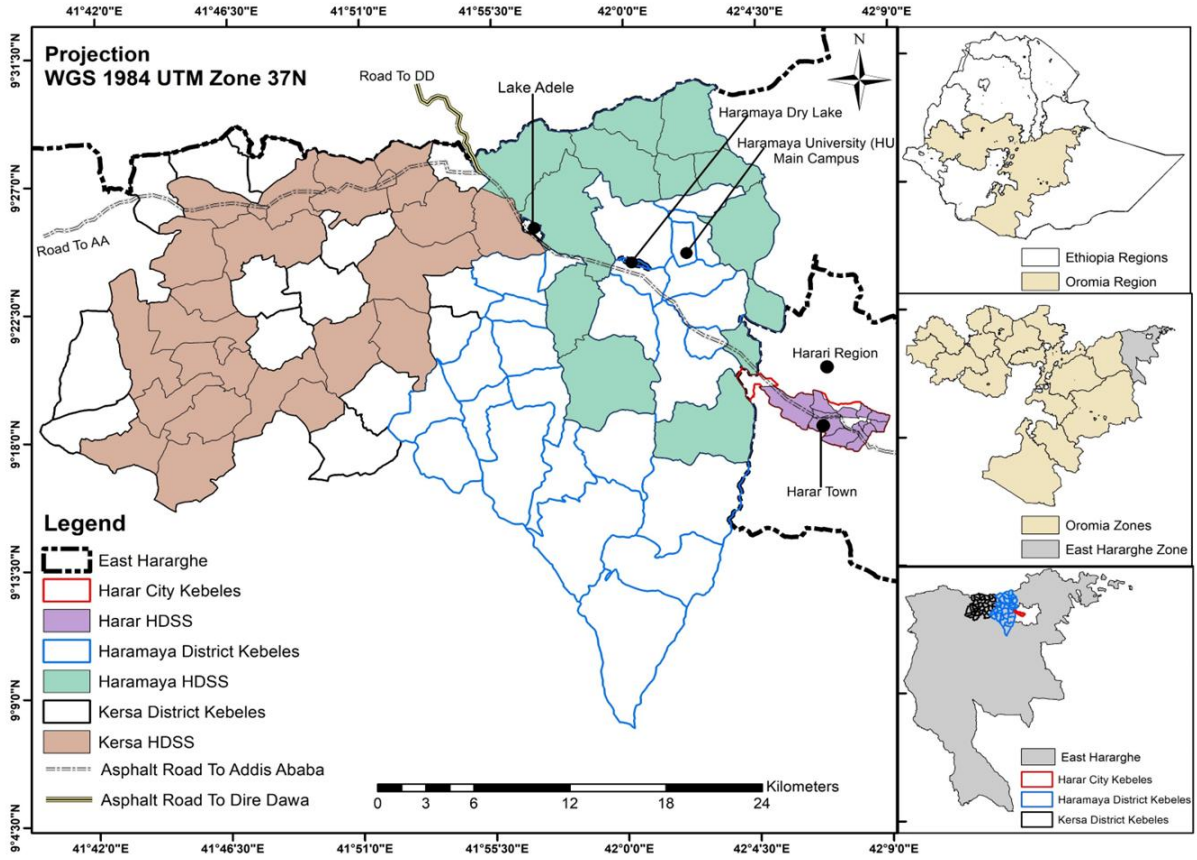
Therefore, this study assessed and compared average household $PM_{2.5}$ concentrations among biomass fuel user rural and mixed cooking fuels user urban households in Eastern Ethiopia. The study also examined seasonal variation in $PM_{2.5}$ concentrations using paired measurements collected from selected households across seasons and assessed factors associated with variation in $PM_{2.5}$ concentrations.

Materials and Methods:

Study Area

The study was conducted in 19 kebeles, the smallest administrative units in Ethiopia, selected through random sampling. Eight rural kebeles were selected from Haramaya District and 11 urban kebeles from Harar Town. Both study areas are part of the Haramaya University (HU) Health and Demographic Surveillance System (HDSS). The rural Haramaya HDSS was established in 2018 and covers 12 kebeles, while the Harar HDSS was established in 2021 and likewise covers 12 kebeles. Both surveillance sites operate as longitudinal population-based cohorts, generating comprehensive data on demographic and health-related characteristics.

According to the HU-HDSS Coordinating Office (2023), the Harar HDSS covers 12 of the 19 kebeles in Harar Town and includes a population of 51,064 and 12,686 active households, with an average family size of 4.2. The rural Haramaya HDSS covers 12 of the 34 kebeles in Haramaya District, excluding urban and peri-urban areas, and includes a population of 101,639 and 20,580 active households, with an average family size of 5.7 **[14]**.



(Source: Haramaya University, HDSS Coordinating Office, Harar)

Figure 1: Geographic location of the study kebeles in Haramaya District and Harar Town, Eastern Ethiopia.

Study Design

A community-based comparative cross-sectional study was conducted to determine 24-hour mean household $PM_{2.5}$ concentrations in household kitchens using PurpleAir II-SD optical particle sensors. In addition, repeated measurements were conducted in a subset of selected households to assess seasonal variation in household $PM_{2.5}$ concentrations between the wet and dry seasons.

Source and Study Population

The source population comprised households residing in selected kebeles of Harar town and Haramaya district and covered by the Haramaya University Health and Demographic Surveillance System (HU-HDSS). The study population consisted of eligible households selected from the HU-HDSS database.

Sample Size Determination

The sample size was calculated for comparison of two independent means using parameters reported by Dionisio et al.**[15]** and Yacob et al.**[16]**. The assumed mean $PM_{2.5}$ concentrations were 135.0 and 141.3

μg/m³ for the two comparison groups, with standard deviations of 38.0 and 37.5 μg/m³, respectively. Using a two-sided significance level of 5%, 80% statistical power, and an adjustment factor of 1.64, the calculated sample size was 906 households.

To account for potential non-response, 10 additional households were included into each group, resulting in a total target sample size of 926 households. Following data cleaning, three urban households were excluded because of duplicate household identification numbers. Consequently, the final analytical sample comprised 923 households, including 573 rural and 350 urban households.

Sampling Technique

Households were selected using a simple random sampling technique from the HU-HDSS database. A total of 923 households were targeted for inclusion in the study.

Inclusion and Exclusion Criteria

Households were eligible if they had been residing in the selected kebeles for at least six months and had an eligible woman who gave birth irrespective of the birth-outcome within one year preceding this study. Households were excluded when the mother or caregiver was seriously ill, had a mental health problem that prevented participation, or was unable to provide the required information.

Air Quality Measurement

Household kitchen $PM_{2.5}$ concentrations were measured using PurpleAir II-SD optical particle sensors. Measurements were conducted continuously for 3–5 consecutive days in each household. In rural households without electricity, power banks were used to operate the sensors for at least three days. In urban households, measurements were generally conducted for 4–5 days to capture household cooking practices, including injera preparation. The frequency of injera preparation varied according to household size and injera consumption frequency, with preparation occurring approximately every three, four, or five days. Injera preparation was common among urban households.

The sensors were positioned in the kitchen at approximately 1.5–2.5 m above the floor and 0.5–1.0 m from the nearest wall. Placement was arranged as much as possible while considering airflow and ventilation conditions within the kitchen. The sensors were positioned to represent concentrations within the household cooking environment and the breathing zone of household members.

$PM_{2.5}$ concentrations were recorded continuously, and the measurements were used to calculate the 24-hour mean $PM_{2.5}$ concentration (μg/m³) for each household. The resulting mean concentration was used as the primary proxy measure of household $PM_{2.5}$ exposure.

Seasonal Paired Measurements

To assess seasonal variation in household $PM_{2.5}$ concentrations, repeated measurements were conducted in a subset of 96 selected household kitchens, comprising 60 rural and 36 urban kitchens. The same kitchens were monitored during both the wet and dry seasons, allowing within-household comparison of $PM_{2.5}$ concentrations.

For this study, the wet season was defined as the period from mid-June to mid-September, while the remaining months were classified as the dry season. The repeated measurements from the same household kitchens were therefore treated as paired observations for seasonal comparison.

PurpleAir II-SD Sensors and Measurement Principles

A total of 20 PurpleAir II-SD sensors were used for $PM_{2.5}$ monitoring, with 13 sensors allocated to rural households and seven to urban households using proportional allocation. Data collection was conducted from January 2023 to December 2024.

The PurpleAir II-SD sensor contains two PMS-6003 optical particle counters that operate as independent measurement channels (Channels A and B). The sensors estimate particulate matter concentrations based on optical particle counting and report $PM_{2.5}$ mass concentrations in $\mu g/m^3$. The devices also contain Bosch sensors for measuring temperature, atmospheric pressure, and relative humidity. The sensors used the CF_1 indoor correction algorithm **[17, 18]**.

Before deployment, the functionality of each sensor was assessed. The sensors were factory calibrated, and previous studies have reported moderate to high correlations between PurpleAir measurements and reference or equivalent federal measurement methods (**[19 - 22]**.

Temperature has been reported to have a relatively limited influence on PurpleAir measurements under typical environmental conditions [**23- 25]**. But, due to the fact that Purple air monitors do not have aerosol dryers in the present study, the potential effect of high relative humidity on optical particle measurements was considered. Previous studies have reported more substantial humidity-related effects at relatively high relative humidity levels **[19, 21, 23]**. In the present study, observed relative humidity was generally ≤65%, whereas substantial effects have been reported at levels above approximately 75% **[25, 26]**. Therefore, the potential influence of relative humidity on the measurements was considered limited under the present conditions of the study.

Data Quality Assurance and Quality Control

Quality assurance and quality control procedures were adapted from previously published recommendations for the use of PurpleAir sensors **[27, 28]**. The two measurement channels within each sensor were checked for consistency, and sensor performance was monitored throughout the data collection period.

In urban households, sensors were installed away from major roads to minimize the influence of direct traffic emissions. The sensors were positioned approximately 1.5 m away from doors, windows, and other major openings where possible to avoid measuring incoming outside air quality **[12]**. Daily data completeness and consistency were checked, including the amount of valid measurement time obtained from each sensor. A minimum of 20 hours of valid measurements per day was considered a complete measurement per day. Days with substantial missing, incomplete, or corrupted data were excluded from the calculation of daily means.

When technical or household-related problems resulted in loss of valid measurements, the affected households were revisited and measurements were repeated where feasible. These procedures were implemented to improve the completeness and reliability of the household $PM_{2.5}$ measurements.

Data Collection Procedures

Survey data were collected using a pretested structured questionnaire administered electronically using tablets. The questionnaire collected information on household sociodemographic characteristics, kitchen characteristics, ventilation, cooking fuel and stove types, cooking frequency, and cooking duration.

The questionnaire was initially prepared in English and translated into Amharic and Afaan Oromo by subject expert. The translated versions were back-translated into English to assess consistency of meaning. Data collectors received two days of training covering the study objectives, questionnaire administration, informed consent procedures, and $PM_{2.5}$ measurement protocols. Training included practical demonstrations and simulation exercises. Two supervisors monitored field activities and reviewed completed data for completeness and consistency.

Study Variables

The primary dependent variable was the 24-hour mean household $PM_{2.5}$ concentration, expressed in $\mu g/m^3$. $PM_{2.5}$ concentration was analyzed as a continuous variable.

Independent variables included household sociodemographic characteristics, kitchen characteristics, ventilation conditions, cooking fuel and stove types, cooking frequency, cooking duration, residence, and season.

Household cooking fuel was classified as clean or unclean according to the operational definitions used in the study. Clean fuel referred to electricity, whereas unclean fuels included plant residues, wood, animal dung cake, charcoal, and kerosene. Stove types included traditional three-stone stoves, charcoal stoves, kerosene stoves, and electric stoves.

Data Processing and Statistical Analysis

Data were exported, cleaned, and analyzed using Stata version 17. Descriptive statistics were used to summarize household characteristics and $PM_{2.5}$ concentrations. Continuous variables were summarized using appropriate measures of central tendency and dispersion, while categorical variables were summarized using frequencies and percentages.

For each household, three to five days $PM_{2.5}$ measurements taken were processed to obtain daily 24-hour mean concentrations. A minimum of 20 hours of valid measurements was required for a day to be considered complete. The available measurements over the monitoring period were then converted to daily 24-hours mean concentrations and used to characterize the household's mean $PM_{2.5}$ concentration.

An independent-samples t-test was used to compare mean $PM_{2.5}$ concentrations between rural and urban households. For the 96 household kitchens with repeated measurements in both seasons, comprising 60 rural and 36 urban kitchens, a paired-samples t-test was used to compare $PM_{2.5}$ concentrations between the wet and dry seasons within the same household kitchens.

Non-parametric kernel regression was used to assess the relationship between household mean 24-hours $PM_{2.5}$ concentrations and selected household, kitchen, cooking, and sociodemographic characteristics. The model was used to examine associations of variation in household $PM_{2.5}$ concentrations, with the corresponding pseudo-R^2, 95% confidence intervals, and p-values reported where applicable. Statistical significance was considered at $p < 0.05$.

Ethical Considerations

The study was conducted in accordance with the principles of the Declaration of Helsinki. Ethical approval was obtained from the Haramaya University College of Health and Medical Sciences Institutional Health Research Ethics Review Committee (IHRERC/187/2023) on 17 October 2023. Permission to conduct the study was also obtained from the relevant health authorities in East Hararghe Zone and the Harari Regional Health Bureau.

Written informed consent was obtained from eligible participants before data collection. Participants were informed about the purpose and procedures of the study, their voluntary participation, and their right to withdraw from the study at any time without consequence. Confidentiality of the collected information was maintained throughout data collection, processing, and analysis.

Clinical Trial Registration

Clinical trial registration was not applicable because this was an observational household-based study.

Result

Socio-demographic Characteristics of Household Respondents:

Marked differences were observed between rural and urban households across several socio-demographic variables.

Illiteracy was overwhelmingly higher in rural areas, with 79.2% of rural women illiterate compared to only 7.1% in urban households. Conversely, higher educational attainment was concentrated in urban settings. 35.1% of urban mothers had completed secondary school or above, compared to just 2.6% in rural households. Elementary education was also more common in urban areas (52.9%) than rural (14.0%).

Occupational patterns showed sharp contrasts. In rural households, the vast majority of mothers were housewives (96.1%), while in urban households this proportion was lower (51.4%). Urban mothers were more frequently engaged in formal or semi-formal employment, including government positions (20.9%), petty trade (6.9%), and private employment (6.9%). Farming was rare in both settings, though slightly higher in rural households (1.4% vs. 1.1%).

Marriage was the dominant status in both groups, though more prevalent in urban households (98.0%) compared to rural (86.0%). Single mothers were more common in rural areas (13.5%) than urban (0.6%). Divorce or separation was rare in both settings (1.4 vs 0.5%). Likewise, Religious affiliation varied sharply by residence. All rural respondents were Muslim (100%), while urban households were more diverse, 50.3% Muslim, 42.9% Orthodox Christian, and 6.9% Protestant Christian (Table 1).

Large families were more common in rural households, where 47.6% had seven or more members, compared to 20.6% in urban households. In contrast, medium-sized families (4–6 members) were predominant in urban areas (69.7%) compared to rural (43.5%). Small families (≤3 members) were relatively uncommon in both settings (9.7%-urban vs 8.9%-rural) (Table 1).

The distribution of wealth was relatively balanced across rural and urban households. However, urban households had a slightly higher proportion in the middle (24.3%) and rich (20.6%) categories, while rural households had more in the very rich (17.3%) and poor (20.8%) categories (Table 1).

Table 1: Socio-demographic Characteristics of Households by Residence, Eastern Ethiopia.

Variable	Urban n=350	Rural n= 573	Total n=923	Percentage (%)
Mother's Educational Status				
• **Illiterate**	25 (7.1%)	454 (79.2%)	479	51.9%
• **Read and Write only**	17 (4.9%)	24 (4.2%)	41	4.4%
• **Elementary School only**	185 (52.9%)	80 (14.0%)	265	28.7%
• **Secondary School and Above**	123 (35.1%)	15 (2.6%)	138	15.0%
Occupation of the Mother				
• **Farmer**	4 (1.1%)	8 (1.4%)	12	1.3%
• **Merchant**	34 (9.7%)	3 (0.5%)	37	4.0%
• **Petty trade**	24 (6.9%)	10 (1.7%)	34	3.7%
• **Government employee**	73 (20.9%)	0	73	7.9%
• **Daily Laborer**	11 (3.1%)	1 (0.2%)	12	1.3%
• **Private Employee**	24 (6.9%)	0	24	2.6%

• **Housewife**	180 (51.4%)	551 (96.1%)	731	79.2%
Marital Status of Respondent				
• **Single**	2 (0.6%)	77 (13.5%)	79	8.6%
• **Married**	343 (98.0%)	493 (86.0%)	836	90.5%
• **Divorced/Separated**	5 (1.4%)	3 (0.5%)	8	0.9%
Religion				
• **Muslim**	176 (50.3%)	573 (100%)	749	81.1%
• **Orthodox**	150 (42.9%)	0	150	16.3%
• **Protestant**	24 (6.9%)	0	24	2.6%
Family Size				
• **Up to 3**	34 (9.7%)	51 (8.9%)	85	9.2%
• **4 to 6**	244 (69.7%)	249 (43.5%)	493	53.4%
• **7 and above**	72 (20.6%)	273 (47.6%)	345	37.4%
Wealth Index				
• **Very Poor**	85 (24.3%)	124 (21.6%)	209	22.6%
• **Poor**	60 (17.1%)	119 (20.8%)	179	19.4%
• **Middle**	85 (24.3%)	117 (20.4%)	202	21.9%
• **Rich**	72 (20.6%)	114 (19.9%)	186	20.2%
• **Very rich**	48 (13.7%)	99 (17.3%)	147	15.9%

Kitchen and Cooking Characteristics

Most households in both settings reported having a separate kitchen outside the living house. This was slightly more common in rural areas (83.2%) compared to urban (78.9%). Conversely, indoor kitchens inside the living house were more frequent in urban households (21.1%) than rural (16.8%) (Table 2).

The presence of ventilation showed a notable rural advantage. 82.0% of rural kitchens had ventilation, compared to 62.9% in urban households. Lack of ventilation was more common in urban kitchens (37.1%) than rural (18.0%) (Table 2).

Fuel use differed sharply by residence. All rural households (100%) relied on unclean fuels (wood, charcoal, dung, plant residue), while urban households showed a mixed pattern: 58.3% used clean fuel (electricity) and 41.7% used unclean fuels (wood, dung, charcoal and kerosene). Similarly, stove types reflected similar disparities. In rural households, open fire stoves dominated (100%), while urban households used a variety of stoves: electric stoves (58.3%), charcoal stoves (24.0%), open fire stoves (13.4%), and kerosene stoves (4.3%) (Table 2).

Table 2: Kitchen characteristics and cooking practices by residence, Eastern Ethiopia.

Variables	Urban n=350 (%)	Rural n=573 (%)	Total n=923	Percentage (%)
Kitchen Arrangement				
• **Indoor Kitchen inside living House**	74 (21.1%)	96 (16.8%)	170	18.4%
• **Separate Kitchen outside living house**	276 (78.9%)	477(83.2%)	753	81.6%
Presence of Ventilation				

• **Yes**	220 (62.9%)	470 (82.0%)	690	74.8%
• **No**	130 (37.1%)	103 (18.0%)	233	25.2%
Type of Fuel				
• **Unclean Fuel**	146 (41.7%)	573(100%)	719	77.9%
• **Clean Fuel**	204 (58.3%)	0	204	22.1%
Primary Means of Cooking				
• **Open Fire Stove**	47 (13.4%)	573 (100%)	620	67.2%
• **Charcoal Stove**	84 (24.0%)	0	84	9.1%
• **Kerosene Stove**	15 (4.3%)	0	15	1.6%
• **Electric Stove**	204 (58.3%)	0	204	22.1%

Household PM2.5 Concentrations

Marked differences in household kitchen $PM_{2.5}$ concentrations were observed between rural and urban households. The mean 24-hour $PM_{2.5}$ concentration was 473 µg/m³ (SD = 255; median = 418; range = 32–1,461 µg/m³) in rural kitchens, compared with 80 µg/m³ (SD = 92; median = 56; range = 1.3–650 µg/m³) in urban kitchens. The overall mean concentration across the 923 households was 323 µg/m³ (SD = 283; median = 265; 95% CI: 302–341 µg/m³).

The independent-samples t-test demonstrated a statistically significant difference between rural and urban households. Rural households had a mean concentration 393 µg/m³ higher than urban households (95% CI: 370–416 µg/m³, $p < 0.0001$). The observed mean concentrations in both settings were above the Ethiopian guideline value of 37.5 µg/m³ and the WHO 24-hour $PM_{2.5}$ guideline value of 15 µg/m³.

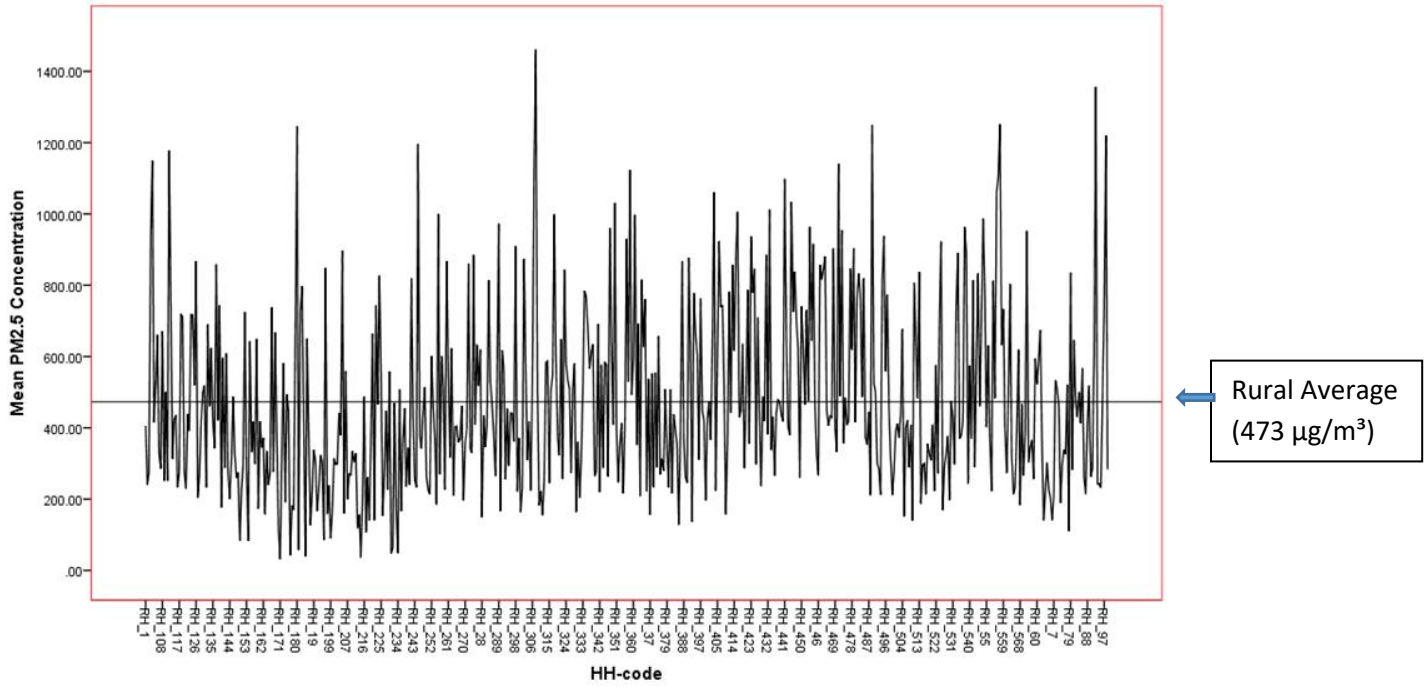


Figure 2: Distribution of 24-hour mean $PM_{2.5}$ concentrations among rural households in Eastern Ethiopia.

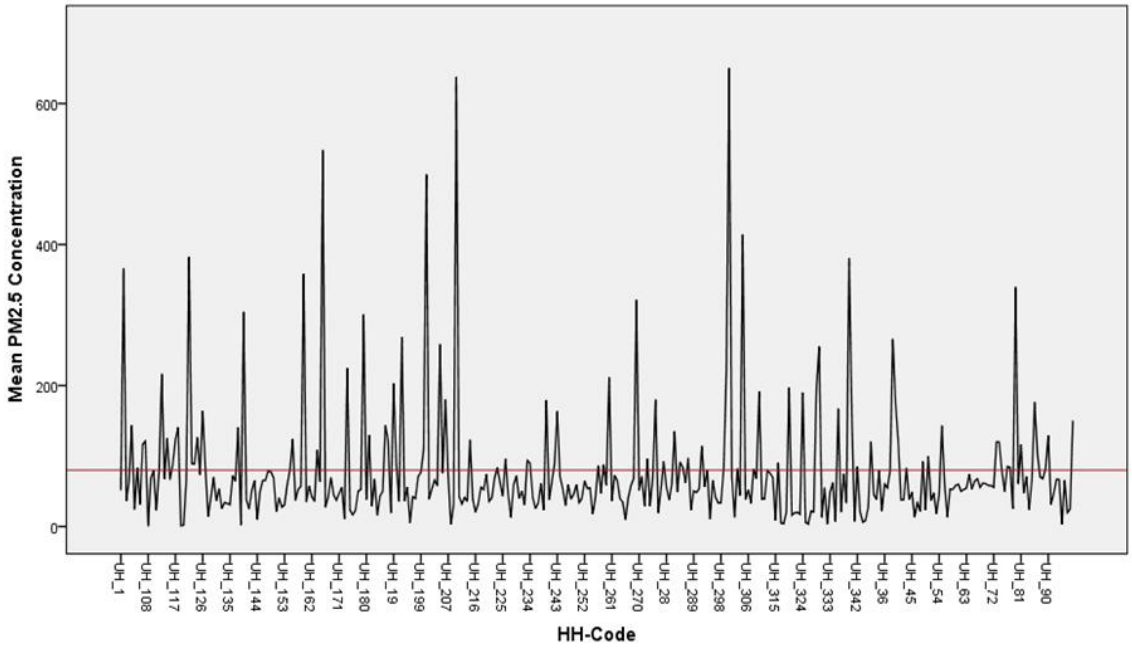


Figure 3: Distribution of 24-hour mean $PM_{2.5}$ concentrations among urban households in Eastern Ethiopia.

Hourly and Weekly Temporal Patterns:

Hourly $PM_{2.5}$ concentrations demonstrated substantial temporal variability across the monitoring period. Rural households generally exhibited higher concentrations than urban households throughout the observed weekly profiles, with hourly PM2.5 concentrations revealed two distinct peaks in rural households, coinciding with meal preparation times (figure 4). Urban households showed less consistent temporal patterns.

Hourly observations were pooled separately for Monday through Sunday across all households and monitoring days for which data were available. The resulting profiles represent an aggregate weekly pattern of household $PM_{2.5}$ concentrations. Descriptively, higher concentrations were observed on weekend periods in rural households; however, these weekday–weekend differences were not subjected to a specific inferential test and should therefore be interpreted as aggregate descriptive patterns.

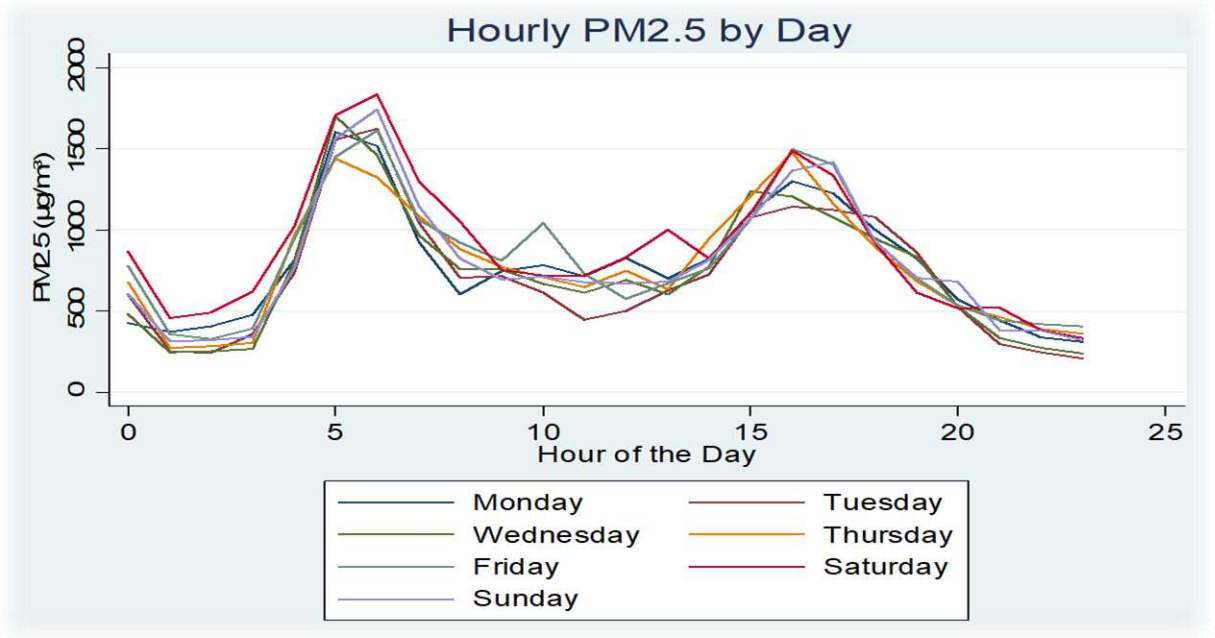


Figure 4: Aggregate hourly $PM_{2.5}$ concentration profiles by day of the week among rural households.

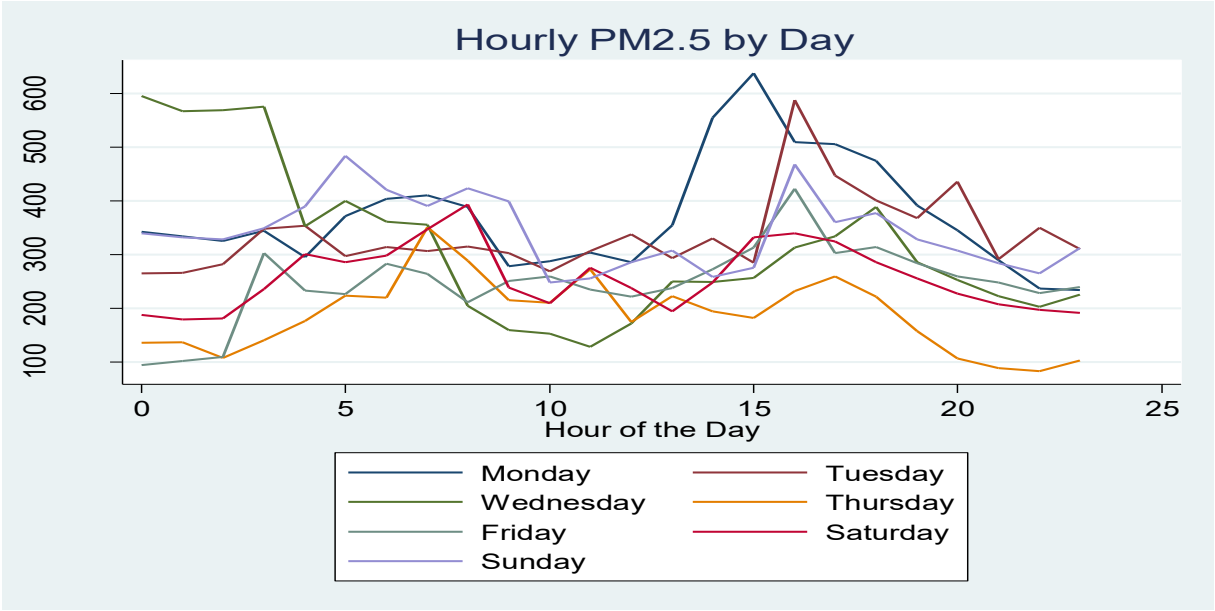


Figure 5: Aggregate hourly $PM_{2.5}$ concentration profiles by day of the week among urban households.

Urban–Rural Seasonal Variations

Seasonal differences were particularly pronounced among the 96 kitchens that were monitored during both seasons, including 60 rural and 36 urban kitchens.

Among rural kitchens, the mean $PM_{2.5}$ concentration was 732 µg/m³ during the wet season compared with 343 µg/m³ during the dry season. The mean within-kitchen difference was 388 µg/m³ (95% CI: 348–430, $p < 0.0001$). Thus, wet-season concentrations were approximately 2.1 times higher than those observed during the dry season.

A similar pattern was observed among urban kitchens, although concentrations were substantially lower than those in rural kitchens. Mean $PM_{2.5}$ concentration was 105 µg/m³ during the wet season and 47 µg/m³ during the dry season, corresponding to a mean within-kitchen difference of 59 µg/m³ (95% CI: 39–78, $p < 0.0001$).

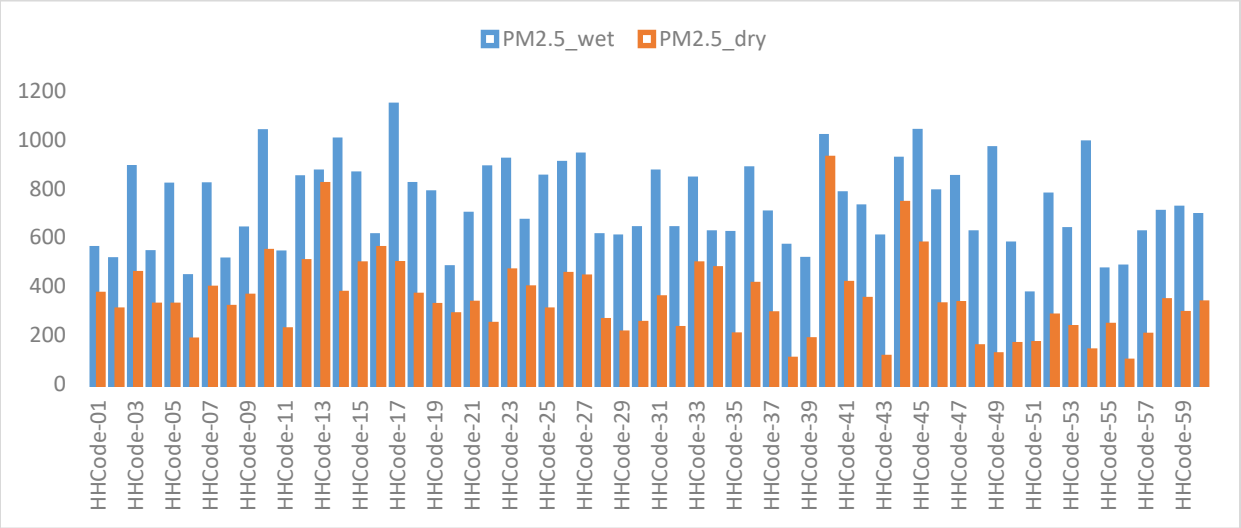


Figure 6: Mean household $PM_{2.5}$ concentrations in the 60 paired rural kitchens during wet and dry seasons.

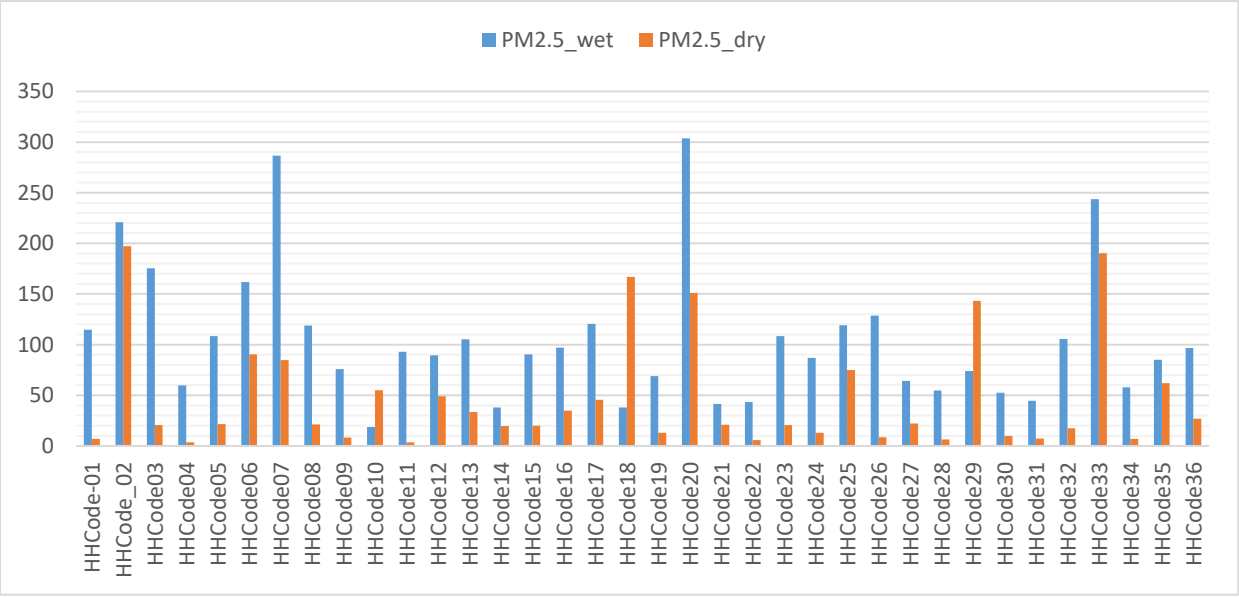


Figure 7: Mean household $PM_{2.5}$ concentrations in the 36 paired urban kitchens during wet and dry seasons, January.

Factors associated with Household PM2.5 Concentrations

The non-parametric kernel regression model explained approximately 47% of the observed variation in household $PM_{2.5}$ concentrations (pseudo-R^2 = 0.465).

Residence was the strongest factor in the model. After accounting for the other variables included in the analysis, rural households had an estimated 383.21 µg/m³ higher $PM_{2.5}$ concentration than urban households (95% CI: 357.52–406.65, p < 0.001). This adjusted estimate was broadly consistent with the observed rural–urban difference of 393 µg/m³ (Table 3).

Household wealth was also associated with $PM_{2.5}$ concentration. Compared with very poor households, rich households had an estimated 7.80 µg/m³ lower $PM_{2.5}$ concentration (95% CI: −14.62 to −0.84, p = 0.031). The corresponding estimate for very rich households was not statistically significant (p = 0.076), indicating that the results did not demonstrate a consistent monotonic gradient across all wealth categories (Table 3).

Ventilation was significantly associated with $PM_{2.5}$ concentration. Households without reported ventilation had an estimated 4.81 µg/m³ higher concentration than households with ventilation (95% CI: 0.30–9.46, p = 0.040). Clean-fuel use was also associated with lower $PM_{2.5}$ concentrations: households using clean fuel had an estimated 4.12 µg/m³ lower concentration than households using unclean fuel (95% CI: −6.48 to −2.07, p < 0.001).

Maternal education, family size, kitchen arrangement, and cooking duration were not statistically significantly associated with $PM_{2.5}$ concentrations in the fitted model (Table 3).

Table 3. Kernel regression estimates of household and kitchen factors associated with $PM_{2.5}$ concentration, (n=923, Bootstrap SEs)

Predictor (Reference Category)	Estimate (µg/m³)	SE	z	p-value	95% CI
Mean PM2.5	323.34	9.53	33.71	—	[302.31, 340.58]
Mother's Education					
Illiterate (Ref)	—	—	—	—	—
Read & Write only	0.64	2.75	0.23	0.815	[−4.55, 5.95]
Elementary school	4.70	4.47	1.05	0.294	[−4.09, 13.25]
Secondary & above	0.58	2.58	0.23	0.822	[−4.34, 5.77]
Family Size					
≤3 members (Ref)	—	—	—	—	—
4–6 members	1.02	2.12	0.48	0.631	[−3.09, 5.01]
≥7 members	−1.06	2.15	−0.49	0.623	[−5.28, 2.99]
Wealth Index					
Very poor (Ref)	—	—	—	—	—
Poor	−1.39	3.76	−0.37	0.712	[−8.67, 5.82]
Middle	−5.09	4.02	−1.26	0.206	[−12.92, 3.09]
Rich*	**−7.80**	3.61	−2.16	0.031	[−14.62, −0.84]
Very rich	−6.53	3.68	−1.77	0.076	[−14.07, 1.03]
Place of Residence					
Urban (Ref)	—	—	—	—	—

Rural*	**383.21**	12.03	31.86	<0.001	[357.52, 406.65]
Ventilation					
Yes (Ref)	—	—	—	—	—
No*	**4.81**	2.34	2.05	0.040	[0.30, 9.46]
Fuel Type					
Unclean (Ref)	—	—	—	—	—
Clean fuel*	**−4.12**	1.12	−3.66	<0.001	[−6.48, −2.07]
Kitchen Arrangement					
Indoor kitchen (Ref)	—	—	—	—	—
Separate kitchen	−1.99	3.02	−0.66	0.509	[−7.72, 4.05]
Cooking Time					
1 hour/day (Ref)	—	—	—	—	—
Two hours	3.08	2.97	1.04	0.300	[−2.69, 8.71]
Three hours	−3.28	2.89	−1.13	0.257	[−9.02, 2.26]
Four+ hours	−1.46	2.71	−0.54	0.590	[−6.96, 3.50]

Discussions

The principal finding of this study was the exceptionally high level of household kitchen $PM_{2.5}$ concentrations, particularly in rural households. The mean 24-hour concentration was 473 μg/m³ in rural kitchens compared with 80 μg/m³ in urban kitchens. The magnitude of this difference is consistent with the markedly different household energy profiles observed in the study. All rural households relied on unclean fuels and open-fire stoves, whereas more than half (58.3%) of urban households used electricity.

The rural $PM_{2.5}$ concentration observed in the present study is comparable to findings from other Ethiopian studies. Enyew et al. (2023), had reported a mean 24-hour kitchen $PM_{2.5}$ concentration of approximately 405 μg/m³ among rural households in Northwest Ethiopia, with concentrations ranging from 52 to 965 μg/m³ **[12]**. Their study also identified cooking fuel, kitchen characteristics, and injera-baking events as important correlates of kitchen $PM_{2.5}$ concentrations. Tamire et al. (2021), similarly reported high $PM_{2.5}$ concentrations (410 μg/m³) among rural households in Butajira, Ethiopia **[10]**. These findings, together with the systematic review by Asefa and Mergia **[29]**, indicate that very high kitchen $PM_{2.5}$ concentrations remain a recurring feature of biomass-dependent households in Ethiopia.

The rural concentration in the present study was somewhat higher than the 405 μg/m³, 410 μg/m³ and 446.8 μg/m³ reported by Enyew et al, **[12]**, Tamire et al, **[10]** and Van Vliet et al, **[30]** in different parts of Ethiopia and Ghana respectively. Differences in sampling duration, household characteristics, fuel composition, stove type, cooking practices, kitchen ventilation, and timing of measurements may contribute to differences between studies. Importantly, the present study monitored households for three to five consecutive days rather than relying on a single 24-hour measurement, potentially capturing greater short-term variation in household activities and cooking practices.

The urban mean of 80 μg/m³ was substantially lower than the rural mean but remained elevated relative to both the Ethiopian guideline value of 37.5 μg/m³ **[31]** and the WHO 24-hour guideline value of 15 μg/m³ **[32].** The lower urban concentration is consistent with the greater availability and use of electric stoves observed in the study. Nevertheless, the presence of charcoal, kerosene, and open-fire cooking among a proportion of urban households indicates that urban households were not uniformly exposed to clean cooking conditions. Thus, the rural–urban contrast appears to reflect differences in household energy systems rather than residence alone.

The urban PM2.5 concentration of 80 µg/m³, found to be lower than values reported by a study conducted in Wolaita Sodo town, Southern Ethiopia (413 µg/m³) [**11]**. This difference likely reflects lower biomass fuel use in our study (37.4% vs. 76.2%).

Similar contrasts between households using biomass and those with greater access to cleaner cooking technologies have been reported internationally. Studies in India and Peru have documented substantial variation in household particulate concentrations according to cooking fuel, stove type, household characteristics, and patterns of cooking activity **[7, 8, 33]**. These comparisons should nevertheless be interpreted cautiously because measurement instruments, monitoring periods, fuel mixtures, kitchen configurations, and analytical approaches differ across studies.

Temporal Patterns of Household PM2.5 Concentration:

The hourly profiles demonstrated considerable temporal variability in household $PM_{2.5}$ concentrations, particularly in rural households. The observed increases during periods corresponding to cooking activities are biologically and operationally plausible because combustion of solid fuels in open or poorly vented stoves can generate substantial quantities of fine particulate matter. The rural average daily $PM_{2.5}$ emissions (figure 4) were higher during weekends (Saturday and Sunday) compared to weekdays. This increase may be attributed to the fact that family members in the study settings typically spend more time at home on weekends than weekdays, which leading to more intense and longer cooking activities and consequently higher particulate matter emissions.

The rural profiles (figure 4) in the present study showed more pronounced temporal variation than the urban profiles (figure 5). This difference may be related to the more uniform dependence on biomass fuels and open-fire cooking in rural households. By contrast, the greater use of electricity and mixed cooking fuels in urban households may produce more heterogeneous temporal patterns (figure 5). A study conducted in both urban and rural households of Peru depicted similar figure and peaks with the present study where the rural emission curve had two peaks and that of urban emission had no quite visible and pronounced emission peaks **[33]**.

Seasonal Variation:

A particularly important finding was the strong seasonal difference in $PM_{2.5}$ concentrations among the paired kitchens. In the same rural kitchens, the mean concentration increased from 343 µg/m³ during the dry season to 732 µg/m³ during the wet season. Urban kitchens showed the same direction of association, with concentrations increasing from 47 to 105 µg/m³.

Because the same kitchens were measured during both seasons, this paired design provides an important advantage over comparisons based on different households. Fixed household characteristics, such as kitchen construction, stove type, and household socioeconomic characteristics, are less likely to explain the observed seasonal difference because the comparison was made within the same kitchens.

The approximately two-fold increase in rural wet-season concentrations may reflect several interacting factors. Wet conditions can increase the moisture content of biomass fuels, potentially altering combustion efficiency and particulate generation. Seasonal changes in ventilation practices and air exchange may also influence pollutant accumulation indoors. Previous studies in Bangladesh, Kenya, and Ethiopia have similarly reported seasonal variation in household particulate concentrations (**[34- 36, 10]**.

The magnitude of the seasonal difference observed here is particularly noteworthy because it occurred despite the same household kitchens being monitored in both seasons. However, the mechanisms

responsible cannot be established directly from the present observational data. Fuel moisture, ventilation behavior, cooking frequency, meteorological conditions, and other seasonal household practices were not independently manipulated or experimentally controlled. Therefore, these factors should be considered plausible explanations rather than demonstrated causal mechanisms.

The findings are also consistent with the broader evidence that indoor particulate concentrations can vary substantially over time according to the seasons and household cooking activities. Gurley et al, had documented seasonal differences in indoor particulate matter in a low-income community in Dhaka **[34]**, while Tamire et al. and Embiale et al, have documented substantial particulate exposures associated with household cooking practices in Ethiopia **[10, 36]**.

Factors Associated with PM2.5 Concentrations:

In the multivariable kernel regression model, rural residence was by far the strongest factor affecting household $PM_{2.5}$ concentration. The adjusted estimate of 383.21 μg/m³ was close to the observed rural–urban mean difference of 393 μg/m³, suggesting that the large residence-associated contrast persisted after accounting for the household and kitchen characteristics included in the model.

Residence should not necessarily be interpreted as an independent factor. Rather, it likely captures a combination of correlated characteristics, including cooking fuel, stove type, household infrastructure, cooking practices, and socioeconomic circumstances. This interpretation is particularly relevant because all rural households in this study used unclean fuels, while a substantial proportion of urban households used electricity. Consequently, residence and cooking-energy characteristics are strongly intertwined. Studies conducted in India **[8]** and Peru **[33]** found to be consistent with findings of the present study where PM2.5 concentrations reported high in rural settings due to the fact that rural households are largely dependent on biomass fuels.

The association between wealth and $PM_{2.5}$ was relatively small. Rich households (-7.80 μg/m³) had lower concentrations than very poor households, but the very-rich category did not reach conventional statistical significance ($p = 0.076$). Thus, the findings do not support a simple linear wealth gradient. Differences in fuel choice, stove type, kitchen structure, ventilation, and housing conditions may partly explain the observed association, as suggested by previous household air-pollution studies **[37, 38]**.

Ventilation was also associated with $PM_{2.5}$ concentration. Households without reported ventilation had concentrations approximately 4.8 μg/m³ higher than those with ventilation after adjustment. Although statistically significant, the magnitude of this association was modest relative to the much larger rural–urban difference. This suggests that ventilation alone may not explain the extremely high concentrations observed in rural households where solid-fuel combustion was ubiquitous. Previous studies from India **[39]**, Bangladesh **[40]**, Kenya **[38]**, and China **[41]** have similarly reported relationships between household ventilation characteristics and indoor particulate matter concentrations/exposure.

Clean-fuel use was associated with a modestly lower $PM_{2.5}$ concentration (-4.12 μg/m³). This finding is consistent with evidence from Ethiopia and other low- and middle-income settings showing lower household air-pollution concentrations among households using cleaner cooking fuels **[8, 42- 44]**. However, the relatively small coefficient in the present model should be interpreted in the context of the strong correlation between fuel type and residence.

Intervention evidence from Ethiopia also supports the importance of cooking technology. Adane et al. (2021), in a cluster-randomized controlled trial in Northwest Ethiopia, evaluated biomass-fueled improved cook-stoves as an intervention for household air pollution. It was revealed that improved cook-stoves can

reduce household $PM_{2.5}$ concentrations by 343 μg/m3 (Ḃ = − 343, 95% CI − 350, − 336) compared with traditional biomass-burning stoves **[45]**. Such experimental evidence is important because it complements the observational associations identified in the present study and indicates that changes in cooking technology can influence household PM2.5 concentrations.

Implications of the Study:

The very high concentrations observed in rural kitchens, together with the substantial seasonal variation, indicate that household $PM_{2.5}$ monitoring in this setting should account for both place of residence and season. Measurements obtained during only one season or from a single 24-hour period may not adequately represent the variability of household PM2.5 concentrations.

The findings also suggest that household air-pollution reduction strategies should consider the broader household energy system rather than focusing on a single factor. The strong rural–urban difference and universal use of unclean fuels among rural households highlight the importance of access to cleaner cooking energy and improved cooking technologies. Evidence from randomized intervention research in Ethiopia indicates that improved biomass cook-stoves can reduce household air-pollution exposure, providing experimental support for technological interventions beyond the observational associations identified in the present study **[45]**.

An important methodological implication of this study is the value of repeated household monitoring. The large differences observed between wet and dry seasons demonstrate that a single short monitoring period may not adequately represent the $PM_{2.5}$ profile of a household, particularly in biomass-dependent settings. The three- to five-day monitoring period used in this study also provided greater opportunity to capture variability associated with cooking schedules and household activities.

Strength and Limitations:

Strength:

This study has several strengths. The relatively large sample of 923 households allowed detailed comparison between rural and urban settings. Direct measurement of kitchen $PM_{2.5}$ provided a more objective assessment of household particulate concentrations than proxy measures based solely on fuel type or cooking technology. Monitoring each household for three to five consecutive days also allowed short-term variability in household $PM_{2.5}$ to be captured. In addition, the repeated seasonal measurements in 96 of the same kitchens provided an important opportunity to assess seasonal variation while minimizing the influence of fixed household characteristics.

Limitations:

The study also has limitations. The PurpleAir II-SD is a low-cost optical particle sensor rather than a gravimetric reference instrument. Optical measurements can be influenced by particle composition, size distribution, soot accumulation, and relative humidity. Previous evaluations have shown that the performance of PurpleAir sensors can vary according to indoor conditions and the calibration approach used **[46]**. Although relative humidity in the present study did not exceed 65%, and quality-control procedures were applied, some measurement uncertainty cannot be excluded. The reported concentrations should therefore be interpreted as sensor-derived estimates rather than equivalent to measurements obtained from a reference gravimetric method.

The study was observational and cross-sectional for the main household sample; therefore, the associations identified in the kernel regression should not be interpreted as causal effects.

The seasonal analysis was based on a smaller subset of 96 kitchens than the full analytical sample. Residence, fuel type, stove type, ventilation, and socioeconomic characteristics are interrelated, making it difficult to isolate the contribution of individual factors completely. Moreover, household kitchen concentrations do not necessarily represent the personal exposure of individual household members. Personal exposure can vary according to time spent in the kitchen, proximity to the stove, cooking activities, and movement between indoor and outdoor environments.

Conclusion and Recommendations:

Conclusions

This study demonstrated substantial variation in household kitchen $PM_{2.5}$ concentrations between rural and urban households in Eastern Ethiopia. Rural kitchens had markedly higher mean 24-hour $PM_{2.5}$ concentrations than urban kitchens (473 $\mu g/m^3$ versus 80 $\mu g/m^3$), reflecting the substantially different household energy and cooking environments.

Marked seasonal variation was also observed. Among the kitchens monitored during both seasons, $PM_{2.5}$ concentrations were substantially higher during the wet season than during the dry season in both rural and urban settings. This finding demonstrates that household $PM_{2.5}$ concentrations can vary considerably over time and that season is an important consideration when characterizing household air-pollution exposure.

In the adjusted analysis, rural residence showed the strongest association with household $PM_{2.5}$ concentration. Wealth, ventilation, and clean-fuel use were also associated with $PM_{2.5}$ concentrations, although their estimated effects were considerably smaller than the rural–urban difference. Overall, the findings indicate that household $PM_{2.5}$ pollution remains particularly high in rural, biomass-fuel-dependent households in Eastern Ethiopia and varies substantially according to residential setting and season.

Recommendations

Based on the findings of this study, the following recommendations are proposed:

Efforts should be made to prioritize improving access to affordable and reliable clean cooking energy, particularly in rural communities where reliance on unclean fuels and open-fire stove was universal.

Where transition to fully clean fuels is not immediately feasible, improved cook-stoves that are appropriate for local cooking practices should be promoted and evaluated for their ability to reduce household $PM_{2.5}$ concentrations.

The substantially higher $PM_{2.5}$ concentrations observed during the wet season indicate that interventions and exposure assessments should account for seasonal variation rather than relying exclusively on measurements from a single period of the year.

Appropriate ventilation measures should be encouraged as a complementary intervention, particularly in households where solid fuels continue to be used. However, ventilation should not be considered a substitute for cleaner fuels or improved combustion technologies.

Public-health and research programs should consider repeated household $PM_{2.5}$ monitoring to capture day-to-day and seasonal variability. Monitoring strategies should also include calibration and appropriate quality-assurance procedures when low-cost optical sensors are used.

Future research should combine kitchen $PM_{2.5}$ measurements with personal exposure monitoring, particularly among women who spend substantial time cooking, because kitchen concentrations do not necessarily represent individual exposure.

Future studies should consider longer monitoring periods covering both wet and dry seasons to better characterize temporal variability and identify household and behavioral factors associated with periods of particularly high $PM_{2.5}$ concentrations.

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Authors' contributions
Solomon Tassew contributed to protocol development, study design, coordination of data collection, statistical analyses, and drafting of the manuscript. Alemayehu Worku, Tesfaye Assebe, and Ebba Malmqvist assisted with protocol development, data analysis, and manuscript review. Tesfaye Gobena, Christina Isaxon, and Kedir Teji conceived the study and supported protocol development, data collection, and manuscript review. All authors read and approved the final manuscript.

Ethical Approval and Consent to Participate:

This study was performed in line with the principles of the Declaration of Helsinki. Ethical approval was granted by the Ethics Review Committee of Haramaya University, College of Health and Medical Sciences (Approval No. IHRERC/187/2023, dated 17 October 2023). In addition, official letters of permission were secured from the East Hararghe Zone and Harari Regional Health Bureaus to ensure compliance with local administrative requirements.

Consent to Participate

Informed written consent was obtained from all study participants prior to data collection.

Human Ethics and Consent to Participate declarations: not applicable

Consent to publish

This study is not a clinical trial and therefore, consent for publication is not applicable.

Competing Interest;

Authors have no financial or non-financial interest to declare.

Data Availability Statement:

The datasets generated and/or analyzed during the current study are not publicly available due to ethical restrictions. However, they are securely stored in a closed file cabinet and can be made available from the corresponding author upon request.