Global burden of chronic obstructive pulmonary disease attributable to ambient particulate matter pollution and household air pollution from solid fuels from 1990 to 2019

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Abstract
We aimed to estimate the spatiotemporal trends in the global burden of chronic obstructive pulmonary disease (COPD) attributable to both household air pollution from solid fuels (HAP) and ambient particulate matter (APM) from 1990 to 2019 and compared the possible differences between the burdens attributable to APM and HAP. The number of deaths, disability-adjusted life-years (DALYs), and years of life lost (YLLs) of COPD attributable to HAP from solid fuels and APM during 1990–2019 were extracted from the Global Burden of Diseases Study 2019. The proportion of YLLs in DALYs and average YLLs per COPD death were also calculated. Subgroup analyses by sex, age, and socio-demographic index (SDI) were conducted. The estimated annual percentage change (EAPC) was used to assess the temporal trend of age-standardized rate of mortality (ASMR) and DALYs (ASDR). Over the past 30 years, we observed a clear downward trend in COPD deaths attributable to HAP and an upward trend by 97.61% in COPD deaths attributable to APM. The global COPD burden attributable to APM in 2019 was higher than those due to HAP, except in low-SDI regions. For both HAP and APM, YLLs continued to predominate in DALYs of COPD, with an average YLLs per death of more than 10 years in different regions. The ASMR was higher in males and lower in high-SDI regions. The ASMR and ASDR attributable to HAP decreased globally in all age groups during 1990–2019, while those attributable to APM increased among people older than 80 years and in regions with lower SDI. Our study reveals an increasing trend in APM-attributable COPD burden over the past three decades. Comparatively, the global burden due to HAP decreased markedly, but it was still pronounced in low-SDI regions. Continued efforts on PM mitigation are needed for COPD prevention.

Keywords Particulate matter · Chronic obstructive pulmonary disease · Global burden of disease · Mortality · Disability-adjusted life-years

Introduction
Chronic obstructive pulmonary disease (COPD) poses a threat to global health, with an estimated prevalence of approximately 300 million in 2017 (GBD Chronic Respiratory Disease Collaborators 2020). It is also a leading cause of mortality and disability-adjusted life-years (DALYs) globally (GBD 2019 Diseases and Injuries Collaborators 2020), accounting for 3.20 million deaths and 81.60 million DALYs in 2017 (Li et al. 2020). The etiology of COPD is complicated and involves multiple factors such as genetics, lifestyle, and environmental exposures (Ni et al. 2020, Sadhra et al. 2020, Singanayagam and Johnston 2020, Tian et al. 2020). Compelling epidemiologic studies suggested that particulate matter (PM) air pollution is an important
environmental risk factor for COPD (Cao et al. 2021; Li et al. 2016; Park et al. 2021).

The source of PM includes ambient PM pollution (APM) mainly originating from transportation and power plants, and household air pollution from the combustion of solid fuels (HAP) (GBD 2019 Risk Factors Collaborators 2020). Long-term exposure to PM pollution, especially PM with an aerodynamic diameter smaller than or equal to 2.5 μm (PM$_{2.5}$), may transport deep into the lung and trigger oxidative stress and inflammatory responses, leading to chronic respiratory inflammation and fibrosis (Liu et al. 2017; Niu et al. 2021; Xia et al. 2020).

However, previous studies have focused on the effects of APM and HAP on COPD and their potential mechanism, usually in a certain region or at a specific time, and no studies have systematically assessed the trend of the population attributable burden over the past 30 years from a global perspective. Furthermore, the majority of previous studies only assessed morbidity and mortality attributable to either APM or HAP, and a comparison is needed to explore the possible differences between APM and HAP. Therefore, we conducted this study to estimate the spatiotemporal trends of the global burden of COPD attributable to both HAP and APM from 1990 to 2019 using data from the Global Burden of Disease Study (GBD) 2019. Given the scope of the present study, our findings would help to inform the development of more effective strategies to reduce the PM-associated COPD burden.

Methods

Data sources

We retrieved the relevant data on the burden of COPD attributable to PM air pollution from the GBD 2019 through the Global Health Data Results Tool (GHDx, http://ghdx.healthdata.org/gbd-results-tool). The GBD 2019 comprehensively estimated the mortality and disability-adjusted life-years (DALYs) of 369 diseases and injuries for 204 countries and territories from 1990 to 2019, using a unified and comparable approach. Details of this study have been described elsewhere (GBD 2019 Risk Factors Collaborators 2020). Four indicators of COPD disease burden attributable to APM and HAP were used in the present study, including mortality, DALYs, years of life lost (YLLs), and years lived with disability (YLDs).

In the GBD 2019, countries and territories were divided into 21 regions according to epidemiological and geographical characteristics (GBD 2019 Diseases and Injuries Collaborators 2020). Their locations are illustrated in Fig. S1. We also classified countries and territories into different regions based on SDI, which was a comprehensive indicator of average year of education, total fertility rate (TFR), and the lag-distributed income per capita in a country (GBD 2019 Demographics Collaborators 2020, GBD 2019 Diseases and Injuries Collaborators 2020).

Assessment of PM air pollution exposure

HAP in the GBD 2019 was defined as the HAP from household combustion of solid fuels, and the estimation methods have been described in detail elsewhere (GBD 2019 Risk Factors Collaborators 2020). Briefly, it was estimated from both the proportion of individuals using solid fuels and the level of excess PM$_{2.5}$ exposure for these individuals. Solid fuels included coal, wood, charcoal, dung, and agricultural residues such as crop stalks, husks, or straw. The GBD 2019 synthesized the household solid fuels use data from a variety of standard multi-country surveys that surveyed the household information, such as Demographic and Health Surveys, Living Standards Measurement Surveys, Multiple Indicator Cluster Surveys, and World Health Surveys (GBD 2019 Risk Factors Collaborators 2020). The proportion of PM exposure from solid fuels at the individual level was then modeled using linear, spatiotemporal, and Gaussian regression three-step modeling strategy. The individual excess PM$_{2.5}$ exposure due to using solid fuels was estimated by a linear model using the study database from the Global Household Air Pollution measurement database from WHO (Shupler et al. 2018a). The level of HAP exposure due to combustion of solid fuels was then estimated using a Bayesian, hierarchical model based on the excess HAP data aforementioned (GBD 2019 Risk Factors Collaborators 2020, Shupler et al. 2018b).

APM exposure in the GBD 2019 study was defined as the population-weighted annual average concentration of PM$_{2.5}$ (μg/m$^3$), which was estimated by multiple sources using ground measurements, satellite observations, chemical transport model simulations, population estimates, and land-use data. The estimation approach has been previously detailed (GBD 2019 Risk Factors Collaborators 2020). In brief, the PM$_{2.5}$ ground measurement database consisted of updated data from the WHO Global Ambient Air Quality Database, including measurements of concentrations of PM$_{10}$ and PM$_{2.5}$ from 10,408 ground air monitors from 116 countries. GEOS Chem chemical transport model was used to evaluate the sum of particulate sulfate, nitrate, ammonium, organic carbon, and the compositional concentrations of mineral dust, combined with elevation and the distance to the nearest urban land surface in a 0.1°×0.1° resolution (van Donkelaar et al. 2016). Satellite-based estimates of PM$_{2.5}$ were calculated based on the algorithms used in the GBD 2017 (van Donkelaar et al. 2016), with updated satellite retrievals, chemical transport modeling, and ground-based monitoring at 0.1°×0.1° resolution. Population data were obtained from the Gridded Population of the World (GPW) database, adjusted by UN2015 Population Prospectus.
A Bayesian model was then used to estimate the gridded concentrations, and data integration model for air quality (DIMAQ) was used to estimate ambient PM2.5 by matching the gridded estimates with the corresponding coefficients from the calibration (Shadrick et al. 2018).

COPD mortality and DALYs attributable to particulate matter pollution

The GBD 2019 used the results of different types of studies that explored the association between COPD and APM and HAP from solid fuels and then used these results to fit the risk curve via meta-regression Bayesian, regularized, trimmed (MR-BRT) splines. Theoretical minimum-risk exposure level (TMREL) was incorporated to fit the risk curve beginning at null exposure (Turner et al. 2016), which was defined as a uniform distribution given by the air pollution exposure distributions from cohort studies conducted in North America (GBD 2019 Risk Factors Collaborators 2020). In the GBD 2019, the lower and upper bounds of the distribution were 2.4 and 5.9 μg/m³, respectively. To calculate the attributable burden due to APM and HAP, the GBD 2019 used the integrated exposure response (IER) to obtain proportional population attributable fraction (PAF). In short, the COPD burden attributable to APM or HAP was estimated by splitting the PAF attributable to PM at a country level based on the average exposure levels.

We utilized age- and sex-specific mortality and DALYs to quantify the global burden of COPD attributable to APM and HAP. Deaths due to COPD were estimated as the number of deaths in a population over the specific study period, identified using the 9th and 10th International Classification of Diseases and Injuries (ICD-9 and ICD-10). DALYs were calculated as the sum of YLLs and YLDs, where YLLs were the number of years of life lost due to premature death under the GBD standard life expectancy for each age group, and YLDs were the number of years lived with any short-term or long-term health loss weighted by severity of the disability.

To further examine whether the disability or premature death contributed more to DALYs, we calculated the proportion of YLLs in DALYs as follows:

\[
\text{proportion of YLLs in DALYs} = \frac{\text{the number of YLLs}}{\text{the number of DALYs}}.
\]

We also estimated average YLLs per COPD death to assess the average life lost due to premature death for COPD patients, using the following algorithm:

\[
\text{the average YLLs per COPD death} = \frac{\text{the number of YLLs}}{\text{the number of deaths}}
\]

Statistical analysis

To control the impact of demographic differences, we used age-standardized mortality rate (ASMR) and DALYs rate (ASDR). We then used percentage change and estimated annual percentage change (EAPC) over 1990 to 2019 to estimate the temporal trends of ASMR and ASDR of COPD attributable to PM air pollution (Liu et al. 2019). Age-standardized rate (ASR) was fitted in a regression model:

\[
\ln(\text{ASR}) = \alpha + \beta x + \epsilon
\]

where \(x\) was the calendar year, and:

\[
EAPC = (\exp(\beta) - 1) \times 100\%
\]

The ASMR and ASDR would increase if the lower boundary of 95% confidence interval (CI) of EAPC is higher than 0 (Liu et al. 2019). In contrast, if the higher boundary of its 95% CI is lower than 0, there is a decreasing trend for the ASMR and ASDR.

Pearson correlation coefficients were calculated between SDI and the ASMR and ASDR. A two-sided \(P\) value of < 0.05 was considered statistically significant. All statistical analyses were performed using R (version 3.6.1).

Results

Disease burden attributable to household air pollution from solid fuels

According to the GBD 2019, the COPD deaths attributable to HAP decreased by 57.28%, from 0.93 [95% uncertainty interval (UI) 0.59, 1.28] million in 1990 to 0.40 (95% UI 0.24, 0.61) million in 2019 (Table S1). In 2019, the largest number of deaths was found in South Asia [0.23 (95% UI 0.13, 0.35) million], accounting for 58.00% of the total COPD deaths attributable to HAP. Figure 1 presents the global distribution of ASMR, ASDR, and their EAPC due to COPD attributable to HAP in 1990 and 2019. In 2019, the largest decreasing EAPC in ASMR was found in high-income Asia Pacific [−10.29% (95% CI −10.97%, −9.60%)]. Over the study period, a clear declining trend was observed in global DALYs of COPD.
attributable to HAP from 21.41 (95% UI 13.75, 29.30) million in 1990 to 9.30 (95% UI 5.69, 14.04) million in 2019 (Fig. 1; Table S2), and the EAPC of ASDR was $-5.48\%$ (95% CI $-5.67\%, -5.29\%$).

The changes of YLL-related indicators in 1990 and 2019 are presented in Table 1. A decreasing trend of the proportion of YLLs in DALYs due to COPD attributable to HAP was found over the past three decades. The proportion of YLLs in DALYs decreased by approximately 10.00% during 1990–2019 at the global level and ranged from 54.48% in high-income Asia Pacific to 88.68% in Oceania in 2019 (Table 1).

The average YLLs per COPD death attributable to HAP also decreased globally from 19.66 years in 1990 to 18.01 years in 2019 (Table 1). However, it increased in four regions, including North Africa and Middle East, Western Sub-Saharan Africa, Central Asia, and Southern Sub-Saharan Africa. The highest average YLLs per COPD death in 2019 was seen in Oceania (23.31 years) and the lowest in high-income Asia Pacific (11.24 years).

**Disease burden of COPD attributable to ambient particulate matter pollution**

In contrast to COPD deaths attributable to HAP, the COPD deaths attributable to APM increased by 97.61%, from 0.35 [95% UI 0.22, 0.51] million people in 1990 to 0.70 (95% UI 0.55, 0.86) million people in 2019 (Table S3). And the global DALYs due to COPD attributable to APM increased by 93.11%, from 7.98 (95% UI 5.06, 11.67) million in 1990 to 15.41 (95% UI 12.39, 18.97) million in 2019. However, the global ASMR and ASDR declined, and the EAPCs of ASMR and ASDR during 1990–2019 were $-0.58\%$ (95% CI $-0.72\%, -0.44\%$) and $-0.40\%$ (95% CI $-0.51\%, -0.29\%$), respectively (Table S4). Figure 2 shows the global distribution of ASMR, ASDR, and their EAPC due to COPD attributable to APM in 1990 and 2019.

The proportion of YLLs in DALYs due to COPD attributable to APM decreased across the world except in the Caribbean and high-income North America, similar to that of HAP (Table 2). However, the proportion of YLLs in DALYs (75.96%) was still much higher than that of YLDs in DALYs (24.04%) in 2019. In 2019, the greatest proportion of YLLs in DALYs was observed in Oceania and the smallest in high-income Asia Pacific.

The global average YLLs per COPD death attributable to APM was 19.08 years in 1990, and declined to 16.85 years in 2019 (Table 2). Among different regions, Oceania had the highest average YLLs per COPD death (23.09 years) in 2019. Other regions with average YLLs per COPD death exceeding 20 years in 2019 included Central Asia, Western Sub-Saharan Africa, Eastern Sub-Saharan Africa, and Central Sub-Saharan Africa. The lowest average YLLs per COPD death in 2019 was observed in high-income Asia Pacific (11.84 years).

**Comparison on COPD burden attributable to HAP and APM**

The contribution of APM and HAP to the global COPD burden has changed over the past three decades. In 1990, HAP was the leading risk factor for COPD. The deaths and DALYs due to COPD attributable to HAP declined since 1990 and reached a similar level to those attributable to
APM in 2010 (Fig. 3). APM became the second leading risk factor of COPD in 2019. The opposite phenomenon was observed in the low-SDI region, in which the ASMR and ASDR due to COPD attributable to HAP were higher than those attributable to APM (Fig. S2).

The sex-specific and age-specific COPD burden was similar between those attributable to APM and HAP (Fig. 4). The global ASR of COPD deaths and DALYs were higher in males than in females and increased with age in 2019. The ASMR and ASDR of COPD in both males and females had declined, with a greater EAPC in males (Table S1; Table S2; Table S3; Table S4). Consequently, the between-sex disparity was narrowed. By contrast to the mortality rate and DALY rate due to COPD attributable to HAP decreasing in all age groups, the mortality rate and DALYs rate from COPD attributable to APM among people younger than 80 years decreased from 1990 to 2019 but increased among people elder than 80 years (Fig. S4).

Figure 5 shows that the ASMR and ASDR of COPD attributable to HAP decreased in all different SDI regions from 1990 to 2019. A greater decline was observed in regions with lower SDI, and the disparity among regions in ASR due to COPD attributable to HAP narrowed over the past 30 years. Compared with the ASMR and ASDR due to COPD attributable to HAP, those attributable to APM decreased in the middle-SDI region, high-middle-SDI

### Table 1

| Focal regions                        | Number of YLLs, number × 10³ | Proportion of YLLs in DALYs | Average YLLs per death |
|--------------------------------------|-------------------------------|----------------------------|------------------------|
|                                      | 1990                          | 2019                       | 1990                   | 2019                   | 1990                   | 2019                   |
| **Global**                           | 18,335.37                     | 7175.21                    | 85.65%                 | 77.15%                 | 19.66                  | 18.01                  |
| **Gender**                           |                               |                             |                        |                        |                        |                        |
| Male                                 | 9903.91                       | 3787.21                    | 88.46%                 | 81.98%                 | 20.67                  | 18.89                  |
| Female                               | 8431.45                       | 3388.00                    | 82.56%                 | 72.38%                 | 18.60                  | 17.12                  |
| **SDI quintile**                     |                               |                             |                        |                        |                        |                        |
| Low SDI                              | 1980.05                       | 1928.54                    | 81.11%                 | 75.37%                 | 21.63                  | 19.78                  |
| Low-middle SDI                       | 6763.86                       | 3913.89                    | 84.72%                 | 79.23%                 | 20.74                  | 18.11                  |
| Middle SDI                           | 6918.40                       | 1142.41                    | 87.37%                 | 74.69%                 | 19.13                  | 15.91                  |
| High-middle SDI                      | 2635.26                       | 183.25                     | 87.39%                 | 69.53%                 | 17.44                  | 14.60                  |
| High SDI                             | 33.33                         | 2.48                       | 76.03%                 | 65.67%                 | 17.38                  | 13.02                  |
| **GBD region**                       |                               |                             |                        |                        |                        |                        |
| High-income Asia Pacific             | 0.94                          | 0.10                       | 62.78%                 | 54.48%                 | 15.85                  | 11.24                  |
| Central Asia                         | 51.66                         | 11.78                      | 82.75%                 | 78.23%                 | 20.61                  | 20.62                  |
| East Asia                            | 9644.79                       | 1329.73                    | 89.73%                 | 78.92%                 | 18.67                  | 15.29                  |
| South Asia                           | 6317.75                       | 4233.46                    | 82.81%                 | 79.27%                 | 20.96                  | 18.32                  |
| Southeast Asia                       | 943.65                        | 470.77                     | 79.84%                 | 71.31%                 | 20.40                  | 18.63                  |
| Australasia                          | 0.24                          | 0.03                       | 68.26%                 | 61.53%                 | 17.08                  | 14.16                  |
| Caribbean                            | 19.13                         | 20.26                      | 87.31%                 | 85.67%                 | 21.05                  | 20.78                  |
| Oceania                              | 39.12                         | 62.36                      | 90.36%                 | 88.68%                 | 23.98                  | 23.31                  |
| Central Europe                       | 63.79                         | 12.03                      | 79.45%                 | 69.53%                 | 18.55                  | 16.51                  |
| Eastern Europe                       | 35.32                         | 3.17                       | 80.68%                 | 74.46%                 | 19.40                  | 17.87                  |
| Western Europe                       | 5.44                          | 0.80                       | 71.87%                 | 64.91%                 | 14.93                  | 11.51                  |
| High-income North America            | 0.65                          | 0.38                       | 61.44%                 | 63.46%                 | 17.45                  | 15.93                  |
| Andean Latin America                 | 13.72                         | 6.15                       | 82.52%                 | 76.62%                 | 17.59                  | 14.54                  |
| Central Latin America                | 67.26                         | 49.91                      | 83.03%                 | 82.35%                 | 17.66                  | 15.46                  |
| Southern Latin America               | 8.04                          | 1.87                       | 80.10%                 | 76.09%                 | 18.09                  | 14.78                  |
| Tropical Latin America               | 120.02                        | 29.52                      | 84.71%                 | 82.08%                 | 19.10                  | 16.68                  |
| North Africa and Middle East         | 159.42                        | 72.09                      | 79.00%                 | 73.44%                 | 21.74                  | 22.84                  |
| Central Sub-Saharan Africa           | 123.81                        | 152.50                     | 78.40%                 | 72.16%                 | 22.70                  | 21.26                  |
| Eastern Sub-Saharan Africa           | 388.50                        | 397.59                     | 77.05%                 | 69.41%                 | 22.41                  | 21.10                  |
| Southern Sub-Saharan Africa          | 39.46                         | 21.11                      | 64.80%                 | 61.50%                 | 19.27                  | 19.49                  |
| Western Sub-Saharan Africa           | 292.67                        | 299.58                     | 70.90%                 | 65.31%                 | 21.25                  | 21.38                  |

**Abbreviations:** COPD chronic obstructive pulmonary disease, DALYs disability-adjusted life-years, GBD Global Burden of Diseases Study, SDI socio-demographic index, YLLs years of life lost
region, and high-SDI region but increased in low- and low-middle SDI regions (Fig. 5). Furthermore, the greatest number of deaths \[0.26 (95\% \text{ UI } 0.20, 0.32) \text{ million}\] was observed in the middle-SDI region in 2019, accounting for 37.03% of the total number of global COPD deaths attributable to APM (Table S4). The correlation between SDI and ASMR or ASDR was negative in both those attributable to APM and HAP (ASDR attributable to APM: \(r = -0.28, p < 0.001\); ASDR attributable to HAP: \(r = -0.70, p < 0.001\); Fig. S5).

**Discussion**

To the best of our knowledge, this is the first study to estimate the global spatial and temporal trends of mortality and DALYs due to COPD attributable to both HAP and APM from 1990 to 2019 and compare the differences between the two risk factors using a comprehensive approach. Notably, we found a clear decreasing trend in COPD mortality and DALYs attributable to HAP from solid fuels exposure, whereas an increasing trend was observed for APM. APM overtook HAP to become the leading risk factor for COPD in 2019.

Several previous studies have explored the potential burden of disease attributable to PM air pollution, but only at a national level (Bennett et al. 2019; Chen et al. 2017; Khomenko et al. 2021). For example, one national study from the USA found that approximately 130 thousand deaths due to cardiorespiratory diseases, including COPD, were estimated attributable to \(\text{PM}_{2.5}\) pollution during 1999–2015 (Bennett et al. 2019). Another study conducted in China showed that 250 thousand COPD deaths were attributable to \(\text{PM}_{2.5}\) in 2017 (Liu et al. 2021). However, most of these studies have focused on the outcome of all-cause mortality, and few studies assessed the COPD burden from a global perspective. In this study, using the latest data of the GBD 2019, we mainly focused on the COPD burden attributable to both APM and HAP from solid fuels exposure. The COPD burden attributable to PM pollution estimated in the GBD 2019 was slightly higher than that in GBD 2017. These differences might be due to the newly added data, updated PM exposure assessment, and the changes in the exposure-risk curve (GBD 2019 Risk Factors Collaborators 2020).

The substantial reduction in COPD mortality and DALYs attributable to HAP observed in our study might have benefited from global efforts on mitigation of household PM air pollution (Watts et al. 2018). Universal access to affordable and clean energy is one of the United Nations Sustainable Development Goals, and government interventions have led to achievements in promoting clean energy, especially in Asia and Sub-Saharan Africa (IEA et al. 2019). For example, the Chinese government had implemented a series of measures to reduce HAP, such as China’s National Improved Stove Program and the Air Pollution Prevention and Control Action Plan (Edwards et al. 2007; Huang et al. 2018), which were aimed to reduce air pollution emission by optimizing the industrial infrastructure, increasing clean energy application, and so on. Some studies reported that such transition in household fuels has resulted in a reduction in household \(\text{PM}_{2.5}\) exposure and HAP-associated burden of diseases (Pope et al. 2017; Quansah et al. 2017; Thakur et al. 2021).
Previous measurements were imperative to reduce the HAP-attributable COPD burden. However, around three billion people globally still rely on solid fuels for cooking and heating (IEA et al. 2019).

Comparatively, the number of COPD deaths and DALYs attributable to APM increased worldwide during 1990–2019. This change was probably due to population growth, population aging, and the increase of ambient PM pollution exposure in regions with lower SDI (GBD 2019 Risk Factors Collaborators 2020). After adjusting for population growth and age structure, the global age-standardized rate of mortality and DALYs for COPD decreased slightly. However, over 90% of the world population still lives in areas with APM exceeding the WHO limits (World Health Organization (WHO) 2021), and APM still remains a challenge to global public health.

Interestingly, we found that the proportion of YLLs in DALYs due to COPD attributable to APM and HAP decreased from 1990 to 2019, which might be due to the improvement of COPD treatment, such as better control of COPD risk factors, advanced pharmacotherapy, and other interventions (Rabe and Watz 2017). Similarly, a decreasing trend of the average YLLs per COPD death attributable to APM and HAP was observed. However, the average loss of life due to COPD premature death attributable to APM and HAP in 2019 was still as high as 16.85 years

| Abbreviations: COPD chronic obstructive pulmonary disease, DALYs disability-adjusted life-years, GBD Global Burden of Diseases Study, SDI socio-demographic index, YLLs years of life lost | Number of YLLs, number \( \times 10^3 \) | Proportion of YLLs in DALYs | Average YLLs per death |
|---|---|---|---|
| Global | 6710.77 | 11,708.53 | 84.07% | 75.96% | 19.08 | 16.85 |
| Gender | | | | | |
| Male | 4222.49 | 7253.28 | 86.78% | 80.47% | 20.02 | 17.62 |
| Female | 2488.28 | 4455.25 | 79.83% | 69.61% | 17.68 | 15.72 |
| SDI quintile | | | | | |
| Low SDI | 287.95 | 1017.38 | 82.64% | 78.10% | 21.41 | 19.13 |
| Low-middle SDI | 1267.55 | 4368.10 | 85.61% | 80.88% | 20.94 | 18.33 |
| Middle SDI | 2724.27 | 4195.93 | 86.42% | 74.94% | 19.50 | 16.30 |
| High-middle SDI | 1968.25 | 1724.52 | 84.98% | 70.99% | 17.88 | 14.60 |
| High SDI | 461.68 | 400.46 | 67.55% | 61.84% | 16.53 | 14.30 |
| GBD region | | | | | |
| High-income Asia Pacific | 38.43 | 63.08 | 60.24% | 53.28% | 15.77 | 11.84 |
| Central Asia | 46.12 | 57.09 | 82.62% | 78.90% | 20.95 | 20.56 |
| East Asia | 3611.58 | 4013.85 | 89.66% | 77.28% | 21.53 | 14.84 |
| South Asia | 1533.88 | 5669.80 | 82.65% | 78.15% | 20.64 | 14.83 |
| Southeast Asia | 252.05 | 452.15 | 78.17% | 70.35% | 20.51 | 18.63 |
| Australasia | 4.34 | 4.15 | 70.13% | 62.29% | 17.03 | 14.04 |
| Caribbean | 6.82 | 17.64 | 78.99% | 79.09% | 18.16 | 17.51 |
| Oceania | 2.48 | 6.88 | 90.54% | 88.96% | 23.69 | 23.09 |
| Central Europe | 132.22 | 85.95 | 78.80% | 68.87% | 19.94 | 16.71 |
| Eastern Europe | 234.40 | 75.27 | 82.05% | 75.60% | 19.64 | 18.21 |
| Western Europe | 291.70 | 186.09 | 71.32% | 63.81% | 15.48 | 12.89 |
| High-income North America | 142.15 | 116.42 | 60.08% | 62.31% | 17.55 | 15.73 |
| Andean Latin America | 9.59 | 18.47 | 83.08% | 75.31% | 17.55 | 14.03 |
| Central Latin America | 59.69 | 129.87 | 82.82% | 80.58% | 17.30 | 14.88 |
| Southern Latin America | 20.89 | 33.32 | 80.98% | 76.81% | 18.43 | 15.04 |
| Tropical Latin America | 59.55 | 88.50 | 86.23% | 82.37% | 19.83 | 17.00 |
| North Africa and Middle East | 165.12 | 408.70 | 74.26% | 64.77% | 21.08 | 19.73 |
| Central Sub-Saharan Africa | 12.32 | 37.46 | 79.59% | 71.04% | 22.64 | 21.50 |
| Eastern Sub-Saharan Africa | 20.46 | 62.28 | 77.73% | 69.76% | 22.11 | 20.99 |
| Southern Sub-Saharan Africa | 25.63 | 48.63 | 67.14% | 64.53% | 20.04 | 19.48 |
| Western Sub-Saharan Africa | 41.36 | 132.93 | 70.02% | 64.29% | 20.79 | 20.57 |

Table 2 The number of YLLs, proportion of YLLs in DALYs, and average YLLs per death due to COPD attributable to ambient particulate matter pollution in 1990 and 2019

(IEA et al. 2019).
and 18.01 years, respectively, which were close to 23% and 25% of global life expectancy (World Health Organization (WHO) 2020). Given the high average YLL per death, more attention should be allocated to COPD amelioration efforts.

In 2019, considerable regional differences in the age-standardized mortality rate and DALYs of COPD attributable to HAP and APM were observed. These differences could be attributable to multiple factors, such as the geographical differences in the composition of the PM and the influence of SDI. Differences in chemical compositions with different toxicity might result in different health impacts (Yang et al. 2019). Moreover, the correlation analysis in this study revealed a negative correlation between SDI and the ASMR of COPD attributable to HAP and APM. The finding is consistent with previous studies (Liu et al. 2008; Siddharthan et al. 2018), suggesting the development inequalities across different SDI regions may affect the impact of PM on COPD death and DALYs. As low- and middle-income countries mainly rely on traditional energy sources for household cooking and heating, HAP exposure levels are much higher in these countries than in high-income countries (Gordon et al. 2014). In addition, the lack of high-quality public health care in low-income countries due to economic deprivation and the relatively poor health awareness of the population may amplify the COPD burden due to PM pollution (Bazargani et al. 2014; GBD 2019 Demographics Collaborators 2020). Interestingly, the largest mortality and DALYs attributable to APM were observed in the middle-SDI region, which was possibly due to the rapid industrialization in these countries driven by massive energy
consumption and power generation (GBD 2019 Risk Factors Collaborators 2020). On the other hand, a series of air quality control measures were conducted in the study period in countries with higher SDI, such as coordinated policies and other interventions on industries and vehicles, which promoted the reduction of APM in these regions (Burns et al. 2020).

Given the increasing trend in COPD burden attributable to APM observed in our study, continued efforts are needed to mitigate ambient air pollution to reduce COPD disease burden, especially in more developed regions (i.e., regions with middle and high SDI). As for low-SDI regions, HAP still remains an important risk factor to COPD, and effective measures targeting household air pollution are needed, such as the promotion of the transitions from solid fuels to clean energy.

In subgroup analyses, we found higher age-standardized mortality and DALYs of COPD attributable to PM in males than in females, except for DALYs attributable to HAP in Oceania and Central Sub-Saharan Africa. Such sex disparity, especially those attributable to HAP, might seem to be unplausible, which could be partially due to the improvement in household energy consumption, the differences in risk behaviors related to COPD, and the higher number of COPD mortality in males (GBD Chronic Respiratory Disease Collaborators 2020; IEA et al. 2019). Males had a greater prevalence of some other risk factors of COPD (GBD 2019 Risk Factors Collaborators 2020, GBD Chronic Respiratory Disease Collaborators 2020), such as smoking and occupational dust exposure, which might influence the effect of PM air pollution on COPD burden. For example, both epidemiological and animal studies have found that the joint effect of smoking and particulate matter on COPD was more pronounced than their separate effects (Su et al. 2021; Wang et al. 2019). However, the underlying mechanisms remain unknown, and more studies are needed to illuminate this sex difference.

Although APM and HAP are mainly composed of air-suspended particles, their sources are different. In the GBD 2019, HAP mainly originated from the combustion of solid fuels, in contrast to APM which had more different types of sources, such as traffic pollution and industrial pollution (GBD 2019 Risk Factors Collaborators 2020, Zhang et al. 2019). These different sources for APM and HAP may result in different compositions, leading to different toxic effects on cardiopulmonary function (Wu et al. 2014;
Zhou et al. 2021). For example, one study found that HAP was associated with a decrement in forced expiratory volume in the first second (FEV1), while APM was associated with a reduction in peak expiratory flow (PEF) (Chi et al. 2019). Other studies also reported that PM from different constituents and sources had different cardiopulmonary effects (Wu et al. 2016; Zhang et al. 2021).

Our study has some limitations. First, the estimates in the GBD 2019 depended on the availability and quality of the primary data in each country or territory with inevitable variations (GBD 2019 Diseases and Injuries Collaborators 2020, Li et al. 2020). Second, misdiagnosis and underdiagnosis due to lack of adequate equipment might lead to underestimation of COPD burden attributable to PM pollution (Li et al. 2020). Third, HAP can originate from various sources other than solid fuel combustion, such as tobacco smoke, furnishing, and construction materials (Ni et al. 2020), whereas HAP exposure in the GBD study was estimated only based on the consumption of solid fuels (GBD 2019 Risk Factors Collaborators 2020). This might have led to an underestimation of the COPD burden attributable to HAP. Fourth, there is possible residual confounding due to unmeasured or unknown confounding factors in these studies included in the GBD 2019, which could have affected the assessment of the risk curves. Finally, the GBD 2019 did not take into account PM components, though studies have shown that different PM components have different health effects (Yang et al. 2019). These limitations increase the uncertainty of the results, and therefore, more studies on HAP and COPD, as well as the component of PM and COPD, are needed in the future.

Fig. 5 The age-standardized rates of COPD mortality and DALYs attributable to household air pollution from solid fuels (A) and ambient particulate matter pollution (B) from 1990 to 2019 by socio-demographic index region. COPD, chronic obstructive pulmonary disease; SDI, socio-demographic index.
Conclusions

In conclusion, we found that the number of mortality and DALYs for COPD attributable to HAP decreased markedly over the past three decades, while those attributable to APM increased. Geographical differences were observed as the global COPD burden attributable to APM in 2019 was higher than those due to HAP in high- and middle-SDI regions, whereas in low-SDI regions, HAP was still a major contributor. More effective control measures should be implemented to reduce the COPD burden associated with APM pollution, while improvement of household clean energy is still needed to reduce household air pollution in low-SDI countries.

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Data availability Data sources are available in the Global Burden of Disease Study 2019 (http://ghdx.healthdata.org/gbd-results-tool).

Declarations

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