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Global lung cancer burden attributable to air fine particulate matter and tobacco smoke exposure: spatiotemporal patterns, sociodemographic characteristics, and transnational inequalities from 1990 to 2021

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Abstract

Background Air fine particulate matter and tobacco smoke exposure are primary risk factors for lung cancer. However, their recent global exposure levels, attributable burden, and patterns of inequalities remain insufficiently quantified.

Methods Utilizing the Global Burden of Disease 2021 study, we analyzed exposure levels of air fine particulate matter (ambient and household) and tobacco smoke (active and secondhand) by age-standardized summary exposure value (ASEV). Age-standardized mortality rate (ASMR) and age-standardized disability-adjusted life years rate (ASDR) were used to assess their attributable lung cancer burden globally. Temporal patterns were examined using weighted average annual percentage change (WAPC). Cross-national health inequalities were evaluated with the concentration index (CI) for ASMR and slope index of inequality (SII) for ASDR.

Results In 2021, air fine particulate (PM2.5) exposure peaked in low socio-demographic index (SDI) countries, while tobacco exposure was highest in high-middle SDI regions. Globally, air PM2.5 contributed to 374.21 thousand (95% uncertainty interval [UI]: 236.36, 520.26) lung cancer deaths [ambient: 297.60 thousand (95% UI: 183.71, 414.74); household: 76.48 thousand (95% UI: 28.6, 187.34)], whereas tobacco exposure caused 1,238.65 thousand (95% UI: 1,075.69, 1,423.12) deaths [active smoking: 1,195.80 thousand (95% UI: 1,054.67, 1,359.22); secondhand smoke: 97.91

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thousand (95% UI: 11.96, 184.91)]. High-middle SDI countries and the Southeast Asia, East Asia, and Oceania regions bore the greatest burden. The attributable burden for males exceeded that for females by approximately twofold for air PM2.5 and fivefold for tobacco exposure. The 55 + age group showed disproportionately high impacts despite lower exposure. From 1990 to 2021, the ASMR attributable to air PM2.5 and tobacco exposure changed annually by -1.32% (95% confidence interval [CI]: -1.48, -1.16) and −0.95% (95% CI: -1.03, -0.88), respectively. The attributable ASDR also showed declining trends. Regarding translational health inequality, the air PM2.5 attributable lung cancer burden shifted from high to low SDI countries (CI: 0.05 to -0.10, SII: 31.00 to -35.50), while the tobacco-attributable burden persisted in higher SDI countries, albeit with diminishing inequalities (CI: 0.34 to 0.25, SII: 572.20 to 304.60).

Conclusions This up-to-date study provides a comprehensive perspective on air fine particulate matter and tobacco smoke exposure's impact on lung cancer burden, highlighting its widespread nature, substantial impact, unequal distribution, and preventability. The findings call for targeted interventions and global cooperation across socioeconomic levels to reduce the overall lung cancer burden in the post-pandemic era.

Keywords Lung cancer, Particulate matter, Tobacco use, Global burden of disease, Health inequalities

Background

Lung cancer is one of the most prevalent and lethal malignancies worldwide. In 2022, it accounted for the highest cancer incidence (12.4%, 2.48 million new cases) and mortality rates (18.7%, 1.81 million deaths), emerging as a critical global public health issue [1]. Air pollution poses a pervasive challenge, with 99% of the world's population residing in areas with suboptimal air quality and 47% exposed to indoor air pollution [2]. In 2021, air pollution was attributed to 8.1 million deaths globally, becoming the second leading risk factor for mortality [3]. Tobacco use remains widespread, with 36.7% of males and 7.8% of females using tobacco products in 2020 [4]. This results in over 8 million annual deaths worldwide, including 7 million from direct use and 1.3 million non-smokers succumbing to secondhand smoke exposure [5].

Air pollution and tobacco exposure are widely recognized as the two primary risk factors for lung cancer [6–8]. Fine particulate matter (PM2.5), including particles from tobacco combustion, can penetrate deep into the lungs and enter the bloodstream, elevating lung cancer risk. Large-scale epidemiological studies have revealed a strong correlation between PM pollution and lung cancer incidence and mortality [6, 9]. Animal experiments have shown that PM2.5 promotes lung cancer development by inducing inflammation in healthy lung tissue cells with pre-existing carcinogenic gene mutations [10]. Genomic analyses have demonstrated that smoking increases mutational burden, cellular heterogeneity, and frequency of driver mutations in human alveolar epithelial cells, increasing lung cancer risk [11]. The International Agency for Research on Cancer (IARC) has classified ambient air pollution (particularly PM2.5), household solid fuel pollution, smoking, and secondhand smoke as Group 1 carcinogens [12, 13].

As industrialization advance, particularly in emerging economies, ambient and household air particulate pollution have significantly change [14]. Despite a global decline in tobacco use from 2000 to 2022, population growth has maintained a substantial number of users. This complex dual threat could potentially increase the global lung cancer burden, exerting immense pressure on healthcare systems and economies worldwide [15]. In the context of evolving air pollution and tobacco smoke epidemics, especially amid the COVID-19 pandemic, a comprehensive assessment of air pollution and tobacco-attributable lung cancer burden at global and regional levels is crucial. Previous investigations extending only to 2017–2019 have scrutinized individual risk factors such as ambient fine particulate matter [16, 17], household air pollution [18], and smoking [19, 20] (without detailed study of secondhand smoke) in relation to the global lung cancer burden. However, an integrated analysis of fine particulate matter (from both ambient and household sources) and tobacco smoke (including active and secondhand exposures) was lacking. Moreover, extant research does not explore the intricate patterns of risk exposure and cross-national disparities, creating a knowledge gap in our understanding of the current global landscape of lung cancer burden attributable to these risk factors. This gap has limited our ability to elucidate long-term trends and persistent disparities in this critical area of public health.

This study utilizes the up-to-date Global Burden of Disease (GBD) 2021 study, aiming to comprehensively investigate: (1) exposure levels to air fine particulate matter (ambient and household air pollution) and tobacco smoke (active smoking and secondhand smoke); (2) attributable tracheal, bronchus, and lung cancer mortality and disability-adjusted life years at global, regional, and national levels in 2021, considering sociodemographic features; (3) trends in the corresponding lung cancer burden; and (4) international health inequalities over the 32-year period from 1990 to 2021. This study may have significant practical implications for alleviating the global disease burden, particularly in lung cancer prevention and control.

Methods

Assessment of lung cancer disease burden

The Global Burden of Disease, Injuries, and Risk Factors Study (GBD) 2021 represents the latest update, providing detailed estimates of risk factor and disease burden from 1990 to 2021, which encompasses 7 super-regions and 204 countries and territories [21]. It defines tracheal, bronchus, and lung cancers using ICD-10 codes C33 and C34-C34.92. Lung cancer mortality estimates are based on an extensive array of 30,078 data points from vital registrations, surveillance systems, surveys/censuses, and cancer registries, which subjected to rigorous quality control (More details see supplementary materials). Sophisticated statistical models were employed by GBD for estimating lung cancer outcomes due to their ability to handle complex epidemiological data with varying levels of completeness and quality [22]. Mortality was estimated using the Cause of Death Ensemble model (CODEm), which was chosen for its superior performance in integrating multiple statistical methods and considering relevant covariates. Incidence was derived through the mortality-to-incidence ratio (MIR) method because of its effectiveness in contexts where direct incidence data are limited. In this approach, MIR was first estimated using either spatiotemporal Gaussian process regression or negative binomial regression models, accounting for factors such as gender, age, time, and healthcare quality index. Final cancer mortality estimates were then divided by the estimated MIR to calculate incidence rates.

Prevalence was generated using DisMod-MR 2.1 Bayesian meta-regression, which was selected for its ability to reconcile data from multiple sources and fill gaps in data-sparse regions. The calculation of disability-adjusted life years (DALYs) involved combining years of life lost (YLLs) and years lived with disability (YLDs), providing a comprehensive measure of disease burden that accounts for both mortality and morbidity. YLLs were calculated to reflect premature mortality, while YLDs were computed based on prevalence and disability weights. These weights were determined through large-scale multinational surveys to ensure cross-cultural validity and were designed to quantify health state severity on a scale from 0 (perfect health) to 1 (death). GBD stratified lung cancer into four stages with specific disability weights: diagnosis and primary therapy (0.288), controlled phase (0.049), metastatic phase (0.451), and terminal phase (0.540) [23]. This stratification approach was implemented to more accurately assess the impact of lung cancer on quality of life across different disease stages and to better capture the varying levels of disability experienced by patients throughout the disease progression.

Estimation of risk factor exposure

This study focuses on air fine particulate (ambient and household) and tobacco smoke (active and secondhand) as risk factors. Ambient fine particulate is defined as population-weighted annual average concentration of particulate matter with an aerodynamic diameter less than 2.5 μm (PM2.5) in μg/m3. Household air pollution (HAP) refers to PM2.5 exposure resulting from the use of solid fuels (e.g., wood, coal, dung, and agricultural residues) in households. Active tobacco smoking was assessed across all forms of smoked tobacco products, not just cigarettes, including cigarettes, cigars, pipes, hookah, and other regional smoking products. Smokers are defined as individuals currently using any smoked tobacco products daily or occasionally. Former smokers are defined as individuals who have abstained from any smoked tobacco products for at least six months. Never smokers are defined as individuals who have never smoked any tobacco product or have smoked fewer than 100 cigarettes (or equivalent amount of other tobacco products) in their lifetime. Secondhand smoke exposure is defined as current exposure of non-smokers (including never smokers and former smokers) to tobacco smoke at home or in the workplace. Following the Global Burden of Disease methodology, household exposure was determined based on living with at least one daily smoker, while workplace exposure was determined using self-reported data from cross-sectional surveys. For workplace exposure, individuals were considered exposed if they reported regular exposure to tobacco smoke while working primarily indoors, with no minimum duration threshold specified. Non-smokers were defined as all persons who were not daily smokers, including ex-smokers and occasional smokers.

Exposure assessment methodologies vary across different risk factors and are synthesized for air fine particulate matter and tobacco smoke. Ambient particulate exposure utilizes the WHO database, meteorological and satellite data, integrated through GEOS-Chem and Bayesian models. HAP assessment uses household surveys and WHO data, employing proportion models for solid fuel use and PM2.5 mapping. Smoking exposure is based on survey microdata and the WHO database, using spatiotemporal Gaussian process regression models. Secondhand smoke exposure utilizes self-reported data and active smoking prevalence to calculate exposure probabilities. All assessments consider Theoretical Minimum Risk Exposure Levels (TMRELs) and multiple covariates including gender, age, geography, and annual variations to enhance estimate accuracy.

Attributable lung cancer mortality and dalys

This study primarily focuses on two health risk indicators: lung cancer mortality rates (Per 100,000) and lung cancer disability-adjusted life years rate (DALYs, Per 100,000). The relative risk assessment phase involved the collection and analysis of extensive research data on the health impacts of ambient air pollution, household solid fuel use, smoking, and secondhand smoke exposure. Risk curves were generated using MR-BRT (Meta-Regression-Bayesian, Regularized, Trimmed) meta-regression analysis. Subsequently, population attributable fractions (PAFs) were calculated by integrating relative risks and exposure levels, stratified by multiple factors. These PAFs reflect the disparity in lung cancer risk between current and ideal exposure levels. The study innovatively adopted a joint PAF methodology, accounting for the overlap and interactive effects between risk factors, thereby enhancing the accuracy of attribution estimates. Through proportional allocation, the specific contributions of individual pollution sources were further delineated. Ultimately, the study quantified the lung cancer burden attributable to each risk factor in terms of deaths, DALYs, YLLs, and YLDs, providing a comprehensive assessment.

Statistical data analysis

This study employed multiple indicators to assess the impact of air particulate pollution and tobacco exposure on lung cancer. The Standardized Summary Exposure Value (SEV), ranging from 0 (no risk exposure) to 100 (maximum risk exposure), was used to evaluate exposure levels. Age standardization and the Socio-demographic Index (SDI) were utilized to facilitate cross-regional and temporal comparisons, accounting for differences in population age structure and socioeconomic conditions. The SDI, integrating total fertility rate, mean education years, and per capita income, categorized regions into five groups: high, high-middle, middle, low-middle, and low SDI. Trend analysis employed the Weighted Average Annual Percent Change (WAPC), a weighted average of segmented annual percentage changes for better characterizing trends. Health inequality was analyzed using the Concentration Index (CI) and the Slope Index of Inequality (SII). CI quantifies health distribution across socioeconomic groups, ranging from − 1 to 1, with 0 indicating perfect equality. Negative values suggest health concentration among poorer groups, while positive values indicate the opposite. SII demonstrates health disparities between highest and lowest socioeconomic groups; larger absolute values signify greater health inequalities. For disease burden forecasting, the Bayesian Age-Period-Cohort (BAPC) model was used, generating age-standardized prediction rates. To maintain accuracy and continuity, the 2020 ambient air exposure data, affected by the unprecedented COVID-19 pandemic, was excluded from the prediction model. All statistical analyses were conducted using the R (version 4.4.1).

Results

Geographical disparities

In 2021, the global age-standardized summary exposure value (ASEV) for air PM2.5 was 39.63 (95% uncertainty interval [UI]: 33.07–47.50). Sub-Saharan Africa was primarily affected by household PM2.5, while the Middle East, East Asia, and South Asia experienced predominantly ambient PM2.5. Air PM2.5 was attributable to 374.21 thousand (95% UI: 236.36-520.26) lung cancer deaths globally [ambient: 297.60 thousand (95% UI: 183.71, 414.74); household: 76.48 thousand (95% UI: 28.60, 187.34)], with associated disability-adjusted life years (DALYs) loss of 8934.12 thousand (95% UI: 5681.09, 12409.78) years [ambient: 6964.53 thousand (95% UI: 4284.31, 9719.78); household: 1966.43 thousand (95% UI: 758.40, 4632.39)]. Southeast Asia, East Asia, and Oceania exhibited the highest age-standardized mortality rate (ASMR) of 8.81 (95% UI: 5.49–12.36) and age-standardized DALYs rate (ASDR) of 198.2 (95% UI: 124.22-277.06) per 100,000 population (Tables 1 and 2, Supplementary Table 1; Fig. 1, Supplementary Fig. 1).

For tobacco exposure, the global ASEV was 28.26 (95% UI: 27.65–28.86). Exposure was extensive in most regions, particularly in Central Europe, Eastern Europe, Central Asia, Southeast Asia, East Asia, and Oceania. Tobacco exposure was associated with 1238.65 thousand (95% UI: 1075.69-1423.12) lung cancer deaths globally [smoking: 1195.80 thousand (95% UI: 1054.67-1359.22); secondhand: 97.91 thousand (95% UI: 11.96-184.91)] and 28768.02 thousand (95% UI: 24948.94-33061.21) years of DALYs loss [smoking: 27713.69 thousand (95% UI: 24404.59-31596.58); secondhand: 2355.87 thousand (95% UI: 290.21–4443.00)]. Southeast Asia, East Asia, and Oceania recorded the highest tobacco-attributable ASMR of 22.48 (95% UI: 18.04–27.75) and ASDR of 501.99 (95% UI: 398.15-621.15) per 100,000 population (Tables 1 and 2, Supplementary Table 2; Fig. 1, Supplementary Fig. 2).

Socioeconomic disparities

In 2021, low SDI countries had the highest overall air PM2.5 exposure level (ASEV) of 73.51 (95% UI: 64.69–83.51), primarily due to high household PM2.5 exposure of 55.28 (95% UI: 42.31–68.72). High SDI countries had the lowest overall air PM2.5 ASEV of 12.52 (95% UI: 9.27–16.19). Ambient PM2.5 was concentrated in high-middle and middle SDI countries, while household PM2.5 was most severe in low SDI countries. The burden attributable to air PM2.5 was highest in high-middle SDI countries [ASMR: 6.22 (95% UI: 3.95–8.83); ASDR: 145.62 (95% UI: 92.82-205.83)] and lowest in high SDI

Table 1 Exposure level of air fine particulate matter and tobacco smoke in 2021 and their trends from 1990 to 2021

	Air fine particulate matter		Tobacco smoke	
	Exposure (2021)	**Trend (1990–2021)**	**Exposure (2021)**	**Trend (1990–2021)**
	ASEV (95% UI)	WAPC (%, 95% CI)	ASEV (95% UI)	WAPC (%, 95% CI)
Global	39.63 (33.07, 47.50)	-1.02 (-1.11, -0.92)	28.26 (27.65, 28.86)	-1.15 (-1.17, -1.12)
SDI Groups				
High SDI	12.52 (9.27, 16.19)	-1.35 (-1.44, -1.26)	29.23 (28.45, 30.00)	-1.34 (-1.38, -1.31)
High-middle SDI	25.18 (20.62, 30.64)	-1.89 (-2.02, -1.77)	40.31 (39.30, 41.41)	-0.46 (-0.48, -0.44)
Middle SDI	33.47 (27.16, 40.84)	-1.90 (-2.02, -1.77)	30.45 (29.72, 31.22)	-1.04 (-1.07, -1.00)
Low-middle SDI	53.43 (44.56, 64.55)	-1.04 (-1.15, -0.94)	25.50 (24.67, 26.31)	-1.01 (-1.05, -0.96)
Low SDI	73.51 (64.69, 83.51)	-0.29 (-0.34, -0.24)	16.33 (15.81, 16.75)	-1.18 (-1.27, -1.09)
World Bank Regions				
Central Europe, Eastern Europe, and Central Asia	18.07 (13.62, 23.09)	-1.80 (-1.91, -1.68)	37.27 (36.33, 38.12)	-0.44 (-0.53, -0.36)
High-income regions*	9.17 (6.11, 12.71)	-2.17 (-2.31, -2.02)	29.30 (28.63, 30.05)	-1.37 (-1.42, -1.33)
Latin America and Caribbean	18.49 (13.59, 24.44)	-2.06 (-2.19, -1.92)	18.72 (18.04, 19.42)	-2.19 (-2.28, -2.10)
North Africa and Middle East	36.78 (31.15, 43.16)	-0.01 (-0.10, 0.07)	32.34 (31.47, 33.09)	-0.39 (-0.41, -0.38)
South Asia	59.33 (50.41, 70.81)	-0.94 (-1.04, -0.84)	24.09 (22.90, 25.27)	-1.30 (-1.39, -1.21)
Southeast Asia, East Asia, and Oceania	35.95 (28.82, 44.25)	-2.12 (-2.27, -1.97)	41.06 (39.80, 42.38)	-0.42 (-0.46, -0.37)
Sub-Saharan Africa	64.35 (55.85, 74.47)	-0.35 (-0.39, -0.30)	13.28 (12.90, 13.55)	-1.18 (-1.23, -1.12)
Sex				
Female	39.31 (32.68, 47.17)	-1.00 (-1.09, -0.91)	23.33 (22.61, 23.96)	-1.37 (-1.41, -1.33)
Male	39.96 (33.42, 47.84)	-1.03 (-1.12, -0.94)	33.31 (32.49, 34.18)	-0.97 (-1.00, -0.95)
Age				
≥ 25 years and < 55 years	42.58 (36.89, 49.71)	-0.99 (-1.08, -0.91)	24.09 (23.10, 24.68)	-1.25 (-1.29, -1.22)
≥ 55	36.58 (31.38, 43.19)	-1.21 (-1.33, -1.10)	17.47 (16.85, 18.11)	-0.84 (-0.89, -0.79)

* ASEV, age-standardized summary exposure value

* UI uncertain interval; CI, confidence interval

* WAPC, weighted average annual percentage change

* SDI, Socio-demographic Index; High-income regions (Australasia, High-income Asia Pacific, High-income North America, Southern Latin America, Western Europe)

countries [ASMR: 2.23 (95% UI: 1.27–3.23); ASDR: 49.61 (95% UI: 28.27–70.76)] (Tables 1 and 2, Supplementary Table 1; Supplementary Fig. 3–4). Global tobacco exposure also demonstrated a similar SDI-related pattern. High-middle SDI countries had the highest tobacco ASEV of 40.31 (95% UI: 39.30-41.41), including the highest smoking exposure rate of 22.76 (95% UI: 22.10–23.50) and secondhand smoke exposure rate of 46.84 (95% UI: 44.19–48.25). Low SDI countries had the lowest exposure rate of 16.33 (95% UI: 15.81–16.75). The burden attributable to tobacco exposure was highest in high-middle SDI countries [ASMR: 21.36 (95% UI: 18.05, 25.18); ASDR: 506.41 (95% UI: 428.35-599.67)] and lowest in low SDI countries [ASMR: 2.08 (95% UI: 1.66–2.54); ASDR: 51.07 (95% UI: 40.41–62.81)] (Tables 1 and 2, Supplementary Table 2; Supplementary Figs. 3 and 5).

Gender disparities

In 2021, global air PM2.5 ASEV showed no significant overall gender differences, but subtle variations were observed. Men had slightly higher ambient PM2.5 exposure [29.33 (95% UI: 20.52–36.43) vs. 27.37 (95% UI: 18.21–34.72)], while women experienced marginally higher household PM2.5 [18.16 (95% UI: 10.96–30.11) vs. 16.47 (95% UI: 9.70-27.33)]. However, the health impacts of air PM2.5 demonstrated marked gender disparities: male ASMR [6.37 (95% UI: 3.97–9.03)] and ASDR [146.93 (95% UI: 91.82-207.58)] attributable to total air PM2.5 were approximately twice those of females. This disparity was evident in both ambient and household PM2.5 effects (Tables 1 and 2, Supplementary Table 1; Supplementary Fig. 6). Global tobacco smoke exposure also exhibited significant gender differences: male ASEV [33.31 (95% UI: 32.49–34.18)] exceeded female ASEV [23.33 (95% UI: 22.61–23.96)]. This disparity was more pronounced in health impacts: male tobacco exposure-attributable ASMR [25.03 (95% UI: 21.61–28.89)] and ASDR [561.60 (95% UI: 484.02-650.16)] were substantially higher than female rates [ASMR: 5.36 (95% UI: 4.21–6.57), ASDR: 119.31 (95% UI: 93.03-145.86)]. This difference was primarily reflected in smoking impacts, with male smoking-attributable ASMR and ASDR approximately five times higher than female rates. Secondhand smoke exposure effects showed a slightly higher trend in males, but the difference was relatively small (Tables 1 and 2, Supplementary Table 2; Supplementary Fig. 7).

Age-related disparities

Global air PM2.5 ASEV showed significant age-related differences in 2021: the 25–55 age group [42.58 (95% UI:

Table 2 Lung cancer burden attributable to air fine particulate matter and tobacco smoke in 2021 and their trends from 1990 to 2021

	Mortality (95% UI) in 2021			Trend (1990–2021)	Disability-Adjusted Life Years (95% UI) in 2021			Trend (1990–2021)
	Number (×10^3)	Mortality rate (/10^5)	ASMR (/10^5)	WAPC (%, 95% CI)	Number (×10^3)	DALYs rate (/10^5)	ASDR (/10^5)	WAPC (%, 95% CI)
Air fine particulate matter	374.21 (236.36, 520.26)	4.74 (3, 6.59)	4.34 (2.74, 6.04)	-1.32 (-1.48, -1.16)	8934.12 (5681.09, 12409.78)	113.21 (71.99, 157.26)	102.08 (64.89, 141.62)	-1.64 (-1.80, -1.49)
SDI Groups								
High SDI	48.53 (27.70, 70.72)	4.44 (2.53, 6.46)	2.23 (1.27, 3.23)	-2.73 (-2.92, -2.54)	989.77 (561.81, 1421.10)	90.47 (51.35, 129.89)	49.61 (28.27, 70.76)	-3.10 (-3.31, -2.90)
High-middle SDI	124.60 (79.14, 176.65)	9.55 (6.07, 13.55)	6.22 (3.95, 8.83)	-1.29 (-1.49, -1.10)	2903.79 (1851.05, 4099.49)	222.68 (141.95, 314.37)	145.62 (92.82, 205.83)	-1.75 (-1.94, -1.55)
Middle SDI	148.63 (91.55, 208.34)	6.07 (3.74, 8.51)	5.66 (3.49, 7.96)	-1.14 (-1.33, -0.95)	3595.57 (2244.13, 5032.68)	146.85 (91.65, 205.54)	129.71 (80.65, 181.5)	-1.47 (-1.65, -1.30)
Low-middle SDI	40.60 (26.07, 54.81)	2.11 (1.36, 2.85)	2.84 (1.82, 3.83)	-0.45 (-0.53, -0.38)	1112.98 (716.55, 1503.84)	57.93 (37.30, 78.28)	72.66 (46.67, 98.15)	-0.49 (-0.56, -0.42)
Low SDI	11.55 (7.45, 15.73)	1.03 (0.67, 1.41)	2.36 (1.54, 3.21)	-0.32 (-0.40, -0.23)	324.58 (207.27, 444.11)	29.05 (18.55, 39.75)	58.84 (37.73, 80.23)	-0.44 (-0.53, -0.36)
World Bank Regions								
Central Europe, Eastern Europe, and Central Asia	19.33 (11.5, 27.91)	4.63 (2.75, 6.68)	2.92 (1.74, 4.22)	-3.12 (-3.29, -2.95)	476.19 (283.09, 685.66)	113.97 (67.75, 164.10)	73.63 (43.71, 105.95)	-3.53 (-3.71, -3.35)
High-income regions*	38.88 (20.94, 58.47)	3.56 (1.92, 5.36)	1.69 (0.92, 2.55)	-3.37 (-3.58, -3.15)	765.72 (422.37, 1153.41)	70.14 (38.69, 105.66)	36.79 (20.44, 55.38)	-3.77 (-4.00, -3.54)
Latin America and Caribbean	9.60 (5.70, 13.75)	1.62 (0.96, 2.31)	1.56 (0.93, 2.24)	-2.60 (-2.75, -2.45)	230.05 (135.87, 329.71)	38.72 (22.87, 55.50)	36.54 (21.60, 52.38)	-2.73 (-2.89, -2.58)
North Africa and Middle East	15.71 (9.80, 22.36)	2.52 (1.57, 3.59)	3.6 (2.23, 5.12)	-0.05 (-0.23, 0.13)	417.71 (261.11, 594.19)	67.05 (41.91, 95.38)	86.17 (53.78, 122.46)	-0.30 (-0.47, -0.12)
South Asia	33.87 (21.96, 46.7)	1.83 (1.19, 2.53)	2.29 (1.48, 3.15)	-0.45 (-0.55, -0.35)	942.92 (609.52, 1295.87)	51.06 (33.01, 70.18)	59.64 (38.61, 82.06)	-0.45 (-0.55, -0.36)
Southeast Asia, East Asia, and Oceania	246.05 (153.71, 344.13)	11.26 (7.03, 15.75)	8.81 (5.49, 12.36)	-0.94 (-1.20, -0.68)	5801.53 (3641.23, 8113.29)	265.52 (166.65, 371.32)	198.20 (124.22, 277.06)	-1.31 (-1.56, -1.06)
Sub-Saharan Africa	10.77 (6.84, 14.59)	0.95 (0.60, 1.29)	2.36 (1.53, 3.19)	-0.35 (-0.40, -0.30)	300.00 (188.90, 409.74)	26.47 (16.67, 36.16)	57.79 (36.60, 78.45)	-0.53 (-0.58, -0.48)
Sex								
Female	121.79 (76.05, 168.79)	3.10 (1.93, 4.29)	2.63 (1.64, 3.64)	-0.91 (-1.07, -0.75)	2839.79 (1788.76, 3943.29)	72.22 (45.49, 100.29)	62.00 (39.07, 86.08)	-1.22 (-1.37, -1.06)
Male	252.42 (157.29, 356.20)	6.38 (3.97, 9.00)	6.37 (3.97, 9.03)	-1.53 (-1.70, -1.36)	6094.33 (3813.18, 8640.72)	153.92 (96.31, 218.23)	146.93 (91.82, 207.58)	-1.83 (-1.99, -1.67)
Age								
≥ 25 years and < 55 years	45.21 (29.24, 62.39)	1.20 (0.78, 1.66)	——	-1.57 (-1.77, -1.37)	1934.36 (1252.79, 2668.25)	51.32 (33.23, 70.78)	——	-1.65 (-1.85, -1.44)
≥ 55	329.00 (207.14, 459.00)	22.14 (13.94, 30.89)	——	-1.16 (-1.34, -0.99)	6999.76 (4428.81, 9773.12)	471.05 (298.04, 657.69)	——	-1.48 (-1.63, -1.33)
Tobacco smoke	1238.65 (1075.69, 1423.12)	15.7 (13.63, 18.03)	14.35 (12.45, 16.49)	-0.95 (-1.03, -0.88)	28768.02 (24948.94, 33061.21)	364.55 (316.16, 418.95)	327.78 (284.22, 376.81)	-1.27 (-1.34, -1.20)
SDI Groups								
High SDI	356.04 (315.58, 393.65)	32.54 (28.84, 35.98)	16.61 (14.84, 18.3)	-1.73 (-1.84, -1.62)	7536.85 (6787.94, 8256.69)	688.90 (620.44, 754.69)	377.82 (341.72, 412.93)	-2.05 (-2.17, -1.93)
High-middle SDI	430.57 (364.00, 507.63)	33.02 (27.91, 38.93)	21.36 (18.05, 25.18)	-0.58 (-0.66, -0.49)	10188.02 (8624.14, 12064.66)	781.27 (661.34, 925.18)	506.41 (428.35, 599.67)	-1.01 (-1.09, -0.94)
Middle SDI	369.03 (296.88, 446.87)	15.07 (12.12, 18.25)	13.97 (11.25, 16.89)	-0.11 (-0.20, -0.03)	8854.3 (7114.55, 10796.89)	361.61 (290.56, 440.95)	318.25 (254.98, 387.63)	-0.41 (-0.48, -0.33)

Table 2 (continued)

	Mortality (95% UI) in 2021			Trend (1990–2021)	Disability-Adjusted Life Years (95% UI) in 2021			Trend (1990–2021)
	Number (×10^3)	Mortality rate (/10^5)	ASMR (/10^5)	WAPC (%, 95% CI)	Number (×10^3)	DALYs rate (/10^5)	ASDR (/10^5)	WAPC (%, 95% CI)
Low-middle SDI	71.66 (62.84, 82.08)	3.73 (3.27, 4.27)	5.07 (4.45, 5.80)	-0.19 (-0.22, -0.16)	1883.42 (1642.14, 2163.69)	98.04 (85.48, 112.63)	125.16 (109.42, 143.48)	-0.25 (-0.28, -0.22)
Low SDI	10.07 (8.01, 12.35)	0.90 (0.72, 1.11)	2.08 (1.66, 2.54)	-0.56 (-0.62, -0.50)	274.21 (215.94, 338.50)	24.54 (19.33, 30.29)	51.07 (40.41, 62.81)	-0.65 (-0.71, -0.59)
World Bank Regions								
Central Europe, Eastern Europe, and Central Asia	109.92 (99.69, 119.97)	26.31 (23.86, 28.71)	16.56 (15.01, 18.06)	-1.47 (-1.56, -1.38)	2812.54 (2560.95, 3052.24)	673.13 (612.91, 730.49)	432.82 (393.97, 469.63)	-1.86 (-1.95, -1.76)
High-income regions*	350.71 (309.67, 388.25)	32.13 (28.37, 35.57)	15.77 (14.09, 17.35)	-1.79 (-1.90, -1.69)	7395.02 (6654.41, 8095.25)	677.41 (609.56, 741.55)	362.21 (326.74, 394.86)	-2.08 (-2.19, -1.97)
Latin America and Caribbean	36.96 (32.16, 41.67)	6.22 (5.41, 7.01)	6.00 (5.22, 6.78)	-1.84 (-1.94, -1.75)	874.61 (767.37, 982.16)	147.21 (129.16, 165.31)	138.88 (121.80, 156.07)	-2.02 (-2.12, -1.91)
North Africa and Middle East	48.42 (40.22, 57.37)	7.77 (6.46, 9.21)	11.03 (9.14, 13.09)	-0.60 (-0.73, -0.48)	1275.12 (1056.57, 1508.22)	204.67 (169.59, 242.09)	264.96 (219.58, 313.32)	-0.86 (-0.98, -0.74)
South Asia	48.36 (38.52, 58.23)	2.62 (2.09, 3.15)	3.31 (2.64, 3.97)	-0.67 (-0.74, -0.59)	1277.77 (1013.70, 1543.88)	69.20 (54.90, 83.61)	82.39 (65.57, 99.48)	-0.71 (-0.78, -0.64)
Southeast Asia, East Asia, and Oceania	632.78 (503.81, 783.15)	28.96 (23.06, 35.84)	22.48 (18.04, 27.75)	0.31 (0.14, 0.47)	14814.32 (11730.75, 18336.59)	678.00 (536.87, 839.2)	501.99 (398.15, 621.15)	-0.03 (-0.17, 0.12)
Sub-Saharan Africa	11.52 (9.61, 13.49)	1.02 (0.85, 1.19)	2.50 (2.09, 2.94)	-0.76 (-0.90, -0.62)	318.64 (266.13, 376.40)	28.12 (23.49, 33.22)	62.08 (51.83, 72.71)	-0.83 (-0.98, -0.68)
Sex								
Female	249.76 (196.05, 306.05)	6.35 (4.99, 7.78)	5.36 (4.21, 6.57)	-0.54 (-0.68, -0.41)	5516.41 (4306.88, 6740.47)	140.30 (109.54, 171.43)	119.31 (93.03, 145.86)	-0.82 (-0.95, -0.68)
Male	988.89 (852.91, 1142.31)	24.98 (21.54, 28.85)	25.03 (21.61, 28.89)	-1.09 (-1.15, -1.03)	23251.61 (20027.49, 26946.17)	587.25 (505.82, 680.56)	561.60 (484.02, 650.16)	-1.39 (-1.44, -1.33)
Age								
≥ 25 years and < 55 years	113.28 (96.11, 133.64)	3.01 (2.55, 3.55)	——	-1.44 (-1.62, -1.26)	4720.31 (3999.25, 5562.40)	125.22 (106.09, 147.56)	——	-1.51 (-1.69, -1.33)
≥ 55	1125.37 (978.58, 1289.98)	75.73 (65.85, 86.81)	——	-0.80 (-0.87, -0.72)	24047.71 (20934.90, 27501.71)	1618.30 (1408.82, 1850.74)	——	-1.08 (-1.14, -1.03)

* UI uncertain interval; CI, confidence interval

* WAPC, weighted average annual percentage change

* ASMR, age-standardized mortality rate; ASDR, age-standardized Disability-Adjusted Life Years (DALYs) rate

* SDI, Socio-demographic Index; High-income regions (Australasia, High-income Asia Pacific, High-income North America, Southern Latin America, Western Europe)

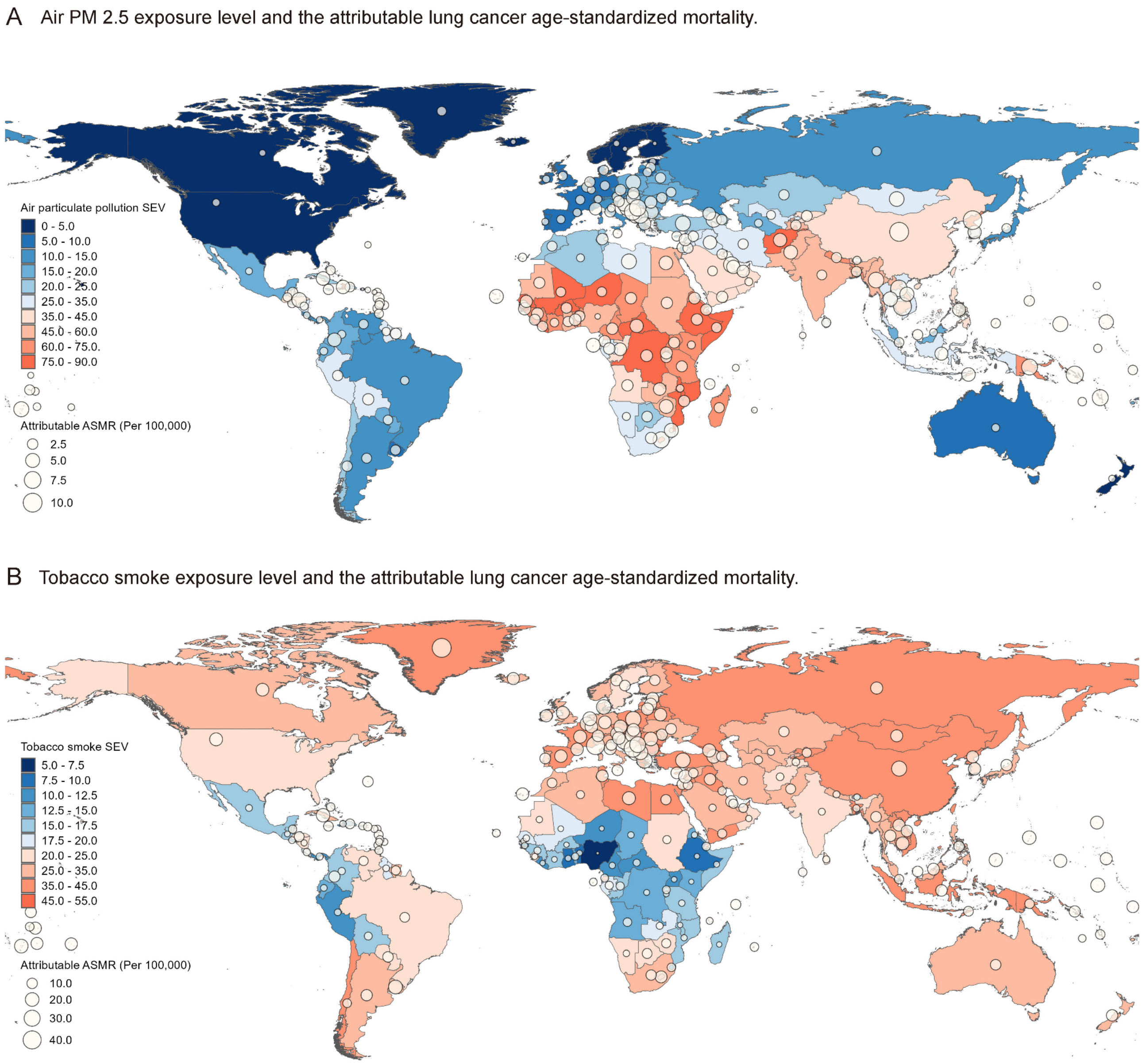

Fig. 1 Global air PM2.5 and tobacco smoke exposure level, and their attributable lung cancer age-standardized mortality rate (ASMR) in 2021. (**A**) Air PM2.5. (**B**) Tobacco smoke

36.89–49.71)] had higher exposure than those 55 and older [36.58 (95% UI: 31.38–43.19)]. However, health impacts displayed an inverse trend: the 55 + group had substantially higher attributable mortality rates [22.14 (95% UI: 13.94–30.89)] and DALYs rates [471.05 (95% UI: 298.04-657.69)] compared to the 25–55 group [mortality rates: 1.20 (95% UI: 0.78–1.66), DALYs rates: 51.32 (95% UI: 33.23–70.78)] (Tables 1 and 2; Fig. 2, Supplementary Fig. 8). Global tobacco smoke exposure showed a similar pattern: the under-55 group had slightly higher ASEV [24.09 (95% UI: 23.10-24.68)] than the 55 + group [17.47 (95% UI: 16.85–18.11)]. The age disparity in health impacts was more pronounced: the 55 + group had significantly higher attributable mortality rates [75.73 (95% UI: 65.85–86.81)] and DALYs rates [1,618.30 (95% UI: 1,408.82-1,850.74)] compared to the under-55 group [mortality rates: 3.01 (95% UI: 2.55–3.55), DALYs rates: 125.22 (95% UI: 106.09-147.56)]. This pattern was evident in both smoking and secondhand smoke exposure effects (Tables 1 and 2; Fig. 2, Supplementary Fig. 9).

Temporal trends and projections

Between 1990 and 2021, overall exposure to air PM2.5 decreased [WAPC: -1.02% (95% CI: -1.11, -0.92)], primarily due to reduced household PM2.5 [-2.50% (95% CI: -2.71, -2.28)], despite increased ambient PM2.5 [1.48%

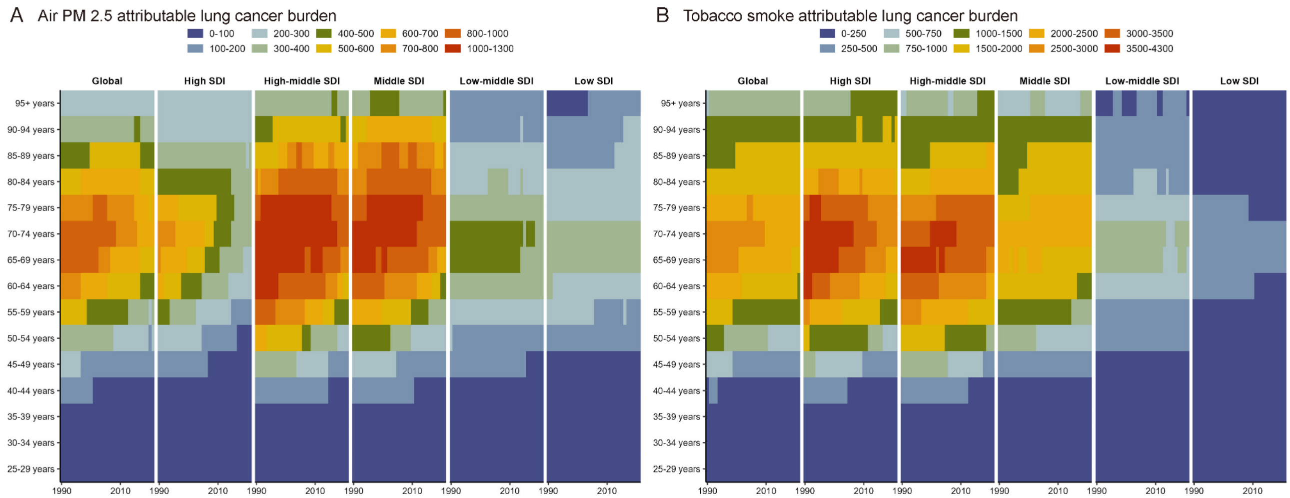

Fig. 2 Lung cancer age-standardized disability-adjusted life years rate (DALYs) (ASDR) attributable to air PM2.5 and tobacco smoke across age and socio-demographic index (SDI) groups over 1990–2021. (**A**) Air PM2.5. (**B**) Tobacco smoke

(95% CI: 1.31, 1.65)]. The global ASMR and ASDR attributable to air PM2.5 declined annually by -1.32% (95% CI: -1.48, -1.16) and − 1.64% (95% CI: -1.80, -1.49) respectively, with high SDI countries experiencing the fastest decrease. Males and the 25–55 age group showed more pronounced improvements. Lung cancer burden due to ambient PM2.5 generally increased, decreasing only in high SDI countries, while the burden from household PM2.5 universally decreased (Tables 1 and 2; Fig. 3, Supplementary Fig. 10). Global tobacco smoke exposure decreased [-1.15% (95% CI: -1.17, -1.12)], with active smoking showing a more decline [-1.27% (95% CI: -1.28, -1.25) VS -0.95% (95% CI: -0.99, -0.92)]. The ASMR and ASDR attributable to tobacco exposure decreased annually by -0.95% (95% CI: -1.03, -0.88) and − 1.27% (95% CI: -1.34, -1.20) respectively, with the largest reductions in high SDI countries. ASDR declines varied across SDI and gender groups for tobacco exposure, with high and high-middle SDI male groups showing the most significant decreases (Tables 1 and 2; Fig. 3, Supplementary Fig. 11). Projections for 2021–2030 suggest continued declines in attributable ASDR for most groups, albeit potentially at a slower pace for PM2.5-attributable lung cancer burden (Fig. 4, Supplementary Fig. 12–13).

Transnational health inequalities

Over the past three decades, global health inequalities attributable to air PM2.5 and tobacco smoke exposure have significantly changed. The lung cancer burden due to air PM2.5 has shifted from high to low SDI countries, as evidenced by the Concentration Index (CI) for ASMR decreasing from 0.05 in 1990 to -0.10 in 2021, and the Slope Index of Inequality (SII) for ASDR declining from 31.00 to -35.50 per 100,000. This trend showed gender disparities, with males experiencing more pronounced changes compared to females. Conversely, health inequalities due to tobacco smoke exposure showed a different trend. The CI for ASMR decreased from 0.34 in 1990 to 0.25 in 2021, and the SII for ASDR declined from 572.20 to 304.60 per 100,000, indicating that the health burden remains concentrated in high SDI countries, albeit with narrowing inter-country disparities. Gender differences were significant: the cross-national inequality gap in tobacco-attributable lung cancer burden for males consistently narrowed, while the inequality gap for females showed minimal change (Fig. 5, Supplementary Fig. 14–15).

Discussion

This study is the first to comprehensively quantify the exposure levels of air fine particulate matter (both ambient and household) and tobacco smoke (active and secondhand), along with their attributable lung cancer burden in 2021. It also analyzes temporal trends and cross-country inequalities at global and transnational levels from 1990 to 2021. By exploring the interactions between environmental factors, social changes, and public health outcomes, this research provides valuable insights into the post-pandemic lung cancer burden, thereby informing future prevention and control strategies.

Global air PM2.5 in 2021 showed widespread prevalence with significant disparities. Ambient PM2.5 exposure exhibited an inverted "U" distribution relative to SDI, peaking in middle SDI countries. From 1990 to 2021, high SDI countries saw declining trends, while high-middle and middle SDI countries experienced increased ambient pollution. Ambient PM2.5 typically originates from industrial emissions, transportation and construction activities. This pattern reflects successful air quality

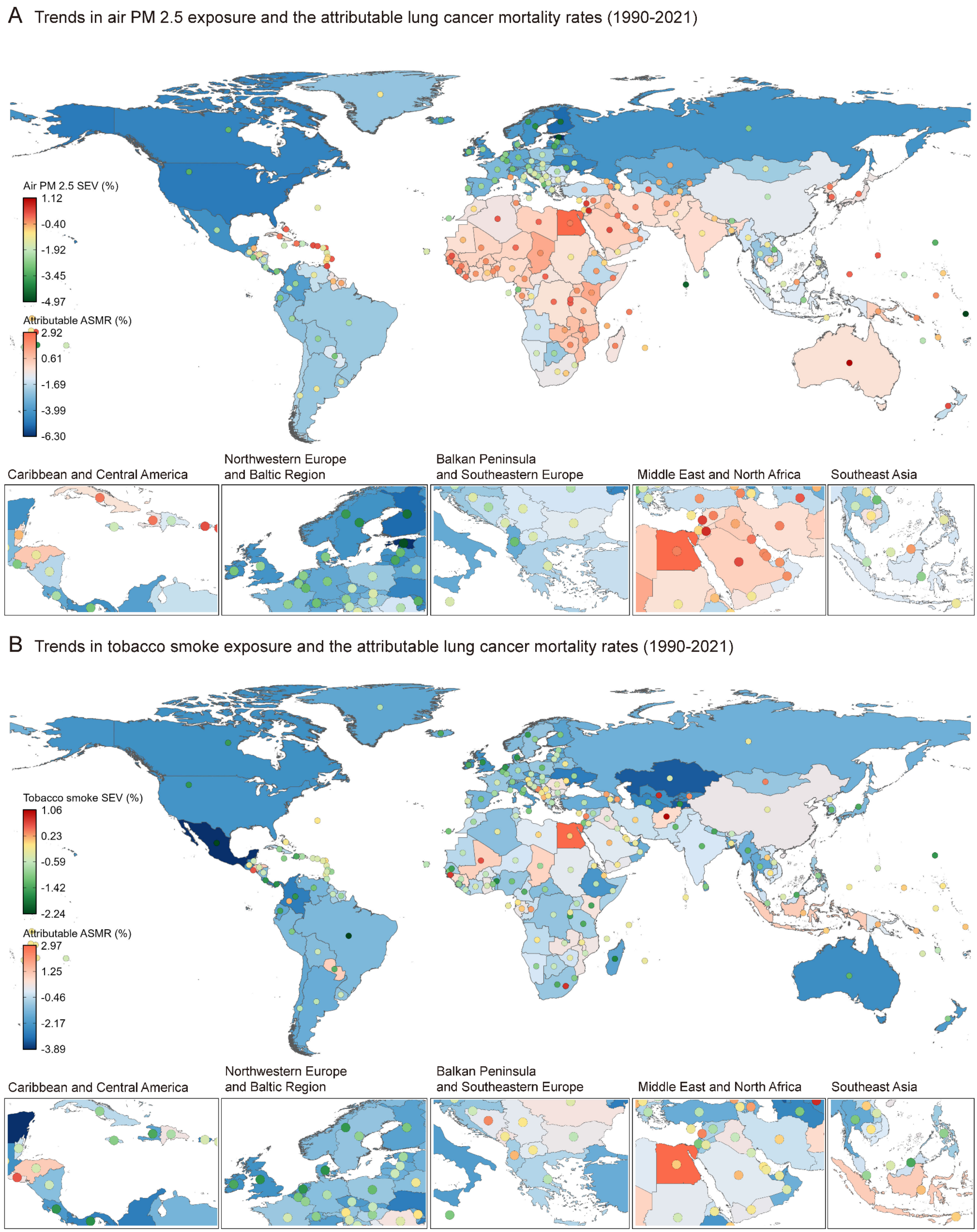

Fig. 3 Global weighted average annual percentage change (WAPC) in air PM2.5 and tobacco smoke exposure level, and their attributable lung cancer age-standardized mortality rate (ASMR) across 1990–2021. (**A**) Air PM2.5. (**B**) Tobacco smoke

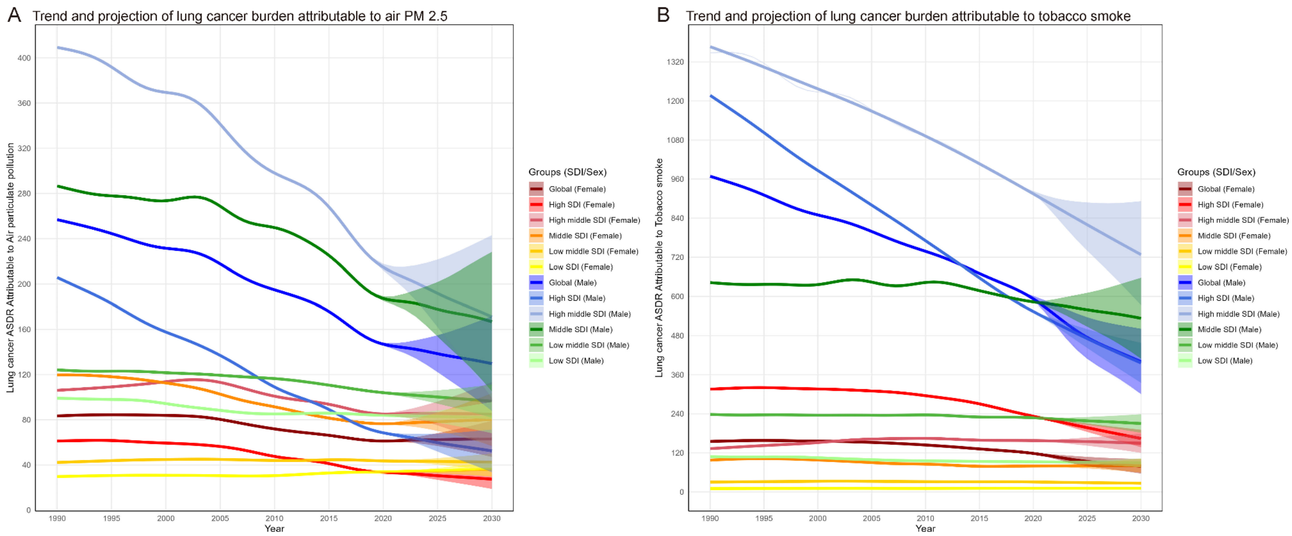

Fig. 4 Trend (1990–2021) and projection (2022–2030) of lung cancer age-standardized disability-adjusted life years (DALYs) rate (ASDR) by sex and socio-demographic index (SDI) groups attributable to air particulate pollution and tobacco smoke. (**A**) Air PM2.5. (**B**) Tobacco smoke

improvements in developed nations and challenges from rapid industrialization in emerging economies, highlighting the need to balance economic growth with environmental protection [24]. Low SDI countries face the highest household PM2.5 exposure due to the prevalent use of solid fuels for cooking and heating, a practice that reportedly affects approximately 2.8 billion people globally [25]. Encouragingly, household PM2.5 exposure has generally declined, reflecting the positive impacts of clean energy policies and technological advancements. However, this downward trend is less pronounced in low SDI countries. There is a pressing need to strengthen ambient particulate pollution management in high-middle SDI developing countries and to upgrade energy sources in low SDI countries [26].

Tobacco exposure exhibited significant gender disparities, with males experiencing higher rates of both active smoking and secondhand smoke exposure, although the gender difference for secondhand smoke was relatively small. Exposure rates peaked in high-middle SDI countries, while low SDI countries demonstrated the lowest rates. These variations reflect complex sociocultural factors and gender roles, emphasizing the need for gender-specific tobacco control strategies. Overall tobacco exposure has declined, particularly in high SDI countries and among females. This reduction can likely be attributed to the implementation of stringent policies and supportive measures, such as tobacco taxes and the provision of smoking cessation aids [27, 28], as well as increased health awareness. However, decline rates varied across socioeconomic levels and gender groups, highlighting the need for tailored interventions. Despite positive trends, tobacco smoke exposure in population remains a significant global health concern, especially in high-middle SDI countries. Persistent gender disparities in exposure patterns underscore the importance of addressing sociocultural factors in tobacco control efforts. Furthermore, the higher prevalence of secondhand smoke exposure among females emphasizes the need for comprehensive smoke-free policies to protect non-smokers.

Despite a slight downward trend in age-standardized attributable burden from 1990 to 2021 overall, the absolute burden has become substantial in 2021, primarily due to population growth, necessitating continued stringent control measures. Lung cancer death attribution to air fine particulate matter was similar for males [18.55% (95%UI: 11.94, 25.54)] and females [18.11% (95%UI: 11.81, 24.44)], while tobacco impact showed a marked gender disparity [males: 72.90% (95%UI: 68.14, 77.18), females: 36.96% (95%UI: 29.29, 43.83)]. This reflects gender-specific lifestyle and environmental exposure patterns, emphasizing tobacco control's crucial role in reducing lung cancer mortality, particularly among males. The burden was heaviest among individuals aged 55 and above, with slower decline trends in older age groups, potentially reflecting cumulative exposure effects and increased sensitivity in the elderly. This underscores the importance of targeted protective measures for older adults and the benefits of early intervention [29]. Elderly populations in high and high-middle SDI countries were more affected by air fine particulate matter and tobacco smoke compared to those in low SDI countries, possibly due to differences in population aging, healthcare resource allocation, and historical exposure. This highlights the need for preventive measures in low SDI countries to avoid similar future challenges.

Over the past three decades, changes in lung cancer burden attributable to fine particulate matter and tobacco

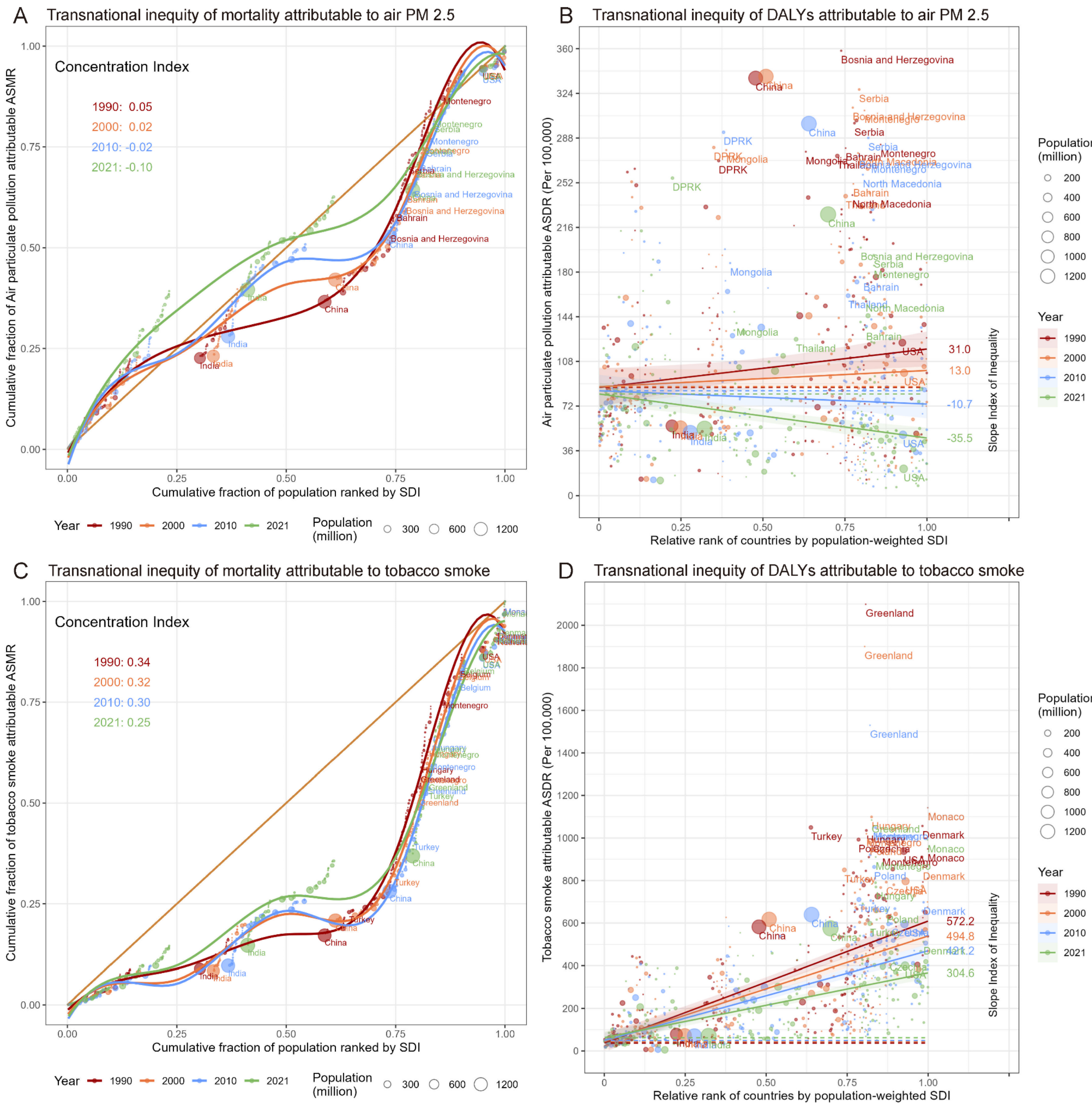

Fig. 5 Cross-national inequalities and trends in lung cancer age-standardized mortality rates (ASMR) and age-standardized disability-adjusted life years (DALY) rate (ASDR) from 1990 to 2021. (**A**) Concentration index of ASMR attributable to PM2.5. (**B**) Slope index of ASDR attributable to PM2.5. (**C**) Concentration index of ASMR attributable to tobacco smoke. (**D**) Slope index of ASDR attributable to tobacco smoke

smoke exposure reflect complex global public health challenges. The shift in particulate matter-related burden from high to low SDI countries mirrors global economic development and environmental policy changes. High SDI countries have likely reduced pollution through stringent regulations and advanced technologies, while low SDI countries face environmental pressures amid rapid industrialization. This transition highlights inequalities in global environmental governance, emphasizing the need for international cooperation, technology transfer, and experience sharing. Although tobacco-related health burden remains concentrated in high SDI countries, the gap is narrowing. This trend may reflect historically higher smoking rates in high SDI countries, recent proactive tobacco control efforts, increased tobacco use in low SDI countries, and the effectiveness of policies in high SDI nations. These patterns underscore the need for strengthened global tobacco control, especially in low SDI countries. Gender disparities persist, with males bearing a higher overall burden but showing faster improvement rates. These findings emphasize the necessity of considering gender specificities in health policy formulation while ensuring women's health needs are not neglected [30].

This study has several limitations that warrant consideration. Firstly, the air pollution exposure assessment assumes uniform PM2.5 toxicity, despite varying health impacts from different sources, potentially causing data heterogeneity [31]. Moreover, the exposure assessment methodology inadequately accounts for human activity patterns, possibly leading to misclassification bias. Secondly, smoking-related burden estimates rely on self-reported daily tobacco use, overlooking other tobacco products and smoking intensity variations, which may underestimate the true burden. An additional limitation is that our analysis focuses primarily on traditional smoked tobacco products. The evolving landscape of tobacco and nicotine consumption, including the increasing prevalence of e-cigarettes and heated tobacco products, represents an important area for future research. Recent evidence suggests dual use of traditional cigarettes and e-cigarettes may increase lung cancer risk fourfold compared to exclusive cigarette smoking [32]. As these products gain market share globally, future research should incorporate their potential contributions to the lung cancer burden. Additionally, lung cancer diagnosis accuracy varies across regions, and histological mortality patterns were not estimated, limiting the granularity of the analysis. Lastly, projections for trends based on historical and demographic changes may be biased due to potential COVID-19 effects and the exclusion of future policy implementations, which could significantly alter future health patterns.

This study provides a comprehensive perspective on air fine particulate matter and tobacco smoke exposure's impact on lung cancer burden, highlighting its widespread nature, unequal distribution, and preventability. We recommend policy interventions and behavioral changes, including strengthening environmental regulations (especially in middle and low SDI countries), enhancing tobacco control policies (particularly for males and high-risk age groups), and developing gender and age-specific interventions. For older adults, enhanced health monitoring and early intervention may be necessary, while younger groups should focus on health education and prevention. Given the global nature and regional disparities of the health burden, international cooperation is crucial, including technology transfer, experience sharing, and resource allocation to help low SDI countries address growing environmental health challenges [21]. Raising public awareness about health risks remains key, especially in high tobacco use areas. Future research should explore specific mechanisms behind these trends, evaluate the effectiveness of intervention strategies.

Conclusions

In conclusion, air fine particulate matter and tobacco smoke exposure significantly impacted lung cancer burden in 2021, with uneven global distribution. Low SDI countries faced higher air PM2.5 exposures, while high-middle SDI regions showed prevalent tobacco use. Males and older adults were disproportionately affected. From 1990 to 2021, the air PM2.5 burden shifted from high to low SDI countries, while the tobacco-attributable burden persisted in higher SDI countries, albeit with diminishing inequalities. Despite annual decreases in ASMR and ASDR, the absolute burden remains significant due to global population growth. Targeted interventions, international cooperation, and gender-specific strategies are crucial to address these preventable risk factors and further reduce global lung cancer burden in the post-pandemic era.

Abbreviations

PM2.5	Fine Particulate Matter
HAP	Household Air Pollution
ASMR	Age-Standardized Mortality Rate
ASDR	Age-Standardized Disability-Adjusted Life Years Rate
ASEV	Age-Standardized Summary Exposure Value
DALYs	Disability-Adjusted Life Years
SEV	Summary Exposure Value
WAPC	Weighted Average Annual Percentage Change
CI	Concentration Index/Confidence Interval
SII	Slope Index of Inequality
SDI	Socio-demographic Index
BAPC	Bayesian Age-Period-Cohort
PAF	Population Attributable Fraction

Supplementary Information

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Supplementary Material 1

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Author contributions

Concept and design: YZ, WW, KD, YH; Accessed and verified the data: YZ, WW, RW; Software and Validation: YZ, KD, RW, DH, YH; Drafting of the manuscript: YZ, WW, KD; Critical review of the manuscript for important intellectual content: All authors; Statistical analysis: YZ, WW, KD, RW; Obtained funding: JH, HL; Supervision: JH, HL. All authors read and approved the final manuscript.

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Data availability

Data is provided within the manuscript or supplementary information files.

Declarations

Ethics approval and consent to participate
The data for this study were obtained from a publicly available database and did not require ethical review or informed consent.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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