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The global burden of cancers attributable to occupational factors, 1990–2021

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Abstract

This study assessed the global cancer burden due to occupational carcinogens (OCs) using data from Global Burden of Disease (GBD) 2021. Mortality and disability-adjusted life years (DALYs) were employed to assess the evolving trend of cancer attributable to occupational risk. The analysis was conducted by age, year, geographical location, and socio-demographic index (SDI). Subsequently, the estimated annual percentage change (EAPC) values were calculated. Globally, asbestos exposure showed the most severe impact on age-standardized death rate (ASDR) and age-standardized DALY rate but decreased significantly. Conversely, diesel engine exhaust exposure increased, with EAPCs of 0.80 for deaths. Trichloroethylene exposure, although low in absolute terms, exhibited the fastest growth with an EAPC of 1.21 in age-standardized DALY rate. Notably, diesel engine exhaust exposure in South Asia and polycyclic aromatic hydrocarbons (PAHs) in Southeast Asia, East Asia, and Oceania increased significantly in age-standardized DALY rate. Regions with low to middle SDI, such as South Asia and sub-Saharan Africa, showed the highest increases in OC-related cancer burdens in age-standardized DALY rate. Lesotho, Kenya, and Egypt exhibited the fastest growth, with EAPCs in age-standardized DALY rate of 3.45, 2.13, and 2.95, respectively. High-income regions like the Netherlands, the United Kingdom, and Italy had the most severe OC-related cancer of ASDR burdens in 2021. OC exposure remains a major contributor to the global cancer burden, especially from asbestos and silica. Exposure to diesel engine exhaust was associated with increased risk of cancers, particularly in low -to -middle SDI regions such as South Asia and sub-Saharan Africa.

Keywords Occupational carcinogens, GBD 2021, Cancer burden, DALYs, SDI, Asbestos

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Introduction

Cancer is a leading cause of global mortality, ranking as the second most common cause of death after cardiovascular diseases [1]. The Global Burden of Diseases, Injuries, and Risk Factors Study (GBD) 2016 estimated that occupational exposure to 14 carcinogens was responsible for an estimated 348,741 cancer deaths in 2016 [2], including larynx, nasopharynx, breast, lung, ovarian, mesothelioma, and leukemia. More than 80% of cancers are related to environmental factors, including external (chemical, physical, biological) and internal (genetic, immune, endocrine) factors [3]. Industries have undergone rapid growth in recent decades. The petroleum industry constitutes the most significant sector, followed by motor vehicle manufacturing, pharmaceutical production, mining and quarrying (particularly copper and aluminum), and the manufacture of metals, rubber, and plastic products [3]. Workers in these industries are potentially exposed to a variety of known or suspected carcinogens, including BTEXs (benzene, toluene, ethylbenzene, and xylene), crystalline silica, and heavy metals [4].

Globally, occupational exposure to carcinogens presents a significant health risk, contributing substantially to the disease burden. This issue has garnered increasing attention at various scales, including global, regional, and national [5]. High-risk occupational environments play a crucial role in the development and progression of various tumors. For example, lung cancer [6] and mesothelioma [7] are widely recognized as being induced by asbestos, while benzene-induced bladder cancer [8] and petroleum pitch–induced skin cancer [9] have also been identified. Notably, lung cancer accounts for the majority of occupational-associated cancers [2].

In recent years, the rising global cancer incidence can be attributed to a combination of demographic shifts (e.g., population growth and ageing) and modifiable risk factors, including environmental and occupational exposures [10]. The Institute for Health Metrics and Evaluation has been systematically conducting the GBD studies since 2010, with a particular emphasis on the influence of risk factors [11]. The results of exposure to occupational carcinogens (OCs) have been extensively reported, with updates at the national and global levels [2, 12]. However, there are no studies that have systematically evaluated the cancer burden due to occupational exposure individually and collectively. The most recent data from GBD 2021 has not been analyzed. Therefore, we aimed to evaluate the cancer burden due to OC exposure using the most recent and comprehensive data.

In light of the consequences of cancers associated with OCs, our study utilizes age-standardized rates (ASRs) to quantify its incidence and disability trends. These include the age-standardized death rate (ASDR) and the age-standardized disability-adjusted life year (DALY) rate. Understanding the global impact of cancers attributable to OCs across all age groups is crucial for devising strategies to prevent and treat cancers and ultimately reduce its incidence.

This study aims to analyze the global burden of cancers attributable to OCs in individuals across all age groups. The data from the GBD 2021 study is examined to accomplish this objective [10]. The analysis encompasses the observation of disease trends over the period from 1990 to 2021, the identification of disparities between different countries and regions, and the evaluation of variations by age.

Materials and methods

Study data and participants

The GBD 2021 geographical hierarchy included 204 countries and territories aggregated into 21 regions and 7 super-regions [13]. Based on the GBD 2021 study, 13 work-environment carcinogens attributable to total cancers types were included: tracheal, bronchial, and lung cancer (exposure to arsenic, asbestos, beryllium, cadmium, chromium, diesel engine exhaust, nickel, polycyclic aromatic hydrocarbons, and silica), leukemia (exposure to benzene and formaldehyde), larynx cancer (exposure to asbestos and sulfuric acid), mesothelioma (exposure to asbestos), nasopharynx cancer (exposure to formaldehyde), ovarian cancer (exposure to asbestos), and kidney cancer (exposure to trichloroethylene) [10]. Each combination of risk and outcome included in the GBD is recognized as a risk-outcome pair, which was obtained on the basis of evidence rules. Data on OC-attributable cancer deaths and DALYs were obtained, along with their respective age-standardized rates, and the summary exposure value of each OC [13].This study did not require ethical approval because it used publicly available databases.

The GBD 2021 framework employs a standardized methodology to estimate risk-outcome pairs through systematic data synthesis, including literature reviews, surveys, and exposure modelling. While this approach allows global comparability, it relies on secondary data sources and may not capture subnational heterogeneity or emerging occupational risks.

This study was based on the GBD database and does not contain identifiable personal information. Therefore, a waiver of informed consent was reviewed and approved by the University of Washington institutional review board. Both sexes were included, and race/ethnicity was not reported.

Definition

The 2021 GBD study defines 13 OCs based on their association with specific cancers, including arsenic, asbestos, beryllium, cadmium, chromium, diesel engine exhaust, nickel, polycyclic aromatic hydrocarbons (PAHs), silica, benzene, formaldehyde, sulfuric acid and trichloroethylene. For example, exposure to asbestos is associated with lung cancer (ICD-10: C34), mesothelioma (C45) and laryngeal cancer (C32), which mainly affect workers in construction and insulation industries. Exposure to benzene is associated with leukemia (C92), which is common among chemical manufacturing and petroleum refining workers. Exposure to diesel engine exhaust is associated with lung cancer (C34), which is common among transportation and construction workers. The classification of occupational carcinogens follows the International

Classification of Diseases, 10th Revision (ICD-10), which allows for standardized identification and classification across populations and time periods. This detailed classification enables a better understanding of the burden of cancer caused by occupational exposures and provides a basis for targeted prevention and control [13].

General estimation

The Social Demographic Index (SDI) serves as a measure of social developmental status, incorporating factors such as the total fertility rate, average years of education attained by individuals aged 15 and above, and the disparity in income distribution per capita. The SDI score varies between 0 (indicating the highest fertility, lowest income, and least educational attainment) to 1 (representing the highest educational level coupled with the lowest fertility). Each GBD location is assigned an annual SDI score, and countries are categorized into five distinct SDI quintiles: high, high-medium, medium, medium–low, and low. This study explores the correlation between the SDI value and the burden of cancer attributable to oral cancer [13].

The age-standardized death rate (ASDR) and the age-standardized DALY with 95% uncertainty interval (UI), and the estimated annual percentage change (EAPC) were used to describe mortality and disability trends. The indicators were calculated by sex, country, and region using data from the Global Health Data Exchange query tool. We also reported the number of deaths and disability-adjusted life years for each age group from 1990 to 2021.

Attributable burden estimation

The relative risks used in the analyses were extracted from the GBD database for burden estimation. For each risk-outcome pair, the same relative risk estimates were applied to both sexes and all age groups. Attributable DALYs were calculated as the total resulting DALY multiplied by the population-attributable fraction (PAF) for the risk-outcome pair for each age, sex, cause, and location. The same approach was used to estimate attributable deaths, years of life lost, and years lived with disability. The PAF for each individual risk-outcome pair was estimated separately along with the combined burdens of all cancer types attributable to the specific risk factor, either directly or indirectly. The PAFs for each age-sex-country group of OCs were calculated using the formula estimates in Levin's study [14]:

The PAF can be estimated using the following equation, which takes into account multiple categories or levels of exposure:

$$\mathrm{PAF} = \frac{\left[\sum_{x=1}^{n} \mathrm{RR}(x)\mathrm{P}(x) - 1\right]}{\left[\sum_{x=1}^{n} \mathrm{RR}(x)\mathrm{P}(x)\right]}$$

The relative risk, denoted as "RR" (x), is associated with the x-th exposure level. Additionally, "P" (x) represents the proportion of the population exposed to this specific exposure level, and n signifies the total number of distinct exposure levels.

Statistical analysis

According to the GBD 2021 study, 13 OCs corresponding to 7 cancer types were included. The annual OC-attributable cancer deaths and DALYs data, their age-standardized rates, and the summary exposure value of each OC from 1990 to 2021 were collected. EAPC is a widely used indicator for evaluating rate trends over specific time periods. It was calculated by fitting a regression line to the natural logarithm of the rates ($y = \alpha + \beta x + \varepsilon$), where y is the natural logarithm of the rate and x is the calendar year. The calculation of EAPC was performed by multiplying 100 by ($\exp[\beta] - 1$). In this study, Pearson correlation analysis was used to explore the association between the SDI value and OC-attributable cancer burden. A two-sided $P < 0.05$ was considered statistically significant. All statistical analyses were conducted using R program version 4.0.2 (R Foundation for Statistical Computing) with the following packages: ggplot2 for data visualization, dplyr for data manipulation, and gbd for GBD-specific metric calculations.

Results

Global exposure to OCs

We have reported the age-standardized DALY and ASDR for 13 OCs globally in 1990 and 2021. Exposure-related cancer burdens have changed substantially during this period (Supplemental Fig. 1, Supplemental Fig. 2).

There were significant increases in several exposures. The age-standardized DALY rate of diesel engine exhaust increased from 5.83 (95% UI: 5.04–6.73) in 1990 to 7.09 (95% UI: 5.93–8.33) in 2021, and the age-standardized DALY rate of PAHs increased from 1.65 (95% UI: 1.37–1.95) to 1.98 (95% UI: 1.63–2.40), and the death rate increased from 0.05 (95% UI: 0.04–0.06) to 0.07 (95% UI: 0.06–0.08). The EAPCs for diesel engine exhaust and PAHs were positive, suggesting an increasing burden.

The occupational exposure to trichloroethylene demonstrated the most rapid increase in EAPC, with the age-standardized DALY rate rising from 0.02 (95% UI: 0.00–0.04) in 1990 to 0.03 (95% UI: 0.01–0.05) in 2021, and an EAPC of 1.21 (95% CI: −2.50 to 5.07).

On the contrary, some exposures showed a decrease. The most significant reduction was observed in asbestos exposure, with a substantial decline in the age-standardized DALY rate from 78.70 (95% UI: 58.52–99.73) to 47.78 (95% UI: 35.61–60.39). The ASDR also decreased from 3.97 (95% UI: 2.97–4.96) to 2.71 (95% UI: 2.00–3.39), indicating that there were substantial improvements in reducing the risk of asbestos exposure (EAPC: − 1.08; 95% CI: − 2.12 to − 0.03).

The age-standardized DALY rate for sulfuric acid exposure decreased from 2.03 (95% UI: 0.81–3.73) to 1.29 (95% UI: 0.54–2.32), and the ASDR decreased from 0.06 (95% UI: 0.02–0.11) to 0.04 (95% UI: 0.02–0.07). The age-standardized DALY rate for formaldehyde exposure decreased from 0.85 (95% UI: 0.65–1.07) to 0.67 (95% UI: 0.53–0.84), and the ASDR decreased from 0.02 (95% UI: 0.01–0.02) to 0.01 (95% UI: 0.01–0.02). The EAPCs were − 1.67 (95% CI: − 1.95 to − 1.40) and − 1.07 (95% CI: − 1.50 to − 0.64), respectively (Table 1, Figs. 1 and 2, Supplemental Fig. 3, Supplemental Fig. 4).

Geographic-attributable burden for OCs

The global age-standardized DALY rate attributable to occupational carcinogens decreased from 117.04 (95% UI: 93.01–142.33) per 100,000 population in 1990 to 82.13 (95% UI: 65.63–101.45) in 2021, with an EAPC of − 1.11% (95% CI: − 5.55 to 3.54). The ASDR also declined from 5.17 (95% UI: 4.13–6.26) to 3.87 (95% UI: 3.03–4.68), with an EAPC of − 0.86% (95% CI: − 2.25 to 0.55). (Table 2, Supplemental Fig. 1, Supplemental Fig. 2).

Table 1 Global age-standardized rates and rate change attributable to occupational factors for total cancers, 1990 and 2021

Factors	DALYs (Disability-Adjusted Life Years)	Deaths	DALYs (Disability-Adjusted Life Years)	Deaths	DALYs (Disability-Adjusted Life Years)	Deaths
	Age-standardized rate per 100 000 population (95% UI)				Estimated annual percentage change from 1990 to 2019 (95% CI)	
	1990	1990	2021	2021		
	DALY rate	Death rate	DALY rate	Death rate	DALY rate	Death rate
Occupational carcinogens	117.04(93.01,142.33)	5.17(4.13,6.26)	82.13(65.63,101.45)	3.87(3.03,4.68)	−1.11(−5.58,3.57)	−0.85(−2.25,0.57)
Occupational exposure to asbestos	78.70(58.52,99.73)	3.97(2.97,4.96)	47.78(35.61,60.39)	2.71(2.00,3.39)	−1.50(−5.42,2.58)	−1.08(−2.12,−0.03)
Occupational exposure to sulfuric acid	2.03(0.81,3.73)	0.06(0.02,0.11)	1.29(0.54,2.32)	0.04(0.02,0.07)	−1.67(−1.95,−1.40)	−1.56(−4.81,1.80)
Occupational exposure to nickel	3.76(−0.26,10.69)	0.12(−0.01,0.35)	3.17(0.29,8.21)	0.11(0.01,0.29)	−0.61(−1.81,0.60)	−0.40(−2.67,1.93)
Occupational exposure to polycyclic aromatic hydrocarbons	1.65(1.37,1.95)	0.05(0.04,0.06)	1.98(1.63,2.40)	0.07(0.06,0.08)	0.54(−0.18,1.26)	0.76(−2.04,3.65)
Occupational exposure to diesel engine exhaust	5.83(5.04,6.73)	0.19(0.16,0.22)	7.09(5.93,8.33)	0.24(0.20,0.29)	0.59(−1.45,2.67)	0.80(−0.70,2.31)
Occupational exposure to beryllium	0.10(0.08,0.12)	0.00(0.00,0.00)	0.10(0.08,0.12)	0.00(0.00,0.00)	−0.11(−2.48,2.33)	0.12(−5.65,6.26)
Occupational exposure to silica	21.70(8.49,34.53)	0.71(0.28,1.13)	17.31(7.76,27.36)	0.61(0.26,0.96)	−0.77(−3.69,2.24)	−0.56(−1.08,−0.03)
Occupational exposure to arsenic	3.97(0.20,7.48)	0.13(0.01,0.25)	3.36(0.70,5.89)	0.12(0.02,0.21)	−0.60(−1.85,0.67)	−0.38(−2.59,1.87)
Occupational exposure to cadmium	0.23(0.19,0.28)	0.01(0.01,0.01)	0.26(0.21,0.33)	0.01(0.01,0.01)	0.32(−1.07,1.74)	0.55(−4.29,5.64)
Occupational exposure to formaldehyde	0.85(0.65,1.07)	0.02(0.01,0.02)	0.67(0.53,0.84)	0.01(0.01,0.02)	−1.07(−1.50,−0.64)	−1.01(−5.31,3.48)
Occupational exposure to chromium	0.47(0.41,0.54)	0.02(0.01,0.02)	0.57(0.48,0.68)	0.02(0.02,0.02)	0.56(−0.04,1.16)	0.79(−3.29,5.03)
Occupational exposure to trichloroethylene	0.02(0.00,0.04)	0.00(0.00,0.00)	0.03(0.01,0.05)	0.00(0.00,0.00)	1.21(−2.50,5.07)	1.26(−5.93,8.99)
Occupational exposure to benzene	1.15(0.35,1.85)	0.02(0.01,0.04)	1.05(0.30,1.72)	0.02(0.01,0.04)	−0.40(−0.49,−0.31)	−0.31(−4.21,3.74)

Regionally, the age-standardized DALY rate increased in South Asia from 20.92 (95% UI: 15.58–26.32) in 1990 to 25.05 (95% UI: 19.08–32.63) in 2021 with an EAPC of 0.49% (95% CI: − 2.85 to 3.94), and the ASDR increased from 0.74 (95% UI: 0.55–0.93) to 0.92 (95% UI: 0.70–1.18) with an EAPC of 0.60% (95% CI: 0.48 to 0.72). In Southeast Asia, East Asia, and Oceania, the age-standardized DALY rate increased from 69.31 (95% UI: 50.40–90.42) to 82.45 (95% UI: 59.10–111.52) with an EAPC of 0.60% (95% CI: − 3.95 to 5.36), and the ASDR increased from 2.56 (95% UI: 1.88–3.29) to 3.34 (95% UI: 2.41–4.49) with an EAPC of 0.99% (95% CI: − 0.29 to 2.28). Central Europe reported an increase in the age-standardized DALY rate from 105.58 (95% UI: 72.59–142.88) to 120.18 (95% UI: 87.97–159.06) with an EAPC of 0.77% (95% CI: − 4.17 to 5.96), and the ASDR increased from 3.77 (95% UI: 2.68–4.97) to 4.97 (95% UI: 3.66–6.54) with an EAPC of 1.33% (95% CI: − 0.37 to 3.06). (Table 2, Figs. 1 and 2, Supplemental Fig. 3, Supplemental Fig. 4).

At the country level, Honduras had the largest increase in age-standardized DALY rate (35.91 [95% UI: 25.20–48.51] to 72.66 [95% UI: 49.53–103.68]) with an EAPC of 2.64% (95% CI: − 1.88 to 7.36). The ASDR also increased from 1.35 (95% UI: 0.92–1.84) to 2.97 (95% UI: 2.00–4.21) with an EAPC of 3.04% (95% CI: 1.85 to 4.25). Vietnam had a similar trend with age-standardized DALY rate increasing from 45.22 (95% UI: 29.86–65.27) to 72.00 (95% UI: 45.91–104.34), corresponding to an EAPC of 1.71% (95% CI: − 2.75 to 6.37), and ASDR increasing from 1.58 (95% UI: 1.04–2.24) to 2.52 (95% UI: 1.61–3.63) with an EAPC of 1.61% (95% CI: 0.63 to 2.60). Indonesia also showed a significant increase in age-standardized DALY rate from 34.79 (95% UI: 23.17–46.14) to 56.19 (95% UI: 35.45–79.22) with an EAPC of 1.53% (95% CI: − 2.67 to 5.90), and ASDR increasing from 1.18 (95% UI: 0.77–1.57) to 2.08 (95% UI: 1.30–2.91) with an EAPC of 1.81% (95% CI: 1.03 to 2.60) (Supplemental Table 1, Fig. 3, Supplemental Fig. 5).

In 2021, the highest burden attributable to occupational carcinogens was observed in some countries. The age-standardized DALY rate in Croatia increased from 133.68 (95% UI: 95.09–175.52) to 222.76 (95% UI: 158.73–298.51), with an EAPC of 2.75% (95% CI: − 2.96 to 8.79), and the ASDR increased from 5.31 (95% UI: 3.73–7.00) to 9.90 (95% UI: 7.00–13.24), with an EAPC of 3.26% (95% CI: 0.70 to 5.88). Although a decline was observed, Australasia remained significantly affected, with the age-standardized DALY rate decreasing from 318.51 (95% UI: 259.38–375.11) to 170.91 (95% UI: 137.83–200.49), and the ASDR decreasing from 14.55 (95% UI: 11.88–16.99) to 9.02 (95% UI: 7.24–10.58), with an EAPC of − 2.04% (95% CI: − 7.17 to 3.37) and − 1.52% (95% CI: − 3.75 to 0.76), respectively. Western Europe also had a high burden, with the age-standardized DALY rate decreasing from 274.76 (95% UI: 218.36–331.12) to 171.55 (95% UI: 137.22–205.06), and the ASDR decreasing from 12.31 (95% UI: 9.79–14.72) to 8.59 (95% UI: 6.80–10.20), with EAPCs of − 1.29% (95% CI: − 6.48 to 4.18) and − 0.90% (95% CI: − 3.12 to 1.36), respectively (Supplemental Table 1, Fig. 3, Supplemental Fig. 5).

Age-specific trends in DALYs and deaths attributable to occupational risks by sex in 2021

The age-specific and sex-specific distribution of DALYs and deaths due to occupational risks in 2021 showed that the number and rate of DALYs increased with age in both females and males. The burden of DALYs was significantly higher in males than in females across all ages. The highest number of DALYs in males was 774,372.86 (60–64 years), while the highest number of DALYs in females was 253,046.00 (65–69 years). The DALY rate was also higher in males than in females across all ages. The highest DALY rate in males was 1,393.32 per 100,000 (85–89 years), while the highest DALY rate in females was 213.34 per 100,000 (70–74 years) (Supplemental Table 2, Supplemental Fig. 6).

Mortality-related occupational risks increased with age in both sexes, and the number of deaths and mortality rate were higher in males than in females. The highest number of deaths was 44,224.34 in the 70–74 years age group for males, while it was 11,521.06 for females in the same age group. The highest mortality rate was 142.82 per 100,000 in the 85 + years age group for males, while it was 21.25 per 100,000 in the 85 + years age group for females (Supplemental Table 2, Supplemental Fig. 6).

SDI and occupational carcinogen burden

The global age-standardized DALY rate for occupational cancers decreased overall from 1990 to 2021. In Afghanistan, the age-standardized DALY rate increased slightly

(See figure on next page.)

Fig. 1 Age-standardized Rate of DALYs attributable to occupational risks factors in 2021 (**A** Occupational risks. **B** Occupational exposure to nickel. **C** Occupational exposure to asbestos. **D** Occupational exposure to polycyclic aromatic hydrocarbons. **E** Occupational exposure to sulfuric acid. **F** Occupational exposure to diesel engine exhaust. **G** Occupational exposure to beryllium. **H** Occupational carcinogens. **I** Occupational exposure to silica. **J** Occupational exposure to cadmium. **K** Occupational exposure to arsenic. **L** Occupational exposure to formaldehyde. **M** Occupational exposure to chromium. **N** Occupational exposure to trichloroethylene. **O** Occupational exposure to benzene

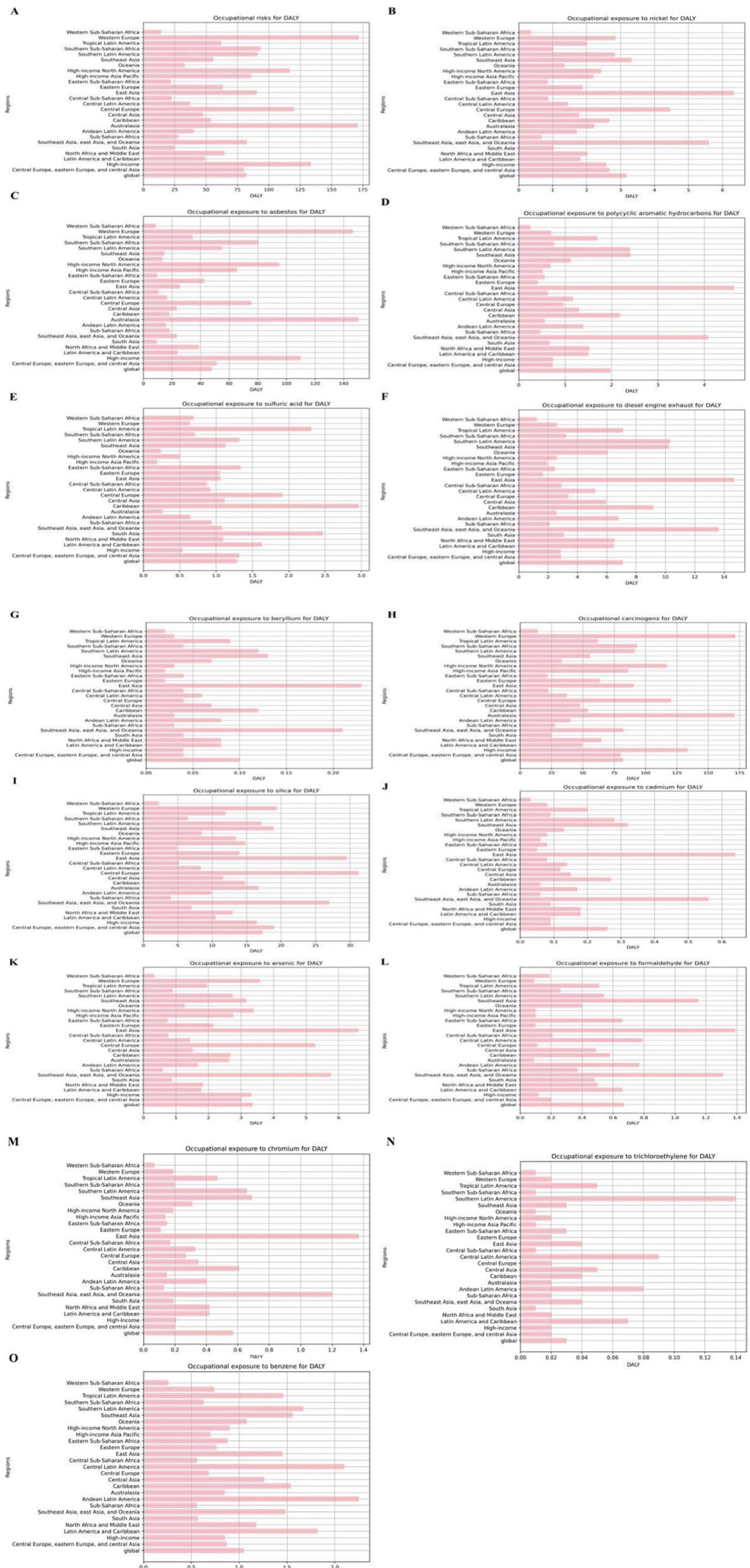

Fig. 1 (See legend on previous page.)

from 19.58 (95% UI: 10.11–34.55) in 1990 to 20.25 (95% UI: 11.98–32.29) in 2021 with an EAPC of 0.09 (95% CI: − 3.01 to 3.29). The ASDR also increased slightly.

The age-standardized DALY rate in high-SDI regions (Australia) decreased significantly from 327.19 (95% UI: 264.93–385.40) to 176.31 (95% UI: 141.91–206.98), with an EAPC of − 2.04 (95% CI: − 7.20 to 3.40). The ASDR also decreased significantly from 14.88 (95% UI: 12.14–17.41) to 9.33 (95% UI: 7.48–10.95), with an EAPC of − 1.49 (95% CI: − 3.75 to 0.83).

Regions with intermediate SDI, such as Egypt, experienced an increase in the burden. The age-standardized DALY rate increased from 18.30 (95% UI: 14.62–22.62) to 34.27 (95% UI: 24.39–48.62), with an EAPC of 2.77 (95% CI: − 0.98 to 6.67). The ASDR increased from 0.62 (95% UI: 0.51–0.76) to 1.23 (95% UI: 0.88–1.70), with an EAPC of 2.95 (95% CI: 2.54 to 3.36).

At the national level in 2021, there was no significant association between SDI and ASDR or age-standardized DALY rates for occupational carcinogens and their corresponding EAPCs ($R = -0.12$ for ASDR; $R = -0.14$ for DALY rates). This indicates that the burden of occupational carcinogens does not change significantly with socio-economic development. However, the burden increased slightly with socio-economic development up to an SDI threshold of approximately 0.6, and then decreased with further increases in SDI. The lowest age-standardized DALY rates and ASDR were observed in areas with SDI values around 0.6. This trend suggests that areas in transition may be at higher risk from OCs due to industrialization without proper occupational health protection (Table 1, Fig. 4).

Discussion

Our results suggest that OC exposure is a major contributor to global cancer deaths and DALYs, with substantial regional variation in the cancer burden by age, sex, and socio-economic development. The cancer burden attributable to each OC was markedly different, with asbestos and silica exposure having the highest global cancer burden.

This study included 13 OCs related to overall cancer burden according to GBD 2021. Consistent with previous reports, lung cancer was the most common cancer type associated with OCs, and asbestos was the leading cause of death and DALYs. Unlike previous GBD reports that considered smoking and secondhand smoke as behavioral risk factors, this study focused on OCs. Therefore, our study is one of the few studies that provide summary exposure values for these OCs and their regional and country differences, which can be used for exposure control and future cancer burden estimation. Exposure to OCs, especially asbestos, silica, and diesel engine exhaust, has been reported in many high-income countries [15–18]. In addition, exposure to OCs may be more widespread and poorly controlled in middle- and low-income countries due to a lack of automated monitoring equipment and self-protection at workplaces [19, 20].

Over the past three decades, many high-income countries have taken measures to reduce asbestos-related OC exposure. The asbestos industry grew rapidly during the twentieth century, first in Western Europe and then in low-income countries before the 2010s [7]. A study published in 1960 showed that asbestos exposure was associated with malignant tumor development [21]. Since then, European countries have gradually restricted asbestos production, transportation, and demolition of asbestos-containing buildings [22, 23]. Although some European countries banned blue asbestos disposal during this period, a complete ban on asbestos use was not implemented from 1960 to 1993. Moreover, even if asbestos exposure is completely eliminated, it will take another 40 to 50 years for asbestos-related cancer deaths to disappear [2].

The cancer burden of silica exposure was the second highest after asbestos, and both the number of cases and age-standardized rates increased from 2007 to 2017. Silica is widely distributed in nature and is used extensively in many industries, making it a common source of OC exposure ([23]). Workers can be exposed to silica during mining, quarrying, pottery, ceramics, foundries, and other construction and manufacturing activities [24]. Epidemiological studies on the association between silica exposure and lung cancer have mainly focused on industrial settings such as mines, quarries, and granite production sites. A cohort study of 58,677 German uranium miners from 1946 to 2003 showed that high silica exposure (> 10 mg/m^3) was significantly associated with lung cancer mortality [25]. In addition, a Chinese cohort study [26, 27] reported that long-term exposure to low levels of

(See figure on next page.)
Fig. 2 Age-standardized Rate of Deaths attributable to occupational risks factors in 2021 (**A** Occupational risks. **B** Occupational exposure to nickel. **C** Occupational exposure to asbestos. **D** Occupational exposure to polycyclic aromatic hydrocarbons. **E** Occupational exposure to sulfuric acid. **F** Occupational exposure to diesel engine exhaust. **G** Occupational exposure to beryllium. **H** Occupational carcinogens. **I** Occupational exposure to silica. **J** Occupational exposure to cadmium. **K** Occupational exposure to arsenic. **L** Occupational exposure to formaldehyde. **M** Occupational exposure to chromium. **N** Occupational exposure to trichloroethylene. **O** Occupational exposure to benzene

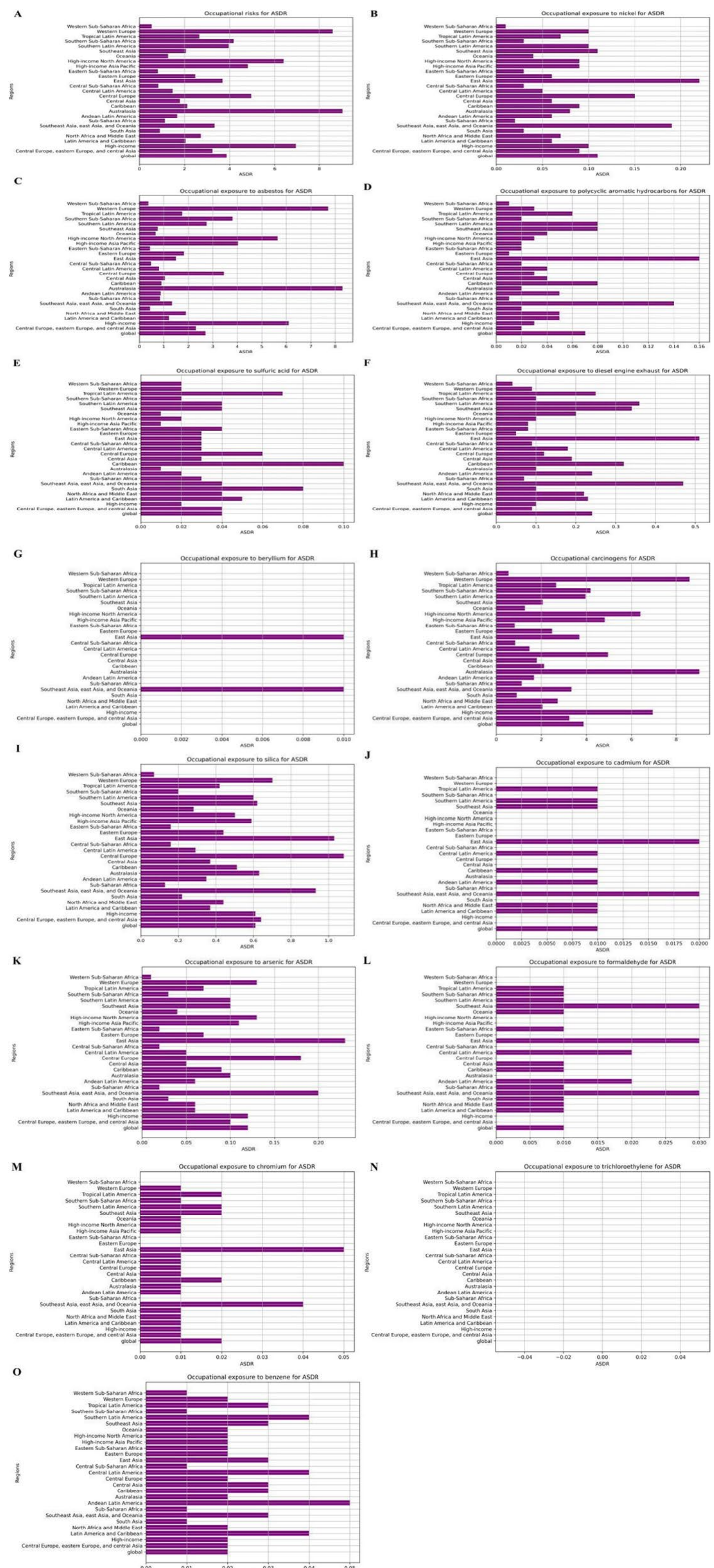

Fig. 2 (See legend on previous page.)

Table 2 Age-standardized rates and estimated annual percentage change for occupational-related cancers by Super Region and regions, 1990 and 2021

	DALYs (Disability-Adjusted Life Years)	Deaths	DALYs (Disability-Adjusted Life Years)	Deaths	DALYs (Disability-Adjusted Life Years)	Deaths
	Age-standardized rate per 100 000 population (95% UI)				Estimated annual percentage change from 1990 to 2019 (95% CI)	
	1990	1990	2021	2021		
	DALY rate	Death rate	DALY rate	Death rate	DALY rate	Death rate
Global						
Both	117.04(93.01,142.33)	5.17(4.13,6.26)	82.13(65.63,101.45)	3.87(3.03,4.68)	−1.11(−5.55,3.54)	−0.86(−2.25,0.55)
Female	33.58(25.43,42.58)	1.40(1.07,1.76)	34.47(25.70,43.91)	1.50(1.11,1.89)	0.03(−3.59,3.79)	0.23(−0.19,0.66)
Male	218.57(171.75,269.01)	10.19(7.96,12.56)	138.29(106.61,170.20)	6.88(5.31,8.50)	−1.42(−6.36,3.78)	−1.17(−3.14,0.85)
Super_Region						
Central Europe, eastern Europe, and central Asia	107.96(75.23,141.66)	3.78(2.70,4.88)	80.27(59.52,103.91)	3.25(2.43,4.18)	−1.00(−5.46,3.66)	−0.47(−1.70,0.78)
High-income	229.42(181.12,278.14)	10.50(8.27,12.68)	133.59(105.20,160.40)	6.95(5.34,8.38)	−1.67(−6.59,3.51)	−1.22(−3.21,0.81)
Latin America and Caribbean	58.02(46.80,69.98)	2.33(1.87,2.79)	49.19(40.15,59.97)	2.05(1.65,2.49)	−0.54(−4.52,3.61)	−0.37(−1.13,0.39)
North Africa and Middle East	95.40(66.87,127.65)	3.83(2.65,5.18)	64.68(47.38,85.46)	2.74(1.93,3.66)	−1.31(−5.54,3.12)	−1.09(−2.18,0.01)
South Asia	20.92(15.58,26.32)	0.74(0.55,0.93)	25.05(19.08,32.63)	0.92(0.70,1.18)	0.49(−2.85,3.94)	0.60(0.48,0.72)
Southeast Asia, east Asia, and Oceania	69.31(50.40,90.42)	2.56(1.88,3.29)	82.45(59.10,111.52)	3.34(2.41,4.49)	0.60(−3.95,5.36)	0.99(−0.29,2.28)
Sub-Saharan Africa	28.56(21.66,36.54)	1.12(0.85,1.44)	27.73(20.78,36.75)	1.14(0.85,1.52)	−0.35(−3.78,3.20)	−0.18(−0.57,0.22)
Regions						
Andean Latin America	50.39(37.35,63.22)	2.16(1.59,2.75)	40.03(28.61,55.33)	1.68(1.20,2.29)	−1.02(−4.79,2.89)	−1.11(−1.72,−0.49)
Australasia	318.51(259.38,375.11)	14.55(11.88,16.99)	170.91(137.83,200.49)	9.02(7.24,10.58)	−2.04(−7.17,3.37)	−1.52(−3.75,0.76)
Caribbean	54.68(42.84,68.34)	2.23(1.74,2.80)	54.02(40.49,70.36)	2.12(1.61,2.75)	0.11(−4.00,4.39)	0.00(−0.80,0.80)
Central Asia	92.52(71.23,116.38)	3.11(2.42,3.87)	47.46(36.20,58.85)	1.80(1.37,2.22)	−2.15(−6.05,1.91)	−1.74(−2.37,−1.11)
Central Europe	105.58(72.59,142.88)	3.77(2.68,4.97)	120.18(87.97,159.06)	4.97(3.66,6.54)	0.77(−4.17,5.96)	1.33(−0.37,3.06)
Central Latin America	46.75(37.57,56.66)	1.85(1.48,2.23)	37.25(29.38,47.06)	1.48(1.17,1.89)	−0.86(−4.55,2.97)	−0.81(−1.23,−0.39)
Central Sub-Saharan Africa	25.84(14.91,42.16)	0.93(0.52,1.64)	22.52(12.28,40.18)	0.83(0.43,1.56)	−0.48(−3.69,2.83)	−0.41(−0.73,−0.08)
East Asia	77.34(55.37,102.02)	2.87(2.11,3.77)	90.45(63.79,123.21)	3.69(2.60,5.06)	0.57(−4.07,5.43)	0.97(−0.41,2.38)
Eastern Europe	111.22(78.58,144.83)	3.87(2.77,4.98)	63.43(46.47,82.80)	2.47(1.81,3.21)	−2.20(−6.38,2.16)	−1.79(−2.74,−0.83)
Eastern Sub-Saharan Africa	20.54(14.50,30.39)	0.74(0.50,1.11)	21.69(15.28,30.63)	0.81(0.55,1.17)	0.04(−3.13,3.32)	0.20(−0.06,0.45)
High-income Asia Pacific	91.03(66.18,117.12)	4.47(3.24,5.67)	86.11(63.34,108.18)	4.82(3.46,6.02)	0.12(−4.45,4.90)	0.58(−1.07,2.25)
High-income North America	246.22(189.95,302.41)	11.45(8.84,14.10)	116.85(90.10,141.97)	6.41(4.81,7.77)	−2.70(−7.44,2.28)	−2.11(−4.01,−0.18)
North Africa and Middle East	95.40(66.87,127.65)	3.83(2.65,5.18)	64.68(47.38,85.46)	2.74(1.93,3.66)	−1.31(−5.54,3.12)	−1.09(−2.18,0.01)
Oceania	29.23(19.28,42.90)	1.14(0.74,1.68)	32.92(22.69,47.79)	1.28(0.88,1.91)	0.48(−3.14,4.23)	0.46(0.19,0.73)
South Asia	20.92(15.58,26.32)	0.74(0.55,0.93)	25.05(19.08,32.63)	0.92(0.70,1.18)	0.49(−2.85,3.94)	0.60(0.48,0.72)
Southeast Asia	42.93(31.64,54.46)	1.54(1.14,1.96)	55.72(39.75,73.60)	2.06(1.47,2.71)	0.68(−3.47,5.01)	0.74(−0.02,1.51)
Southern Latin America	116.37(92.93,141.29)	4.55(3.60,5.59)	91.07(73.22,112.51)	3.96(3.16,4.87)	−0.31(−4.95,4.55)	0.10(−1.38,1.61)
Southern Sub-Saharan Africa	97.52(73.55,125.06)	3.95(2.94,5.09)	93.33(68.26,120.37)	4.18(3.08,5.34)	−0.47(−5.14,4.44)	−0.11(−1.75,1.56)

Table 2 (continued)

	DALYs (Disability-Adjusted Life Years)	Deaths	DALYs (Disability-Adjusted Life Years)	Deaths	DALYs (Disability-Adjusted Life Years)	Deaths
	Age-standardized rate per 100 000 population (95% UI)				Estimated annual percentage change from 1990 to 2019 (95% CI)	
	1990	1990	2021	2021		
	DALY rate	Death rate	DALY rate	Death rate	DALY rate	Death rate
Tropical Latin America	71.14(57.50,85.25)	2.86(2.31,3.42)	62.02(50.17,73.39)	2.67(2.12,3.20)	−0.36(−4.59,4.05)	−0.06(−1.10,1.00)
Western Europe	274.76(218.36,331.12)	12.31(9.79,14.72)	171.55(137.22,205.06)	8.59(6.80,10.20)	−1.29(−6.48,4.18)	−0.90(−3.12,1.36)
Western Sub-Saharan Africa	14.29(9.70,19.22)	0.54(0.37,0.74)	14.01(9.40,19.24)	0.54(0.36,0.73)	−0.12(−2.85,2.68)	−0.10(−0.76,0.57)

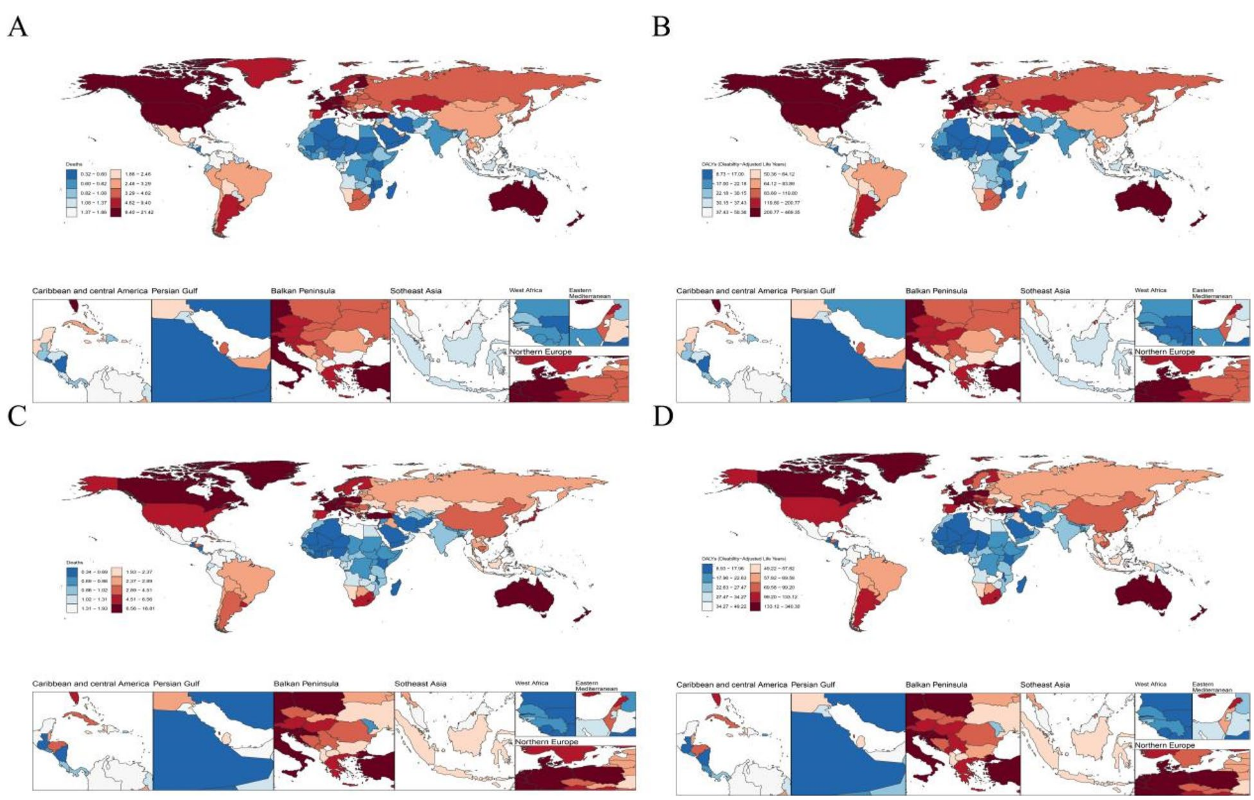

Fig. 3 Age-standardized rates for occupational-related cancers by countries in 1990 and 2021 (**A**) ASDR in 1990 (**B**) age-standardized DALY rate in 1990 (**C**) ASDR in 2021 (**D**) age-standardized DALY rate in 2021

silica (≤ 0.05, ≤ 0.10, or ≤ 0.35 mg/m^3 increased the risk of all-cause and cause-specific mortality, including lung cancer (hazard ratio, 1.08; 95% CI, 1.02–1.14. Therefore, it is important to control airborne silica concentrations and use personal protective equipment in workplaces.

Exposure to asbestos and silica was associated with increased risk of tracheal, bronchial and lung cancers; other risk-outcome associations were also examined. Exposure to asbestos has been associated with malignant mesothelioma, particularly malignant pleural mesothelioma [28, 26, 27]. Due to the long latency period for malignant mesothelioma (30–40 years), a reduction in this cancer burden is not yet apparent, although a decline in new cases is expected in highincome countries [29].

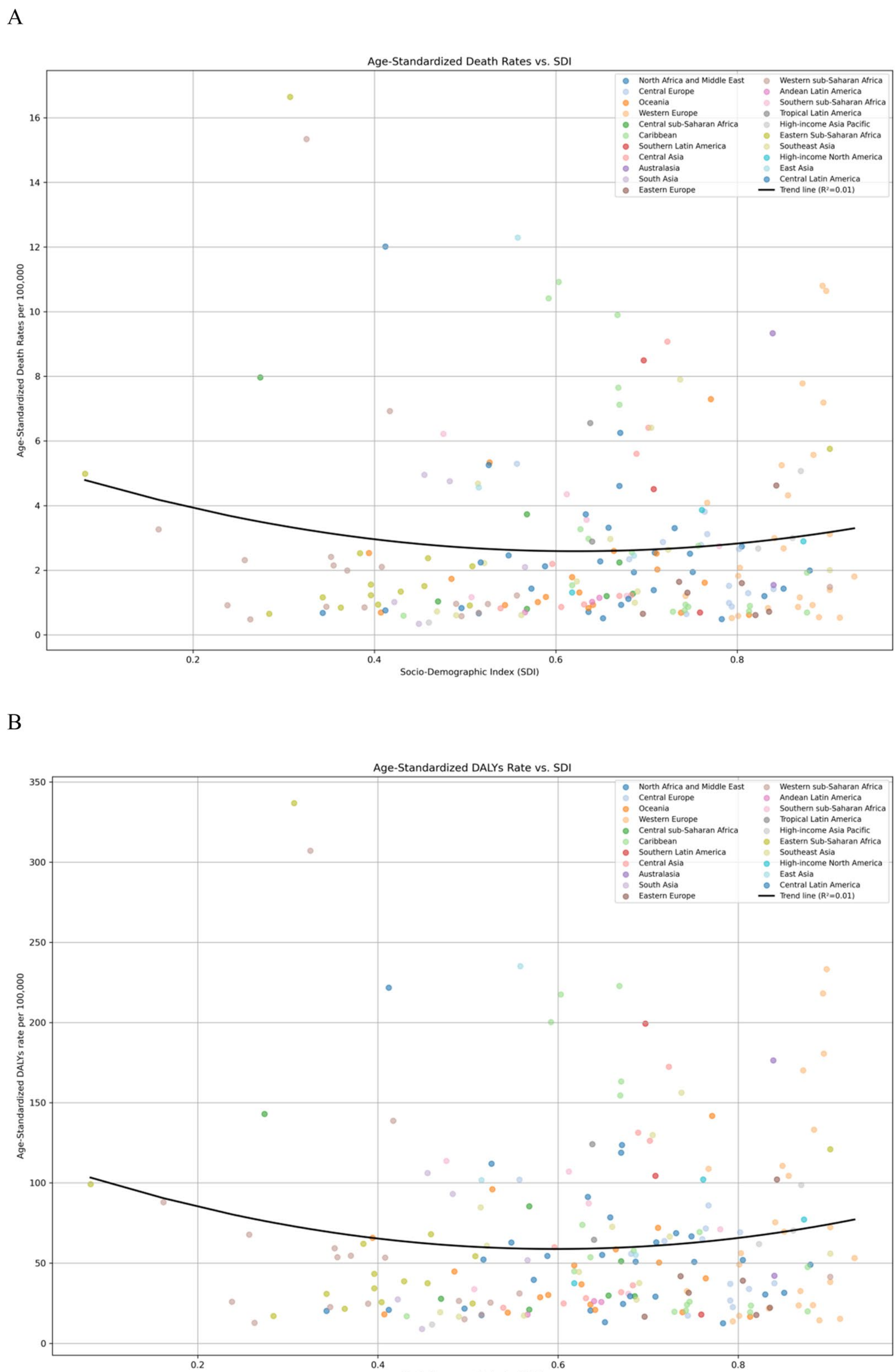

Fig. 4 Age-standardized rates attributable to occupational factors across 204 countries and territories by Socio-demographic Index, 2021 (**A** Death **B** DALYs)

Leukemia was associated with exposure to benzene and formaldehyde. Occupational exposure to benzene occurs in many industries including petroleum, chemical production, manufacturing, shoemaking, painting, printing and rubber manufacturing [30]. Formaldehyde is an important economic chemical that is encountered by more than 2 million workers in the US [31]. The prevalence of formaldehyde exposure is increasing due to its presence in tobacco smoke and emissions from household products such as furniture, particleboard and carpets.

The strengths of this study include the broad spectrum of occupational carcinogens assessed, the long time period covered, and the use of recent GBD 2021 data. The assessment of trends over a long time period allows for an understanding of the long-term effects of occupational exposures. The inclusion of a wide range of carcinogens and their different effects in different regions increases the generalizability and applicability of our results. Furthermore, the detailed information on exposure levels and health outcomes enables a better understanding of the risks associated with specific occupational settings. This analysis can be used to inform public health policies and occupational safety regulations to reduce cancer risk from occupational carcinogens. By using recent data and expanding the number of carcinogens assessed, we provide a solid basis for future research and policy development to reduce the global burden of occupationally induced cancers.

We acknowledge several important limitations in the study, including gaps in data related to carcinogen exposures such as UV radiation, limited epidemiological data for certain cancers, and the lack of explicit consideration for unrecognized occupational carcinogens (OCs), mismatched risk-outcome pairs, and interactions between multiple occupational and non-occupational risk factors. Additionally, the potential overestimation or underestimation of the attributable burden due to methodological constraints, reliance on population-level estimates, and insufficient accounting for latency periods are noted [32].

For instance, in low-resource settings, where comprehensive exposure monitoring and advanced healthcare infrastructure may be lacking, we could recommend prioritizing cost-effective interventions such as promoting personal protective equipment (PPE) use, implementing workplace safety training programs, and encouraging policy-level advocacy for stricter enforcement of existing occupational health regulations. In middle-income regions, where some resources may be available but unevenly distributed, strategies could focus on enhancing surveillance systems for occupational exposures, fostering public–private partnerships to improve workplace safety, and investing in community-based education campaigns about OC risks. For high-income regions, where advanced technologies and robust regulatory frameworks are more accessible, the emphasis could shift toward adopting precision medicine approaches, conducting region-specific exposure assessments using wearable sensors or environmental monitoring tools, and funding research into emerging occupational risks linked to evolving industries [33].

Conclusions

OC exposure has caused a large global cancer burden. Among the 13 OCs included in the GBD 2021 study, asbestos and silica have been responsible for a large proportion of the cancer burden over the past 31 years. Although the average exposure to these carcinogens has decreased, the total cancer burden has increased due to the long latency period between exposure and disease onset. Our results show the cancer burden attributable to OCs by sex, age, location, and socio-economic development. These results are important for guiding prevention and control programs to reduce exposure to OCs.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s12885-025-13914-6.

Supplementary Material 1.

Supplementary Material 2.

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Authors' contributions

B.Z., P.W., J.C. and J.L. contributed to conception, the design of the study, analysis and interpretation of data; Y.L., Q.L., B.Z and M.Z. made substantial contributions to investigation and the acquisition of data. All authors and contributors have agreed to conditions noted on the Authorship Agreement form.

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Data availability

This study was based on the GBD database and does not contain identifiable personal information. The datasets used and analyzed during the current study are available from the corresponding author on a reasonable request. Requests to access these datasets should be directed to zhouming_0321@163.com.

Declarations

Ethics approval and consent to participate

This study did not require ethical approval because it used publicly available databases.

Competing interests

The authors declare no competing interests.

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