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Burden of type 2 diabetes due to high body mass index in different SDI regions and projections of future trends: insights from the Global Burden of Disease 2021 study

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Abstract

Aim The aim of our study was to assess the impact of high body mass index (BMI) on type 2 diabetes mellitus (T2DM) in different Socio-Demographic Development Index (SDI) regions using data from the Global Burden of Disease (GBD) 2021 study.

Methods Using data from the GBD study, the burden of disease for T2DM was measured by analyzing the age-standardized disability-adjusted life year rate (ASDR) and age-standardized mortality rate (ASMR) for type 2 diabetes due to high BMI and the associated estimated annual percentage change (EAPC). Decomposition analyses, frontier analyses, and predictive models were used to analyze changes and influencing factors for each metric.

Results The study revealed the significant global health burden of T2DM induced by high BMI, which EAPC of 1.82 with confidence intervals (CI) ranging from 1.78 to 1.87 for disability-adjusted life years (DALYs) and 0.85 with CIs ranging from 0.77 to 0.93 for mortality. The results of the analysis emphasized the geographic variability of T2DM disease burden associated with SDI Within the area covered by the study, a decreasing trend in ASMR for T2DM was observed in high SDI areas, with an EAPC value of − 1.07 and a confidence interval ranging from − 1.39 to − 0.76. At the same time, in the other SDI areas, the ASMR and ASDR for T2DM showed an increasing trend. In addition, the study noted that individuals in the 65- to 75-year-old age group accounted for a higher proportion of T2DM-related deaths and DALYs, with females affected at a greater rate than males. Projections for future trends indicate that the ASDR and ASMR for T2DM are expected to continue an upward trajectory over the next decade.

Conclusion This study investigates the variation in T2DM burden attributable to high BMI across regions with different SDI levels. The analysis reveals that, in high-SDI regions, the ASMR decreased from 1990 to 2021 and stabilized around 4.4 deaths per 100,000 people, while the ASDR increased, reaching approximately 416 cases per 100,000 people in 2021. Conversely, both ASDR and ASMR exhibited an upward trend in other SDI regions over the same period.

Keywords Death, Disability-adjusted life-years, Global burden of disease study, T2DM, High BMI

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Introduction

Type 2 diabetes mellitus (T2DM) is a widespread chronic disease that presents a significant global health challenge by increasing mortality risk and contributing substantially to disability [1]. Since 1990, the prevalence of T2DM has escalated from 3.2 to 6.1% in 2021, with projections indicating a further 59.7% increase by 2050, potentially affecting approximately 1.31 billion people worldwide[2]. Despite this, comprehensive research on the health burden associated with T2DM and elevated body mass index (BMI) remains limited. The Global Burden of Disease (GBD) 2021 report synthesizes findings from previous studies to provide an updated evaluation of T2DM and its associated risk factors. Examining five different Sociodemographic Index (SDI) regions, the study assesses age-standardized mortality and disability-adjusted life-year rates for T2DM attributed to high BMI in relation to SDI[3].

Among the numerous risk factors for T2DM, elevated BMI is a significant predisposing factor[4]. Currently, approximately 60% of adults worldwide are affected by overweight and obesity [5]. It is projected that annual global spending on overweight and obesity will reach $3 trillion by 2030 and may exceed $18 trillion by 2060 [6]. A comprehensive understanding of the global burden of disease associated with high BMI-related T2DM, particularly in terms of disability-adjusted life years (DALYs) and mortality, is crucial. This knowledge is essential for developing management strategies for obesity related T2DM and for rationalizing the allocation of related resources.

This study aims to address a research gap by quantifying the impact of T2DM associated with high BMI on DALYs and mortality, utilizing data from the GBD for 2021. The study encompasses the years 1990 to 2021 and assesses age-standardized DALYs and mortality rates for high BMI-associated T2DM across different SDI regions. Additionally, we examined the correlation between age-standardized disability-adjusted life years (ASDR) and age-standardized mortality rates (ASMR) with the SDI using Pearson correlation analysis, and we projected ASDR and ASMR for high BMI-associated T2DM over the next decade.

Materials and methods

Overview and data sources

The GBD 2021 study is one of the most extensive and systematic analyses of global health to date, aiming to assess the health impacts of 369 specific diseases and injuries from 1990 to 2021 while tracking trends in these impacts. Additionally, it evaluates 87 diverse health risk factors. The GBD 2021 study spans 21 major regions and compiles data from 204 countries and territories. In its latest iteration, the study incorporates insights from over 3600 experts worldwide and utilizes data from 145 countries to provide updated information on the incidence, prevalence, mortality, and DALYs associated with 369 diseases. For this research, we accessed data on the burden of T2DM related to high BMI using the Institute for Health Metrics and Evaluation's (IHME) Online Outcomes Tool. The GBD 2021 study employs publicly accessible, anonymized data, eliminating the requirement for additional ethical review approval. This approach ensures both study transparency and participant privacy protection.

Autoregressive integrated moving average model

The Autoregressive Integrated Moving Average (ARIMA) model combines autoregressive (AR) and moving average (MA) components to analyze temporal fluctuations and identify inherent autocorrelations. This approach allows the ARIMA model to capture data dependencies over time. The model's general form is: $Y_t = \varphi 1 Y_{t-1} + \varphi 2 Y_{t-2} + \dots + \varphi p Y_{t-p} + e_t - \theta_1 e_{t-1} - \dots - \theta_q e_{t-q}$, where $(\varphi 1 Y_{t-1} + \varphi 2 Y_{t-2} + \dots + \varphi p Y_{t-p} + e_t)$ is the AR model part, $e_t - \theta_1 e_{t-1} - \dots - \theta_q e_{t-q}$ is the MA model part, Y_{t-p} is the observed value at the period of $(t-p)$, p and q represent the model order of AR and MA, and et is the random error at the period of t.This model uses historical data to predict future trends. For constructing an ARIMA model, it is standard to assume the time series data is stationary, meaning it has a constant mean and variance over time. This assumption ensures the data has a stable central tendency without significant long-term growth or decline, which is essential for accurate forecasting and model reliability. As a result, the ARIMA model effectively captures time series dynamics, providing a robust framework for forecasting.

Join-point regression model

The join-point regression model, developed by Kim in 2000, employs segmented regression to analyze temporal trends in disease distribution. This model enables the fitting and optimization of trends over time, facilitating comprehensive analysis of global disease trends. In this study, we applied the join-point regression model to evaluate trends in disability-adjusted life-year (DALY) rates and mortality rates for type 2 diabetes, calculating the average annual percentage change (AAPC) and annual percentage change (APC) with corresponding 95% confidence intervals (CI). The model incorporates multiple regression stages based on observed disease trends over time, partitioning the study period into intervals defined by specific connection points. Trend optimization within each interval is achieved by setting these connection points to capture distinct patterns of disease progression. Monte Carlo random permutation tests were conducted to determine the number and location of breakpoints, with statistical significance assessed at α = 0.05 (two-sided test). The join-point regression models were constructed in both linear and log-linear forms, with a preference for log-linear models in the analysis of population-based DALY rates and mortality rates for type 2 diabetes mellitus:$E[y|x] = e^{\beta 0+\beta 1x+\delta 1(x-\tau 1)^{+}+\cdots+\delta k(x-\tau k)}$, Where e is the natural base, k indicates the number of turning points, τk indicates the unknown turning points, $\beta 0$ is the invariant parameter, $\beta 1$ is the regression coefficient, δk indicates the regression coefficient of the segment function in paragraph$k$. When $(x-\tau k) > 0$,$(x-\tau 1)^{+} = x-\tau k$, otherwise$(x-\tau 1) = 0$. Formula for calculating APC:$APC = (e^{(}\beta 1) - 1) \times 100$. Formula for calculating AAPC:$AAPC = [exp(\sum wi\beta i/\sum wi) - 1] \times 100$. Where $\beta 1$ is the regression coefficient, wi is the width of the interval span (i.e., the number of years included in the interval) for each segmentation function, and $\beta 1$ is the regression coefficient corresponding to each interval.

Statistical analysis

In our investigation of the impact of high BMI on T2DM, we utilize age-standardized DALYs and mortality as primary metrics for disease burden. DALYs serve as a composite indicator, offering a comprehensive overview of health losses by summing years lost to disability and years of life lost due to premature mortality. Each lost DALY corresponds to a loss of one full year of healthy life. To examine trends in DALYs from 1990 to 2021 across various countries, regions, and globally, we employed linear regression analysis, focusing on the natural logarithms of age-standardized ratios. Our model was constructed using the equation:$ln(ASR) = \alpha + \beta X + \lambda$, where X represents time (in years). The annual average percentage change (EAPC) serves as a crucial measure for quantifying changes in ASRs over a specified timeframe. During model fitting, we utilized the natural logarithm of the temporal variable alongside corresponding empirical data, ensuring that each datum contributes to the EAPC computation. The EAPC and its 95% confidence interval (CI) are determined using the formula $100 \times (exp(\beta) - 1)$ [7]. A stable trend is indicated if the 95% CI for the EAPC includes 0, equivalent to a p-value of 0.05 or higher. An upward trend is denoted by both the EAPC and its 95% CI exceeding 0, while a downward trend is signified when these values fall below 0. Furthermore, we employed a locally weighted scatterplot smoothing (LOWESS) method to examine the correlation between the SDI and age-standardized DALYs induced by high BMI. This analytical approach provided a deeper understanding of the interplay between socioeconomic development levels and health burdens. By employing this method, we discerned and elucidated the relationship between these factors with greater nuance. Additionally, we utilized an integrated statistical approach, specifically meta-regression combined with Bayesian regularization pruning techniques (commonly referred to as meta-regression modeling), to explore correlations between various health indicators and the SDI. This meta-regression model allowed us to analyze multiple health indicators at different SDI levels in depth, identifying potential associations among them [8]. Alongside meta-regression models, we introduced a decomposition technique developed by Das Gupta to refine and quantify the impact of different factors on the burden of T2DM induced by high BMI, including the population's age structure, population growth, and epidemiological changes [9]. To assess the interrelationship between T2DM disease burden and SDI comprehensively, we collected and analyzed long-term data from 1990 to 2021. Based on this analysis, we constructed an advanced analytic framework that benchmarks ASDR and ASMR while correlating them with SDI. This framework aims to explore and assess the potential for improvement and advancements in ASDR and ASMR for T2DM that can be achieved in each country or region [10].

Results

Global burden of disease

In 2021, the global ASMR for type 2 diabetes mellitus attributed to high BMI was 8.46, with a 95% uncertainty interval (UI) of 3.55 to 12.62. The ASDR for this condition was 452.55, with a 95% UI of 220.36 to 650.49 (Table 1). Notably, the ASMR for type 2 diabetes mellitus due to high BMI was higher in low and medium-low SDI regions, reaching 12.71 (95% UI: 5.14–19.56), compared to 4.83 in high SDI regions (95% UI: 2.11–7.01). In low- and medium-low SDI regions, the ASMR for type 2 diabetes associated with high BMI exhibited the most significant upward trend, with an EAPC of 2.37 (95% UI: 2.16–2.59). Conversely, the ASMR in high SDI regions showed a downward trend, with an EAPC of − 1.07 (95% UI: − 1.39 to − 0.76). Between 1990 and 2021, deaths from type 2 diabetes mellitus due to high BMI rose from 238,136 to 723,719, while DALYs increased from 104,348,885 to 139,309,214, with annual growth rates of 2.03% and 2.76%, respectively (Table 1).

Five SDI regions and type 2 diabetes burden and trends and trends analyzed by sex and age

In 2021, deaths and DALYs due to type 2 diabetes attributed to high BMI varied significantly across age groups and the five SDI regions. The analysis indicated that type 2 diabetes-related deaths and DALYs peaked in the 65- to 75-year age group for both males and females, with a subsequent decline observed with

Table 1 Changes in global age-standardized mortality and disability-adjusted life-year rates for type 2 diabetes mellitus due to high body mass index, 1990 and 2021

Location	Numbers with uncertainty interval (95% UI)				Age-standardized rate per 100 000 population (95% UI)					
	1990		2021		1990		2021			
	Numbers of Death	Numbers of DALYs	Numbers of Death	Numbers of DALYs	Death rate	DALY rate	Death rate	EAPC, 95% CI	DALY rate	EAPC, 95% CI
Global	238,136 (98,915,358,326)	10,434,885 (4,873,204,15,314,308)	723,719 (306,923,1,075,367)	39,309,214 (19,146,834,56,417,300)	6.32 (2.55,9.64)	251.52 (115.51,372.35)	8.46 (3.55,12.62)	0.85 (0.77 to 0.93)	452.55 (220.36,650.49)	1.82 (1.78 to 1.87)
High SDI	64,892 (26,078,96,994)	2,590,434 (1,223,249,3,801,967)	105,187 (43,536,156,231)	7,325,086 (3,546,218,10,628,651)	5.85 (2.37,8.72)	241.5 (115.62,352.58)	4.83 (2.11,7.01)	−1.07 (−1.39 to −0.76)	408.78 (205.11,583.64)	1.49 (1.22 to 1.77)
High-middle SDI	48,776 (20,203,72,482)	2,275,753 (1,071,495,3,347,580)	119,391 (49,936,178,277)	7,045,408 (3,498,419,10,187,003)	5.23 (2.11,7.87)	223.41 (103.93,331.47)	6.05 (2.52,9.06)	0.35 (0.28 to 0.43)	370.56 (186.07,536.24)	1.52 (1.47 to 1.57)
Low SDI	18,380 (7550,29,231)	716,441 (305,458,1,113,908)	56,027 (23,261,87,132)	2,710,493 (1,233,859,3,995,715)	8.24 (3.26,13.44)	278.03 (115.15,442.28)	11.54 (4.44,18.5)	1.01 (0.92 to 1.09)	454.43 (195.05,684.38)	1.5 (1.42 to 1.59)
Low-middle SDI	37,680 (15,654,59,014)	1,605,713 (712,728,2,428,041)	174,265 (72,963,261,401)	8,372,423 (3,895,470,12,252,945)	6.46 (2.56,10.37)	235.85 (101.24,362.55)	12.71 (5.14,19.56)	2.37 (2.16 to 2.59)	536.85 (242.02,788.25)	2.8 (2.62 to 2.97)
Middle SDI	67,939 (29,021,101,362)	3,226,820 (1,513,647,4,718,810)	267,860 (118,285,394,674)	13,805,912 (6,741,593,19,638,166)	6.99 (2.83,10.74)	279.98 (127.15,417.5)	10.23 (4.37,15.24)	1.22 (1.02 to 1.41)	493.11 (239.09,700.68)	1.74 (1.61 to 1.87)
East Asia	22,304 (9421,35,069)	1,479,828 (662,910,2,261,376)	42,924 (16,498,69,811)	6,192,821 (2,922,801,9,327,285)	2.7 (1.09,4.36)	149.77 (65.43,232.92)	3.75 (1.45,6.01)	0.97 (0.76 to 1.19)	296.17 (138.85,443.31)	2.09 (1.97 to 2.2)
Southeast Asia	16,841 (6926,27,302)	714,244 (312,109,1,113,665)	70,590 (28,086,110,330)	3,328,763 (1,455,105,4,989,791)	6.42 (2.56,10.61)	243.64 (103.68,387.91)	10.79 (4.08,17.3)	1.69 (1.4 to 1.98)	467.11 (199.39,713.96)	2 (1.78 to 2.21)
Oceania	1322 (627,2041)	50,711 (26,107,74,463)	4062 (1959,5859)	181,077 (94,338,248,177)	44.25 (19.6,69.68)	1430.32 (696.83,2148.85)	54.05 (24.06,79.82)	0.63 (0.54 to 0.72)	1982.78 (980.17,2768.45)	1.04 (0.95 to 1.12)
Central Asia	2364 (1088,3300)	120,143 (61,180,168,179)	8098 (3963,11,336)	480,857 (246,896,672,959)	5 (2.25,7.04)	208.51 (100.2,299.36)	9.73 (4.53,13.73)	1.81 (1.56 to 2.07)	527.83 (264.06,744.8)	2.31 (2.13 to 2.49)
Central Europe	9796 (4258,14,115)	479,885 (225,980,684,412)	17,654 (7531,26,320)	919,917 (443,112,1,325,371)	6.55 (2.82,9.49)	316.37 (149.02,452.7)	7.6 (3.33,11.24)	0.66 (0.48 to 0.84)	412.33 (207.89,578.42)	1.17 (1.03 to 1.32)
Eastern Europe	5856 (2645,8255)	1,003,061 (482,768,1,437,909)	25,155 (10,817,35,348)	1,195,660 (594,288,1,665,284)	2.06 (0.92,2.91)	143.77 (69.83,205.24)	6.96 (3.02,9.76)	2.84 (2.04 to 3.65)	352.51 (178.19,487.29)	2.48 (2.26 to 2.7)
High-income Asia Pacific	5565 (2211,8798)	357,775 (162,218,546,302)	45,649 (20,351,63,549)	958,542 (408,514,1,532,779)	2.81 (1.1,4.48)	173.53 (78.67,265.39)	1.42 (0.54,2.23)	−2.46 (−2.89 to −2.03)	286.8 (128.72,443.13)	1.47 (1.11 to 1.83)
Australasia	1207 (492,1800)	45,599 (20,501,66,370)	2643 (1060,3910)	132,470 (62,762,193,461)	5.21 (2.12,7.79)	196.89 (89.44,285.48)	4.55 (1.9,6.6)	−0.95 (−1.36 to −0.53)	268.49 (130.96,387.16)	0.77 (0.48 to 1.06)

Table 1 (continued)

Location	Numbers with uncertainty interval (95% UI)				Age-standardized rate per 100 000 population (95% UI)					
	1990		2021		1990		2021			
	Numbers of Death	Numbers of DALYs	Numbers of Death	Numbers of DALYs	Death rate	DALY rate	Death rate	EAPC, 95% CI	DALY rate	EAPC, 95% CI
Western Europe	36,850 (13,766,56,890)	1,177,117 (523,722,1,743,972)	42,741 (15,593,66,602)	2,182,373 (1,027,446,3,242,189)	6.15 (2.32,9.44)	212.45 (96.88,313.75)	3.87 (1.49,5.87)	−1.57 (−1.84 to −1.31)	281.56 (138.26,409.66)	0.78 (0.52 to 1.03)
Southern Latin America	4804 (2074,6949)	167,303 (79,270,236,348)	7422 (3222,10,639)	396,128 (195,733,561,376)	10.55 (4.5,15.38)	357.29 (168.92,505.51)	8.33 (3.67,11.87)	−0.91 (−1.2 to −0.61)	466.8 (232.98,658.3)	0.71 (0.54 to 0.89)
High-income North America	26,581 (11,102,38,644)	1,057,241 (517,649,1,497,722)	45,649 (20,351,63,549)	3,384,028 (1,677,241,4,812,739)	7.52 (3.23,10.83)	317.99 (158.67,446.06)	6.91 (3.19,9.48)	−1.03 (−1.43 to −0.63)	569.5 (291.44,801.78)	1.58 (1.29 to 1.88)
Caribbean	4625 (1983,6829)	181,761 (84,543,263,246)	9689 (4337,14,784)	501,760 (239,521,724,500)	18.28 (7.72,27.2)	679.87 (312.98,987.9)	17.89 (8.03,27.25)	−0.17 (−0.47 to 0.13)	938.44 (449.48,1352.56)	0.98 (0.72 to 1.24)
Andean Latin America	1855 (803,2741)	75,683 (37,333,106,649)	7620 (3585,11,544)	353,939 (178,500,498,182)	9.2 (3.87,13.76)	343.83 (164.56,490.44)	13.05 (6.05,19.88)	1.04 (0.81 to 1.27)	582.78 (289.82,826.57)	1.63 (1.49 to 1.76)
Central Latin America	19,604 (8972,27,685)	838,218 (423,138,1,147,961)	70,287 (35,125,97,647)	3,059,746 (1,656,920,4,123,354)	24.16 (10.63,34.84)	911.75 (445.37,1269.44)	28.24 (13.86,39.54)	0.27 (0.08 to 0.47)	1179.35 (633.32,1599.42)	0.58 (0.45 to 0.72)
Tropical Latin America	12,868 (5562,18,565)	552,268 (268,325,772,970)	36,553 (15,819,52,543)	1,656,755 (828,268,2,313,462)	14.55 (6.02,21.48)	553.15 (260.68,790.17)	14.42 (6.16,20.88)	0.04 (−0.15 to 0.22)	633.16 (314.94,886.38)	0.41 (0.31 to 0.52)
North Africa and Middle East	17,690 (7929,25,715)	750,989 (367,282,1,047,806)	70,424 (34,831,98,732)	4,270,997 (2,273,605,5,829,839)	11.6 (4.83,17.24)	414.77 (194.58,589.64)	17.16 (8.02,24.37)	1.65 (1.45 to 1.85)	854.36 (431.82,1180.23)	2.55 (2.41 to 2.69)
South Asia	23,166 (8672,38,201)	1,092,237 (437,304,1,747,028)	132,941 (48,869,209,748)	6,665,104 (2,838,298,10,061,732)	4.23 (1.5,7.19)	164.4 (62.95,268.33)	9.49 (3.37,15.28)	2.73 (2.6 to 2.85)	413.84 (172.35,626.04)	3.1 (3 to 3.19)
Central Sub-Saharan Africa	2990 (1241,4824)	110,199 (48,633,175,662)	10,727 (4226,17,076)	484,509 (214,931,723,566)	13.6 (5.4,22.18)	425.13 (178.68,689.16)	20.74 (7.66,34.37)	1.3 (1.05 to 1.54)	733.02 (304.09,1127.04)	1.71 (1.46 to 1.95)
Eastern Sub-Saharan Africa	8188 (3370,12,886)	289,453 (123,487,448,780)	21,577 (8957,34,684)	865,946 (379,671,1,289,084)	11 (4.31,17.6)	336.49 (137.55,531.48)	13.31 (5.21,22.16)	0.38 (0.23 to 0.53)	433.79 (181.06,669.31)	0.5 (0.46 to 0.7)
Southern Sub-Saharan Africa	5291 (2237,7792)	180,540 (85,619,251,447)	23,383 (10,627,32,803)	787,110 (396,716,1,066,168)	20.48 (8.35,30.81)	626.45 (286.62,888.38)	43.92 (19.11,63.24)	2.88 (2.53 to 3.22)	1308.02 (636.33,1799.12)	2.73 (2.43 to 3.03)

Table 1 (continued)

Location	Numbers with uncertainty interval (95% UI)				Age-standardized rate per 100 000 population (95% UI)					
	1990		2021		1990		2021			
	Numbers of Death	Numbers of DALYs	Numbers of Death	Numbers of DALYs	Death rate	DALY rate	Death rate	EAPC, 95% CI	DALY rate	EAPC, 95% CI
Western Sub-Saharan Africa	8366 (3239,13,275)	310,658 (133,190,483,557)	29,652 (11,727,45,278)	1,310,713 (622,641,1,925,358)	10.21 (3.8,16.65)	324.64 (133.2,514.14)	16.81 (6.17,26.45)	1.61 (1.55 to 1.68)	581.74 (256.55,873.87)	1.87 (1.8 to 1.93)

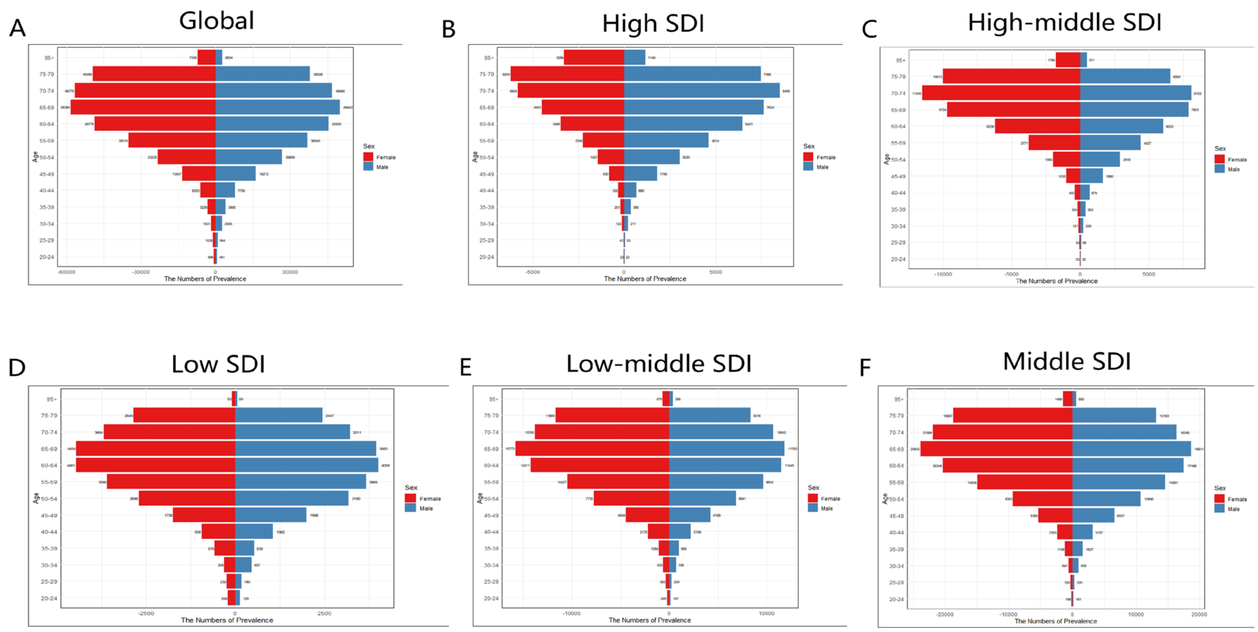

Fig. 1 Number of T2DM deaths due to high BMI in different regions and age groups **A** Number of deaths globally in 2021 **B** Number of deaths in high SDI regions **C** Number of deaths in high-medium SDI regions **D** Number of deaths in low SDI regions **E** Number of deaths in low-medium SDI regions **F** Number of deaths in medium SDI regions

advancing age (Fig. 1). In high SDI regions, the 70- to 74-year age group recorded the highest death toll, totaling 14,305, with 8498 deaths in males, exceeding 5809 deaths in females. Conversely, in low-to-moderate SDI regions, the 65- to 69-year age group had the highest number of deaths, amounting to 27,555, where 15,773 deaths occurred among females, surpassing 11,782 deaths among males (Fig. 1). In terms of DALYs, high BMI-related type 2 diabetes peaked at a relatively older age in high SDI regions, whereas it peaked at younger ages in other SDI regions. Specifically, DALYs peaked in the 50- to 59-year age group in low SDI regions and in the 55- to 60-year age group in low-to-moderate SDI regions, while in high SDI regions, DALYs peaked in the 65- to 70-year age group. Additionally, males exhibited higher DALYs than females in high SDI regions, while females had higher DALYs than males in other SDI regions (Supplementary Figure S1).

Global burden of diabetes disease by year, 1990–2021

A study of trends in the incidence of type 2 diabetes attributed to high BMI from 1990 to 2021 revealed a strong association with SDI levels. In high SDI areas (Fig. 2A), the ASDR for T2DM associated with high BMI increased from 237 to 415 cases per 100,000 population, while the ASMR declined from 6 to 5 per 100,000 population. Overall, the ASDR for T2DM due to high BMI showed an upward trend, though both ASDR and ASMR remained generally higher in low and low-to-moderate SDI areas compared to high SDI areas (Fig. 2A). For instance, in 1990, the ASDR for T2DM due to high BMI was 230 and 279 per 100,000 in low and low-to-middle SDI regions, respectively; by 2021, these values had risen to 537 and 457 per 100,000, respectively (Fig. 2A). Additionally, the ASMR of T2DM due to high BMI increased from 8 and 6.5 per 100,000 in 1990 to 11.5 and 12.7 per 100,000 in low and low-to-moderate SDI areas, respectively (Fig. 2D). Gender differences in ASDR and ASMR for T2DM due to high BMI were also observed. Connected-point regression analyses indicated that ASDR and ASMR were consistently higher in males than females in high SDI areas, while in low and intermediate SDI regions, ASDR and ASMR were higher in females than in males (Fig. 2B, C). For example, in 2021, ASDR and ASMR in low and intermediate SDI regions were 509 and 11.7 per 100,000 in males (Fig. 2B, E), compared with 560 and 13.5 per 100,000 in females (Fig. 2C, F).

Correlation between SDI and ASDR and ASMR in T2DM due to high BMI

Figure 3A illustrates the correlation between ASMR and ASDR for T2DM due to high BMI and the SDI across 21 regions from 1990 to 2021. Analysis by region indicates

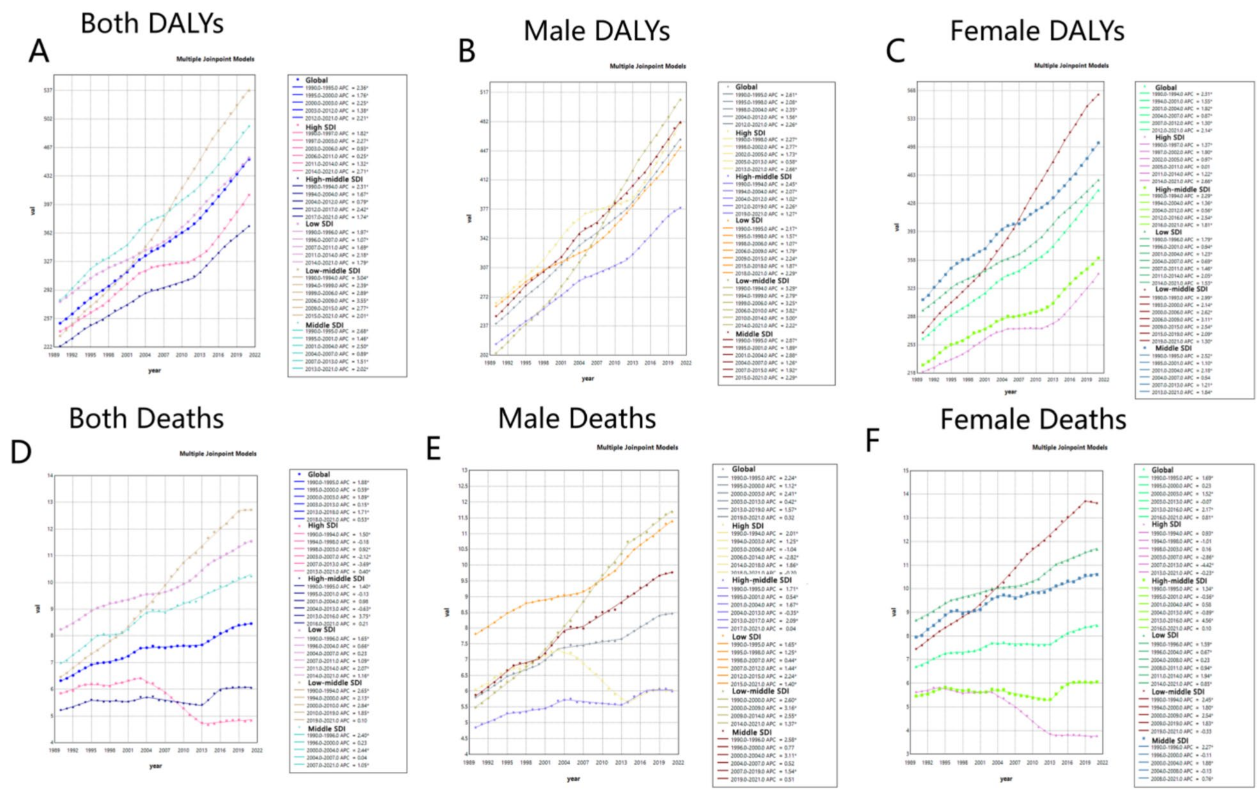

Fig. 2 Trends in ASDR and ASMR for T2DMA due to high BMI in five SDI regions, 1990–2021. **A** ASDR trends; **B** female ASDR trends; **C** male ASDR trends; **D** ASMR trends; **E** female ASMR trends; and **F** male ASMR trends

a significant positive correlation ($p < 0.05$) between SDI and ASDR for T2DM due to high BMI, suggesting a strong association between the T2DM burden due to high BMI and the level of regional socioeconomic development. Some regions, particularly Oceania, Sub-Saharan Africa, Central America and the Caribbean, and the Middle East, exhibit higher-than-average ASDR compared to SDI-based projections. In contrast, other regions, such as the high-income Asia-Pacific, Western Europe, East Asia, and South and Southeast Asia, show lower-than-expected burdens. Figure 3B further explores these trends by examining SDI-related ASDR and ASMR at the country level over the same period. Overall, the ASDR for T2DM due to high BMI rises with increasing socioeconomic levels, but this upward trend plateaus near an SDI value of 0.7, followed by a gradual decline as SDI continues to increase. Notably, countries in low SDI regions, such as Fiji, Kiribati, Afghanistan, Benin, and Haiti, experience a significantly higher T2DM burden than expected, whereas countries in high SDI regions, including the United States, France, Australia, and Canada, have a notably lower burden.

Decomposition analysis of age standardized DALYs rates

Over the past three decades, deaths and DALYs associated with T2DM due to high BMI have risen significantly. The data reveal a more substantial increase in DALYs from high BMI-induced T2DM among women than men, primarily driven by population growth and evolving disease prevalence patterns. Although DALYs for T2DM due to high BMI have also increased in men, this rise is less pronounced than in women, with epidemiologic trends playing a more prominent role (Fig. 4A). Additional analyses indicate a similarly significant rise in T2DM-related deaths due to high BMI, impacting both men and women equally. Figure 4B shows that while the marked increase in female mortality is mainly due to population growth, the primary factor for men is epidemiologic change.

Frontier analysis of age standardized DALYs rates

Figure 5A presents a chronological overview of the unmet potential for health improvement across countries and regions at various stages of development from 1990 to 2021. In 2021, Fig. 5B emphasizes disparities in disability-adjusted life-year (DALY) burdens and health outcomes across different sociodemographic levels.

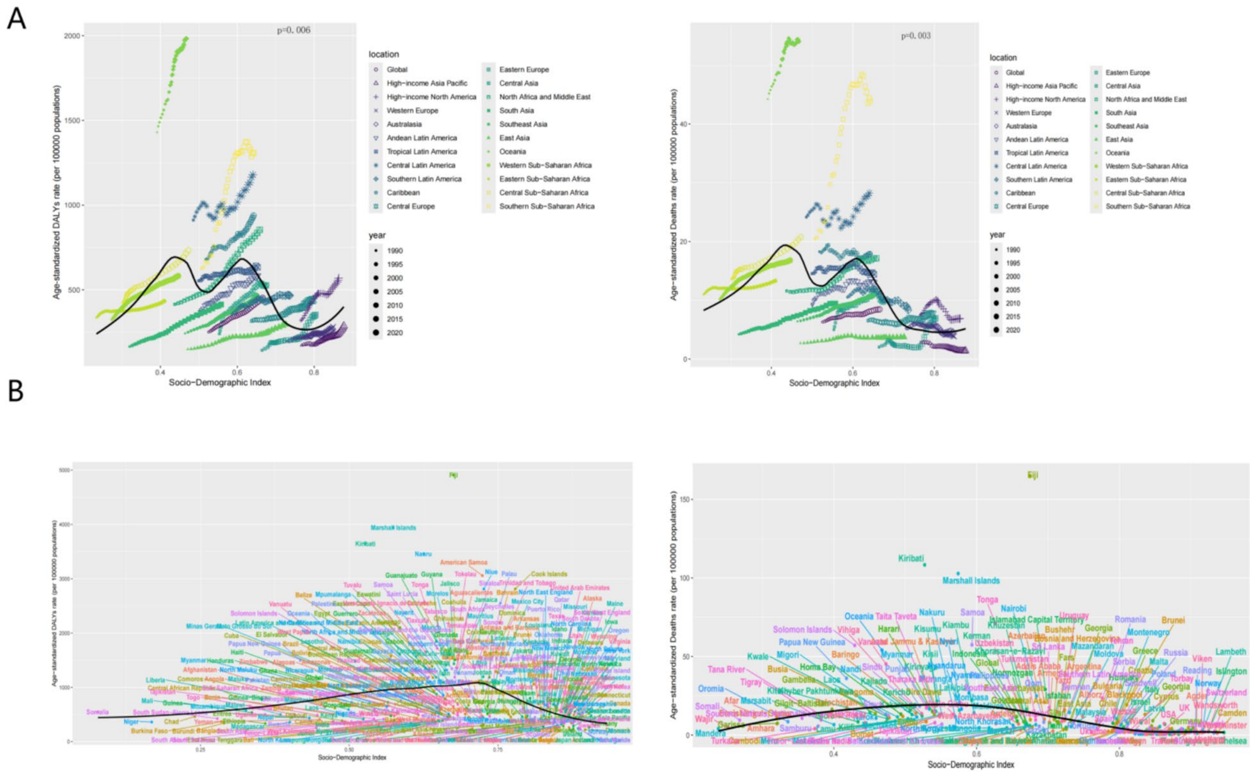

Fig. 3 Correlation between SDI and ASDR and ASMR in T2DM due to high BMI in different regions and countries, 1990–2021. **A** The solid line is a locally weighted scatterplot smoothing smoother, which displays the global expected values based on the Socio-Demographic Index (SDI) values. **B** Each point represents the age-standardized Disability-Adjusted Life Year (DALY) rate and mortality rate observed in a specific country in 2021. ASDR: Age-Standardized Disability-Adjusted Life Year rate; ASMR: Age-Standardized Mortality rate; SDI: Socio-Demographic Index

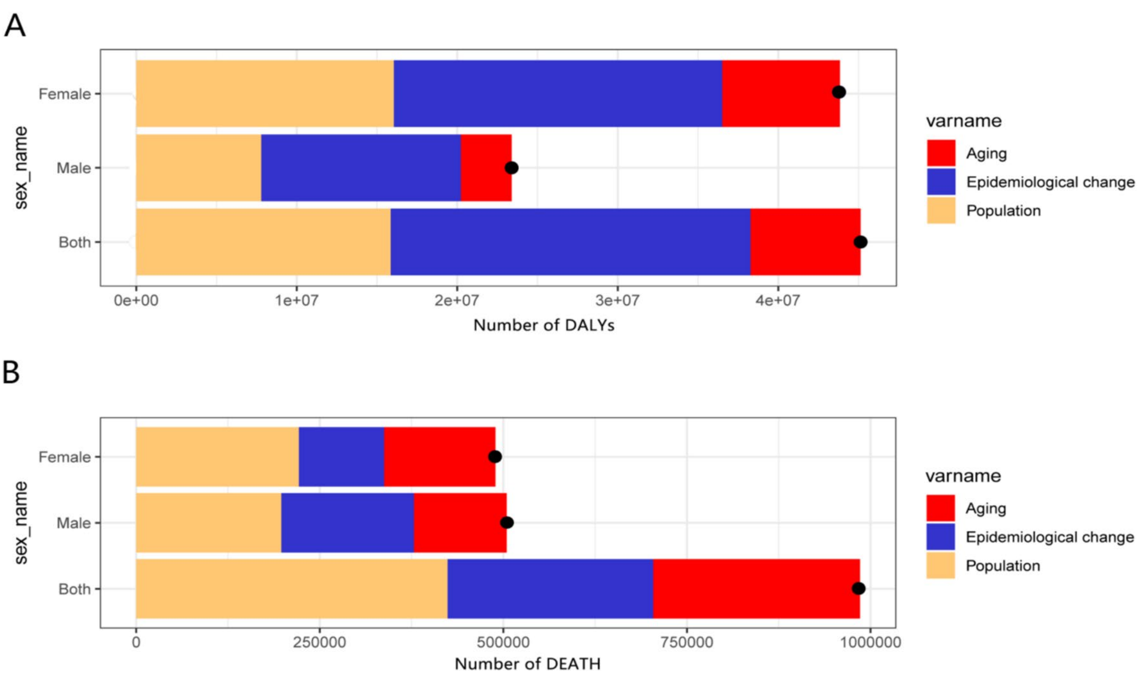

Fig. 4 Changes in disability-adjusted life years and deaths from 1990 to 2021 for T2DM globally based on population-level determinants such as population growth, ageing, and epidemiological changes, and grouped by sex. Black dots represent the overall value of change due to all 3 factors. For each component, the magnitude of the positive value indicates a corresponding increase in the number of T2DM DALYs and deaths attributable to that component. **A** Number of DALYs. **B** Number of DEATH. SDI: sociodemographic index; DALYs: disability-adjusted life years

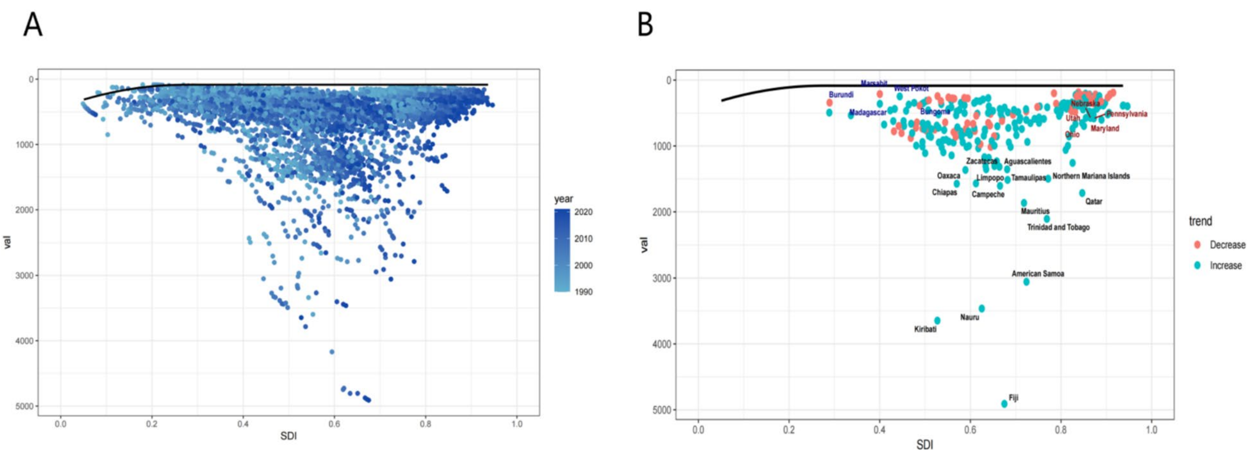

Fig. 5 Frontier analysis of the age-standardized type 2 diabetes DALY rate related to high body mass index based on the Socio-Demographic Index in 2021. **A** The frontier is represented by a solid black line, and countries and regions are denoted by dots. **B** The top 15 countries with the largest effective differences are marked in black. The frontier countries with low SDI (0.85) and relatively high development levels in terms of effective differences are marked in red. Red dots indicate an increase in the age-standardized Disability-Adjusted Life Years ratio between 1990 and 2021, and blue dots indicate a decrease in the age-standardized Disability-Adjusted Life Years ratio during the same period. SDI: Socio-Demographic Index; DALYs: Disability-Adjusted Life Years

The effective difference, defined as the distance from the "frontier," represents the gap between the observed burden in a country or region and the anticipated burden based on its SDI. A substantial effective difference suggests unrealized potential for health improvement, depending on a country's or region's development level. Using 2021 DALYs and SDI, we estimated each country's or region's effective difference from the frontier (Fig. 5B). The five countries or territories with the largest effective differences included Fiji, Nauru, Kiribati, Samoa, Greenland, and Trinidad and Tobago (Fig. 5B). Conversely, the five countries or territories with the smallest effective differences, indicating lower DALY burdens relative to their development levels, were Burundi, Madagascar, Bungoma, West Pokot, Marsabit, and El Salvador (Fig. 5B).

Predicting the next decade ASDR and ASMR in T2DM due to high BMI

We employed ARIMA models to forecast trends in DALYs and mortality associated with T2DM due to high BMI across various SDI regions over the next decade. Using the auto.arima () function for model selection, we identified optimal ARIMA models with corresponding Akaike Information Criterion (AIC) values for different SDI levels. Specifically, the optimal global model was ARIMA (1,2,1) with an AIC of − 56.19. For the high SDI region, the optimal model was ARIMA (1,1,1) with an AIC of − 37.29; for the medium-high SDI region, ARIMA (1,2,1) with an AIC of − 70.44; for the low SDI region, ARIMA (0,2,1) with an AIC of − 106.82; for the medium-low SDI region, ARIMA (0,2,2) with an AIC of − 79.24; and for the medium SDI region, ARIMA (0,2,1) with an AIC of − 54.19. Through analysis of normal Q-Q plots, autocorrelation function (ACF), and partial autocorrelation function (PACF) plots, we confirmed the residuals' normal distribution properties (Supplementary Figure S2-S3). Additionally, the Ljung-Box test indicated that the residuals for all SDI regions conformed to a white noise process (all p-values > 0.05, Supplementary Figure. S4), supporting the models' validity. Using a comparable methodology, we also constructed an ARIMA model for the DALYs rate of T2DM and verified its stability through the Ljung-Box test. Across SDI regions, ASMR projections were consistent with observed values (Fig. 6). In low SDI regions, the ASMR for T2DM is projected to increase from 11.8 cases per 100,000 population in 2021 to 13.1 cases per 100,000 in 2031 (Fig. 6). This upward trend is notably more pronounced in low and middle SDI regions, where ASMR is expected to rise from 12.5 to 15.9 per 100,000 population by 2031 (Fig. 6E), while high SDI regions are anticipated to remain relatively stable (Fig. 6A). However, in high SDI areas, the ASDR for T2DM due to high BMI is projected to significantly increase from 415 cases per 100,000 population in 2021 to 547 per 100,000 in 2031 (Supplementary Figure S5A). ASDRs in other SDI regions showed similar upward trends (Supplementary Figure S5).

Discussions

A comprehensive analysis of the latest GBD data, specifically GBD2021, demonstrated significant temporal and regional variations in the ASDR and ASMR of

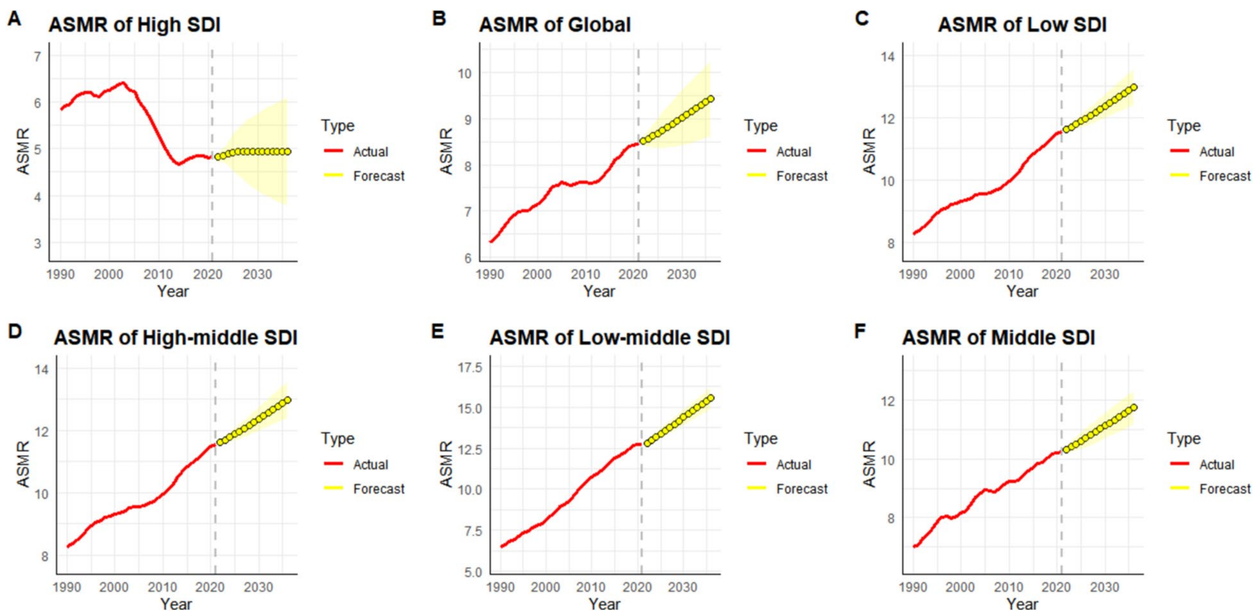

Fig. 6 Projected trends in global T2DM mortality due to high BMI over the next 10 years. The red line represents the true trend in T2DM mortality between 1990–2021; the yellow dashed line and shaded area represent the projected trend and its 95% CI

T2DM associated with elevated body mass index (BMI). Across SDI regions, both deaths and DALYs attributed to T2DM linked to high BMI substantially increased from 1990 to 2021. This trend is likely driven by changes in dietary habits, genetic predispositions, and lifestyle modifications associated with rising socioeconomic levels. In particular, the increasing prevalence of obesity-related dietary patterns is notable. Consequently, the interaction of these factors is expected to further elevate the incidence of T2DM, impacting quality of life and escalating the disease's associated health burden.

Given the global surge in obesity and diabetes cases, the World Health Organization (WHO) has classified these conditions as global epidemics. Current scientific consensus identifies a strong correlation between excess body weight—especially abdominal obesity—and insulin resistance, a condition where the body's sensitivity to insulin decreases, impairing glucose absorption and utilization. This impairment places increased stress on pancreatic beta cells, which must produce higher insulin levels to regulate blood glucose, potentially leading to beta cell dysfunction and the progression of T2DM over time [11, 12]. Studies estimate that in 2017, T2DM accounted for over 1 million deaths globally, with nearly half of these deaths associated with elevated BMI levels [13]. Extensive research has examined the intricate relationship between diabetes and obesity, with findings indicating that obesity significantly elevates the risk of developing T2DM compared to individuals of normal weight. Specifically, obese men and women face up to a sevenfold and twelvefold higher risk, respectively [14]. Additionally, obesity prevalence among T2DM patients ranges from 50.9 to 98.6% in Europe and from 56.1 to 69.2% in Asia [15].

Our study reveals significant gender and regional differences in the development of T2DM. Specifically, the T2DM burden attributable to elevated BMI was notably higher among women over 60, and ASDR were elevated in regions with low-to-moderate SDI. Several factors may account for these findings. First, women's longer life expectancy compared to men may partially explain the increased T2DM burden observed among older women [16]. Second, the rising incidence of sarcopenic obesity—characterized by concurrent declines in muscle mass and strength in older adults—may contribute to an elevated T2DM risk [17]. Sarcopenic obesity adversely impacts physical function and quality of life and is closely associated with metabolic dysregulation [18, 19]. Furthermore, in low-to-moderate SDI regions, a higher prevalence of central obesity may promote insulin resistance, thereby raising T2DM prevalence [20]. Data from 1990 to 2019 show a marked increase in diabetes prevalence among older adults in these regions, particularly those aged 65 and above, correlating with higher T2DM-related ASDR [21].

A high BMI typically arises from daily nutrient intake exceeding the body's requirements. In high-SDI regions, lifestyle and dietary habits are the primary contributors to elevated BMI levels. Key factors include reduced physical activity, frequent consumption of high-calorie and sugary beverages, increased fast food intake, and insufficient consumption of fruits and vegetables [22–24]. Our analysis indicates that the ASDR for T2DM associated with high BMI has consistently trended upward over recent decades. Population growth, aging, and epidemiological transitions have variously influenced this trend. Our findings highlight the substantial impact of epidemiological factors on the increasing ASDR and ASMR among T2DM patients, including fluctuating incidence rates, pre-T2DM ASDR, socioeconomic disparities, demographic shifts, and earlier T2DM onset. Studies show that the ASDR for adult T2DM in China rose from 4.7 in 1990 to 8.0% in 2019, with projections suggesting it may reach 9.7% by 2030 [25–27]. Concurrently, the ASDR for pre-T2DM is also increasing, affecting a significant portion of the population and closely linked to factors such as aging, urbanization, and lifestyle shifts [28, 29].

A regional analysis of the GBD revealed that ASDR and ASMR for T2DM associated with high BMI have been rising in most regions. The study highlighted that regions with the highest T2DM burden are predominantly those with low and medium SDI, including Angola, Bangladesh, and Cameroon. This increasing burden of T2DM and obesity in low- and middle-SDI regions, such as Oceania, is attributed to the high importation of processed meat and calorie-dense diets [30]. Globally, it is reported that at least 72% of adults do not meet the recommended daily intake of fruits and vegetables, while in Southern Africa, approximately 31–75% of the population is physically inactive, exacerbating the T2DM burden associated with high BMI [31]. In contrast, high-SDI countries, such as Japan, Singapore, and San Marino, demonstrated relatively low T2DM burdens in 2021. Singapore's successful reduction in diabetes burden is credited to its comprehensive obesity prevention and management strategies, which include supportive public policies, promotion of healthy lifestyles, public health campaigns, and improved clinical management of obesity [32]. Conversely, low-SDI regions, like Fiji, reported the highest ASDR and ASMR for T2DM in 2019. The study attributes Fiji's increased obesity rates to a rise in imported sugar and processed foods, compounded by socio-cultural, economic, political, and environmental factors that limit access to and knowledge of nutritious foods [33]. T Consequently, future strategies should prioritize both individual- and policy-level interventions to reduce the impact of high BMI on T2DM.

Over the past three decades, DALYs and mortality linked to T2DM due to high BMI have risen markedly worldwide, especially among women. Decomposition analyses indicate that the increased T2DM burden associated with high BMI is more pronounced in women, largely due to population growth and shifts in disease prevalence. This disparity may be attributed to a combination of physiological, social, and behavioral factors. Notably, women are more susceptible to weight gain and insulin resistance at certain life stages, such as pregnancy and menopause, heightening their risk of diabetes [34, 35]. Additionally, socioeconomic status, cultural norms, and gender roles pose further challenges for women in managing obesity and diabetes risk factors, including fewer opportunities for physical activity and heightened dietary pressures [36]. Supporting this, other studies report that BMI increases are more substantial among women than men in specific high- and lower-middle-income countries, possibly linked to global dietary shifts and urbanization [37]. While the T2DM burden due to high BMI in men has not increased as sharply as in women, it still shows a clear upward trend, largely driven by changing epidemiological patterns. Recent lifestyle shifts among men, such as the rise of sedentary work and high-calorie diets, are key contributors to this trend [38]. Furthermore, the relationship between obesity and metabolic health may be more directly observable in men, particularly through the link between abdominal fat accumulation and insulin resistance [39]. Antonietta et al. highlight that with the global rise in ultra-processed foods and high-sugar beverages, obesity rates are increasing among men, particularly in middle-income countries, which directly contributes to the growing T2DM burden [40]. Further analysis reveals that T2DM-related mortality has risen significantly in both male and female populations, albeit driven by different factors. Among women, population growth is the primary driver of increased mortality, while in men, epidemiological changes play a more crucial role [41]. These trends underscore the complexity of global diabetes management and prevention. Despite advances in medical technology, obesity rates and the related diabetes burden continue to rise, suggesting that current preventive strategies may be insufficient. Future policies should place greater emphasis on gender-specific factors, particularly by enhancing women's health awareness, expanding opportunities for physical activity, and improving dietary composition.

Ongoing surveillance of disease epidemiology and trend forecasting are essential for effective disease management. Forecasts using ARIMA models indicate that by 2031, the global ASDR associated with T2DM will rise to 550 cases per 100,000 for men and 9.5 cases per 100,000 for women, with higher rates projected among women. Improvements in medical technology and increased health awareness are anticipated to enhance T2DM diagnosis over the coming decade [42]. By 2021, the global T2DM population is expected to reach 530 million, accounting for approximately 6% of the world population

[43]. Key factors driving this rise include global population growth, aging, and unhealthy lifestyle choices [44], particularly physical inactivity, high-calorie diet consumption, and obesity [45]. Additionally, socioeconomic disparities across countries and regions influence the prevention, diagnosis, and treatment of T2DM, with lower-middle-income countries experiencing a faster increase in T2DM prevalence than high-income countries [46]. A comprehensive strategy is crucial to alleviate the health burden of T2DM linked to high BMI and improve the well-being of affected individuals. Such a strategy should focus on primary health care prevention, timely T2DM detection in elderly and high-risk groups, lifestyle interventions, equitable healthcare resource distribution, and advocacy for early T2DM diagnosis and prevention.

This study is based on an analysis of the GBD database, which, while providing extensive data on global health trends across multiple countries and regions, has certain limitations. First, the GBD database depends on health reporting systems in different countries and regions, leading to variability in data quality and completeness. Incomplete data may have impacted the accuracy of our findings; for instance, underreporting of high BMI-related T2DM in some developing countries could result in underestimating cases. Limited healthcare resources can exacerbate this underdiagnosis, causing an inaccurate perception of the burden of high BMI-associated T2DM. Additionally, some GBD health indicators are estimated through modeling rather than direct observation, introducing potential errors, especially in regions with sparse or inconsistent data reporting. Second, as GBD estimates are based on assumptions and parameterizations, these modeling assumptions may not fully apply across all study scenarios, particularly in estimating regional distributions of specific diseases or risk factors. Finally, while the GBD database offers global health burden data, its limited spatial and temporal resolution may hinder capturing certain changes when examining localized or short-term trends. Thus, although this study provides valuable insights into the global health burden, future research should incorporate higher-resolution local data and further validate the model to reduce bias and enhance result accuracy.

Conclusions

This study presents a thorough analysis of the global burden of T2DM attributable to high BMI using data from the 2021 GBD study. The findings reveal substantial differences in ASMR and ASDR for T2DM across SDI regions, genders, and age groups. Between 1990 and 2021, the number of deaths and DALYs associated with T2DM due to high BMI increased worldwide, with the most significant rise observed in regions with low and low-middle SDI. These results indicate that the influence of SDI disparities on disease burden must be carefully considered in T2DM prevention and treatment strategies. Consequently, future public health interventions should implement targeted approaches based on SDI levels in each region to effectively reduce the global T2DM burden.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s13098-024-01554-y.

Supplementary Material 1. Figure S1: Number of DALYs for T2DM due to high BMI in different regions and age groups

Supplementary Material 2. Figure S2: Autocorrelation function and partial autocorrelation graphs after differencing

Supplementary Material 3. Figure S3: Residual Q-Q plots, autocorrelation function and partial autocorrelation graphs of the ARIMA models

Supplementary Material 4. Figure S4: Ljung-Box test result graph

Supplementary Material 5. Figure S5: Trends in global ASDR projections for T2DM due to high body mass index over the next 10 years

Ackonwledgment

We thank the GBD collaborators to provide the data.

Author contributions

YD: Conceptualization, Writing—original draft. AD: Formal Analysis, Methodology, Supervision, Writing—original draft, Writing—original draft. HY: Conceptualization, Writing—original draft. TQ: Conceptualization, Methodology, Writing—original draft. LW：conceptualization, Methodology, Validation, Writing–original draft, ZH: Methodology, Validation, Writing—review and editing.

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Availability of data and materials

The data that support the findings of this study are openly available in Institute for Health Metrics and Evaluation IHME website at [http://ghdx.healthdata.org/gbd-results-tool]. In addition, the original data and code supporting the conclusions of this paper are in an additional file.

Declarations

Ethics approval and consent to participate

Ethical approval and consent to participate were not necessary for this study. This study follows the Guidelines for Accurate and Transparent Health Estimates Reporting (GATHER).

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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References

1. Baena-Diez JM, Penafiel J, Subirana I, Ramos R, Elosua R, Marin-Ibanez A, et al. Risk of cause-specific death in individuals with diabetes: a competing risks analysis. Diabetes Care. 2016;39(11):1987–95.
2. GBDD Collaborators. Global, regional, and national burden of diabetes from 1990 to 2021, with projections of prevalence to 2050: a systematic analysis for the Global Burden of Disease Study 2021. Lancet. 2023;402(10397):203–34.
3. Diseases GBD, Injuries C. Global burden of 369 diseases and injuries in 204 countries and territories, 1990–2019: a systematic analysis for the Global Burden of Disease Study 2019. Lancet. 2020;396(10258):1204–22.
4. ElSayed NA, Aleppo G, Aroda VR, Bannuru RR, Brown FM, Bruemmer D, et al. 8. Obesity and weight management for the prevention and treatment of type 2 diabetes: standards of care in diabetes-2023. Diabetes Care. 2023;46(Suppl 1):S128–39.
5. Collaboration NCDRF. Worldwide trends in body-mass index, underweight, overweight, and obesity from 1975 to 2016: a pooled analysis of 2416 population-based measurement studies in 128.9 million children, adolescents and adults. Lancet. 2017;390(10113):2627–42.
6. Safiri S, Carson-Chahhoud K, Noori M, Nejadghaderi SA, Sullman MJM, Ahmadian Heris J, et al. Burden of chronic obstructive pulmonary disease and its attributable risk factors in 204 countries and territories, 1990–2019: results from the Global Burden of Disease Study 2019. BMJ. 2022;378: e069679.
7. Hankey BF, Ries LA, Kosary CL, Feuer EJ, Merrill RM, Clegg LX, et al. Partitioning linear trends in age-adjusted rates. Cancer Causes Control. 2000;11(1):31–5.
8. GBDD Collaborators. Global age-sex-specific fertility, mortality, healthy life expectancy (HALE), and population estimates in 204 countries and territories, 1950–2019: a comprehensive demographic analysis for the Global Burden of Disease Study 2019. Lancet. 2020;396(10258):1160–203.
9. GBDDF Collaborators. Estimation of the global prevalence of dementia in 2019 and forecasted prevalence in 2050: an analysis for the Global Burden of Disease Study 2019. Lancet Public Health. 2022;7(2):e105–25.
10. Xie Y, Bowe B, Mokdad AH, Xian H, Yan Y, Li T, et al. Analysis of the Global Burden of Disease study highlights the global, regional, and national trends of chronic kidney disease epidemiology from 1990 to 2016. Kidney Int. 2018;94(3):567–81.
11. Boutari C, DeMarsilis A, Mantzoros CS. Obesity and diabetes. Diabetes Res Clin Pract. 2023;202: 110773.
12. Artasensi A, Mazzolari A, Pedretti A, Vistoli G, Fumagalli L. Obesity and type 2 diabetes: adiposopathy as a triggering factor and therapeutic options. Molecules. 2023. https://doi.org/10.3390/molecules28073094.
13. Khan MAB, Hashim MJ, King JK, Govender RD, Mustafa H, Al KJ. Epidemiology of type 2 diabetes—global burden of disease and forecasted trends. J Epidemiol Glob Health. 2020;10(1):107–11.
14. Wilding JP. The importance of weight management in type 2 diabetes mellitus. Int J Clin Pract. 2014;68(6):682–91.
15. Chobot A, Gorowska-Kowolik K, Sokolowska M, Jarosz-Chobot P. Obesity and diabetes-not only a simple link between two epidemics. Diabetes Metab Res Rev. 2018;34(7): e3042.
16. Zarulli V, Kashnitsky I, Vaupel JW. Death rates at specific life stages mold the sex gap in life expectancy. Proc Natl Acad Sci U S A. 2021. https://doi.org/10.1073/pnas.2010588118.
17. Batsis JA, Villareal DT. Sarcopenic obesity in older adults: aetiology, epidemiology and treatment strategies. Nat Rev Endocrinol. 2018;14(9):513–37.
18. Huang SW, Ku JW, Lin LF, Liao CD, Chou LC, Liou TH. Body composition influenced by progressive elastic band resistance exercise of sarcopenic obesity elderly women: a pilot randomized controlled trial. Eur J Phys Rehabil Med. 2017;53(4):556–63.
19. Gutierrez-Lopez L, Olivares-Corichi IM, Martinez-Arellanes LY, Mejia-Munoz E, Polanco-Fierro JA, Garcia-Sanchez JR. A moderate intensity exercise program improves physical function and oxidative damage in older women with and without sarcopenic obesity. Exp Gerontol. 2021;150: 111360.
20. Ravuvu A, Waqa G. Childhood obesity in the pacific: challenges and opportunities. Curr Obes Rep. 2020;9(4):462–9.
21. Slurink IA, Chen L, Magliano DJ, Kupper N, Smeets T, Soedamah-Muthu SS. Dairy product consumption and incident prediabetes in the Australian diabetes, obesity, and lifestyle study with 12 years of follow-up. J Nutr. 2023;153(6):1742–52.
22. Chao AM, Quigley KM, Wadden TA. Dietary interventions for obesity: clinical and mechanistic findings. J Clin Invest. 2021. https://doi.org/10.1172/JCI140065.
23. Bales CW, Porter Starr KN. Obesity interventions for older adults: diet as a determinant of physical function. Adv Nutr. 2018;9(2):151–9.
24. Jackson RE, Lang W, Rogers RJ, Schelbert EB, Kovacs SJ, Creasy SA, et al. Accumulated physical activity and the association with obesity, fitness, and cardiometabolic risk factors in healthy adults. Obesity (Silver Spring). 2024;32(1):23–31.
25. Li Y, Teng D, Shi X, Qin G, Qin Y, Quan H, et al. Prevalence of diabetes recorded in mainland China using 2018 diagnostic criteria from the American Diabetes Association: national cross sectional study. BMJ. 2020;369: m997.
26. Liu J, Liu M, Chai Z, Li C, Wang Y, Shen M, et al. Projected rapid growth in diabetes disease burden and economic burden in China: a spatio-temporal study from 2020 to 2030. Lancet Reg Health West Pac. 2023;33: 100700.
27. Liu J, Shen M, Zhuang G, Zhang L. Investigating the temporal trends of diabetes disease burden in China during 1990–2019 from a global perspective. Front Endocrinol (Lausanne). 2024;15:1324318.
28. Liu M, Liu SW, Wang LJ, Bai YM, Zeng XY, Guo HB, et al. Burden of diabetes, hyperglycaemia in China from to 2016: Findings from the 1990 to 2016, global burden of disease study. Diabetes Metab. 2019;45(3):286–93.
29. Li Y, Guo C, Cao Y. Secular incidence trends and effect of population aging on mortality due to type 1 and type 2 diabetes mellitus in China from 1990 to 2019: findings from the Global Burden of Disease Study 2019. BMJ Open Diabetes Res Care. 2021. https://doi.org/10.1136/bmjdrc-2021-002529.
30. Luo J, Zhao X, Li Q, Zou B, Xie W, Lei Y, et al. Evaluating the global impact of low physical activity on type 2 diabetes: insights from the global burden of disease 2019 study. Diabetes Obes Metab. 2024;26(6):2456–65.
31. Madlala SS, Hill J, Kunneke E, Kengne AP, Peer N, Faber M. Dietary diversity and its association with nutritional status, cardiometabolic risk factors and food choices of adults at risk for type 2 diabetes mellitus in Cape Town, South Africa. Nutrients. 2022. https://doi.org/10.3390/nu14153191.
32. Foo LL, Vijaya K, Sloan RA, Ling A. Obesity prevention and management: Singapore's experience. Obes Rev. 2013;14(Suppl 2):106–13.
33. Li Y, Zhang H, Jiang Y. Research on the changes and predictions of the burden of type 2 diabetes mellitus in Pacific Island countries from 1990 to 2019. PLoS ONE. 2023;18(12): e0293681.
34. Hivert MF, White F, Allard C, James K, Majid S, Aguet F, et al. Placental IGFBP1 levels during early pregnancy and the risk of insulin resistance and gestational diabetes. Nat Med. 2024;30(6):1689–95.
35. Lambrinoudaki I, Paschou SA, Armeni E, Goulis DG. The interplay between diabetes mellitus and menopause: clinical implications. Nat Rev Endocrinol. 2022;18(10):608–22.
36. Koceva A, Herman R, Janez A, Rakusa M, Jensterle M. Sex- and gender-related differences in obesity: from pathophysiological mechanisms to clinical implications. Int J Mol Sci. 2024. https://doi.org/10.3390/ijms25137342.
37. Liu C, Zhang Z, Wang B, Meng T, Li C, Zhang X. Global health impacts of high BMI: a 30-year analysis of trends and disparities across regions and demographics. Diabetes Res Clin Pract. 2024;217: 111883.
38. Goodarzynejad H, Meaney C, Brauer P, Greiver M, Moineddin R, Monavvari AA. Recent trends in adult body mass index and prevalence of excess weight: data from the Canadian Primary Care Sentinel Surveillance Network. Can Fam Physician. 2022;68(2):128–38.
39. Schulze MB, Stefan N. Metabolically healthy obesity: from epidemiology and mechanisms to clinical implications. Nat Rev Endocrinol. 2024;20(11):633–46.

40. Monda A, de Stefano MI, Villano I, Allocca S, Casillo M, Messina A, et al. Ultra-processed food intake and increased risk of obesity: a narrative review. 2024. Foods. https://doi.org/10.3390/foods13162627.
41. Tinajero MG, Malik VS. An update on the epidemiology of type 2 diabetes: a global perspective. Endocrinol Metab Clin North Am. 2021;50(3):337–55.
42. American Diabetes Association Professional Practice C. 7 Diabetes technology: standards of care in diabetes-2024. Diabetes Care. 2024;47(1):S126–44.
43. Sun H, Saeedi P, Karuranga S, Pinkepank M, Ogurtsova K, Duncan BB, et al. IDF Diabetes Atlas: Global, regional and country-level diabetes prevalence estimates for 2021 and projections for 2045. Diabetes Res Clin Pract. 2022;183: 109119.
44. Ho LJ, Sheu WH, Lo SH, Yeh YP, Hwu CM, Huang CN, et al. Unhealthy lifestyle associated with increased risk of macro- and micro-vascular comorbidities in patients with long-duration type 2 diabetes: results from the Taiwan Diabetes Registry. Diabetol Metab Syndr. 2023;15(1):38.
45. Lambrinou E, Hansen TB, Beulens JW. Lifestyle factors, self-management and patient empowerment in diabetes care. Eur J Prev Cardiol. 2019;26(2_suppl):55–63.
46. Liu J, Bai R, Chai Z, Cooper ME, Zimmet PZ, Zhang L. Low- and middle-income countries demonstrate rapid growth of type 2 diabetes: an analysis based on Global Burden of Disease 1990–2019 data. Diabetologia. 2022;65(8):1339–52.

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