Human exposure to indoor air pollution in Ethiopian households

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A R T I C L E   I N F O

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A B S T R A C T

Because most people spend the majority of their time in microenvironments, indoor air pollution (IAP) has gained more attention than outdoor air pollution recently. It is indeed crucial to understand IAP sources and the factors that influence human exposure. We synthesized evidence on IAP levels and contributing factors in Ethiopia from available literature, utilizing findings from 19 studies to retrieve 66 relevant values. Particulate matters (PM2.5, PM10, TSP), as well as gaseous pollutants such as carbon monoxide (CO), nitrogen dioxide (NO2), polyaromatic hydrocarbons (PAHs), and total volatile organic compounds (TVOCs), were analyzed. The calculated mean concentrations for PM2.5, PM10, NO2, TVOCs, and CO were 477.47 μg/m3, 228.38 μg/m3, 63.84 μg/m3, 1361.79 μg/m3, and 18.82 ppm, respectively, all of which exceeded the annual WHO exposure guidelines.

1. Introduction

In the past decades, outdoor air pollution has received more attention than indoor air pollution (IAP). However, because most people spend the majority of their time indoors (>90%) (Vardoulakis and Kinney, 2019) and are more exposed to pollutants at higher concentrations in the indoor environment, the focus has shifted to indoor air pollution recently. It has become important to characterize IAP contributors, their sources, and environmental and occupant factors that influence human exposure to the pollutants. Nevertheless, IAP has been linked to four million premature deaths each year, and it is categorized as a high environmental health risk exposure (WHO, 2014).

The primary source of IAP in developing countries has been linked to household combustion activities. This activity is largely related to the use of solid fuel for cooking and heating, which is considered unimproved energy source (Bruce et al., 2000; Smith and Mehta, 2003). In such indoor microenvironments, particulate matter (PM), polycyclic aromatic hydrocarbons (PAHs), and other gaseous pollutants such as volatile organic compounds (VOCs), carbon oxides (COx), and nitrogen oxides (NOx) are emitted at higher levels (Zhao and Zhao, 2018). Moreover, exposure to these higher IAPs may result in direct and indirect health effects. The African birth cohort study investigated the indoor environment and risk for child mortality and found a significant association between using fossil fuels for cooking and increased benzene [OR 3.4 (95% CI 2.1–5.4)], carbon monoxide (CO) [OR 2.9 (95% CI 1.7–5.0)] and nitrogen dioxide (NO2) levels [OR 18.6 (95% CI 3.9–88.9)] (Vanker et al., 2015). Studies have highlighted that indoor air pollutants fluctuate under different conditions and need attention while measuring them. Also, identifying and quantifying indoor air pollutants is important in evaluating public health policy related to IAQ and building safety.

Despite recent rapid economic progress, urbanization, and lifestyle improvements in Ethiopia, little is known about IAP and associated

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health problems. There is, however, an evidence that biomass fuel use attributes more to IAP emission (Kumie et al., 2009a, 2009b; Sanbata et al., 2014b). Biomass fuel accounts for approximately 90% of total primary energy consumption in Ethiopian homes, with principal utilization for cooking in 84% of urban and 95% of rural households (Tadesse and Johnson, 2013). However, the link between biomass fuel use and IAP emission as well information on human exposure is not clear yet. A few studies have examined the concentrations of indoor air pollutants attributed to biomass fuel consumption when various contributing factors, such as ventilation, outdoor air, and occupants’ activities and behavior, are taken into account (Kumie et al., 2009a, 2009b; Sanbata et al., 2014a; Okello et al., 2018; Adane et al., 2021). Even if there is some heterogeneity across these studies (spatial vs. temporal, methodology of measurement vs. analysis, and finding report), the evidence needs to be synthesized to have a clear picture at a national level. This enables us to contribute to the wide call for IAP-related studies required in less developed countries as recommended by, Mentese et al. (2015), Mishra (2003) and Smith et al. (2000).

Besides, the level of air contaminants in the indoor environment is governed by source capacity and elimination rate, which needs to be studied under different geography, time, and socioeconomic variables. Nevertheless, to design effective mitigation measures for IAP, studying the concentration levels of the pollutants is important for estimating the total human exposure as well as identifying main sources of pollutants. Therefore, the primary goal of our work is to synthesize evidence on levels of indoor air pollutants and their contributing factors at a national level (Ethiopia) based on available literature. Our specific objectives are to (i) assess the concentrations and exposure to indoor air pollutants in urban and rural households, (ii) conclude the relationship between a source of pollution and specific pollutant, (iii) investigate the associated factors with IAP, and (iv) make recommendations for mitigation of IAP. The study is the first of its kind in summarizing the concentration of indoor air pollutants to pool mean estimates of PMs, CO, NO2, PAHs, and VOCs contaminants in Ethiopia. The output of this study can be utilized in policymaking related to IAP and can be used for planning and implementing mitigation strategies at the lowest cost available.

2. Methodologies

2.1. Study source and selection

The data were gathered using electronic databases such as PubMed, SCUPOS, and Google Scholar. The search was conducted without any date restrictions and the literature search technique was developed using the keywords “Indoor Air Pollution”, “Biomass”, “Household Fuel”, “Smoke”, “Particulate Matter”, “Carbon Monoxide”, “Nitrogen Dioxide”, “Polyaromatic Hydrocarbons”, “Volatile Organic Compounds”, “Coffee Ceremony”, “Injera Baking”, “Cooking Wat”, “Household Air Pollution”, “Ethiopia”, “PM2.5”, “PM10”, “CO”, “NO2”, “PAH”, “VOC”. The Boolean operators “and” or “or” were used to link the keywords and the searching strategy was customized to suit each database. In addition, the reference lists of all relevant articles were scanned to identify relevant studies missed by electronic database searching. To reduce the risk of publication biases as much as possible, the Ethiopian university repositories were searched to retrieve thesis and dissertations that reported indoor air pollution.

Upon selection of studies for inclusion, we used flexible eligibility criteria. This is because of the challenges in finding a high-quality study reporting indoor air pollution levels and associated factors in Ethiopia. Based on this fact, studies were included if they investigated the level of indoor air pollutants and reported them quantitatively, with the measured indoor air pollutants concentration presented as a mean value, or in such a way that a mean value could be calculated. Studies examining the level of indoor air pollutants found that measuring 24-hr concentrations was preferred over studies measuring a single time concentration on certain occasions, such as coffee ceremonies, a cultural daily habits and common as welcoming guests, or baking injera, a staple food prepared from Teff flour, but both were included after careful investigation. Furthermore, although longitudinal studies were preferred, there were no restrictions on study dates or settings. Studies that controlled for confounders were preferred, but if none were available, how the confounders were managed should be discussed.

On the contrary, studies reported the outdoor air pollutants, or studies reported the concentration based on invalid measurement instruments or did not mention in a detailed description of how the indoor air pollutants were measured, and studies computed the analysis using statistics not suitable for our analysis were immediately excluded. Moreover, the eligible studies must be within the boundary of Ethiopia and not restricted to either urban or rural areas. Preprints, reviews, non-English language articles, conference abstracts, and news articles were excluded.

2.2. Evidence synthesis

Based on the included studies, a narrative synthesis of key findings on the level of indoor air pollution, its contributing factors, variation with season and geography, association with the cooking stove used and the purpose of cooking, associated health effects, and most vulnerable groups in the Ethiopian household was performed. For the studies that were included, the summaries were presented in the form of tables and figures. Evidence was synthesized by categorizing the above-mentioned key findings into sub-groups to deal with heterogeneity in included studies. For example, we used urban and rural for geographic variation, improved and unimproved (mixed) energy sources for primary source variation, personal exposure sampling and indoor air sampling for methodology variation, etc. Thus, the area where the study was conducted, the type of pollutant assessed, the number of households/samples analyzed, the concentration, confounders, and comparison with the guidelines were summarized in supplementary material Table S1 and S2. Almost all of the studies included reported mean pollutant concentrations in geometric mean in μg/m³, except CO, which was reported in parts per million, ppm. Therefore, we used geometric means for our analysis and calculated average mean estimates for each category extracted.

Furthermore, cookstoves were categorized as unimproved (open fire) and improved (electric stoves and reinvented cookstoves). Unimproved stoves are more common in rural Ethiopian households than in urban Ethiopian households, and they are characterized by an open fire with three stone stoves, high biomass fuel use, and higher IAP emissions. Improved stoves, on the other hand, are more common in urban Ethiopian households. It is characterized by low biomass fuel usage and IAP emissions, which result in less deforestation and human exposure. The difference between improved type stoves lies in their design, level of biomass fuel use, or applicability to different household activities. For example, based on its design, an electric stove that uses a heating wire coil as a source of energy can be used for both injera baking (coils are used to heat a circular shape like a griddle) or cooking (coils directly heat cooking pans). The Mirt stove, reinvented stove, is designed to bake and cook at the same time, although it uses biomass fuel in a more controlled manner than unimproved stoves. In this review, we focused on the variation in IAP emissions and human exposure from unimproved and improved stoves. The details on fuel usage for these stove types and related environmental degradation, as well as their design, efficiency, and acceptance level, were detailed in Adem and Ambie (2017), Benti et al. (2021), Gebreeziabher et al. (2018) and Liyew et al. (2021).

3. Results and discussions

3.1. Study characteristics

The primary search resulted in 1561 articles from which 410 title and abstract and 247 full texts were assessed for eligibility and finally 19 articles were included based on eligibility criteria mentioned under
methodology section. Figure 1 shows the sources of articles, their identification, screening, and selection process.

Based on our objectives, we extracted sixty-six relevant pieces of information related to study geography, pollutants included, measurement methodology, and reported mean for each subgroup, as presented in supplementary material Table S1. The detailed extraction, including study period, study aim, study area, study setting, the sample analyzed, pollutant measured, factors analyzed, major findings, and conclusions, is presented in supplementary material Table S2. About seventy-one percent (43 values) of the reports were from urban areas, while only twenty-nine percent (18 values) of the reports were from rural areas. There was a reported mean for improved fuel use of 45%, an unimproved source of 49%, and mixed-use of 6%. Particulate matter (PM2.5) was reported more (39%) followed by carbon monoxide (CO), which was 23%. Furthermore, more than 34 study values investigated IAPs using at least an average of 8 h for CO and 24 h for PMs through direct indoor air sampling rather than personal exposure sampling. A summary of study characteristics is provided in Figure 2a–d.

3.2. Indoor air pollutants in Ethiopian households

3.2.1. Particulate matters (PM2.5, PM10, TSP)

Compared to other pollutants, particulate matters (PM) were studied the most where thirty-eight mean concentration values were analyzed for PM2.5 (Adane et al., 2021; Admasie, 2019; Downward et al., 2018; Edlund, 2019; Embiale et al., 2020a, 2021; Graham, 2011; Okello et al., 2018; Pennise et al., 2009; Sanbata et al., 2014a; Tamire et al., 2021; Zwaag, 2016), PM4 (Keil et al., 2010), PM10 (Embiale et al., 2019, 2020b, 2021), and TSP (Embiale et al., 2019, 2020a, 2021; Keil et al., 2010; Tadesse, 2015). The calculated mean average concentration for PM2.5 was 477.47 μg/m³ in the households of Ethiopia as shown in Figure 3 and Table S1. Accordingly, the average mean concentration of PM2.5 calculated for urban was 499 μg/m³ while it was 473 μg/m³ in rural areas which is far beyond the annual mean exposure level according to WHO standard (10 μg/m³). The maximum PM2.5 concentration reported was in Adama city, 1170 μg/m³, during a coffee ceremony with a stove ignited indoor and incense use (Edlund, 2019). The minimum PM2.5 concentration reported was in Addis Ababa, 18.1 μg/m³, in a living room (Embiale et al., 2020a).

Inhalable particulate matter fraction (PM10) measured using personal exposure and indoor area sampling indicated a nearly mean concentration of 1125 μg/m³ (Keil et al., 2010). Also, a study by Embiale et al. (2019, 2020b, and 2021) assessed PM10 concentration during injera baking, wot or stew preparation, and sitting in the living room under different seasons showed that the mean concentration was higher during injera baking in the wet season, 389 μg/m³, and lower in the living room, 80.2 μg/m³ which exceeded WHO standard for annual exposure of 20 μg/m³, Figure 3. The maximum total suspended matter (TSP) mean concentration was recorded in Anelimo woreda (rural area), 6821.74 μg/m³, in a household where the mixed cooking stove is widely common (Tadesse, 2015), whereas the minimum concentration was recorded in Addis Ababa, 101.57 μg/m³, in the living room (Embiale et al., 2020a).

In general, for studies investigating particulate matters, both the 24-hr and annual mean exposure levels set by WHO were not met in any of the Ethiopian households. This was due to the highest emissions from indoor biomass fuel use, domestic activities such as coffee ceremony, baking injera, wot preparation, poor ventilation, and housing conditions. According to Tamire et al. (2021), households using only traditional
stoves and those that did not open the door or window during cooking had a significantly higher mean concentration compared with their counterparts. Furthermore, using an improved cooking stove, which was expected to reduce IAP, did not protect against exposure to indoor air pollutants because it was found to exceed the standards in all cases (Embiale et al., 2019; Sanbata et al., 2014a). This can be due to fact some improved stoves depend on biomass fuels (Example, Mirt and Lakech stoves). A detailed explanation for the factors that influenced the concentration of PMs was provided under section 3.4 and Table 1.

### 3.2.2. Gaseous pollutants (CO, NO₂, TVOC, and PAHs)

Following PM₂.₅, carbon monoxide (CO) concentration was reported in most of the studies as shown in Figure 2c. The indoor CO level was reported by (Admasie, 2019; Downward et al., 2018; Gizaw and Teka, 2020; Graham, 2011; Kebede, 2018; Keil et al., 2010; Okello et al., 2018; Pennise et al., 2009; Tadesse, 2015; Yosef, 2008). As a result, the average mean CO concentration calculated was 18.82 ppm, which was 24 ppm in urban areas and 13.63 ppm in rural areas, above the WHO limit of 7 ppm for a 24-hour exposure level, shown in Figure 4. The
highest average mean CO concentration measured was 42.55 ppm at the Kebribeyah Refugee Camps, where unimproved energy sources contributed (Pennise et al., 2009). In Kumbursa, the lowest average mean CO concentration reported was 0.41 ppm (within the WHO limit of 24-hour exposure level), indicating a personal exposure among males (Okello et al., 2018).

Nitrogen dioxide (NO2), on the other hand, was only measured in rural households (Butajira) where the maximum average mean concentration was reached 77.2 μg/m³ in highland villages and the minimum average mean concentration was 50.5 μg/m³ in lowlands showing a strong variation across ecology (Kumie et al., 2009a, 2009b). In both cases annual exposure level set by WHO which is 40 μg/m³ were exceeded. Similarly, Total Volatile Organic Compounds (TVOC) showed a strong variation with the season, calculated mean average of 1361.79 μg/m³, maximum in wet season during injera baking (3157.25 μg/m³) (Embiale et al., 2019). PAHs concentration increased when stoves are ignited indoors and the use of incense further increases PAH concentrations where the highest concentrations of Benzo[a]pyrene were reported (Edlund, 2019).

The WHO standard for a 24-hour and annual mean exposure level was substantially surpassed in practically all households. Indoor biomass fuel use resulted in the highest concentrations of gaseous pollutants, particularly CO and NO2. Furthermore, according to Gizaw and Teka (2020), access to health information, the number of rooms, the area of occupied rooms, buildings located away from main roads/garages, clean energy sources, the presence of a separate kitchen, no incensing in the room, and measurements in the afternoon were all significantly associated with indoor CO concentrations. Section 3.4 and Table 1 detail the factors that influenced the concentration of gaseous pollutants.

As shown in Table 1 and Figures 5 and 6, there was a huge variation between geography, stove used, and domestic activities in the contribution to indoor air pollutants as shown in Table 1. PM10, NO2, and TVOC values were reported only in urban, rural, and urban areas, respectively. However, PM2.5 and CO show variation among the three mentioned sub-groups, where the mean concentration value of both pollutants was higher in urban areas (Figure 5a-b). This may be due to outdoor air influence from near vehicle routes as the majority of the measurements were done in the highly congested capital city, Addis Ababa. Furthermore, the type of stove used was highly correlated with the highest concentration of pollutants according to studies included in Table S2. This was also shown in Table 1 as unimproved cooking stoves, such as open fires, contribute more to the mean concentration of PM2.5, CO, and TVOC than the improved ones. Domestic activities such as injera baking, wet preparation, and coffee ceremony have been shown to increase the exposure to indoor air pollutants, with the highest PM2.5 and CO mean concentration during the coffee ceremony, see Figure 6a-b. This may be due to the summation of pollutants emitted from traditional stoves, charcoal burning, roasting coffee beans, and the use of incense. Aside from geography, stove type, and domestic activities, factors such as season, ventilation rate, time spent cooking, household condition, and environmental tobacco smoke all contributed significantly to the reported indoor air pollution concentration (see section 3.3).

### 3.3. Factors affecting indoor air pollution concentration and human exposure

#### 3.3.1. Biomass fuel type

The majority of included articles examined the indoor combustion process from biomass fuel for cooking and heating as a potential source of

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**Table 1.** Variation in indoor air pollutants across geography, stove used, and household activities.

| Sub-group             | PM2.5 (μg/m³) | PM10 (μg/m³) | CO (ppm) | NO2 (μg/m³) | TVOC (μg/m³) |
|-----------------------|---------------|--------------|----------|-------------|--------------|
| **Geography**         |               |              |          |             |              |
| Urban                 | 499.04        | 228.38       | 24.05    | NR          | 1361.79      |
| Rural                | 437           | NR           | 13.63    | 64.34       | NR           |
| **Cook-stove**        |               |              |          |             |              |
| Improved            | 221.3         | 163.6        | 11.54    | 64.34       | 981.38       |
| Unimproved          | 750.76        | 367.25       | 28.64    | NR          | 2273.75      |
| **Domestic activities** |           |              |          |             |              |
| Injera baking    | 314.56        | 376.4        | 11.82    | NR          | 2591.5       |
| Wot preparation  | 40.18         | 154.5        | NR       | NR          | 753.6        |
| Coffee ceremony | 1233.25       | NR           | 29.00    | NR          | NR           |

NR-Not Reported.

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Figure 4. Mean concentration of indoor gaseous pollutants in Ethiopia; where the minimum, 25 percentiles, median, mean, 75 percentiles, and maximum mean concentrations for CO, NO2, and VOC are shown in a box and whisker plot.
IAP, measuring an average 24-hr average concentration for PM and gases (in some cases, CO was reported as an 8-hr average). For example, Kumie et al. (2009a, 2009b) measured indoor emission concentrations of NO₂ using biomass fuel (wood, dung, and straw) as a proxy indicator and found variation in 24-hr averaged NO₂ concentrations by type of biomass fuel used, where the maximum concentration (107 μg/m³) was observed in wood and cow dung fuel-using households. Similarly, Sanbata et al. (2014a) measured concentrations of PM in homes using fuelwood, charcoal, and kerosene and reported that the PM₂.₅ concentration in households that use wood fuel was six times higher and kerosene was three times higher than in homes that use clean fuels.

On the other hand, variation in IAP concentration in households using improved stoves like the Mirt stove has significantly lowered IAP emissions. Adane et al. (2021), Pennise et al. (2009), and Yosef (2008) investigated the effectiveness of improved stoves and IAP exposure and concluded that there was a huge reduction in IAP compared to unimproved ones. However, the concentration reported still exceeded WHO standards for both 24-hour and annual exposure levels. There is a clear trend that the use of household energy sources from either biomass, natural gas, or electricity for cooking and heating is linked to IAP. Also, there is a huge variation between biomass fuels used, where wood and dung have a leading role in contributing to the higher emission rate.
3.3.2. Household activities

Several studies investigated domestic activities such as injera baking, wot preparation, and coffee ceremony, as well as liquor distillation (Arake) and personal exposure to indoor air pollutants from them (Adane et al., 2021; Embiale et al., 2020b; Keil et al., 2016; Zwang, 2016). Injera is a flatbread, common in all households where Teff flour is baked on a griddle heated mostly by unimproved biomass fuel. Wot, or stew, is also one of the main constituents of dishes in Ethiopian households where the cooking is done using an open fire most often. On the other hand, the traditional coffee ceremony, which is characterized by the indoor brewing of coffee beans with an unimproved stove, is found in almost all Ethiopian households. People gather two to three times a day to enjoy drinking coffee while it is prepared. Studies have shown that owing to these activities alone, there is a higher exposure to indoor air pollutants than the guidelines suggest. These activities, baking, cooking, and brewing, are conducted most often using unimproved stoves. Even though the scale and frequency of these activities vary, the reliance on biomass fuel would result in higher emissions since open burning is common.

These activities are conducted traditionally, with the heavy exposure of vulnerable groups like women and girls most often engaged in the activities. Zwang. 2016 showed that injera baking is exclusively done by women, and the exposure of these groups can be reduced by 48% by only shifting to electric stoves. In an investigation of local liquor (Arake) distillation, which exclusively depends on fuelwood for its preparation and processing (Kebede, 2018), found an average CO mean concentration of 58 ppm. Also, Edlund (2019) showed that PM concentration during coffee ceremonies increases when stoves are ignited indoors, and the use of incense further increases the number of particles. The variation in indoor air pollutants during different domestic activities is shown in Figure 6. In Ethiopian households where these traditional practices are deeply engrained in daily life and culture, the long-time exposure or combined effects may increase health burdens. Moreover, it has been shown that, depending on domestic activity and occupants’ behavior, the concentration of indoor air pollutants varies across households.

3.3.3. Season and ecology

Embialle et al. (2019 and 2021), Kumie et al. (2009a, 2009b), and Tamire et al. (2021) have demonstrated the impact of season and ecology on IAP variation. Embiale et al. (2019 and 2021) found that the level of IAP can vary depending on both the dry and wet seasons, besides the activities performed indoors. As shown in Table 2, the pollutants’ mean concentration is higher in the dry season for PM$_{2.5}$ and PM$_{10}$ during wot preparation. Similarly, TVOC means concentration was higher in the wet season during injera baking. The IAP variation may occur due to the moisture content of the biomass used, the status of the fire, the location of the stove, or the type of ventilation. In addition, since these studies are conducted in urban areas (Addis Ababa), the influence of outdoor air related to vehicle engine combustion can be possible. However, detailed information on factors influencing the variation of indoor air pollutants is still lacking and should be considered in future studies. On the other hand, ecology (highland or lowland) was also found to significantly contribute to the differences in NO$_2$ average concentrations according to Kumie et al. (2009a, 2009b). Higher concentrations were found in the highlands in households that use crop residues, use fire at least once a day, and cook any number of food items in a day.

3.3.4. Outdoor source

Most often, outdoor air is the primary contributor to indoor air, and several studies have found that in the absence of indoor emission sources, there is a good correlation with outdoor pollutant levels. A study that assessed outdoor-indoor concentrations of PMs and other gaseous pollutants in low-income homes in Colorado found that, in the absence of indoor sources, all outdoor pollutant concentrations were higher than indoors (Shrestha et al., 2019). They also reported that indoor pollutant concentrations were higher indoors in homes closer to roadways compared to those further away. In the included articles, there is a limited investigation into the influence of outdoor air. In a study analyzing PM concentration variation between traditional and improved baking stoves, measuring the personal and stationary exposure with the outdoor PM concentration, it was found that the huge difference in indoor level between the baking stoves was either caused by emissions from the bakery polluting the outdoor air or furthermore, the study confirmed that outdoor air quality is statistically significant compared to indoor levels (Zwang, 2016).

3.3.5. Ventilation

Inadequate ventilation can exacerbate indoor pollutant levels by failing to bring in enough outside air to dilute emissions from interior sources and failing to transport indoor air pollutants out of the room (United States Environmental Protection Agency, 2014). The relationships between IAQ and ventilation differ depending on where the principal source of each pollutant is located (outdoor vs. indoor) and whether the source is related to occupant activity or continuous emission (Canha et al., 2016). When compared to their contemporaries, households utilizing just traditional stoves and not keeping the door or window open had much higher mean concentrations (Embialle et al., 2019, 2021; Okello et al., 2018; Sanbata et al., 2014a; Tadesse, 2015).

3.4. Health effects of indoor exposure to IAPs

Several studies have conducted health risk assessments for exposure to indoor air pollution during different domestic activities (Embialle et al., 2019, 2021), and some have associated biomass fuel use with an acute respiratory infection (Addisu et al., 2021; Admasie, 2019) in the most exposed groups: girls, women, and children. Okello et al. (2018) assessed personal exposure to IAP across inhabitant groups, ranging from young children to the elderly and discovered that adult females had the highest personal exposure, while younger males had the lowest. These substantial differences were due to differences in household cooking activity and time spent indoors among these groups. This study highlighted that even though there is the highest IAP in the households of Ethiopians, there is a difference in exposure among the inhabitants. A study by Embiale et al. (2019 and 2021) investigated health risks related to IAP exposure during injera baking, wot preparation, and sitting in the living room while cooking is done in the separate kitchen. Their results showed that baking of injera could not induce any health problems for all types of pollutants and stove types. They also reported that there is no health impact from exposure to indoor air pollutants except for PM$_{10}$ during charcoal use. Also, any person who stays at home for about 2 h per

| Table 2. Domestic activities and indoor air pollution variation with seasons. |
|-----------------------------------------------|-----------------|-----------------|----------------------------------|
| IAPs | Activities | Dry season (µg/m$^3$) | Wet season (µg/m$^3$) | References |
|------|------------|-----------------|-----------------|------------------|
| PM$_{2.5}$ | Injera baking | 106.95 | 158 | (Embialle et al., 2021) |
| | Wot preparation | 45 | 35.35 | (Embialle et al., 2019) |
| PM$_{2.5}$ | Cooking using unimproved fuel | 120 | 400 | (Tamire et al., 2021) |
| PM$_{10}$ | Injera baking | 363.75 | 389 | (Embialle et al., 2021) |
| | Wot preparation | 185 | 123.95 | (Embialle et al., 2019) |
| TVOC | Injera baking | 1845.75 | 3157.25 | (Embialle et al., 2021) |
| | Wot preparation | 643.25$^a$ | 864$^a$ | (Embialle et al., 2019) |
| NO$_x$ | Cooking using unimproved fuel | 59.64$^a$ | 70$^a$ | (Kumie et al., 2009a, 2009b) |

$^a$ ppm.
day for their life will not have any health problems due to PM2.5, PM10, or TSP exposure separately. However, these findings have their limitations where exposure measurement was conducted in a short period and the factors that influence both personal exposure and indoor concentration of pollutants were not taken into account. In addition, these results do not necessarily indicate the contribution of individual activities under unimproved fuel use as it becomes small for total chronic exposure and their cumulative effect can induce health problems. Moreover, these findings should be further investigated in future studies supported by epidemiological and health data for better understanding.

Besides, there is still a lack of epidemiological data on IAP in developing countries, including Ethiopia. IAP is a less studied subject in Ethiopia, and synthesizing available evidence in the literature is very challenging owing to the evidence quality and heterogeneity. Several studies have found a link between biomass fuel use and acute respiratory infections, asthma, chronic obstructive pulmonary disease, and tuberculosis in Ethiopian households (Andarge et al., 2021; Balidemaj et al., 2021; Desalegn et al., 2011; Downward et al., 2018; Mengesha et al., 2004; Tamire et al., 2020; Andualem et al., 2020). According to a study conducted in Gondor, the prevalence of respiratory symptoms among women was 46.1% [95% CI: 42.6 %–49.7 %], with a runny nose, shortness of breath, and phlegm accounting for 32.07 %, 15.03 %, and 12.63 %, respectively (Andualem et al., 2020). In a study to assess the prevalence of acute respiratory infection in under-five children in an Addis Ababa slum, the two-week prevalence of acute respiratory infection was 23.9%, with odds ratios of 2.97 (95% CI: 1.38–3.87) and 1.96 (95% CI: 0.78–4.89) in households using biomass fuel and kerosene, respectively, compared to households using cleaner fuels (Sanbata et al., 2014b). In a study conducted based on the 2016 Ethiopian health and demographic survey (EHDS), the prevalence of anemia among polluting fuel type users ranged from 13.6% to 46%, depending on the level of consumption. Anemia in pregnant women in Ethiopia has been linked to the use of either kerosene or charcoal fuel types (AOR 4.6; 95% CI: 1.41–18.35) and is in the third trimester (AOR 1.72; 95% CI: 1.12–2.64) (Andarge et al., 2021).

4. Limitations and future works

In this study, we collected evidence on levels of indoor air pollutants and their contributing factors in Ethiopia. We presented the pollutants' mean concentration in urban vs. rural areas, improved vs. nonimproved cookstoves, and traditional household activities. The justification for increased pollutant concentration was given based on the strong pollution sources identified and associated factors. However, this study has its limitations; primarily there might be a publication bias as the search strategy focused on a broad range of keywords and there was sole dependence on the title and abstract in the primary screening stage. Secondly, the included studies had their limitations, which limited our ability to conduct an in-depth analysis of the findings. This can be explained by the heterogeneity between studies in which the methodology of pollutant measurement and exposure assessment vary. Thirdly, the study focused on household exposure to IAP in general. However, the exposure level differed among different groups and also, occupational-related exposure was not included. In urban areas, some people spend their time in offices and schools that are highly influenced by the outdoors, which is not included in this study. The major limitations for studies assessing the health effects of IAP were a lack of measurements of specific indoor air pollutants to indicate cause-effect correlations, and the study setting was cross-sectional, with data gathered through questionnaires or interviews, with the possibility of recall and social desirability biases. In addition, only a few studies have taken into account factors that influence human exposure to IAP, such as tobacco smoke exposure and outdoor air pollution.

The results of this study revealed that the amount of IAP in Ethiopian households exceeds WHO standards for 24-hour and annual mean exposure levels. Variation among households and measurement methods is also influenced by several factors, including biomass fuel type, household activities and behaviors, housing characteristics, and ventilation type. However, there is a paucity of research on the link between indoor and outdoor air in Ethiopia. Paul and Sarkar, 2021 concluded in their review that indoor exposure to air pollutants (typically NO2) from ambient air infiltration can be significant in metropolitan locations and cases of high traffic volume. As a result, future research is likely to look into the link between indoor and outdoor air pollution and human exposure.

This study is based primarily on studies that assessed human exposure using IAQ monitoring. According to Ferguson et al. (2020) however, such a system comes with a hurdle. Indoor air pollution exposure monitoring is more expensive than outdoor ones owing to the difficulty of obtaining representative sample sizes, as well as differences in housing conditions, occupant behavior, and ambient air infiltration. When it comes to IAP modeling for assessing indoor air pollution exposure, there is a dearth of evidence in Ethiopia. Because of several behavioral and environmental factors, such as opening windows or doors during measurement across all households and its impact on pollutant dispersion, IAQ modeling may not always yield correct pollution measurements (Taylor et al., 2014). However, modeling is a strategy for thoroughly examining facts about built-environment adaptations before implementing them promptly (Ferguson et al., 2020). Isolating factors that contribute to indoor air pollution exposure, such as outdoor traffic density, enables the development of focused interventions, which have a higher policy success rate in terms of health protection. As a result, future studies should prioritize this methodology.

Using improved cookstoves reduces pollution emissions significantly, yet the concentrations reported still exceed WHO guidelines as shown in this study. Improved cooking stoves have been widely distributed in many developing nations to limit human exposure to indoor air pollution. It has been suggested as a significant source of indoor pollution reduction, yet investigations in Ethiopia have revealed a similar trend, indicating that there is still room for improvement in terms of public health protection. When implementing exposure reduction interventions, it is critical to consider differences in IAP exposure across the life course and to characterize age and gender differences. In addition to adopting improved cookstove technology, future studies should focus on minimizing exposure to IAP from solid fuels, which can be accomplished by interventions in emissions source and energy technology, housing and ventilation, and behavior and time-activity budget.

5. Conclusion

The calculated mean average PM2.5 concentration was 477.47 µg/m³, which was 400 times higher than the 10 µg/m³ WHO annual mean exposure guideline. The mean PM10 concentration ranged from 80.2 µg/m³ to 389 µg/m³ exceeding the WHO annual mean exposure guideline level of 20 µg/m³. The calculated mean average concentration for CO was 18.82 ppm, which was above the WHO limit of 7 ppm for a 24-hour exposure level. NO2 was only measured in rural households where the maximum and minimum mean concentrations reported were 77.2 µg/m³ and 50.5 µg/m³, respectively exceeding the annual WHO guideline of 40 µg/m³. Similarly, TVOC’s calculated mean concentration was 1361.79 µg/m³. Emissions from biomass fuel use for domestic activities such as coffee ceremonies, baking injera, and wet preparation, as well as poor ventilation and housing conditions all contributed to the higher concentrations of these pollutants. The reported pollutants concentration was varied greatly depending on geography, stove type, and domestic activities. Injera baking, wet preparation, and coffee ceremonies have all shown to increase indoor air pollution exposure. Season, ventilation rate, cooking time, household condition, and environmental tobacco smoke all had a significant impact on the reported IAP concentration. Furthermore, health risk assessments for exposure during various domestic activities were found to be acceptable, except PM10, and IAP has significantly correlated with acute respiratory infection. Even though
improved cookstove technology has been suggested as a significant pollution emission control, investigations in Ethiopia have revealed that there is still room for research in terms of public health protection. Moreover, studies are based primarily on the assessment of human exposure using IAQ monitoring, which comes with a hurdle. There is a paucity of research on the link between indoor and outdoor air pollution in Ethiopia. Future research should prioritize these problems, and the link between indoor and outdoor air pollution and human exposure should be focused on. Nonetheless, it is recommended that the community be made aware of IAP, as well as its health effects and how to mitigate them. Changes in fuel consumption patterns, improved combustion technology, and reduced traffic-related emissions for outdoor infiltration are all potential IAP mitigation strategies to consider.

Declarations

Author contribution statement

Elaisi Mati Asefa: Conceived and designed the experiments; Performed the experiments; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Mekuria Teshome Mergia: Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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Declaration of interest’s statement

The authors declare no conflict of interest.

Additional information

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