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Global, regional, and national burden of esophageal cancer using the 2019 global burden of disease study

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Esophageal cancer, with its aggressive nature and high mortality, poses diverse epidemiological challenges worldwide. Over the past three decades, esophageal cancer has exhibited a substantial global burden, marked by a significant increase in absolute numbers, contrasting with a decline in age-standardized metrics. Prevalence nearly doubled, reaching 0.961 million in 2019, while the age-standardized rate (ASR) decreased to 11.6 per 100,000 cases. New incidence cases surged by 67.07%, yet the age-standardized incidence rate reduced to 6.5 per 100,000 cases. Deaths increased to 0.498 million, with a decline in age-standardized mortality to 6.1 per 100,000 cases. Disability-Adjusted Life Years (DALYs) rose to 11.67 million, but the ASR decreased to 139.8 per 100,000 cases. Gender-specific analysis revealed consistently higher rates in males, with increasing gaps over time. Correlations with SDI indicated a negative association, and frontier analysis underscored the impact of socio-economic progress on disease control. Projections suggest a continued rise in prevalence, incidence, deaths, and DALYs, with gender-specific variations. The research underscores the importance of continued efforts in public health and medical research to adapt to and manage the changing landscape of esophageal cancer globally.

Keywords Esophageal cancer, The global burden of disease study, Average annual percentage change, Frontier analysis, The bayesian age-period-cohort model

Esophageal cancer, as a major global health concern, presents a diverse and complex epidemiological landscape[1]. Its incidence and mortality rates, exhibiting significant geographical variation, underscore the need for a comprehensive understanding of its global burden[2]. This malignancy, characterized by aggressive progression and poor prognosis, ranks among the leading causes of cancer-related deaths worldwide. The variability in its occurrence, influenced by a myriad of factors including dietary habits, lifestyle choices, and genetic predispositions, necessitates an in-depth exploration of its global, regional, and national impact[2,3].

The burden of esophageal cancer extends beyond mere incidence and mortality rates. Its impact on public health is profound, with substantial implications for healthcare systems worldwide[4]. The disease not only leads to a significant loss of life but also imparts considerable morbidity among survivors[5]. This dual burden, encompassing both fatal and non-fatal outcomes, amplifies the need for a detailed analysis that goes beyond traditional epidemiological measures. Such an analysis must encompass a comprehensive assessment of the disease's prevalence, its incidence trends, and the resultant mortality, alongside an evaluation of the broader impact encapsulated by Disability-Adjusted Life Years (DALYs).

Despite growing awareness and research efforts, there remains a gap in a systematic, multi-dimensional analysis of esophageal cancer at a global scale. Current literature often focuses on isolated aspects of the disease, lacking a holistic view that integrates various epidemiological metrics across different regions[6–8]. This gap hinders the formulation of effective global health strategies and policies, essential for addressing the challenges posed by esophageal cancer. Moreover, with changing global health dynamics and evolving risk factors, there is an urgent need for updated and comprehensive data that reflect current and future trends.

In light of these considerations, our study seeks to bridge this gap by leveraging the Global Burden of Disease (GBD) database to conduct a systematic and expansive analysis of esophageal cancer. By utilizing this robust

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and extensive dataset, we aim to provide a detailed exploration of the disease's prevalence, incidence, deaths, and DALYs, alongside forecasting trends up to 2030. This approach not only enriches our understanding of esophageal cancer's epidemiological patterns but also furnishes critical insights for public health decision-making and healthcare planning. Ultimately, our study endeavors to inform and shape the global response to this formidable health challenge, contributing significantly to the improvement of health outcomes for affected populations worldwide.

Methods

Study design and data source

Our research, grounded in a comprehensive analysis of esophageal cancer, utilized the 2019 GBD Study data. This study employed advanced statistical tools, including DisMod-MR 2.1, a meta-regression tool adept at integrating diverse epidemiological data, particularly for chronic diseases[9,10]. By applying a sophisticated modeling framework, we ensured a rigorous and thorough synthesis of the data, providing a robust foundation for our analysis.

Scope and variables

Focusing on esophageal cancer, our analysis centered on four primary variables: prevalence, incidence, deaths, and DALYs. We obtained data from the Global Health Data Exchange (GHDx), which offers comprehensive annual data from 1990 to 2019, segmented by age, sex, and location. Our study encompassed a broad range, covering 204 countries and territories. These were grouped into 21 regions based on geographical proximity and categorized into five clusters using the Socio-demographic Index (SDI) as a benchmark.

SDI

The SDI, a composite indicator reflecting a region's socio-economic status, combines factors like income per capita, educational attainment, and fertility rates[11]. It ranges from 0 to 1, with higher values indicating better socio-economic conditions. We divided SDI into quintiles for detailed analysis.

Data analysis

Our initial data analysis involved calculating both raw and age-standardized rates (ASRs) for the primary outcome measures. We analyzed the variations in these metrics from 1990 to 2019 at global, regional, and national levels. The analysis also involved calculating the percentage of relative changes in prevalence, incidence, mortality, and DALYs over this period.

For temporal trend analysis, we employed Joinpoint regression analysis to detect statistically significant changes in esophageal cancer trends over time. This approach identifies "joinpoints," points at which the slope of the trend significantly shifts, thus segmenting the entire study period into multiple sub-intervals. For each sub-interval, we calculated the Annual Percentage Change (APC) to quantify the magnitude and direction of changes. We then computed the Average Annual Percentage Change (AAPC) over predefined intervals, weighting segment-specific APCs by their respective time spans, in line with established methodologies[12,13]. Trends were deemed increasing if both the APC/AAPC estimate and its lower CI boundary were greater than zero, decreasing if both the APC/AAPC estimate and its upper CI boundary were less than zero, and stable otherwise. Additionally, we used Pearson correlation to examine the association between the SDI and various esophageal cancer indicators, providing insight into the intensity and direction of their linear relationships across diverse geographic settings.

To explore optimal benchmarks for esophageal cancer burden in relation to socio-economic development, we utilized a frontier analysis encompassing multiple disease indicators—including prevalence, incidence, deaths, and DALYs—to identify the lowest potentially achievable levels at any given SDI[14,15]. This approach employs a data envelope analysis using the free disposal hull method to derive non-linear frontiers, reflecting the minimal expected burden across these metrics for each SDI value. To account for uncertainty, we performed 1,000 bootstrapped samples with replacement, calculated mean values for each SDI, and applied LOESS regression (local polynomial degree 1, span 0.3) to generate a stable, smoothed frontier curve. Super-efficient outliers were excluded to prevent distortion. Countries or territories performing closer to this frontier are considered leaders in managing esophageal cancer relative to their development status, while those with greater distances from the frontier have greater scope for improvement.

To forecast esophageal cancer trends up to 2030, we employed the Bayesian Age-Period-Cohort (BAPC) model, which incorporates age, period, and cohort effects to capture temporal and generational influences on disease trends[16]. The model utilizes a second-order random walk (RW2) framework with prior distributions to ensure smoothness and account for similarities between adjacent effects[17]. By leveraging the integrated nested Laplace approximation (INLA) method, the BAPC model achieves efficient approximation of marginal posterior distributions, avoiding the mixing and convergence challenges often associated with traditional Markov Chain Monte Carlo techniques[17]. Statistical analyses were executed using R version 4.2.3.

Results

Global trends

Over the last three decades, the global esophageal cancer burden has seen a substantial increase in absolute numbers, yet a contrasting trend is observed in the age-standardized metrics. Prevalence nearly doubled from 0.489 million cases in 1990 to 0.961 million in 2019. Despite this rise, the age-standardized prevalence rate (ASPR) decreased from 12 to 11.6 per 100,000 individuals. New incidence cases surged by 67.07%, from 0.320 million to 0.535 million, while the age-standardized incidence rate (ASIR) saw a reduction from 8.1 to

6.5 per 100,000 individuals. The number of deaths also increased from 0.319 million to 0.498 million, yet the age-standardized mortality rate fell from 8.2 to 6.1 per 100,000 individuals. DALYs went up from 8.21 million to 11.67 million, but the ASR decreased from 199.3 to 139.8 per 100,000 individuals (Tables 1, 2, 3 and 4).

Temporal trends from joinpoint regression analyses reveal marked variations over the studied period. The prevalence of esophageal cancer showed distinct phases, with a sharp decrease in APC from 2004 to 2010 at -1.90%. Incidence rates witnessed a notable reduction, especially between 2004 and 2014 with an APC of -2.88%. Mortality trends also showed a significant decline in APC during the same period at -3.19%, and DALYs followed suit with the most substantial decrease in APC from 2004 to 2014 at -3.49%. The overall trend, as indicated by

Characteristic	Number in 1990 (95% CI)	Age-standardized Rate in 1990 (95% CI)	Number in 2019 (95% CI)	Age-standardized rate in 2019 (95% CI)	Relative change of numbers from 1990 to 2019(%)	Relative change of age-standardized rate from 1990 to 2019(%)	AAPC (Age-standardized rate, 95% CI)	*P* value
Global	489,194 (388,238 to 536,586)	12 (9.6 to 13.1)	960,610 (840,399 to 1,068,485)	11.6 (10.1 to 12.9)	96.37	-3.58	-0.14 (-0.24 to -0.04)	0.005
High SDI	96,681 (93,981 to 98,748)	9.5 (9.3 to 9.8)	219,163 (197,989 to 241,176)	12.3 (11.1 to 13.6)	126.69	29.03	0.84 (0.74 to 0.94)	< 0.001
High-middle SDI	127,273 (106,634 to 140,142)	11.6 (9.7 to 12.8)	255,801 (195,116 to 300,313)	12.4 (9.5 to 14.5)	100.99	7.1	0.23 (0.13 to 0.33)	< 0.001
Middle SDI	200,314 (118,186 to 232,065)	18.7 (11.1 to 21.7)	355,071 (282,700 to 414,306)	14 (11.1 to 16.3)	77.26	-25.38	-1.04 (-1.17 to -0.9)	< 0.001
Low-middle SDI	44,174 (38,923 to 56,965)	6.9 (6.1 to 8.9)	89,058 (78,281 to 124,219)	6.2 (5.5 to 8.8)	101.61	-9.31	-0.33 (-0.46 to -0.2)	< 0.001
Low SDI	20,636 (17,041 to 23,835)	8.1 (6.7 to 9.2)	41,265 (33,963 to 49,382)	7.4 (6.1 to 8.8)	99.97	-7.97	-0.29 (-0.35 to -0.22)	< 0.001
Andean Latin America	528 (446 to 599)	2.5 (2.2 to 2.9)	1,140 (912 to 1,427)	2 (1.6 to 2.5)	115.74	-20.01	-0.75 (-1.19 to -0.31)	0.001
Australasia	1,827 (1,726 to 1,921)	7.8 (7.4 to 8.2)	4,006 (3,232 to 4,968)	8.3 (6.7 to 10.4)	119.23	6.91	0.23 (-0.04 to 0.5)	0.095
Caribbean	1,399 (1,312 to 1,507)	5.4 (5 to 5.8)	2,961 (2,517 to 3,426)	5.7 (4.8 to 6.6)	111.7	6.06	0.33 (0.19 to 0.47)	< 0.001
Central Asia	9,088 (8,798 to 9,427)	18.8 (18.2 to 19.6)	7,010 (6,186 to 8,290)	9 (8 to 10.6)	-22.87	-52.02	-2.51 (-2.76 to -2.26)	< 0.001
Central Europe	6,274 (6,122 to 6,430)	4.2 (4.1 to 4.3)	8,957 (7,763 to 10,243)	4.6 (3.9 to 5.2)	42.77	8.21	0.17 (0 to 0.33)	0.044
Central Latin America	2,671 (2,588 to 2,743)	3.2 (3.1 to 3.3)	5,634 (4,767 to 6,583)	2.4 (2 to 2.8)	110.93	-25.08	-1.03 (-1.33 to -0.72)	< 0.001
Central Sub-Saharan Africa	3,564 (1,631 to 4,761)	14.3 (6.6 to 19)	6,470 (3,453 to 8,786)	11.2 (6 to 15.3)	81.53	-21.47	-0.84 (-0.97 to -0.7)	< 0.001
East Asia	258,241 (164,354 to 303,318)	28.3 (18.2 to 33.1)	511,950 (394,879 to 608,640)	23.9 (18.3 to 28.3)	98.25	-15.57	-0.59 (-0.74 to -0.44)	< 0.001
Eastern Europe	18,127 (17,431 to 19,232)	6.3 (6.1 to 6.7)	17,805 (15,466 to 20,314)	5.3 (4.6 to 6.1)	-1.77	-15.97	-0.56 (-1.45 to 0.33)	0.215
Eastern Sub-Saharan Africa	12,070 (9,071 to 14,199)	14.9 (11.3 to 17.5)	24,095 (18,215 to 30,635)	13.7 (10.4 to 17.4)	99.63	-8.01	-0.3 (-0.49 to -0.11)	0.002
High-income Asia Pacific	32,110 (30,719 to 33,522)	15.6 (14.9 to 16.2)	78,954 (66,451 to 93,361)	19.1 (16 to 22.6)	145.88	22.45	0.61 (0.36 to 0.86)	< 0.001
High-income North America	22,093 (21,483 to 22,664)	6.6 (6.4 to 6.8)	46,983 (40,331 to 54,880)	7.8 (6.7 to 9.1)	112.66	17.68	0.52 (0.38 to 0.66)	< 0.001
North Africa and Middle East	6,446 (4,389 to 7,728)	3.5 (2.5 to 4.2)	15,729 (11,584 to 18,012)	3.5 (2.6 to 3.9)	144.02	-1.54	-0.05 (-0.16 to 0.06)	0.345
Oceania	91 (68 to 127)	2.8 (2.2 to 4)	216 (161 to 289)	2.8 (2.1 to 3.8)	136.89	-0.07	-0.02 (-0.06 to 0.02)	0.286
South Asia	37,657 (33,048 to 47,049)	6.1 (5.4 to 7.6)	79,148 (68,370 to 105,673)	5.3 (4.6 to 7.2)	110.18	-12.48	-0.41 (-0.6 to -0.22)	< 0.001
Southeast Asia	10,483 (8,903 to 11,904)	3.8 (3.3 to 4.3)	24,639 (20,694 to 28,965)	3.8 (3.2 to 4.5)	135.04	0.25	0 (-0.14 to 0.15)	0.979
Southern Latin America	4,660 (4,506 to 4,802)	10.1 (9.7 to 10.4)	5,751 (4,555 to 7,276)	7 (5.5 to 8.8)	23.41	-30.87	-1.32 (-1.57 to -1.07)	< 0.001
Southern Sub-Saharan Africa	5,514 (4,122 to 6,777)	18.8 (14 to 23.2)	8,570 (7,624 to 10,186)	14.6 (13 to 17.1)	55.43	-22.38	-0.88 (-1.57 to -0.18)	0.014
Tropical Latin America	9,071 (8,747 to 9,431)	9.4 (9 to 9.8)	19,366 (18,364 to 20,289)	7.8 (7.4 to 8.1)	113.48	-17.23	-0.65 (-0.8 to -0.49)	< 0.001
Western Europe	44,691 (43,644 to 45,585)	8.3 (8.1 to 8.4)	84,093 (73,119 to 96,578)	10.4 (9 to 12)	88.17	25.35	0.78 (0.58 to 0.99)	< 0.001
Western Sub-Saharan Africa	2,588 (2,217 to 3,026)	2.8 (2.4 to 3.3)	7,133 (5,425 to 8,651)	3.6 (2.7 to 4.3)	175.59	28.62	0.89 (0.82 to 0.96)	< 0.001

Table 1. Numbers and ASRs per 100,000 cases of prevalence of esophageal cancer in 1990 and 2019, along with the ralative changes and AAPC in ASRs per 100,000 cases from 1990–2019, categorized by global, SID and GBD regions.

Characteristic	Number in 1990 (95% CI)	Age-standardized Rate in 1990 (95% CI)	Number in 2019 (95% CI)	Age-standardized Rate in 2019 (95% CI)	Relative change of numbers from 1990 to 2019(%)	Relative change of age-standardized rate from 1990 to 2019(%)	AAPC (Age-standardized Rate, 95% CI)	*P* value
Global	319,969 (253,395 to 351,210)	8.1 (6.4 to 8.8)	534,563 (466,513 to 595,342)	6.5 (5.7 to 7.2)	67.07	-19.28	-0.75 (-0.85 to -0.65)	< 0.001
High SDI	52,157 (50,608 to 53,200)	5.1 (4.9 to 5.2)	95,911 (86,719 to 105,092)	5.2 (4.7 to 5.7)	83.89	2.45	0.03 (-0.06 to 0.12)	0.552
High-middle SDI	86,734 (73,335 to 95,038)	8.1 (6.9 to 8.8)	145,267 (113,247 to 169,316)	7.1 (5.5 to 8.2)	67.49	-12.64	-0.5 (-0.74 to -0.26)	< 0.001
Middle SDI	136,240 (81,440 to 157,389)	13.5 (8.1 to 15.5)	205,237 (164,588 to 237,934)	8.4 (6.7 to 9.7)	50.64	-37.57	-1.66 (-1.81 to -1.5)	< 0.001
Low-middle SDI	30,394 (26,887 to 39,269)	5.1 (4.5 to 6.5)	59,864 (52,707 to 84,056)	4.4 (3.9 to 6.2)	96.96	-13.83	-0.51 (-0.66 to -0.36)	< 0.001
Low SDI	14,366 (11,901 to 16,558)	6 (5 to 6.9)	28,132 (23,219 to 33,412)	5.4 (4.5 to 6.4)	95.83	-10.52	-0.38 (-0.44 to -0.32)	< 0.001
Andean Latin America	386 (325 to 436)	2 (1.6 to 2.2)	827 (670 to 1,021)	1.5 (1.2 to 1.9)	114.37	-22.86	-0.87 (-1.36 to -0.39)	< 0.001
Australasia	1,076 (1,024 to 1,120)	4.6 (4.4 to 4.8)	2,192 (1,767 to 2,707)	4.4 (3.5 to 5.5)	103.66	-3.72	-0.25 (-0.39 to -0.12)	< 0.001
Caribbean	985 (921 to 1,062)	3.8 (3.6 to 4.1)	1,920 (1,641 to 2,200)	3.7 (3.2 to 4.2)	94.99	-3.7	0 (-0.08 to 0.07)	0.969
Central Asia	6,415 (6,206 to 6,653)	13.8 (13.3 to 14.3)	4,834 (4,274 to 5,679)	6.7 (6 to 7.8)	-24.65	-51.48	-2.45 (-2.65 to -2.25)	< 0.001
Central Europe	4,277 (4,165 to 4,386)	2.9 (2.8 to 3)	5,853 (5,109 to 6,664)	2.9 (2.5 to 3.3)	36.84	-0.16	-0.02 (-0.21 to 0.17)	0.804
Central Latin America	1,909 (1,838 to 1,965)	2.4 (2.3 to 2.5)	3,869 (3,281 to 4,511)	1.7 (1.4 to 1.9)	102.65	-30.54	-1.29 (-1.63 to -0.95)	< 0.001
Central Sub-Saharan Africa	2,482 (1,149 to 3,296)	10.8 (5 to 14.3)	4,431 (2,378 to 6,020)	8.4 (4.5 to 11.6)	78.54	-22.38	-0.87 (-1 to -0.74)	< 0.001
East Asia	176,236 (114,354 to 205,921)	20.5 (13.4 to 23.7)	284,908 (220,166 to 338,886)	13.7 (10.6 to 16.3)	61.66	-33	-1.4 (-1.54 to -1.25)	< 0.001
Eastern Europe	12,165 (11,699 to 12,875)	4.3 (4.1 to 4.5)	11,086 (9,669 to 12,604)	3.2 (2.8 to 3.7)	-8.87	-23.92	-0.79 (-1.64 to 0.06)	0.07
Eastern Sub-Saharan Africa	8,438 (6,393 to 9,881)	11.2 (8.5 to 13)	16,391 (12,431 to 20,713)	10 (7.7 to 12.6)	94.25	-10.3	-0.38 (-0.51 to -0.25)	< 0.001
High-income Asia Pacific	13,198 (12,650 to 13,571)	6.5 (6.2 to 6.7)	25,159 (21,213 to 29,616)	5.7 (4.8 to 6.8)	90.63	-12.19	-0.53 (-0.67 to -0.39)	< 0.001
High-income North America	13,204 (12,784 to 13,565)	3.9 (3.7 to 4)	26,162 (22,461 to 30,594)	4.2 (3.6 to 5)	98.14	9.36	0.26 (0.17 to 0.35)	< 0.001
North Africa and Middle East	4,371 (3,077 to 5,236)	2.5 (1.8 to 3)	10,024 (7,415 to 11,436)	2.4 (1.8 to 2.7)	129.34	-7.21	-0.25 (-0.32 to -0.18)	< 0.001
Oceania	63 (47 to 89)	2.2 (1.7 to 3.1)	147 (110 to 196)	2.2 (1.7 to 2.9)	132.82	-1.42	-0.08 (-0.13 to -0.02)	0.004
South Asia	25,604 (22,501 to 32,082)	4.5 (4 to 5.7)	53,488 (46,152 to 72,051)	3.8 (3.3 to 5.1)	108.9	-16.48	-0.58 (-0.78 to -0.38)	< 0.001
Southeast Asia	7,090 (6,040 to 8,059)	2.7 (2.4 to 3.1)	15,543 (13,193 to 18,202)	2.5 (2.2 to 3)	119.22	-7.5	-0.27 (-0.41 to -0.14)	< 0.001
Southern Latin America	3,382 (3,259 to 3,495)	7.4 (7.1 to 7.7)	3,945 (3,158 to 4,943)	4.7 (3.8 to 5.9)	16.64	-36.7	-1.61 (-1.86 to -1.35)	< 0.001
Southern Sub-Saharan Africa	3,724 (2,788 to 4,579)	13.3 (9.9 to 16.5)	5,941 (5,316 to 6,943)	10.7 (9.6 to 12.3)	59.56	-19.92	-0.64 (-1.07 to -0.21)	0.004
Tropical Latin America	6,131 (5,908 to 6,371)	6.7 (6.4 to 6.9)	12,684 (11,993 to 13,294)	5.2 (4.9 to 5.4)	106.88	-22.4	-0.88 (-0.99 to -0.76)	< 0.001
Western Europe	26,996 (26,237 to 27,496)	4.8 (4.7 to 4.9)	40,174 (35,133 to 45,706)	4.6 (4.1 to 5.3)	48.82	-3.99	-0.23 (-0.29 to -0.18)	< 0.001
Western Sub-Saharan Africa	1,838 (1,584 to 2,145)	2.1 (1.8 to 2.4)	4,986 (3,776 to 5,992)	2.7 (2.1 to 3.2)	171.31	28.85	0.89 (0.78 to 0.99)	< 0.001

Table 2. Numbers and ASRs per 100,000 cases of incidence of esophageal cancer in 1990 and 2019, along with the ralative changes and AAPC in ASRs per 100,000 cases from 1990–2019, categorized by global, SID and GBD regions.

the AAPC, was negative for all measures: -0.14% for prevalence, -0.75% for incidence, -1.02% for mortality, and – 1.23% for DALYs (Fig. 1).

Global trends by sex

The ASR for both prevalence and incidence in males consistently exceeded that of females throughout the three-decade period. A declining trend in ASR over time is observed for both sexes, with the rates for males remaining

Characteristic	Number in 1990 (95% CI)	Age-standardized Rate in 1990 (95% CI)	Number in 2019 (95% CI)	Age-standardized Rate in 2019 (95% CI)	Relative change of numbers from 1990 to 2019(%)	Relative change of age-standardized rate from 1990 to 2019(%)	AAPC (Age-standardized rate, 95% CI)	*P* value
Global	319,332 (248,666 to 350,802)	8.2 (6.4 to 9)	498,067 (438,411 to 551,462)	6.1 (5.4 to 6.8)	55.97	-25.32	-1.02 (-1.11 to -0.92)	< 0.001
High SDI	47,439 (45,967 to 48,389)	4.6 (4.4 to 4.7)	79,088 (73,600 to 83,089)	4.2 (3.9 to 4.4)	66.72	-8.85	-0.32 (-0.41 to -0.23)	< 0.001
High-middle SDI	88,112 (73,501 to 96,912)	8.3 (7 to 9.1)	135,757 (108,339 to 156,606)	6.6 (5.3 to 7.6)	54.07	-20.64	-0.83 (-1.02 to -0.63)	< 0.001
Middle SDI	138,218 (80,643 to 159,517)	14.1 (8.4 to 16.2)	193,720 (157,830 to 223,774)	8.1 (6.5 to 9.4)	40.16	-42.34	-1.92 (-2.06 to -1.77)	< 0.001
Low-middle SDI	30,842 (27,388 to 39,603)	5.3 (4.7 to 6.9)	60,670 (53,987 to 85,565)	4.5 (4 to 6.4)	96.71	-15.2	-0.57 (-0.72 to -0.42)	< 0.001
Low SDI	14,642 (12,029 to 16,772)	6.4 (5.2 to 7.3)	28,684 (23,834 to 34,252)	5.7 (4.8 to 6.8)	95.9	-10.86	-0.4 (-0.46 to -0.33)	< 0.001
Andean Latin America	412 (347 to 464)	2.1 (1.8 to 2.4)	889 (723 to 1,090)	1.6 (1.3 to 2)	115.74	-23.69	-0.91 (-1.38 to -0.43)	< 0.001
Australasia	1,016 (970 to 1,054)	4.3 (4.1 to 4.5)	2,035 (1,830 to 2,218)	4 (3.6 to 4.4)	100.33	-7.24	-0.26 (-0.49 to -0.03)	0.03
Caribbean	1,022 (955 to 1,106)	4 (3.8 to 4.4)	1,923 (1,649 to 2,197)	3.7 (3.2 to 4.2)	88.17	-8.15	-0.19 (-0.26 to -0.11)	< 0.001
Central Asia	6,622 (6,392 to 6,871)	14.5 (14 to 15.1)	4,924 (4,359 to 5,769)	7.1 (6.3 to 8.2)	-25.63	-51.27	-2.43 (-2.62 to -2.25)	< 0.001
Central Europe	4,328 (4,206 to 4,443)	3 (2.9 to 3)	5,856 (5,124 to 6,670)	2.9 (2.5 to 3.2)	35.28	-3.46	-0.14 (-0.32 to 0.04)	0.13
Central Latin America	2,008 (1,921 to 2,070)	2.6 (2.5 to 2.7)	4,021 (3,391 to 4,707)	1.7 (1.5 to 2)	100.29	-32.79	-1.4 (-1.73 to -1.07)	< 0.001
Central Sub-Saharan Africa	2,528 (1,184 to 3,312)	11.6 (5.4 to 15)	4,509 (2,426 to 6,141)	9 (4.8 to 12.4)	78.36	-22.41	-0.87 (-1 to -0.74)	< 0.001
East Asia	179,088 (114,836 to 208,583)	21.6 (13.9 to 24.9)	263,307 (209,014 to 314,860)	13 (10.2 to 15.4)	47.03	-39.88	-1.79 (-1.91 to -1.67)	< 0.001
Eastern Europe	12,145 (11,682 to 12,854)	4.3 (4.1 to 4.6)	10,655 (9,298 to 12,077)	3.1 (2.7 to 3.5)	-12.27	-27.74	-1 (-1.79 to -0.19)	0.015
Eastern Sub-Saharan Africa	8,621 (6,513 to 10,074)	11.9 (9 to 13.9)	16,940 (12,941 to 21,344)	10.8 (8.3 to 13.5)	96.5	-9.26	-0.34 (-0.53 to -0.14)	0.001
High-income Asia Pacific	10,133 (9,655 to 10,392)	5.1 (4.8 to 5.2)	16,337 (14,650 to 17,795)	3.5 (3.2 to 3.8)	61.23	-30.39	-1.26 (-1.41 to -1.11)	< 0.001
High-income North America	12,515 (12,085 to 12,862)	3.6 (3.5 to 3.7)	24,152 (22,876 to 25,147)	3.8 (3.7 to 4)	92.98	6.05	0.19 (0.1 to 0.29)	< 0.001
North Africa and Middle East	4,442 (3,157 to 5,290)	2.7 (2 to 3.2)	9,968 (7,385 to 11,383)	2.4 (1.9 to 2.7)	124.43	-9.2	-0.33 (-0.41 to -0.24)	< 0.001
Oceania	63 (48 to 89)	2.3 (1.8 to 3.3)	147 (111 to 197)	2.3 (1.8 to 3)	132.7	-1.6	-0.09 (-0.14 to -0.03)	0.001
South Asia	25,840 (22,630 to 32,260)	4.8 (4.2 to 5.9)	54,161 (46,992 to 72,771)	3.9 (3.4 to 5.2)	109.6	-17.95	-0.66 (-0.87 to -0.44)	< 0.001
Southeast Asia	7,181 (6,113 to 8,103)	2.9 (2.5 to 3.3)	15,330 (13,164 to 17,964)	2.6 (2.2 to 3.1)	113.47	-10.35	-0.38 (-0.51 to -0.25)	< 0.001
Southern Latin America	3,543 (3,408 to 3,668)	7.9 (7.6 to 8.2)	4,067 (3,769 to 4,359)	4.8 (4.5 to 5.2)	14.79	-38.96	-1.67 (-1.84 to -1.5)	< 0.001
Southern Sub-Saharan Africa	3,764 (2,820 to 4,657)	13.8 (10.4 to 17.1)	6,095 (5,489 to 7,002)	11.3 (10.2 to 12.8)	61.92	-18.4	-0.57 (-1.03 to -0.12)	0.013
Tropical Latin America	6,205 (5,949 to 6,465)	6.9 (6.6 to 7.3)	12,767 (11,996 to 13,448)	5.2 (4.9 to 5.5)	105.75	-24.41	-0.96 (-1.07 to -0.85)	< 0.001
Western Europe	25,954 (25,117 to 26,463)	4.6 (4.5 to 4.7)	34,847 (32,416 to 36,620)	3.9 (3.6 to 4.1)	34.26	-15.7	-0.6 (-0.65 to -0.55)	< 0.001
Western Sub-Saharan Africa	1,900 (1,642 to 2,234)	2.2 (1.9 to 2.6)	5,135 (3,916 to 6,146)	2.9 (2.2 to 3.4)	170.25	29.32	0.9 (0.8 to 0.99)	< 0.001

Table 3. Numbers and ASRs per 100,000 cases of deaths of esophageal cancer in 1990 and 2019, along with the ralative changes and AAPC in ASRs per 100,000 cases from 1990–2019, categorized by global, SID and GBD regions.

notably higher. In terms of absolute numbers, a steady increase in cases for both prevalence and incidence among males, with a more pronounced rise observed in deaths and DALYs. Although females also exhibit an increase in cases, the gap between the sexes appears to widen over time, particularly in the number of deaths and DALYs (Figs. 2 and 3).

Characteristic	Number in 1990 (95% CI)	Age-standardized Rate in 1990 (95% CI)	Number in 2019 (95% CI)	Age-standardized rate in 2019 (95% CI)	Relative change of numbers from 1990 to 2019(%)	Relative change of age-standardized rate from 1990 to 2019(%)	AAPC (Age-standardized rate, 95% CI)	*P* value
Global	8,208,267 (6,334,289 to 9,075,711)	199.3 (154.2 to 220)	11,666,017 (10,378,747 to 12,938,949)	139.8 (124.4 to 155)	42.13	-29.85	-1.23 (-1.32 to -1.14)	< 0.001
High SDI	1,116,159 (1,091,372 to 1,135,517)	111.3 (108.9 to 113.2)	1,653,972 (1,570,861 to 1,731,345)	95.8 (91.4 to 100.5)	48.18	-13.88	-0.52 (-0.6 to -0.45)	< 0.001
High-middle SDI	2,235,279 (1,851,568 to 2,479,332)	203 (168.2 to 224.7)	3,105,596 (2,487,365 to 3,596,286)	151 (121.2 to 174.7)	38.94	-25.59	-1.06 (-1.26 to -0.86)	< 0.001
Middle SDI	3,574,428 (2,120,546 to 4,144,035)	330.1 (194.3 to 382.9)	4,485,644 (3,737,169 to 5,192,821)	175.2 (145.4 to 202.5)	25.49	-46.94	-2.19 (-2.31 to -2.08)	< 0.001
Low-middle SDI	863,275 (763,527 to 1,104,285)	132 (117 to 169)	1,611,655 (1,433,392 to 2,250,321)	111.3 (99 to 155.7)	86.69	-15.69	-0.58 (-0.72 to -0.44)	< 0.001
Low SDI	417,176 (342,900 to 481,147)	159.6 (131.3 to 183.2)	805,543 (662,160 to 973,246)	141.1 (116.5 to 168.9)	93.09	-11.59	-0.42 (-0.48 to -0.36)	< 0.001
Andean Latin America	9,890 (8,331 to 11,215)	46.7 (39.4 to 53)	18,839 (15,081 to 23,638)	33.4 (26.9 to 42)	90.49	-28.48	-1.14 (-1.66 to -0.61)	< 0.001
Australasia	22,212 (21,393 to 23,001)	95.5 (91.9 to 98.9)	39,885 (36,426 to 43,385)	85.2 (78 to 92.4)	79.57	-10.78	-0.39 (-0.62 to -0.17)	0.001
Caribbean	24,294 (22,600 to 26,553)	92.4 (86 to 100.7)	47,316 (40,107 to 54,718)	90.7 (76.9 to 104.8)	94.76	-1.79	0.11 (0.02 to 0.19)	0.012
Central Asia	170,813 (165,262 to 177,210)	351.7 (340.4 to 365.7)	129,818 (114,167 to 153,552)	164.8 (145.6 to 193.1)	-24	-53.15	-2.57 (-2.8 to -2.35)	< 0.001
Central Europe	115,388 (112,612 to 118,310)	78.1 (76.2 to 80)	143,701 (124,717 to 164,319)	74.7 (64.5 to 85.3)	24.54	-4.37	-0.19 (-0.4 to 0.02)	0.071
Central Latin America	48,243 (46,833 to 49,490)	56 (54.1 to 57.5)	90,775 (76,781 to 107,044)	38 (32.1 to 44.8)	88.16	-32.17	-1.4 (-1.76 to -1.03)	< 0.001
Central Sub-Saharan Africa	72,458 (33,619 to 94,381)	285.6 (132.7 to 372.7)	127,510 (68,514 to 172,764)	215.2 (115.5 to 294)	75.98	-24.65	-0.97 (-1.11 to -0.83)	< 0.001
East Asia	4,562,936 (2,892,718 to 5,350,134)	495.6 (316.2 to 579.4)	5,922,865 (4,733,467 to 7,156,234)	275.4 (221.9 to 331.8)	29.8	-44.43	-2.02 (-2.14 to -1.89)	< 0.001
Eastern Europe	320,906 (308,770 to 341,033)	112.2 (107.8 to 119.6)	277,541 (240,922 to 316,272)	83.5 (72.6 to 95.1)	-13.51	-25.58	-0.76 (-1.67 to 0.16)	0.106
Eastern Sub-Saharan Africa	244,963 (182,809 to 288,763)	296.4 (223.8 to 348.1)	476,744 (361,802 to 608,685)	263.4 (200.5 to 332.9)	94.62	-11.13	-0.41 (-0.61 to -0.21)	< 0.001
High-income Asia Pacific	243,863 (229,035 to 250,246)	117.5 (110.6 to 120.6)	306,118 (281,921 to 333,763)	75.8 (70.6 to 82.6)	25.53	-35.55	-1.53 (-1.69 to -1.37)	< 0.001
High-income North America	292,713 (285,562 to 300,085)	89 (87 to 91.2)	524,630 (503,915 to 544,030)	88.3 (85 to 91.4)	79.23	-0.78	-0.02 (-0.17 to 0.14)	0.837
North Africa and Middle East	122,368 (81,913 to 147,739)	65.4 (45.4 to 78.5)	259,488 (183,343 to 301,673)	55.6 (40.5 to 63.8)	112.06	-14.99	-0.56 (-0.62 to -0.49)	< 0.001
Oceania	1,828 (1,354 to 2,558)	55.3 (41.9 to 77.6)	4,213 (3,133 to 5,650)	53.6 (40.4 to 71.7)	130.54	-3.09	-0.14 (-0.19 to -0.08)	< 0.001
South Asia	744,462 (652,926 to 927,062)	117.9 (103.1 to 146.8)	1,476,590 (1,282,692 to 1,962,191)	98.3 (85.5 to 131.1)	98.34	-16.61	-0.56 (-0.76 to -0.36)	< 0.001
Southeast Asia	201,111 (169,876 to 228,343)	71.6 (60.7 to 80.9)	403,725 (342,843 to 472,284)	61.7 (52.7 to 72.4)	100.75	-13.83	-0.51 (-0.65 to -0.37)	< 0.001
Southern Latin America	80,442 (77,833 to 83,110)	173.2 (167.5 to 179)	83,206 (77,617 to 89,098)	101.1 (94.4 to 108.2)	3.44	-41.65	-1.83 (-1.99 to -1.66)	< 0.001
Southern Sub-Saharan Africa	106,970 (79,140 to 131,561)	356.6 (265.8 to 439.4)	159,882 (142,561 to 188,481)	267.1 (239.2 to 310.8)	49.46	-25.09	-1.01 (-1.65 to -0.36)	0.002
Tropical Latin America	170,087 (164,206 to 176,763)	172.8 (166.6 to 179.7)	328,430 (311,722 to 345,187)	131 (124.3 to 137.7)	93.1	-24.17	-0.95 (-1.01 to -0.89)	< 0.001
Western Europe	601,312 (588,465 to 611,699)	112.5 (110.2 to 114.4)	706,817 (669,630 to 741,655)	88.6 (84.3 to 92.9)	17.55	-21.18	-0.84 (-0.91 to -0.78)	< 0.001
Western Sub-Saharan Africa	51,009 (43,559 to 60,395)	54.3 (46.6 to 64.1)	137,923 (104,912 to 167,521)	67.8 (51.5 to 81.6)	170.39	24.89	0.79 (0.73 to 0.86)	< 0.001

Table 4. Numbers and ASRs per 100,000 cases of DALYs of esophageal cancer in 1990 and 2019, along with the ralative changes and AAPC in ASRs per 100,000 cases from 1990–2019, categorized by global, SID and GBD regions.

The ASR trends for esophageal cancer reveal gender-specific patterns in prevalence and incidence across the global spectrum. For prevalence, the ASR in males peaked around 2004 with a notable APC of 2.31% before declining, while females showed a similar trend with a peak APC of 2.10%. Subsequent years marked a decline in prevalence ASRs for both sexes, with females experiencing a sharper fall, particularly from 2010 to 2013

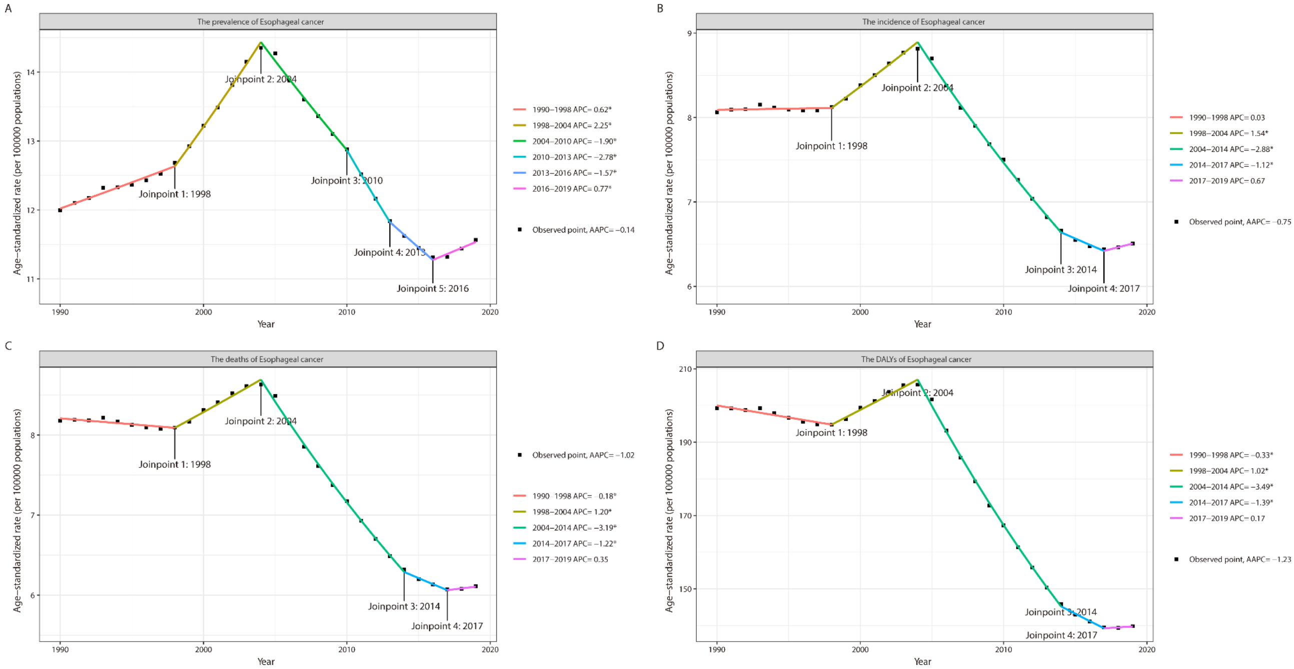

Fig. 1. The APC and AAPC of ASR for the prevalence (**A**), incidence (**B**), deaths (**C**) and DALYs (**D**) associated with esophageal cancer at the global level based on the joinpoint regression analysis model.

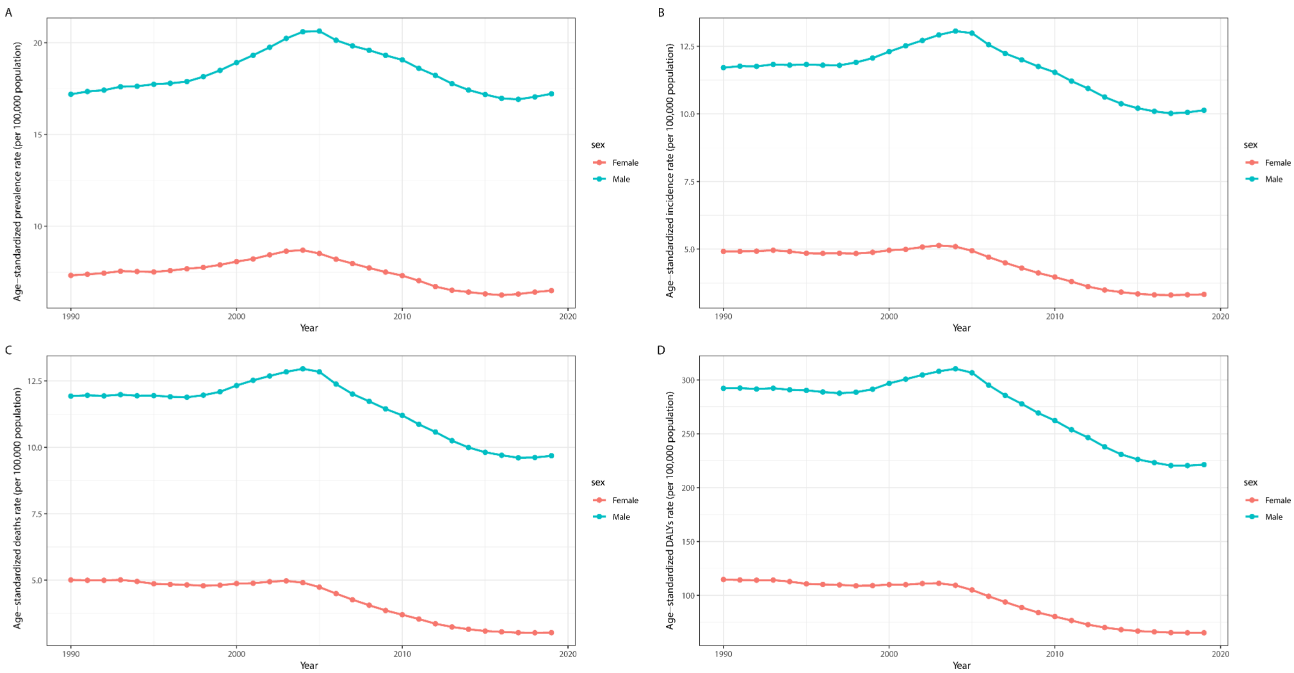

Fig. 2. The trends in ASR of prevalence (**A**), incidence (**B**), deaths (**C**), and DALYs (**D**) for esophageal cancer among different sexes, female and male, from 1990 to 2019.

(APC = -3.75%). The incidence ASRs after 2004 decreased steadily for both genders; however, the fall was more pronounced in females with an APC of -4.26% from 2004 to 2013, compared to males with an APC of -2.18% from 2004 to 2010. The AAPC for both prevalence and incidence was – 0.14% and – 0.75%, indicating a gradual decrease over the study period (Fig. 4).

In examining the death rates and DALYs, both genders showed a downward trend post-2004. The death rates for females declined at an APC of -4.78% from 2004 to 2012, which was more substantial than the decline for males, with an APC of -2.65% from 2004 to 2014. The DALYs also displayed a consistent decrease, with females

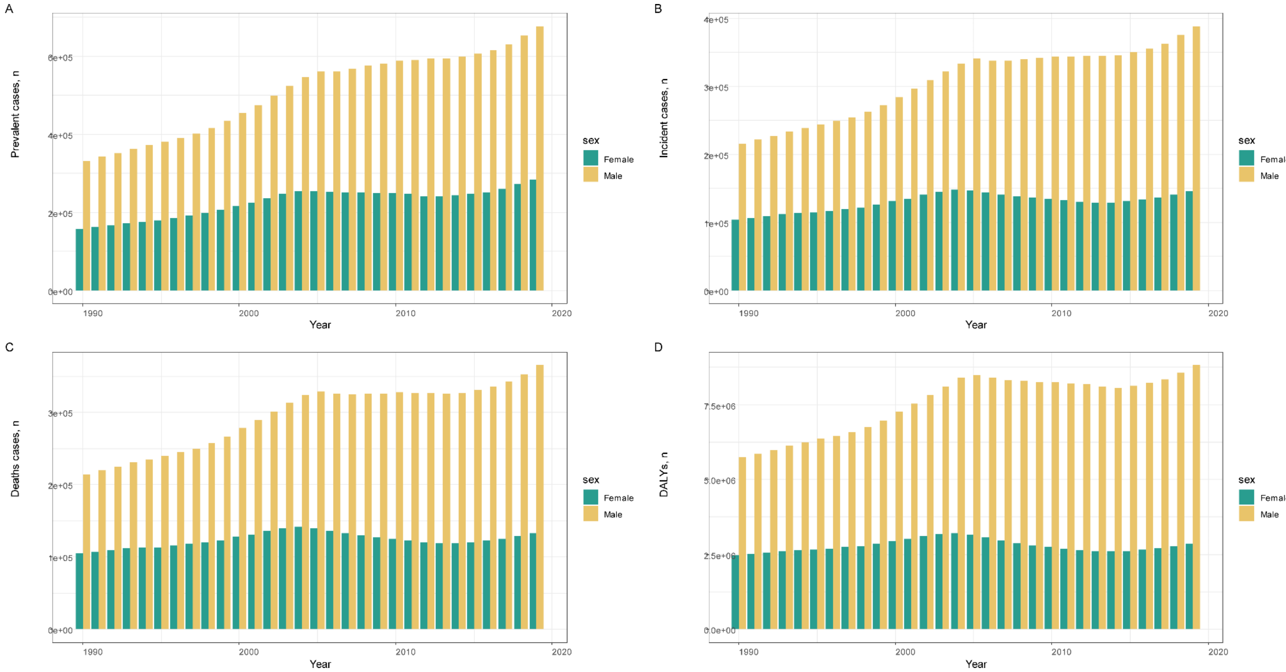

Fig. 3. The trends in numbers of prevalence (**A**), incidence (**B**), deaths (**C**), and DALYs (**D**) for esophageal cancer among different sexes, female and male, from 1990 to 2019.

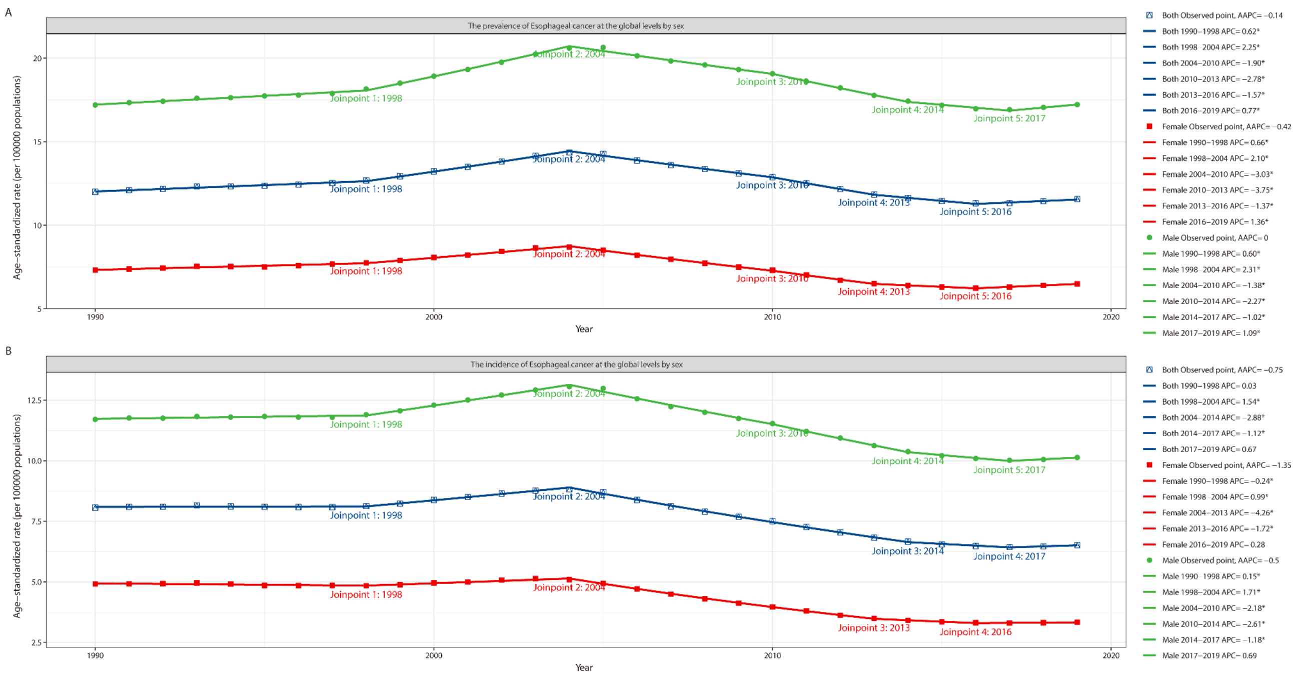

Fig. 4. The APC and AAPC of ASR for prevalence (**A**) and incidence (**B**) by gender (both, female and male) in esophageal cancer at the global level based on the joinpoint regression analysis model.

experiencing a sharper decline (APC = -5.38% from 2004 to 2009). The AAPC for DALYs stood at -1.95% for females and – 0.96% for males (Fig. 5).

Global trends by age group

The age-related distribution of esophageal cancer rates displays significant differences by sex across various age groups. The prevalence and incidence rates for males are considerably higher than for females, particularly in the older age brackets, with a stark increase observed from the age of 40–44 years and peaking in 70–74 years for

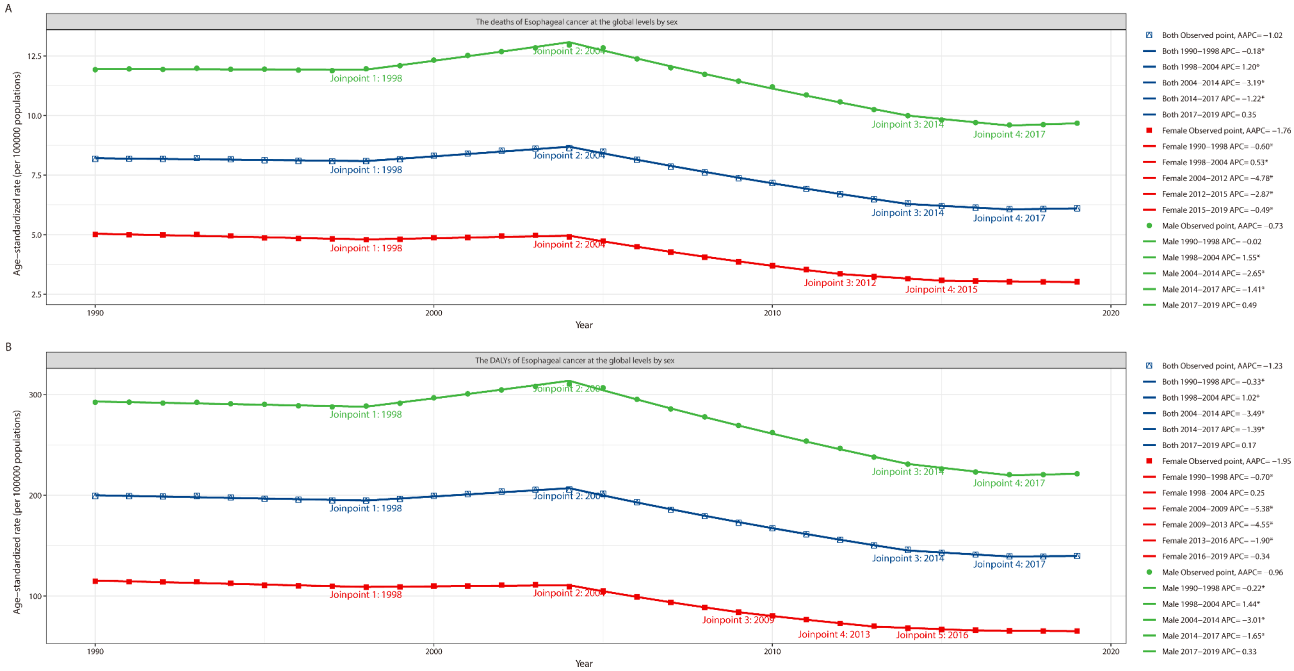

Fig. 5. The APC and AAPC of ASR for deaths (**A**) and DALYs (**B**) by gender (both, female and male) in esophageal cancer at the global level based on the joinpoint regression analysis model.

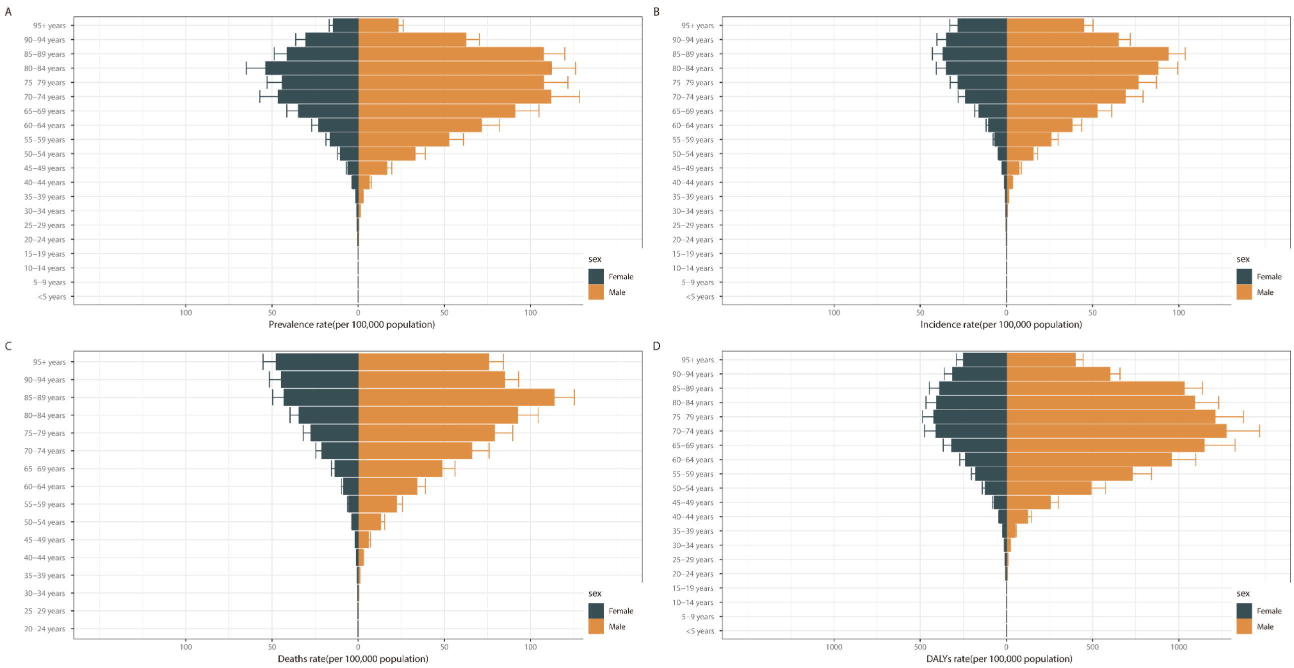

Fig. 6. Comparison of prevalence (**A**), incidence (**B**), deaths (**C**), and DALYs (**D**) for esophageal cancer across different genders (female and male) and age groups ranging from under 5 years to 95 + years.

prevalence and 85–89 years for incidence. The death rates from esophageal cancer follow a similar pattern, where rates escalate with age and are distinctly higher in males, especially pronounced in the 85–89 years age group. In terms of DALYs, the rate is substantially higher in males across all age groups. The DALYs rate dramatically rises from the 45–49 years age group onwards, accentuating the substantial burden of esophageal cancer in the older population (Fig. 6).

Regional trends

The regional trends in esophageal cancer from 1990 to 2019 reveal stark differences in disease dynamics across the 21 GBD regions. Central Asia reports the most pronounced decline in both prevalence and incidence rates, with AAPCs of -2.51% [95% CI, -2.76 to -2.26] and – 2.45% [95% CI, -2.65 to -2.25], respectively. While High-income Asia Pacific indicates a moderate rise in prevalence rates, Western Sub-Saharan Africa's incidence has notably increased with an AAPC of 0.89% [95% CI, 0.78 to 0.99]. In contrast, Southern Latin America has made significant strides in reducing prevalence with an AAPC of -1.32% [95% CI, -1.57 to -1.07], and Central Latin America demonstrates a substantial decrease in incidence rates with an AAPC of -1.29% [95% CI, -1.63 to -0.95]. Despite an uptick in the number of cases, High-income North America shows a slight increase in the ASIR with an AAPC of 0.26% [95% CI, 0.17 to 0.35] (Tables 1 and 2).

Transitioning from prevalence and incidence to deaths and DALYs, the differences are equally pronounced. In Central Asia, the age-standardized death rate (ASDR) and DALYs have significantly decreased, with AAPCs of -2.43% and – 2.57%, respectively. Southern Latin America mirrors this positive trend with reductions in both ASDR (AAPC of -1.67%) and DALYs (AAPC of -1.83%). Conversely, Western Sub-Saharan Africa presents a contrasting scenario, with increases in both ASDR and DALYs (AAPCs of 0.9% and 0.79%, respectively), pointing to a growing burden of esophageal cancer. High-income North America displays a slight increase in the ASDR (AAPC of 0.19%), yet the rate of DALYs remains relatively stable (AAPC of -0.02%). Meanwhile, East Asia shows significant improvements, with notable decreases in both ASDR (AAPC of -1.79%) and DALYs (AAPC of -2.02%) (Tables 3 and 4)

National trends

In the global landscape of esophageal cancer from 1990 to 2019, the trends in prevalence and incidence exhibit significant regional disparities. Among 204 countries, most witnessed a decrease in prevalence numbers, with Kazakhstan recording the steepest decline of -49.24%, while the United Arab Emirates (UAE) exhibited an unprecedented increase of 1183.22%. In ASRs, 107 countries, notably Turkmenistan with a -69.77% reduction, experienced a decline, contrasting with 97 countries where rates increased, the most significant being in a specific Asian region at 174.97%. The AAPC patterns align with these trends: 108 countries saw negative AAPCs, with Turkmenistan having the largest decline at -4.18 [-4.82 to -3.55], and 96 countries reported positive AAPCs. Incidence rates mirrored this variability, with 18 countries including the UAE showing notable increases, up to 1088.98%, and 186 countries, led by Kazakhstan with a -49.93% decrease, observing a decline. Turkmenistan again led the decrease in ASIRs with – 70.11%, while 78 countries, such as Northern Mariana Islands, saw an increase of 88.58%. The AAPC in incidence rates varied accordingly, with 127 countries displaying negative values, Turkmenistan recording the largest at -4.13 [-4.72 to -3.53], and 77 countries including the Netherlands showing positive values, the highest being 2.23 [1.84 to 2.62] (Tables S1–S2, Figs. S1–S6).

The deaths and DALYs due to esophageal cancer during the same period further highlights the varied impact across different regions. In terms of deaths, 19 countries including the UAE saw increases, with the UAE having the highest rise at 1044.14%, while a majority of 185 countries, such as Kazakhstan, experienced a decrease in numbers. The ASDRs reflect a similar pattern, with 136 countries, including Turkmenistan with the most significant decrease of -70.22%, witnessing a decline, and 68 countries, led by Northern Mariana Islands at an increase of 83.62%, showing upward trends. The AAPC in death rates mirrors these observations, with 137 countries showing negative AAPCs, Turkmenistan having the largest decrease at -4.14 [-4.72 to -3.56], and 67 countries recording positive values, Northern Mariana Islands being the highest at 2.08 [1.83 to 2.34]. DALYs followed a comparable trend, with the UAE showing the largest increase in numbers at 1128.5%, and Turkmenistan experiencing the most substantial decrease in ASRs at -70.32%. The AAPCs in DALYs rates varied widely, with 137 countries showing negative AAPCs, led by Turkmenistan at -4.14 [-4.75 to -3.52], and 67 countries displaying positive AAPCs (Tables S3–S4, Figs. S7–S12).

Correlations of ASR with SDI

The prevalence of esophageal cancer and incidence across 21 regions showed no statistically significant correlation with SDI, with p-values of 0.408 and 0.655, respectively. However, a significant negative correlation was found for deaths (R = -0.23, $P = 0.316$) and DALYs (R = -0.269, $P = 0.239$), although the p-values suggest these associations are not statistically significant. In the broader scope of 204 countries and territories, the ASR of prevalence exhibited a weak negative correlation with SDI (R = -0.112, $P = 0.005$), statistically significant. Incidence rates (R = -0.294, $P < 0.001$) and deaths (R = -0.354, $P < 0.001$) both showed moderate and significant negative correlations with SDI, indicating that higher SDI is associated with lower ASRs for both incidence and deaths. DALYs (R = -0.373, $P < 0.001$) also demonstrated a significant negative correlation with SDI (Figs. 7 and 8).

Frontier analysis

The frontier analysis of esophageal cancer from 1990 to 2019 highlights that as countries progress socioeconomically, the age-standardized prevalence and incidence rates of the disease tend to decrease. Specifically, for the year 2019, the analysis identified countries like Japan and the Netherlands as having the most significant effective differences in prevalence rates, far from the aspirational benchmark. Conversely, nations such as Niger, Mali, and Guinea exemplified leading performance, operating closer to the frontier. When examining the incidence rates in 2019, countries with higher SDIs such as Ireland and the United Arab Emirates showed a relatively high effective difference. In contrast, nations with lower SDIs, notably in regions of Africa, stood closer to the frontier, reflecting better-than-expected control of esophageal cancer incidence relative to their SDI (Fig. 9).

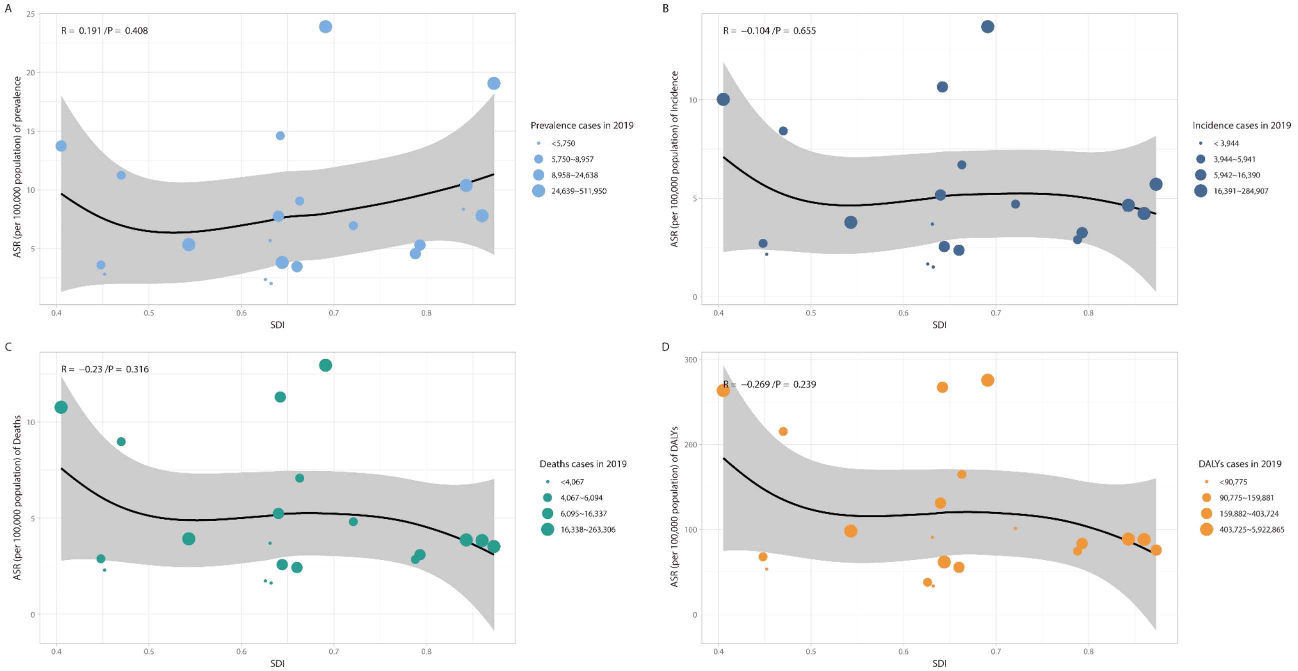

Fig. 7. Pearson correlation analysis between the SDI and ASR of prevalence (**A**), incidence (**B**), deaths (**C**), and DALYs (**D**) for esophageal cancer across 21 regional levels in 2019 (The cases of prevalence, incidence, deaths, and DALYs from 21 regions in 2019 are represented by circles. The size of the circles increased with the cases of prevalence, incidence, deaths, and DALYs).

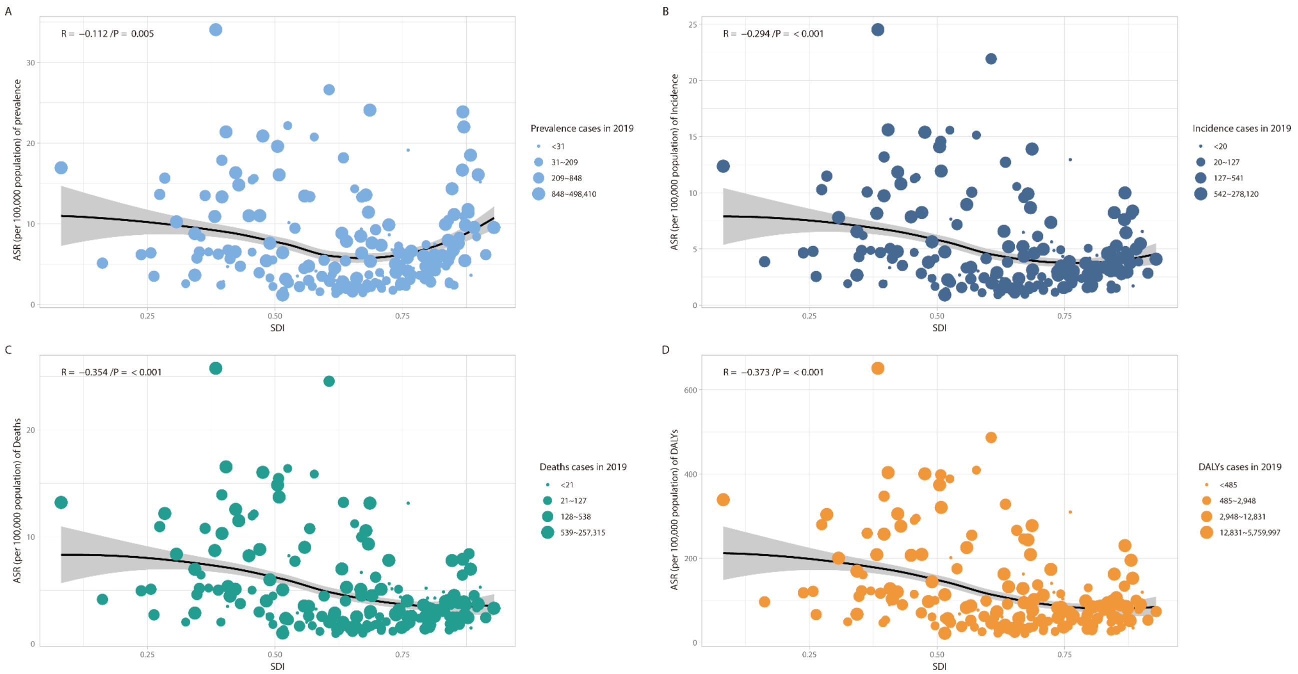

Fig. 8. Pearson correlation analysis between the SDI and ASR of prevalence (**A**), incidence (**B**), deaths (**C**), and DALYs (**D**) for esophageal cancer at the country and territorial levels in 2019 (The cases of prevalence, incidence, deaths, and DALYs from 204 countries and territories in 2019 are represented by circles. The size of the circles increased with the cases of prevalence, incidence, deaths, and DALYs).

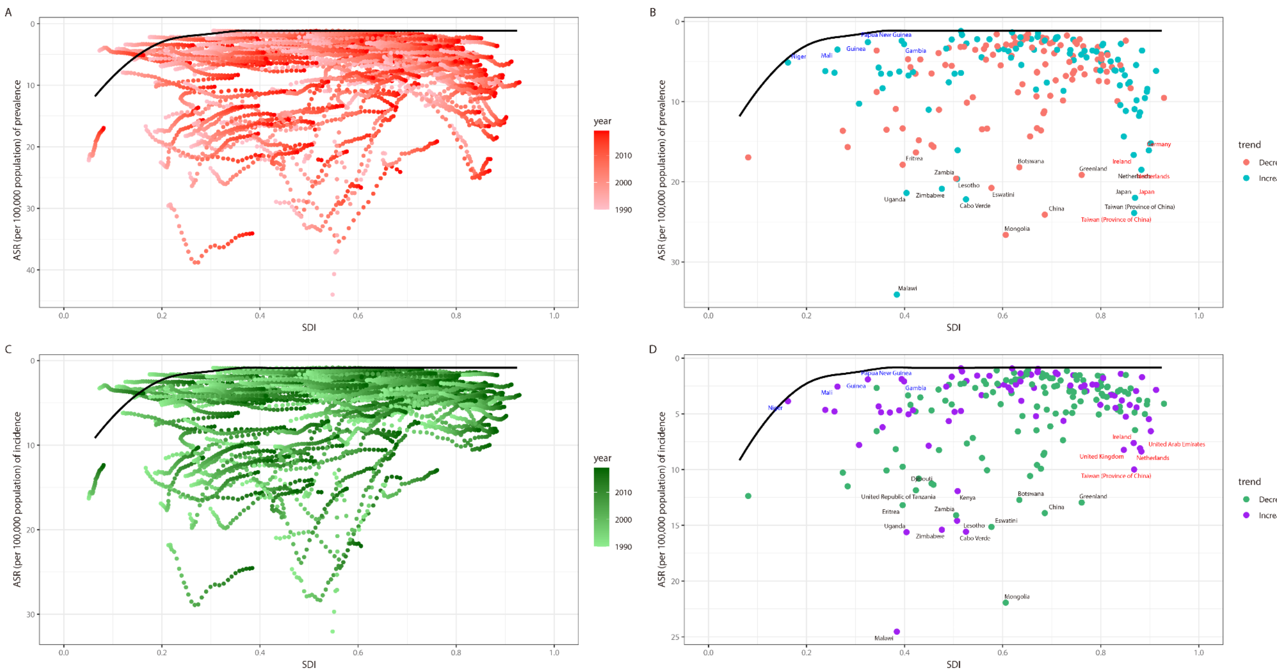

Fig. 9. Frontier analysis, represented by the solid black lines, depicted through solid black lines, delving into the interplay between the SDI and ASR for prevalence (**A**, **B**) and incidence (**C**, **D**) concerning esophageal cancer. The color spectrum in graphs (**A**) and (**C**) serves as a visual timeline, transitioning from lighter shades signifying 1990 to the deepest hues marking 2019. In graphs (**B**) and (**D**), each data point symbolizes a distinct country or territory for the year 2019, with the top 15 nations manifesting the most pronounced deviation from the frontier highlighted in black. Countries characterized by a low SDI (< 0.455) and minimal departure from the frontier are accentuated in blue, whereas those with a high SDI (> 0.805) and conspicuous divergence reflective of their developmental standing are underscored in red. The color of the dots delineates the directional shift from 1990 to 2019 in ASR: decrease dots denote a decrease, while increase dots signify an increase.

The pattern where higher SDI is often accompanied by lower ASRs for both deaths and DALYs of the disease was also discerned from 1990 to 2019. For the death rate and DALYs in 2019, countries with the largest gaps from the frontier, indicative of the greatest potential for improvement, included Greenland, Botswana, Mongolia and other 12 countries. In contrast, despite higher SDIs, Ireland, the United Kingdom and other countries had not reached their potential, as evidenced by their significant effective differences. Countries like Niger, Mali, and Gambia, despite lower SDIs, were closer to the frontier for deaths and DALYs (Fig. 10).

Trends of esophageal cancer from 1990 to 2030

The projections for esophageal cancer suggest a continued increase in prevalence and incidence numbers for both genders leading up to 2030, with a notably sharper rise among males. While the prevalence numbers climb steadily, the ASPRs are expected to see a gradual increase, showing a relative stabilization particularly in females. Incidence trends follow a similar pattern, with the male population driving a significant part of the anticipated increase post-2020, a trend that is likely to continue into the next decade. In contrast, the incidence growth for females is projected to be more tempered. The ASR for incidence also suggests a slight upward trend post-2020, with male rates seeing a modest rise and female rates tending towards stability, resulting in an overall incremental but controlled rise in ASR for both genders combined (Figs. 11 and 12).

The BAPC model forecasts a rise in the number of esophageal cancer-related deaths, with a pronounced escalation in males compared to a more gradual increase in females. The ASDRs for both genders indicate a trend towards stabilization after 2020. Similarly, for DALYs, the model predicts a continuous augmentation in numbers for both sexes, with males showing a more significant upward trend. The ASRs of DALYs are expected to see a slight elevation over the coming decade, primarily influenced by male trends, whereas female rates are projected to achieve relative stability (Figs. 13 and 14).

Discussion

Over the past three decades, the global landscape of esophageal cancer has evolved significantly, marked by an increase in absolute numbers but a decline in ASRs, indicative of improved healthcare interventions. Males consistently show higher rates than females in prevalence, incidence, deaths, and DALYs, with the disparity widening over time, particularly in mortality and DALYs. Age-wise, the burden intensifies with advancing age, especially in males. Regional analyses reveal notable variations: Central Asia has seen significant reductions in both prevalence and incidence, contrasting with rising trends in Western Sub-Saharan Africa and High-

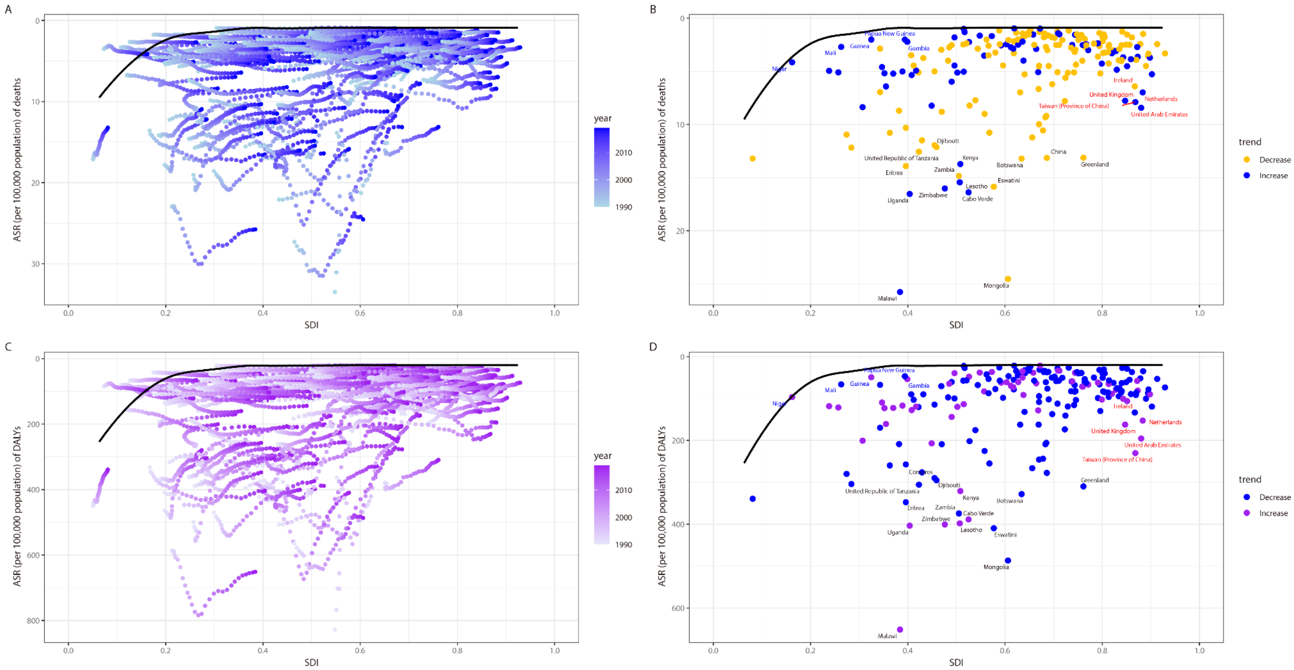

Fig. 10. Frontier analysis, represented by the solid black lines, depicted through solid black lines, delving into the interplay between the SDI and ASR for deaths (**A**, **B**), and DALYs (**C**, **D**) concerning esophageal cancer. The color spectrum in graphs (**A**) and (**C**) serves as a visual timeline, transitioning from lighter shades signifying 1990 to the deepest hues marking 2019. In graphs (**B**) and (**D**), each data point symbolizes a distinct country or territory for the year 2019, with the top 15 nations manifesting the most pronounced deviation from the frontier highlighted in black. Countries characterized by a low SDI (< 0.455) and minimal departure from the frontier are accentuated in blue, whereas those with a high SDI (> 0.805) and conspicuous divergence reflective of their developmental standing are underscored in red. The color of the dots delineates the directional shift from 1990 to 2019 in ASR: decrease dots denote a decrease, while increase dots signify an increase.

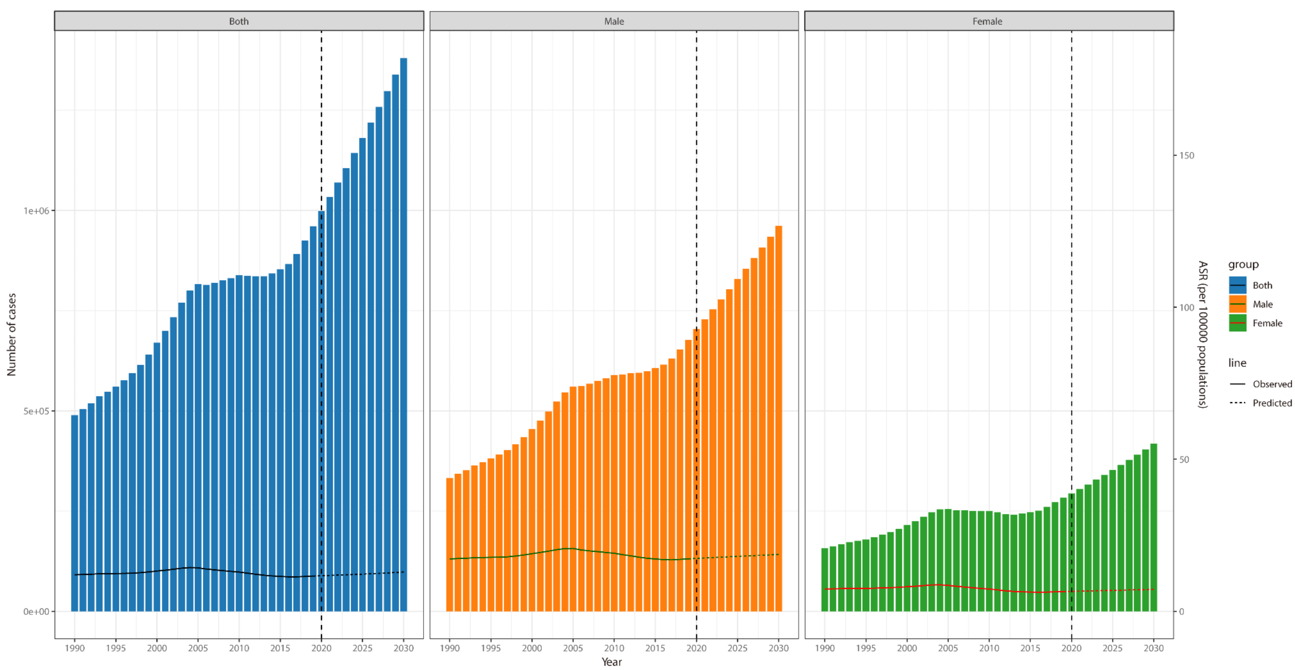

Fig. 11. Projected numbers and ASR of prevalence for esophageal cancer by gender (both, male, and female) from 2020 to 2030 based on the BAPC model.

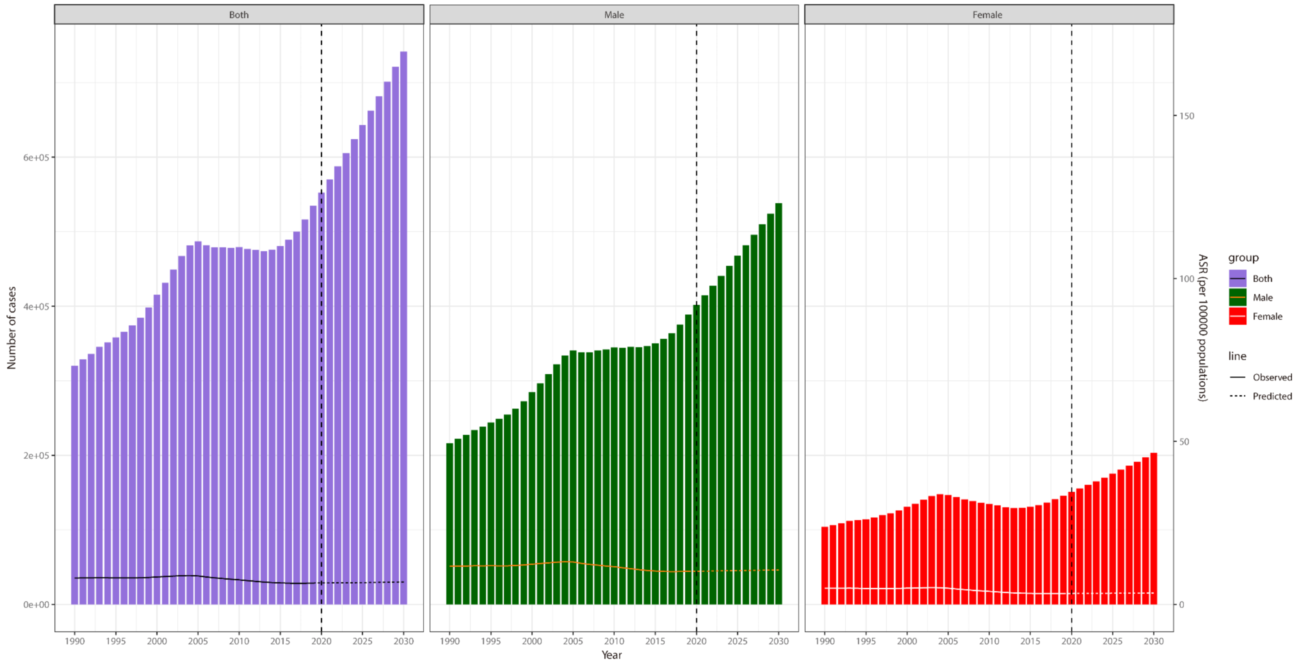

Fig. 12. Projected numbers and ASR of incidence for esophageal cancer by gender (both, male, and female) from 2020 to 2030 based on the BAPC model.

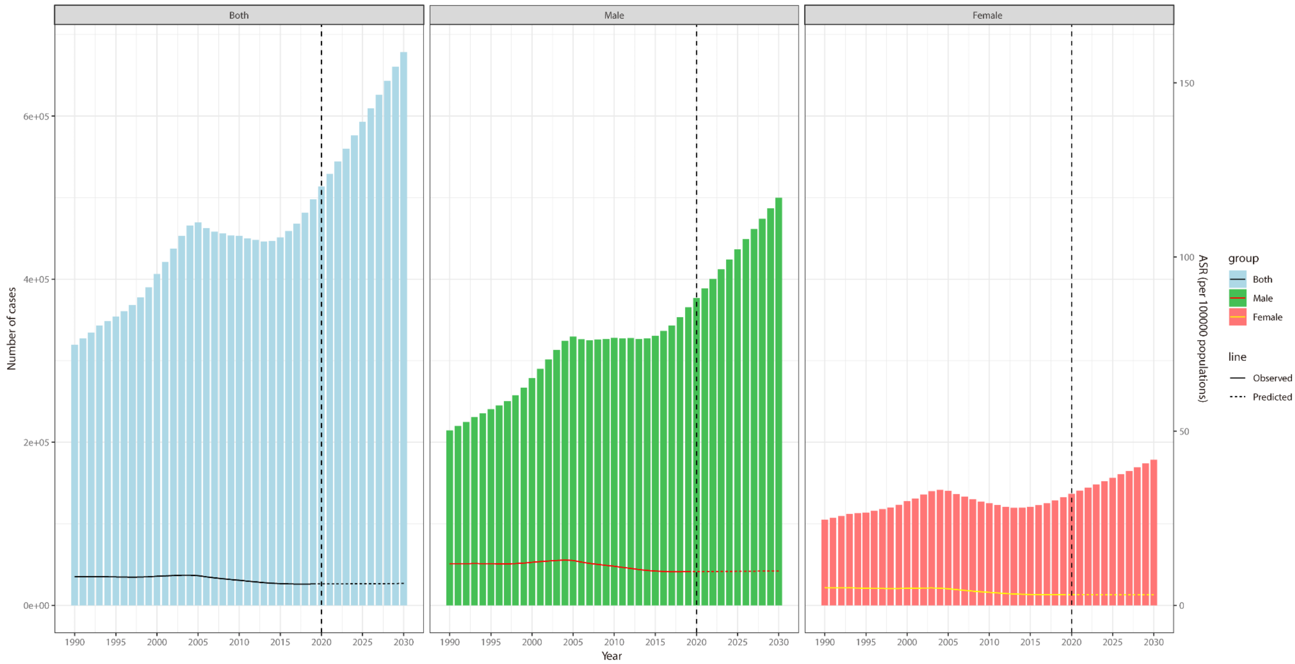

Fig. 13. Projected ASR (**A**) and numbers (**B**) of deaths for esophageal cancer by gender (both, male, and female) from 2020 to 2030 based on the BAPC model.

income North America. Nationally, while Turkmenistan exhibits significant decreases, the United Arab Emirates has experienced drastic increases. Correlation analyses suggest that higher SDI is associated with lower disease rates, a pattern reinforced by frontier analysis highlighting disparities in healthcare efficacy. Projections to 2030 indicate a continued rise in esophageal cancer cases, more pronounced in males, underscoring the need for enhanced public health strategies and healthcare resource allocation to address this escalating burden.

In the global trends of esophageal cancer, the dichotomy between the rise in absolute numbers of esophageal cancer cases and the decline in ASRs over the past three decades calls for a multifaceted interpretation. On the one hand, the doubling of prevalence and the significant surge in incidence cases reflect an undeniable

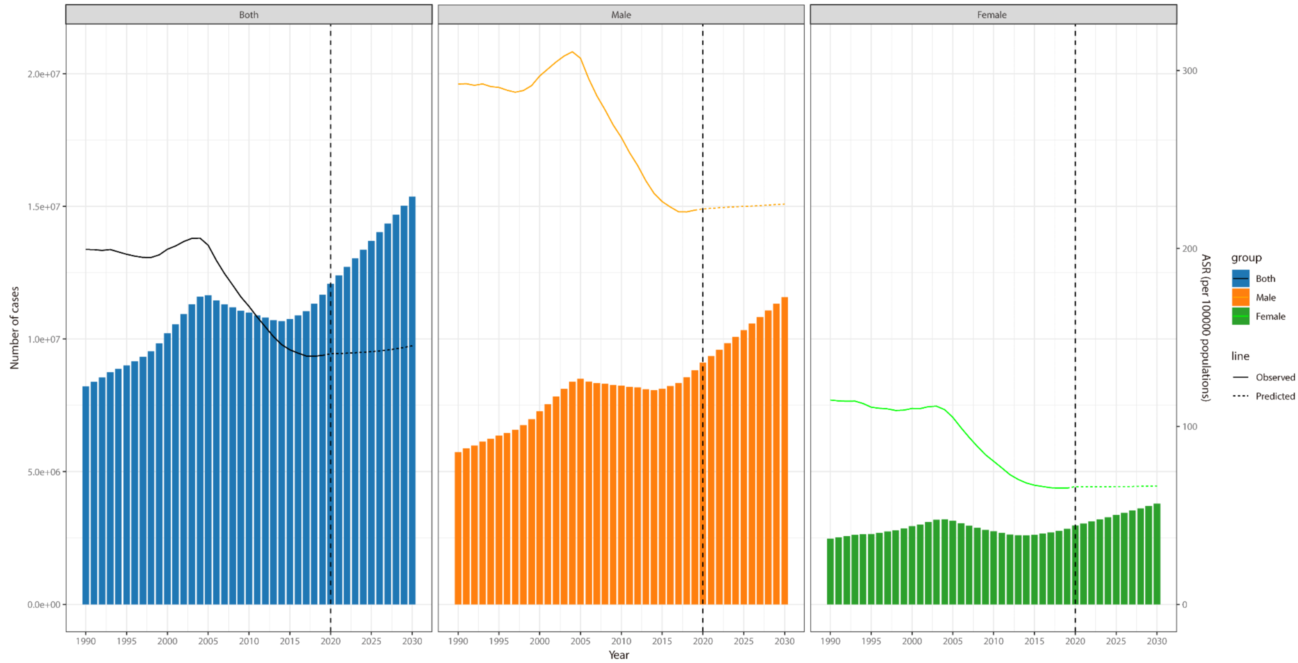

Fig. 14. Projected ASR (**A**) and numbers (**B**) of DALYs for esophageal cancer by gender (both, male, and female) from 2020 to 2030 based on the BAPC model.

growth in the disease's burden. This increase could be attributed to various factors, including aging populations and heightened exposure to risk factors such as tobacco use, dietary patterns, and perhaps even environmental changes that are yet to be fully understood[5,6,18,19]. Additionally, socioeconomic changes, such as urbanization and shifts in dietary habits, could further explain these trends, particularly in regions where traditional diets are being replaced by processed foods, potentially increasing the risk of esophageal cancer. On the other hand, the decline in ASRs suggests that global health initiatives may be yielding positive results. Improvements in healthcare infrastructure, widespread availability of early detection methods, and more effective treatment options could be playing pivotal roles in reducing the per capita disease burden. Public health campaigns focused on reducing tobacco and alcohol consumption, along with better education about cancer risks, may also have contributed to these positive trends. These findings underscore the importance of continuing to focus on both prevention and treatment strategies, particularly in regions where the absolute burden of esophageal cancer continues to rise despite the decline in ASRs.

The gender disparity in incidence and mortality rates, with men consistently at higher risk, highlights potential biological susceptibilities and differences in exposure to risk factors such as tobacco and alcohol use[18]. The sharper decrease in female death rates and DALYs post-2004 may reflect targeted healthcare interventions and the efficacy of public health policies, underlining the necessity for gender-specific strategies. This disparity could also be influenced by differences in healthcare-seeking behaviors between men and women, with women possibly engaging more frequently in preventive health measures, which may contribute to earlier detection and better outcomes. As the global burden of esophageal cancer shifts, with rising cases but decreasing ASRs, future research and policy must focus on understanding and mitigating gender-based risk, improving diagnostic and treatment pathways, and ensuring that advancements in esophageal cancer care are equitable across all demographics. It will be critical to develop targeted interventions that address both biological and behavioral factors, ensuring that prevention efforts are tailored to the specific needs of each gender.

The age-specific analysis of esophageal cancer reveals a pronounced disparity between males and females across various age groups, underscoring the significant impact of gender and age on the disease's epidemiology. Notably, males consistently exhibit higher rates of prevalence, incidence, deaths, and DALYs, with these rates escalating sharply after the age of 40, peaking in the 70–74 and 85–89 age groups for prevalence and incidence, respectively. This trend is particularly alarming in the elderly male population, where the rates of death and DALYs are exceptionally high, suggesting that older males constitute a high-risk group requiring targeted interventions and more rigorous screening protocols. The reasons behind this male predominance may be multifaceted, involving a combination of biological, lifestyle, and environmental factors, such as higher exposure to risk factors like tobacco and alcohol use in men. The dramatic rise in DALYs from the 45–49 years age group onward highlights the considerable burden of esophageal cancer in aging populations, emphasizing the need for age-specific healthcare strategies and resource allocation. It is also crucial to ensure that screening and prevention programs are accessible and tailored to older populations, as early detection in these high-risk age groups could significantly reduce the overall disease burden.

The regional and national trends in esophageal cancer from 1990 to 2019 depict a multifaceted global landscape, marked by varying disease dynamics across different geographies. Central Asia's notable decrease in prevalence and incidence rates reflects the success of region-specific health interventions, contrasting sharply with the rising prevalence in Western Sub-Saharan Africa, which may indicate emerging health challenges or variations in risk factor exposure[20,21]. Southern Latin America's significant reduction in prevalence and incidence highlights the effectiveness of localized health strategies, while the slight increase in ASIR in High-income North America despite a rise in cases suggests a complex interplay of healthcare advances and disease burden[22]. On a national scale, the dramatic rise in prevalence in the UAE and the steep decrease in Kazakhstan underscore the diverse impact of esophageal cancer across countries, further complicated by varied changes in ASRs as seen in Turkmenistan and a specific Asian region. These regional and national disparities, coupled with the varied trends in deaths and DALYs, emphasize the need for tailored esophageal cancer control strategies that consider the unique socioeconomic, healthcare, and lifestyle factors of each region[23–25]. Future efforts should focus on addressing the gaps in healthcare access and risk factor control, especially in regions experiencing rising trends, to better manage the global burden of esophageal cancer.

While the prevalence, incidence, deaths and DALYs of esophageal cancer across 21 regions did not show a significant correlation with SDI, the moderate and significant negative correlations observed in broader analyses across 204 countries indicate that higher SDIs are generally associated with lower ASRs for both incidence and deaths. This trend suggests that socioeconomic advancement may contribute to more effective health interventions and risk factor management, thereby reducing the ASR of esophageal cancer. Frontier analysis further accentuates this complexity; countries like Japan and the Netherlands, despite high SDIs, show significant effective differences in prevalence rates, indicating a gap in achieving the lowest possible burden of the disease. In contrast, countries with lower SDIs, such as Niger, Mali, and Guinea, demonstrate better-than-expected control relative to their development status. This disparity highlights that while economic and social progress is a crucial component, it is not the sole determinant in the fight against esophageal cancer. A comprehensive approach, considering both socioeconomic and health system factors, is imperative to effectively tackle the global burden of this disease.

The projected trends of esophageal cancer up to 2030 depict an escalating burden, particularly emphasized by a more pronounced increase in prevalence and incidence among males. This gender disparity signals underlying differences in exposure to risk factors, potentially necessitating gender-specific public health interventions[26,27]. While prevalence numbers steadily rise, the ASRs exhibit a relative stabilization, especially in females, suggesting effectiveness in early detection and management strategies. However, the anticipated rise in incidence, predominantly driven by male trends post-2020, highlights the urgent need for enhanced prevention and screening programs[28,29]. The forecasted increase in esophageal cancer-related deaths, with males experiencing a steeper escalation, underscores a pressing need for improved therapeutic and palliative care approaches[1]. Additionally, the predicted growth in DALYs for both sexes, more so in males, reflects not only the increasing incidence and mortality but also the prolonged impact of the disease on quality of life[30–32]. These trends collectively point towards the necessity of a multifaceted approach in combating esophageal cancer, encompassing prevention, early detection, effective treatment, and supportive care, tailored to address the distinct patterns observed in both genders.

Our study has several limitations. First, there are inherent uncertainties in the predictive models due to evolving risk factors, advancements in diagnostic and screening methodologies, and the possibility of unforeseen global health events. Second, relying predominantly on historical data may not fully reflect emerging trends or the influence of recent healthcare innovations. Third, geographical variability in disease prevalence and healthcare infrastructure could limit the generalizability of our findings across different regions. Moreover, variations in data collection methods and the absence of detailed histological stratification in some sources may introduce bias, potentially affecting the interpretation and comparability of results. Lastly, as global lifestyles shift—most notably with rising obesity rates—changing risk profiles may alter the patterns of disease incidence and outcomes over time. Future research should aim to address these limitations by improving data quality and granularity, accounting for regional differences, and refining predictive models to remain robust in the face of evolving epidemiological landscapes.

Conclusions

Our study highlights a rising global burden of esophageal cancer up to 2030, with a notable increase in cases, especially among males. Despite advancements in healthcare leading to stabilized ASRs, the escalating prevalence and incidence underscore the need for enhanced prevention and targeted treatment strategies. The findings stress the importance of addressing gender disparities and regional variations in disease dynamics, guiding future healthcare policies and research efforts towards effective management and reduction of esophageal cancer's impact worldwide.

Data availability

The data comes from a public database, can through this link: https://vizhub.healthdata.org/gbd-results/ for the relevant data.

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Author contributions
Liangchao sun: Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Roles/Writing - original draft, Writing - review & editing. Kaikai Zhao: Investigation, Validation. Xiaoli Liu: Conceptualization, Data curation, Formal analysis, Methodology, Resources, Software, Visualization, Roles/Writing - original draft, Writing - review & editing. Xue Meng: Funding acquisition, Project administration, Supervision, Writing - review & editing.

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Declarations

Competing interests
The authors declare no competing interests.

Ethical approval
Our research involved a secondary evaluation of the publicly accessible GBD Study dataset, without primary data collection. Hence, no ethical approval was necessary.

Informed consent
No informed consent was required since our research is a secondary analysis of public data.

Additional information
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