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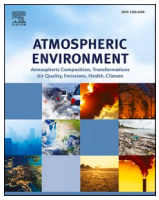
Atmospheric Environment 337 (2024) 120763



Contents lists available at ScienceDirect

Atmospheric Environment

journal homepage: www.elsevier.com/locate/atmosenv





Sex disparities in the burden of air particulate matter-related unhealthy years and life-years lost in Asia-Pacific countries, 1990–2019

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HIGHLIGHTS

- Sex disparities in health from HAP and APM were present in all APAC countries.
- HAP harms more women, but men have higher mortality from APM.
- Pacific islands and West Asia most affected by HAP and APM, respectively.
- Pollution, demographic, and female empowerment associated with female health.

ARTICLE INFO

Keywords:
Air pollution
Unhealthy years
Life-years lost
Life expectancy
Asia-Pacific
Mortality
Sex disparity

ABSTRACT

Air quality, particularly in the Asia-Pacific region (APAC), significantly impacts human health and mortality. This study aims to quantify and compare the effects of ambient particulate matter (APM) and household air pollution (HAP) from solid fuels on unhealthy years and life-years lost in APAC from 1990 to 2019. It also examines factors influencing unhealthy years among females due to HAP. Our findings show that females were more vulnerable to HAP, whereas males were at a higher mortality risk from APM. Pacific islands encountered the greatest burden from HAP, while West Asia was most affected by APM. Over the studied period, the impact of APM on unhealthy years and life-years lost increased, primarily affecting the elderly and adults more than children and youth. Conversely, health impacts from HAP declined across all age groups in the Pacific Islands, though less so compared to other subregions. Key predictors of female unhealthy years from HAP included pollution, demographics, and women's empowerment, with no significant economic influences. Understanding these impacts, along with age and gender differences, is crucial for developing targeted environmental health policies and interventions.

1. Introduction

The adverse effects of air particulate matter (PM) on human health have gained significant attention from the global public health community. In 2019, air pollution was a leading contributor to worldwide deaths and Disability-Adjusted Life Years (DALYs) for both males and females (Ärnlöv and Collaborators, 2020). Moreover, addressing air pollution-related mortality has become a pivotal aspect of the Sustainable Development Goals, set by the United Nations for global advancement by 2030 (Desa, 2016). The prominence of ambient particulate matter (APM) as a health risk has risen from the 13th leading risk in 1990 to the 7th in 2019. Meanwhile, household air pollution from solid fuels (HAP) ranked as the 4th most significant risk in 1990, and although it dropped to 10th by 2019, it remains among the top ten risks for all age groups (Ärnlöv and Collaborators, 2020).

Focusing on the global health impacts of PM, the Asia-Pacific (APAC) region has observed a rise in air pollution-related mortality and morbidity, making it a critical hotspot for particulate matter concentrations (Jia et al., 2021; North et al., 2019; Sharma et al., 2024; Shi et al., 2022; Wang et al., 2013, 2024). The surge is driven by factors such as the widespread use of high-emission vehicles and fuels, certain industrial and agricultural practices, and the lack of impactful

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https://doi.org/10.1016/j.atmosenv.2024.120763
Received 5 June 2024; Received in revised form 14 August 2024; Accepted 15 August 2024
Available online 21 August 2024
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environmental health policies (Al-sareji et al., 2022; Apte et al., 2015; Lelieveld et al., 2015). Furthermore, several APAC regions, especially the Pacific Islands, continue to rely heavily on polluting or solid fuels for cooking, which intensifies health risks from indoor air pollution (Bonjour et al., 2013; Wu et al., 2022). Previous studies, focusing on cause-specific life-years lost (LYL) in 2019, highlighted that several Pacific Island nations such as the Solomon Islands, Vanuatu, Kiribati, and Papua New Guinea had more LYL due to HAP compared to other Asian countries. A prime example is the Solomon Islands, where wood-fired ovens, the dominant cooking method, pose a significant health threat to local communities (Di Michiel et al., 2021; Somboonsin et al., 2023).

Air pollution research frequently highlights sex and age disparities in mortality and morbidity, yet the disparities of APM- and HAP-related mortality and health effects are still unclear. While many studies found that men, children, and the elderly often face the highest exposure levels (Abtahi et al., 2017; Sang et al., 2022; Shen et al., 2024; Wang et al., 2024; Xia et al., 2021; Yin et al., 2020), some findings contradict these observations by showing more females and adults impacted by air pollution (Aliyu and Ismail, 2016; Wang et al., 2022). The disparities in the effects of air pollution, particularly indoor pollution, between genders are shaped by factors such as pollution levels, economic conditions, demographic patterns, and women's empowerment (Austin and Mejia, 2017; Liao et al., 2023). Specifically, research has shown that the rate of female deaths due to HAP is influenced by factors such as the proportion of the population using solid fuels, gross domestic product (GDP), the proportion of the population living in rural areas, health expenditure, and women's socio-health status (Austin and Mejia, 2017). However, comprehensive studies connecting these determinants to health effects from air pollution are sparse. Existing research often narrowly focuses on vulnerable populations in specific regions, or on a single pollutant and specific causes of death (James et al., 2020; Patel et al., 2018; Wang et al., 2019; Zhu et al., 2023). Our study seeks to provide a holistic understanding of the effect of pollution differentials between females and males across countries within the region, and to examine key drivers of those effects by including country-specific determinants of health.

To enhance our findings, we introduce a new model to assess unhealthy years (UY) and LYL due to air pollution. Using Sullivan and demographic methods in our calculations, our model provides a clear way to evaluate the health and mortality effects of air pollution. Similar to the concept of life expectancy, UY and LYL are measured in years. UY refers to the average number of years individuals spend in poor health (Sullivan, 1971), while LYL refers to the number of years lost from premature death (Andersen, 2013; Erlangsen et al., 2017). As our approach relies on life tables, we can compare life expectancy, UY, and LYL across APAC countries without biases from population-composition differences. The strength of our method is that UY and LYL are based on life table calculations, which can be compared across time and across populations, making it more consistent and comprehensive than other metrics that depend on population and death counts as well as fixed standard populations (Cheng et al., 2021; Etchie et al., 2018; Hadei et al., 2020; W. Hu et al., 2023; Zeng et al., 2018).

This study aims to comprehensively quantify and compare the burden of UY and LYL arising from exposure to two major sources of air particulate matter: APM and HAP over the past three decades. The analysis spans across various countries, and between males, females and age groups within APAC. Additionally, considering that females are more likely to be exposed to indoor air pollution than males, and that many studies have indicated a higher impact of HAP on women, this study will investigate key determinants affecting UY in women due to HAP, including pollution, economic and socio-demographic factors. The goal is to understand the underlying reasons for women's vulnerability to HAP and to examine how various determinants influence their health outcomes. By analysing these health outcomes, our study provides valuable insights into the comparative impact of these pollutants and their effects on public health within the region.

2. Materials and methods

2.1. Data sources

We obtained the data for this study from several sources. To calculate UY and LYL, we accessed data from the Institute for Health Metrics and Evaluation (IHME) through the Global Burden of Disease (Ärnlöv and Collaborators, 2020). Results Tool updated in 2019 (Institute for Health Metrics and Evaluation, 2020). IHME employed a comprehensive methodology to estimate exposure to $PM_{2.5}$ (particles with a diameter of $2.5\mu g/m^3$), using various data sources and techniques. This involved incorporating annual concentrations of pollution obtained from satellite remote sensing, simulations of a chemical transport model, ground station data, land-use information, and population size estimations. Further details regarding the data sources and methodology have been presented elsewhere (Vos et al., 2020). From IHME, age- and sex-specific information on the number of years lived with disability (YLD) attributable and non-attributable to $PM_{2.5}$, as well as the number of deaths attributable and non-attributable to $PM_{2.5}$, were sourced. Additionally, we obtained population counts and age-specific probabilities of death from this source.

The IHME data included age- and sex-specific information on the number of YLD and deaths attributable to two categories of particulate matter: APM and HAP—we included both types of pollution in our calculations. We accessed data from age 0–95 years between 1990 and 2019 for each country in APAC. The age-specific probabilities of death were used for calculating abridged life tables from age 0 to 95 from 1990 to 2019 for each country. This enabled us to estimate life expectancy, UY and LYL within that age range.

We used linear regression models to examine the factors that help explain the levels of females UY attributable to indoor air pollution. The dependent variable corresponded to UY attributable to household air pollution for females, derived from the country-specific UY calculations. For each country, we sourced the independent variables from the World Health Organisation (WHO) for data on the proportion of people primarily using polluting fuels for cooking (World Health Organisation, 2023); Air Quality Life Index (AQLI) for measures on the level of $PM_{2.5}$ (Air Quality Life Index) (additional measures of $PM_{2.5}$ were used for sensitivity analysis included in Table S4 in the supplementary information); The World Bank for data on health expenditure per capita, GDP per capita, population growth, the proportion of people living in rural areas, and the percentage of female labour force (The World Bank, 2023); IHME which reported the percentage of female deaths from HAP and the total fertility rate (Institute for Health Metrics and Evaluation, 2020); the United Nations Population Division for the percentage of contraceptive use; and the United Nations Development Programme which has data on the female mean years of schooling (United Nations Development Programme, 2023).

Our analysis focused on 69 countries in APAC. We based the classification of countries into six regions from the categorisation by the United Nations (United Nations, 2019): North, East, West, South and Southeast Asia, and Oceania. However, some Pacific Island nations in APAC were not included in the analysis due to unavailable information (a detailed country list is included in the supplementary material). Since this study relied on data from publicly accessible sources and did not involve personal information, it was exempt from requiring ethics approval from our respective Institutional Review Board (IRB).

2.2. Statistical analysis

2.2.1. Life-years lost attributable air particulate matter

We calculated life tables and, in particular, life expectancy from the probability of deaths data by employing standard demographic techniques (Preston et al., 2000). Life expectancy, denoted as ${}_{95}e_0$, represents the average number of years lived by individuals in each of the populations between ages 0 to 95. LYL is the complement of life

expectancy, which measures years lost in the population before age 95 in this study. The number of years between ages 0 to 95 is 95 years, and it is equal to the addition of life expectancy and LYL between these ages (life expectancy + LYL = 95). We analysed LYL attributable to HAP and APM in APAC using the following equation:

$$95 = {}_{95}e_0 + \sum_{i=1}^{n} {}_{95}\text{ə}_0^i, \tag{1}$$

where ${}_{95}\text{ə}_0^i$ is the number of LYL for cause of death i from ages 0 to 95, with n causes of death including air pollution, as well as other causes of death. We calculated sex ratios of LYL attributable to $PM_{2.5}$ using the air pollution LYL for females, denoted as ${}_0\text{ə}_{95}^{i,f}$, divided by the corresponding value for males, ${}_0\text{ə}_{95}^{i,m}$. The LYL can be further separated by age-group to obtain their corresponding age allocation as:

$$95 = {}_{95}e_0 + \sum_{i=1}^{n} {}_5\text{ə}_0^i + \sum_{i=1}^{n} {}_{30}\text{ə}_5^i + \sum_{i=1}^{n} {}_{30}\text{ə}_{35}^i + \sum_{i=1}^{n} {}_{30}\text{ə}_{65}^i, \tag{2}$$

where the life table notation is used, with ${}_y\text{ə}_x^i$ as the LYL between ages x and $x+y$. Detailed information on the calculation procedures for LYL has been presented elsewhere (Andersen et al., 2013; Erlangsen et al., 2017; Somboonsin and Canudas-Romo, 2021), and a brief description of all metrics used in the calculation is included in the supplementary information.

2.2.2. Unhealthy years attributable to air particulate matter

Healthy life expectancy (HLE) and life expectancy are needed for the calculation of UY. The number of years in healthy life is a component of life expectancy and was calculated using Sullivan's method (Sullivan, 1971). The age- and sex-specific probability of death (q_x) was used to calculate the other values in the life table for all countries in APAC. The calculation of healthy life expectancy was summarised by Molla (2001) in the following equation:

$$e_0^H = \sum_{x=0}^{\omega} \pi_H(x) L_x, \tag{3}$$

where e_0^H represents healthy life expectancy at birth, ω is the last age in the life table, $\pi_H(x)$ is the proportion experiencing healthy conditions at age x which is calculated from the age-specific YLD and the population in each country; the radix of the population equals 1, $l_0 = 1$, and L_x is the life table person-years. Further details of the calculation procedures for healthy life expectancy are presented elsewhere (Jagger et al., 2014; Johnson, 2008; Lau et al., 2012; Molla, 2001).

UY measures the number of years people live in an unhealthy state attributable to air pollution. Specifically, UY attributable to particulate matter were calculated using the Sullivan method and distinguished between specific air pollutants (HAP and APM). Formally written, UY due to both pollutants were calculated by subtracting the healthy years due to particulate matter ${}_{95}e_0^{i,H}$ from life expectancy as:

$${}_{95}e_0^{i,\cup Y} = {}_{95}e_0 - {}_{95}e_0^{i,H}, \tag{4}$$

where ${}_{95}e_0^{i,\cup Y}$ and ${}_{95}e_0^{i,H}$ are the unhealthy years and healthy years attributable to air particulate matter i at age 0 to 95. Additionally, sex ratios of UY were calculated using UY for females, denoted as ${}_{95}e_0^{i,\cup Y,f}$, divided by the corresponding value for males, ${}_{95}e_0^{i,\cup Y,m}$. The UY can be further separated by age-group to obtain their corresponding age allocation as:

$${}_{95}e_0^{i,\cup Y} = {}_5e_0^{i,\cup Y} + {}_{30}e_5^{i,\cup Y} + {}_{30}e_{35}^{i,\cup Y} + {}_{30}e_{65}^{i,\cup Y}. \tag{5}$$

More information on the calculation is provided in the supplementary information.

2.2.3. Multiple linear regression analysis

We used linear regression modelling to study the associations between unhealthy years attributable to household air pollution, $UY(HAP)$, for females and a set of predictors including pollution, economic, demographic and women empowerment factors (details on variables within each factor are provided in Fig. S2 in supplementary information). Prior to conducting the regression analysis, we addressed missing data through imputation. This step was necessary due to the absence of independent data from public sources (see details on the imputation approach in the supplementary information). Drawing from literature reviews focused on indicators influencing health outcomes from indoor pollution (e.g. Austin and Mejia (2017) and Liao et al. (2023)), we selected predictors that could significantly influence variations in $UY(HAP)$ for females. The regression analysis involved four models—including only the pollution factors in the first model, adding economic indicators in the second, and subsequently introducing demographic shifts in the third—our final selected model, which includes all predictors, was chosen based on its fit, as determined by the adjusted R-squared value, as:

$$UY(HAP^F) = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4, \tag{6}$$

where $UY(HAP^F)$ represents UY due to household air pollution for females and β_0 is the model intercept. β_1, β_2, β_3 and β_4 are the estimated coefficient for pollution (x_1), economic (x_2), demographic (x_3), and women empowerment indicators (x_4), respectively. The models are presented with a significance level of 0.05.

We used the R statistical software version 4.0.3 for all the analyses. Details of the additional calculations and sensitivity analysis are provided in the supplementary information.

3. Results

3.1. Sex disparities in air particulate matter-related health and mortality

Fig. 1 shows the sex ratios (SR) of UY and LYL due to APM from 1990 to 2019. Both UY and LYL caused by indoor and outdoor air pollution exhibit similar trends over the period studied. For UY due to HAP, evident sex disparities are observed across all countries in the APAC, with females experiencing more UY than males (SR for $UY(HAP)$ between 1.14 and 2.48). Regarding UY caused by APM ($UY(APM)$), the distribution is around 1 meaning similar trends for females and males (SR for $UY(APM)$ between 0.68 and 1.68). Moreover, Kazakhstan emerged as an outlier of sex ratios, where females had a higher incidence of unhealthy years than males for both pollutants.

When examining LYL, males showed higher SR for both HAP (SR ranging between 0.47 and 3.45) and APM (SR from 0.48 to 1.21) in many countries. A significant outlier was found for $LYL(HAP)$ in Qatar, where females lost more years of life from 1990 to 2000, but from 2010 to 2019, males surpassed females in LYL. Females in Qatar still experienced higher LYL due to outdoor air pollution compared to males. Furthermore, Japanese males experienced higher $LYL(APM)$ than females.

Because females experienced higher UY due to household air pollution than males, we further examined the variation among countries or regions within APAC in terms of females exposed to poor health from HAP. To be able to see the ratios for all countries including the small Pacific Islands instead of a map (available in Fig. S5 in the supplementary information), Fig. 2 displays the SR of $UY(HAP)$ categorized by 6 subregions in 2019 with the corresponding latitude and longitude geographic coordinates. The results show relatively consistent SRs among the subregions. Kazakhstan stood out with the highest SR for $UY(HAP)$, following by East Asian countries, such as China, North Korea and Taiwan, exhibited SRs higher than 2.0. Additionally, small islands in Oceania, including Cook Islands, Nauru, Palau and Niue, showed SRs around 1.8–1.9. Despite females in all countries in the APAC region

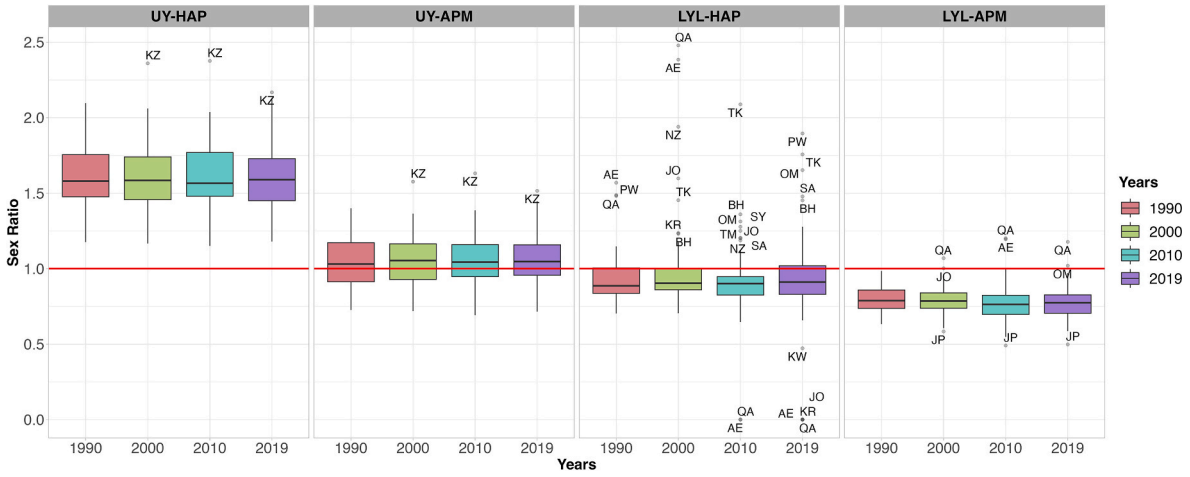

Fig. 1. Sex ratios (females divided by males) of unhealthy years (UY) and life-years lost (LYL) attributable to household air pollution (HAP) from solid fuels and ambient particulate matter (APM) in Asia-Pacific countries from 1990 to 2019.
Note: The red lines represent equal UY and LYL between females and males. The lower and upper lines of the boxes represent the 25th and 75th percentiles, respectively, and the lines within each box indicate the median. Two-letter country codes are presented in Table S1 in the supplementary information.
Source: Author's calculation based on data from the Institute for Health Metrics and Evaluation (IHME).

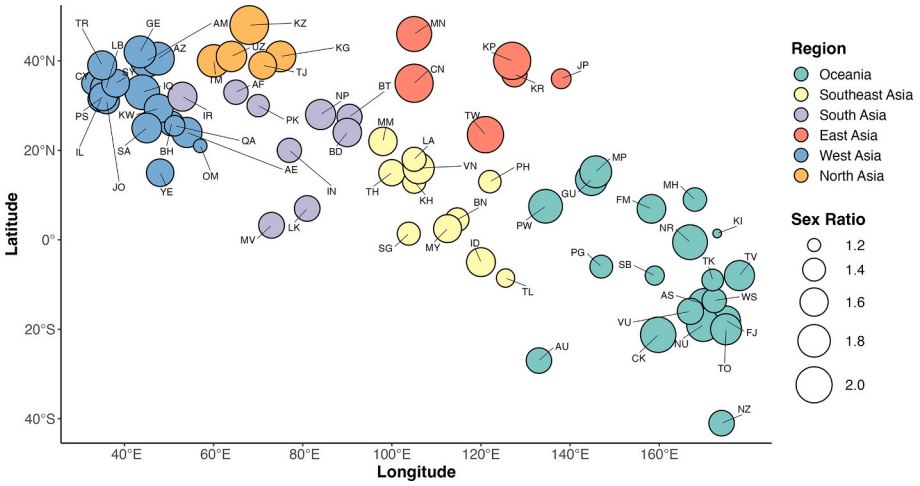

Fig. 2. Sex ratios (females divided by males) of unhealthy years attributable to household air pollution from solid fuels (HAP) in Asia-Pacific countries and their regions in 2019, in the corresponding latitude and longitude geographic coordinates.
Note: Two letter country codes are presented in Table S1 in the supplementary information.
Source: Author's calculation based on data from the Institute for Health Metrics and Evaluation (IHME).

experiencing higher UY due to HAP, some countries, mainly in West Asia, such as Oman, Timor-Leste, and Qatar, exhibited comparatively lower SRs (SR = 1.2–1.3).

Table 1 presents the multiple linear regression models for the relationship between female UY from HAP and various predictors between 2000 and 2019. In the first model, a significant relationship was observed between $UY(HAP^F)$ in females and pollution factors. Specifically, our findings indicate that for every 1% increase in the proportion of people predominantly using polluting fuels for cooking, there is a corresponding 0.265% (95% CI = 0.246, 0.285) increase in unhealthy years due to indoor air pollution among females. Higher $PM_{2.5}$ concentrations and elevated percentages of female deaths due to HAP were associated with increased $UY(HAP^F)$ among females, as evidenced by coefficients of 0.003 and 1.559, respectively. The second model, which integrated economic factors, indicated similar associations to polluting factors: the use of polluting fuels, $PM_{2.5}$, and female deaths from HAP. Countries with a higher GDP were associated with a decrease in $UY(HAP^F)$ for females, as indicated by the negative coefficient of −0.001. The third model, which introduced demographic factors, reinforced prior associations with polluting fuels, $PM_{2.5}$, female HAP deaths, and revealed a significant association with rural populations (0.002, 95% CI = 0.002, 0.002). Despite GDP exhibiting a positive relationship with $UY(HAP^F)$ in this model, its impact was minimal. Introducing the women empowerment factors, in the model 4, highlighted that for every 1% increase in various predictors, there were increases in $UY(HAP^F)$: 0.215% (95% CI = 0.197, 0.233) for using polluting fuels, 0.001% (95% CI = 0.001, 0.002) for $PM_{2.5}$, 1.162% (95% CI = 1.008, 1.316) for female HAP deaths, and 0.002% (95% CI = 0.002, 0.002) for proportion of people living in rural areas. Yet, higher fertility rates (−0.011, 95% CI = −0.016, −0.006) and mean schooling years for females (−0.009, 95% CI = −0.011, −0.007) were associated with a decline in female $UY(HAP^F)$, although individual correlations of the former with fertility rates were positive (see Fig. S3 in the supplementary information). The inclusion of women empowerment rendered economic factors non-significant. Therefore, these findings emphasise the existence of significant sex

Table 1
Multiple linear regression coefficients for unhealthy years attributable to household air pollution for females by pollution, economic, demographic and women empowerment factors.

Predictors	Model 1	Model 2	Model 3	Model 4
	Pollution	Model 1 + Economic	Model 2 + Demographic	Model 3 + Women's empowerment
Pollution variables				
Proportion of people primarily using polluting fuels for cooking	0.265*** (0.246, 0.285)	0.251*** (0.231, 0.271)	0.225*** (0.207, 0.244)	0.215*** (0.197, 0.233)
$PM_{2.5}$ level	0.003*** (0.002,0.003)	0.003*** (0.002, 0.003)	0.002*** (0.002, 0.003)	0.001*** (0.001, 0.002)
Percentage of female death from HAP	1.599*** (1.444,1.754)	1.554*** (1.400, 1.708)	1.093*** (0.943, 1.243)	1.162*** (1.008, 1.316)
Economic variables				
Health expenditure		0.001 (−0.006, 0.008)	0.001 (−0.005, 0.008)	0.006 (0.000, 0.013)
GDP per capita		−0.001*** (−0.001, −0.001)	0.000* (0.000, 0.001)	0.000 (0.000, 0.001)
Demographic variables				
Population growth			0.001 (−0.001, 0.003)	0.000 (−0.002, 0.002)
Proportion of people living in rural areas			0.002*** (0.002, 0.002)	0.002*** (0.002, 0.002)
Women empowerment variables				
Total Fertility Rate				−0.011*** (−0.016, −0.006)
Female labour participation				0.000 (−0.042, 0.042)
Female mean years of schooling				−0.009*** (−0.011, −0.007)
Contraceptive use				0.001 (−0.029, 0.030)
Intercept	−0.027*** (−0.035, −0.020)	−0.010 (−0.019, 0.000)	−0.087*** (−0.099, −0.075)	0.037* (0.002,0.072)
Adjusted R-squared	0.837	0.842	0.872	0.881
Observations	1380	1380	1380	1380

Notes: *** = p-value<0.001, ** = p-value<0.01, * = p-value<0.05. The values of 95% confidence intervals are presented in the parentheses. HAP represents household air pollution from solid fuels; GDP refers to gross domestic product.
Sources: Author's calculation based on data from the Institute for Health Metrics and Evaluation (IHME), World Health Organisation (WHO), Air Quality Life Index (AQLI), the World Bank and the United Nations (UN).

disparities in air particulate matter-related health outcomes in the APAC region.

3.2. Age group-specific unhealthy years and life-years lost caused by air pollution

Given the small difference between females and males in the time trends of age group-specific UY from 2000 to 2019, the rest of the study focuses on female findings in the main text, while male results are provided in the supplementary information. Fig. 3a shows age group-specific UY for females in 2019 and changes between 2000 and 2019. Papua New Guinea exhibited the highest UY due to HAP in 2019 among Oceania countries and the APAC region, with $UY(HAP) = 0.59$ years (CI = 0.57, 0.61), while West and North Asia had lower $UY(HAP)$. Female adults (35–64 years) and older people (65–95 years) experienced higher $UY(HAP)$. Across most APAC countries, the older population had higher $UY(HAP)$ than adults, except in Oceania (e.g., Vanuatu, Solomon Islands, Kiribati and Marshall Islands). $UY(HAP)$ decreased among the elderly from 2000 to 2019, except in Oceania (Vanuatu, Solomon Islands, Kiribati, Northern Mariana Islands and Guam), Southeast Asia (Myanmar, Cambodia and Laos), and South Asia (Bangladesh and Afghanistan).

In terms of UY attributable to APM, West Asia led with Qatar reporting the highest UY for this pollutant at 0.60 years (CI = 0.48, 0.68). Conversely, Oceania showed the lowest $UY(APM)$, with the Solomon Islands at 0.03 years (CI = 0.01, 0.03). Similar to $UY(HAP)$, female adults and the elderly faced the highest APM exposure. While older individuals had higher exposure in most countries, adults experienced more exposure in certain countries, such as the Pacific Islands (e.g., Solomon Islands, Kiribati, Marshall Islands and Micronesia), Afghanistan, Mongolia, Tajikistan and Uzbekistan. $UY(APM)$ increased from 2000 to 2019, primarily among the elderly, except for countries like Australia, Philippines, Singapore and Cyprus, which experienced a decrease in UY among the elderly. Furthermore, a lower burden of UY caused by HAP and APM was observed among young people (ages 5–34 years).

Turning to LYL, Fig. 3b provides insights into age group-specific LYL and changes for females in the APAC region. Oceania reported the highest LYL due to HAP, notably in Solomon Islands at 6.50 years (CI = 6.27, 6.74) and Papua New Guinea at 4.76 years (CI = 4.58, 4.95). West Asia exhibited the lowest $LYL(HAP)$. However, mortality was higher among older people, followed by adults and younger individuals, while LYL attributable to HAP for children were lower in APAC. Across all APAC countries, there was a decrease in $LYL(HAP)$ between 2000 and 2019, with Afghanistan, Myanmar and Cambodia experiencing the largest decrease. LYL due to HAP among children declined more significantly than in other age groups, particularly in Southeast and South Asia.

LYL trends due to APM mirrored $UY(APM)$, with the highest $LYL(APM)$ in Uzbekistan (3.10, CI = 2.93, 3.26 years) and Qatar (3.02, CI = 2.86, 3.18 years), and the lowest in New Zealand at 0.10 years (CI = 0.08, 0.13). From 2000 to 2019, most APAC countries experienced an increase in $LYL(APM)$, but countries in West and North Asia witnessed a decrease during the studied period.

Among age groups, the adults had the highest changes and levels in $LYL(APM)$ in 2019, while children and older adults had relatively fewer years lost. Fig. 4 shows that in most APAC countries, boys aged 0–4 years experienced more UY attributable to HAP than girls, while females aged

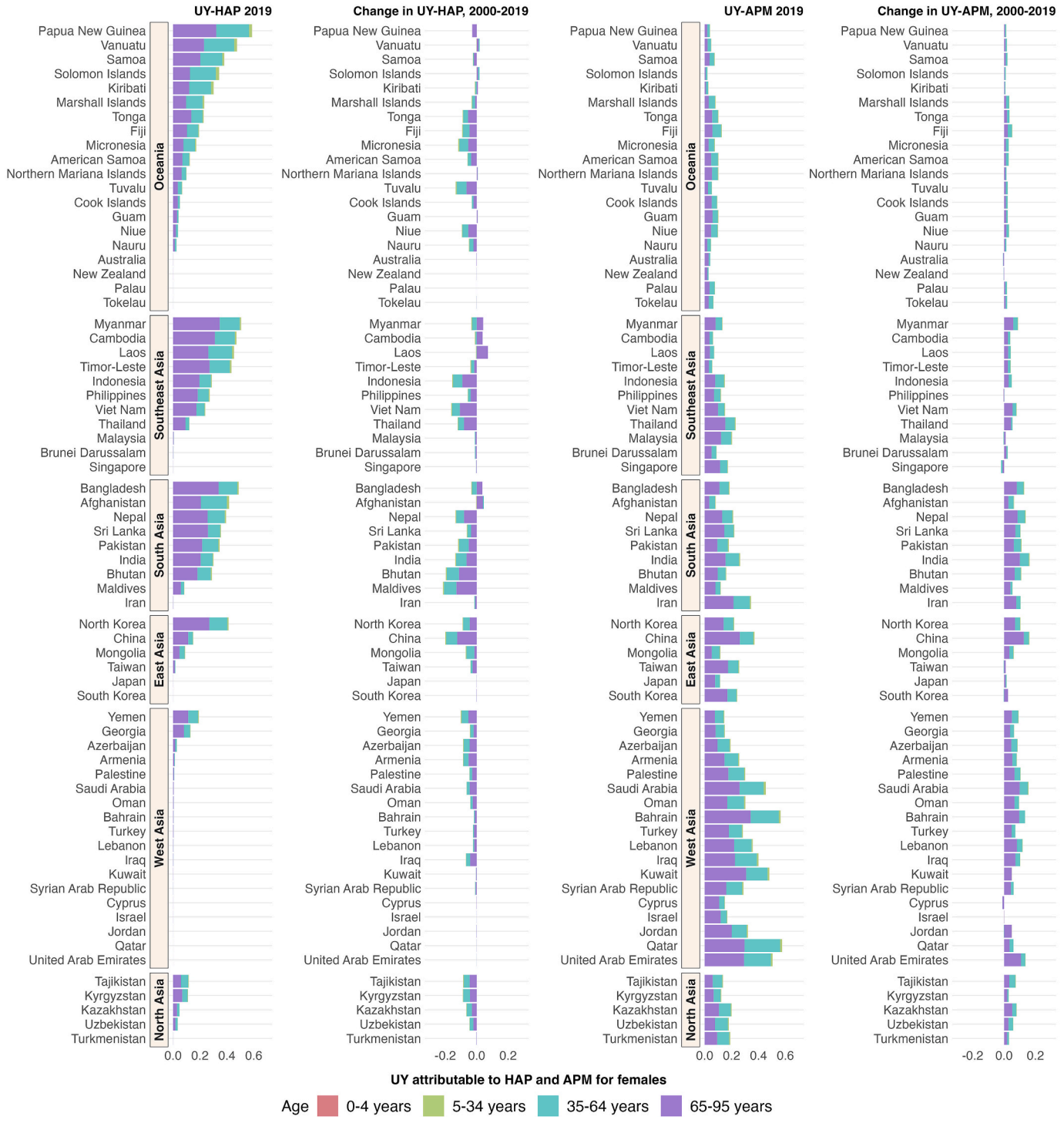

Fig. 3a. Age-specific unhealthy years (UY) in 2019 and changes in age-specific UY attributable to ambient particulate matter (APM) and household air pollution (HAP) from solid fuels between 2000 and 2019 for females in Asia-Pacific countries and their regions.
Sources: Author's calculation based on data from the Institute for Health Metrics and Evaluation (IHME).

5–95 years had higher *UY*(*HAP*) than males for all countries. Thus, results highlight that female older individuals and adults were the predominant age groups contributing to UY and LYL due to both household and outdoor air pollution, whereas children were rarely affected in terms of UY and LYL.

4. Discussion

The detrimental health effects of particulate air pollution have been the subject of numerous investigations across different geographies, including both areas with significant pollution levels and those relatively unaffected (James et al., 2020; Liao et al., 2023; Yin et al., 2020). Most previous research utilized GBD study data to study health metrics including disability-adjusted life years, years of life lost, years lived with disability, age-specific mortality rates, and age-specific death rates. These studies often focused on individual pollutants, specific causes of death, or certain at-risk groups within specified regions (Abtahi et al., 2017; Chen et al., 2018; Chen et al., 2024; Cheng et al., 2021; J. Hu et al.,



Fig. 3b. Age-specific life-years lost (LYL) in 2019 and changes in age-specific LYL attributable to ambient particulate matter (APM) and household air pollution (HAP) from solid fuels between 2000 and 2019 for females in Asia-Pacific countries and their regions.
Sources: Author's calculation based on data from the Institute for Health Metrics and Evaluation (IHME).

2023; Le et al., 2024). In contrast, our study investigated the impact of air pollution on health by analysing UY and LYL using the GBD data. Specifically, we focused on studying the effects of APM and HAP from 1990 to 2019.

Our study significantly contributes to the existing research by introducing a new way to quantify UY and LYL attributed to air pollution. By integrating demographic methodologies, our analysis provides a better understanding of air pollution's health impact in terms of years. Our study is the first to use the UY metric in this context, enhancing the existing knowledge on the global burden of health outcomes attributable to particulate matter. We further compared the UY and LYL to quantify the duration people suffer from poor health and the years lost from life expectancy due to air pollution, with a focus on diverse age groups and sexes within each subregion of the APAC region. Furthermore, we extended this analysis to include individual countries within the region, providing a detailed assessment of the burden of air pollution on a

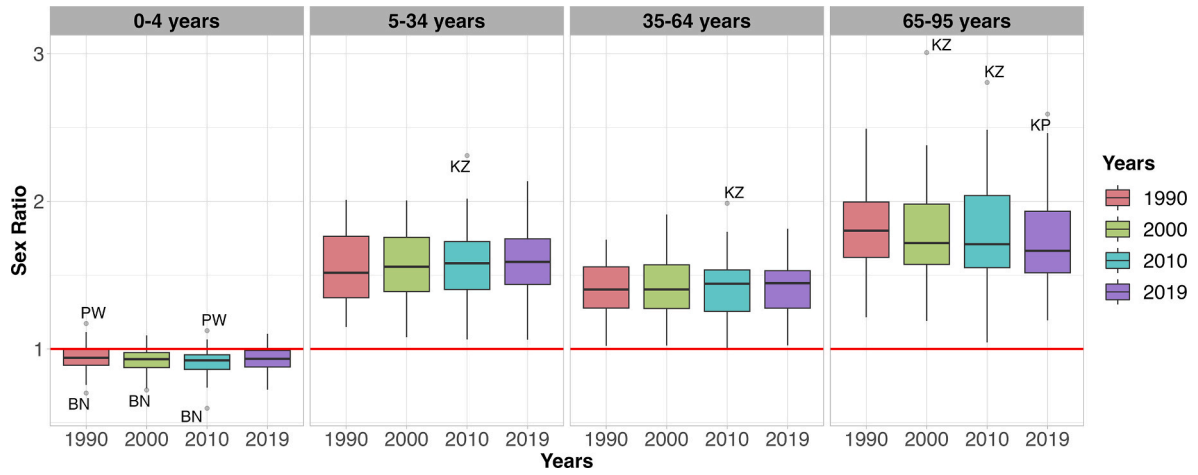

Fig. 4. Sex ratios (females divided by males) of unhealthy years attributable to household air pollution (HAP) from solid fuels in Asia-Pacific countries by age groups including children (0–4 years), young people (5–34 years), adults (35–64 years) and older people (65–95 years) from 1990 to 2019.
Note: The red lines represent equal unhealthy years caused by HAP between females and males. The lower and upper lines of the boxes represent 25th and 75th percentiles, respectively, and the lines within each box indicate the median. Two-letter country codes are presented in Table S1 in the supplementary information.
Sources: Author's calculation based on data from the Institute for Health Metrics and Evaluation (IHME).

national level. Additionally, our research explored the factors related to sex disparities in *UY*(*HAP*), highlighting that females consistently showed higher *UY*(*HAP*) than their male counterparts across all studied countries.

The findings emphasise a significant difference in UY and LYL between females and males. As evident in the sex ratios for UY, females consistently surpassed males, with this difference primarily attributed to HAP. This trend can be reasonably attributed to traditional gender roles prevalent in many regions, where females spend a good amount of time indoors, often in proximity to domestic sources of pollution, such as cooking (Ali et al., 2021; Balmes, 2019; Ipek and Ipek, 2021). Even though women experienced a greater number of unhealthy years, the sex ratio of LYL showed higher rates for males. This could potentially be attributed to the overall mortality patterns observed globally; typically, males tend to have a shorter life expectancy due to both biological and behavioural factors, yielding to mortality at younger ages compared to females (Chen et al., 2022; Kurata et al., 2020; Regan and Partridge, 2013; Singh and Ladusingh, 2016). Multiple studies suggest that women, despite their higher longevity, frequently face poorer health than men, and this is particularly the case across Central Asian countries (Aringazina et al., 2012; Cockerham et al., 2004; Omaleki and Reed, 2019). While outlier values in our finding were observed between the sexes in Kazakhstan, the literature did not provide a comprehensive explanation for such an outcome. However, Kazakhstan, marked by its rank as the 23rd most polluted country, particularly in its capital, intensifies pollution levels due to weak monitoring and control, high coal consumption, and outdated transportation emissions (Kerimray et al., 2020; Mukhtarov et al., 2023; United Nations Development Programme, 2021).

Our analysis reveals that factors like pollution, demographics, and women's empowerment significantly influence female health related to pollutants. This finding aligns with research on mortality and morbidity associated with HAP. Studies have shown that developing countries that rely heavily on solid fuels often report higher female indoor air pollution-related deaths (Balmes, 2019; Oluwole et al., 2012). Prior studies have identified that individuals in rural areas predominantly rely on solid fuels for cooking, exacerbating health risks associated with HAP (James et al., 2020; Yu et al., 2018). Fertility rates are often used as a measure of women's empowerment in examining the health impacts of air pollution, representing women's autonomy and decision-making in households (Austin and Mejia, 2017). It suggests that empowered women, with the ability to make choices at home, may avoid areas with high HAP exposure, both for their own health and that of their children. Interestingly, while previous studies have highlighted that enhancing women's empowerment—by improving their participation in education, the labour force, and decision-making within households—can mitigate health risks from HAP (Austin and Mejia, 2017; Nwaka et al., 2020), our study found a negative statistical association between TFR and *UY*(*HAP*).

The association between TFR and *UY*(*HAP*) from the regression analysis is challenging. When analysing female empowerment indicators alone initially, there appears to be a positive relationship (details of regression analysis and predictor values in Tables S5 and S6 in the supplementary information). However, when including pollution factors, the association turns negative. This shift suggests that confounding factors significantly influence the interpretation of TFR, leading to a potentially misleading association with UY. On the one hand, the relationship between lower fertility and higher *UY*(*HAP*) in females could be due to an interconnection between fertility and UY. Air pollution, known to affect infertility in both males and females by impacting reproductive systems (Carré et al., 2017; Nieuwenhuijsen et al., 2014), suggests that areas with higher pollution levels might experience lower fertility rates, as people in these areas are more affected by air pollution compared to those in less polluted areas (Ahmed et al., 2022; Xue et al., 2021). On the other hand, countries with high TFR, such as Yemen, Tonga, Tajikistan, and Palestine, did not exhibit high usage of solid fuels, resulting in lower *UY*(*HAP*). Contrastingly, countries like Sri Lanka, Bangladesh, and North Korea, despite having lower TFRs (between 1.74 and 1.83), show over 69 percent household reliance on solid fuels (Table S3 in the supplementary information).

Western Asia reported the highest UY and LYL related to APM. A surge in gas and diesel vehicles, industrial emissions, outdoor cooking, and public smoking habits have contributed to deteriorating air quality over recent decades (Al-sareji et al., 2022; Maziak et al., 2008). Conversely, the Pacific Islands, including Papua New Guinea, Vanuatu and the Solomon Islands, predominantly use traditional energy sources for cooking, resulting in the area having the highest UY and LYL attributed to HAP (Di Michiel et al., 2021; Shah, 2021). Introducing cleaner cooking fuels and the use of rangehoods can significantly reduce UY and LYL due to HAP in numerous countries (Chafe et al., 2014). However, there are exceptions, such as Laos. In a survey of 9043 adults in Laos, exposure to household air pollution—from both cooking fires and tobacco smoke—was alarmingly widespread, with nearly three-quarters of households reporting such exposures. This exposure

becomes even more pronounced for adults and children, in the Northern regions of Laos. The prolonged exposure to indoor cooking fires is not just for culinary needs but also to keep homes warm (Hurd-Kundeti et al., 2019).

Numerous studies suggest that children are a particularly vulnerable group adversely affected by air pollution (Abtahi et al., 2017; Sang et al., 2022). Instead, we observed that the elderly were predominantly impacted by APM and HAP. This observation aligns with the finding of Liu et al. (2024) and Yang et al. (2021), which identified individuals aged 65 years and older as being the most significantly affected by air pollution. Following the elderly, adults aged 35–64 were found to be the next most impacted group, with children and younger individuals experiencing a comparatively lower impact. A possible explanation is that our definition of children as ages 0–4, who often stay indoors, may reduce their APM exposure. In our results, children in Southeast and South Asia experienced some of the most pronounced declines in LYL caused by HAP between 2000 and 2019. Even though indoor settings might increase HAP exposure, numerous households have increasingly separated kitchens, meaning that children are frequently located in rooms without direct exposure to cooking smokes. Additionally, the protective role of breastfeeding in the first year might mitigate risks even in high HAP environments (Naz et al., 2017; Rana et al., 2021). Another key distinction of our study compared to previous studies, is its focus on all-cause mortality resulting from air pollution, whereas children are predominantly affected by acute lower respiratory infections (Naz et al., 2015; Sonego et al., 2015).

In our study, boys showed more UY due to HAP than girls, even with comparable indoor exposures. Boys, particularly in infancy, have heightened biological vulnerability, potentially from differing sex hormone levels like testosterone. Moreover, research suggests that boys aged 0–59 months face more nutritional challenges than girls, indicating an inherent susceptibility in early male childhood (Schoenbuchner et al., 2019; Thurstans et al., 2020). In contrast, females aged 5–95 experienced more UY due to HAP compared to males of the same age range. This disparity might be attributed to traditional gender roles, where younger females often assist elder family members, like mothers or grandmothers, in domestic cooking tasks.

Based on this research, there are clear steps policymakers should take to combat the health effects of air pollution. First, in countries with rising UY and LYL from APM, particularly in low- and middle-income regions, it would be beneficial to imitate successful policies from high-income nations that have effectively reduced health risks from outdoor air pollution. These might include adopting strategies such as stricter emission controls, endorsing clean energy, and enhancing public transportation (Vardoulakis et al., 2018; Xiao et al., 2020). The Pacific region, faced with high indoor air pollution, should focus on measures like creating smoke-free home environments, encouraging the use of efficient cookstoves, and facilitating access to cleaner cooking energy sources (Junaid et al., 2018; Li et al., 2023). Given the significant effects on women, policies should also emphasise women's empowerment by supporting their education, economic independence, and active participation in societal decisions (Austin and Mejia, 2017).

Limitations should be acknowledged. Firstly, given the availability of GBD data, our study compared the result in APAC at the national level. This approach provides an average representation of UY and LYL across individual countries, which might miss existing heterogeneity within countries. There is need for more in-depth, sub-national level studies to capture variations within nations. Secondly, although our focus was on APAC, where PM levels have been increasing, other regions, like Africa, also report high PM concentrations. Future research should extend the scope to encompass additional geographical areas, facilitating regional comparisons. Thirdly, this study assessed an overall view of UY without examining specific causes of death from air pollution. A more detailed categorisation of cause-specific health risks could offer insights into particular health impacts. Fourthly, our research grouped ages, which might mask certain age-specific trends. Breaking down results by individual age rather than age groups could provide additional insights. Fifth, our findings indicated minimal effects on children and younger populations, contrasting with studies that highlight their vulnerability to air pollution. Sixth, our approach to deal with missing values in the data used for the regression analysis might introduce bias, potentially affecting the accuracy of our findings. Seventh, while we acknowledge that air pollution encompasses a variety of pollutants, including ozone, nitrogen dioxide, and sulphur dioxide, the decision to focus on $PM_{2.5}$ in this study was based on several factors: (1) the availability and consistency of long-term data for health effects from air pollution across multiple countries, (2) evidence from previous literature as well as data from IHME showing a higher impact of $PM_{2.5}$, both indoors and outdoors, on population health compared to other pollutants like ozone during the study period, and (3) the need for a clear comparative analysis between ambient and household air pollution. The potential for confounding health effects from other pollution sources in the data may influence the accuracy of our findings, as it may be challenging to isolate the specific impacts of $PM_{2.5}$ from other pollutants in the data. Further research should aim to include a broader range of pollutants to provide a more comprehensive assessment of air pollution's health impacts and to identify potential confounding effects. Finally, we used multiple linear regression, which gives an average perspective. This might minimise variations between countries. Using multilevel regression including sub-national and sub-regional information could provide a more detailed understanding of $UY(HAP)$ patterns for females across different countries.

5. Conclusions

This study presents an analysis of the burden of UY and LYL due to exposure to APM and HAP over the past three decades across the APAC region. We found females experience more UY compared to males, while males exhibited a higher SR for both HAP and APM. $UY(HAP)$ was closely related to factors like polluting fuels, $PM_{2.5}$, female HAP fatalities, and rural populations. However, lower female $UY(HAP)$ correlated with higher fertility rates and average schooling years for females. Additionally, when considering women's empowerment, economic factors became non-significant. The Pacific Islands recorded higher UY and LYL due to HAP, while Western Asia experienced greater impacts from APM. Between 2000 and 2019, there was a reduction in $UY(HAP)$ across several countries, with $LYL(HAP)$ diminishing across all Asia-Pacific nations. This was the case even when LYL generally increased in most regions. Predominantly, older and adult females were the most affected by pollution, UY and LYL from both indoor and outdoor air pollution, while children were seldom impacted in these metrics. Understanding the adverse effects of air pollution on health and mortality, while accounting for age and gender differences, is paramount for shaping targeted environmental health policies and interventions. Future efforts should prioritize nations with elevated LYL and UY figures and address the unique vulnerabilities and health risks faced by distinct demographic groups.

Funding

The authors declare that no funds, grants, or other support were received during the preparation of this manuscript.

Ethical approval

Since this study relied on data from publicly accessible sources and did not involve personal information, it was exempt from requiring ethics approval from our respective Institutional Review Board (IRB).

CRediT authorship contribution statement

Pattheera Somboonsin: Writing – original draft, Visualization,

Methodology, Formal analysis, Data curation, Conceptualization. **Brian Houle:** Writing – review & editing. **Vladimir Canudas-Romo:** Writing – review & editing, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.atmosenv.2024.120763.

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