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Global, regional, and national burden of kidney cancer and attributable risk factors in adults aged 65 years and older from 1990 to 2021 and projections to 2040

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Abstract

Background Identifying the past and future burden of kidney cancer (KC) and its temporal trends among older adults (≥ 65 years) at global, regional, and national levels is critical for effective prevention strategies.

Methods The age-standardized incidence, prevalence, mortality, and disability-adjusted life years (DALYs) were calculated using data from the Global Burden of Disease (GBD) study from 1990 to 2021. These indicators were stratified by sex, age, and socio-demographic index (SDI). The correlation between these indicators and SDI was assessed. Temporal trends were quantified using the annual average percentage change (AAPC), and future trends from 2022 to 2040 were predicted using the Bayesian age-period-cohort (BAPC) model.

Results The global age-standardized incidence rate (ASIR) of KC among older adults increased from 21.73 per 100,000 people in 1990 to 26.74 per 100,000 people in 2021, with an AAPC of 0.67%. Age-standardized DALYs rate (ASDR) remained stable, while significant increases were observed in age-standardized prevalence (AAPC = 1.24%, 95%CI: 1.14–1.34%) and mortality rate (AAPC = 0.13%, 95%CI: 0.05–0.22%). From 1990 to 2021, males consistently exhibited a higher disease burden than females, additionally, the ASIR of KC increased significantly in all age subgroups. Regions with higher SDI levels also showed a greater disease burden, while Oceania had the lowest burden of KC in 2021. The ASIR increased in almost all countries and territories. Czechia showed the highest ASIR (92.25 per 100,000 people) and ASDR (819.88 per 100,000 people). Smoking and high body mass index (BMI) remained significant risk factors for DALYs and mortality in the older population, and their effects were greatest in high SDI region. Furthermore, the burden of KC is expected to continue to decline through 2040.

Conclusions The global burden of KC among older adults increased from 1990 to 2021, with notable regional and national variations. However, it is projected to continue to decline through 2040. The management of smoking and high BMI remain major challenges for people with KC, necessitating targeted clinical guidelines, particularly focusing on males and the older adults.

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Keywords Global burden of disease, Incidence, Disability-adjusted life years, Smoking, High body mass index

Background

Cancer remains a significant global public health challenge, with both incidence and mortality continuing to rise [1]. According to the latest Global Cancer Statistics 2022, kidney cancer (KC) ranked 14th globally, with approximately 434,419 incident cases and 155,702 deaths [2]. KC exhibits a rapidly increasing incidence and mortality, accompanied by a poor prognosis [3]. In addition, the incidence of KC varies across countries, with higher rates generally observed in developed nations compared to developing ones [4]. The main risk factors for KC include smoking, high body mass index (BMI), and occupational exposure to trichloroethylene [5]. It is speculated that smoking may increase the risk of KC through chronic tissue hypoxia caused by carbon monoxide exposure and smoking-related diseases such as chronic obstructive pulmonary disease [6]. And obesity causes metabolic filtration stress, which promotes tumorigenesis in clear cell renal cell carcinoma. Additionally, occupational exposure to trichloroethylene has also been associated with an increased risk of KC, as it induces epigenetic changes in cancer-related genes [7]. As a type of genitourinary cancer, KC not only diminishes patients' quality of life but also reduces their life expectancy and imposes significant healthcare costs. In low and middle SDI regions, the impact of KC on socio-economic and healthcare systems is particularly significant, mainly in terms of increased economic burden, increased pressure on healthcare resources, rising health inequalities, and increased public health challenges. Therefore, there is an urgent need for epidemiological studies to inform health policy decisions.

The risk of developing cancer increases exponentially with age, and older adults are particularly susceptible to KC [8], which may be due to mechanisms such as cellular aging, stress responses, and decreased immune function [9–11]. In addition, the treatment of older adults with KC faces more challenges, such as more comorbidities and poor physical function status, which may affect the treatment effect and prognosis. Given the global aging population, it is crucial to recognize the growing potential burden of KC. Previous studies have typically focused on disease burden in all age groups, without specifically addressing the older adults, who are at heightened risk, and in particular lacked projections for future trends in KC in older populations or comprehensive analyses across SDI regions. Therefore, a comprehensive and accurate assessment of the global burden of KC among the older adults is crucial. This study integrates the latest available data to evaluate the incidence, prevalence, mortality, disability-adjusted life years (DALYs), and temporal trends of KC among people aged 65 years and older from 1990 to 2021, and projects public health challenges to 2040. We aim to characterize the global, regional, and national temporal trends and future projections of KC burden in older adults by age, sex and socio-demographic index (SDI), identify associated risk factors, and analyze variations across SDI strata, providing valuable insights for health policy adjustments and the optimal allocation of medical resources.

Methods

Data sources

Global Burden of Disease (GBD) 2021 provides a comprehensive assessment of health losses from 371 diseases, injuries, risk factors, impairments, and causes of death in 204 countries and territories. Incidence, prevalence, mortality, and DALYs for KC were calculated using the DisMod-MR 2.1 tool. More detailed information about the methodology of GBD study has been described extensively in the existing GBD literature [12]. The definition of KC is based on the International Classification of Diseases, version 10 (ICD-10), with the corresponding codes C64-C64.2, and C64.9-C65.9 [12]. In this study, we extracted data on incidence, prevalence, mortality, and DALYs, as well as DALYs and mortality attributable to each risk factor for KC in people ≥ 65 years using the GBD 2021 Results Tool (https://vizhub.healthdata.org/gbd-results/). Data were stratified by seven age groups, including 65–69, 70–74, 75–79, 80–84, 85–89, 90–94, 95 plus. All disease estimates from GBD include 95% uncertainty intervals (UI) for each metric, based on the 25th and 975th ordered values drawn 1000 times from the posterior distribution [13].

Definitions

The DALYs quantifies the years of healthy life lost from the onset of disease to the point of death and is a comprehensive measure of the total health loss caused by disease. The DALYs calculates the sum of years of life lost to premature death (YLLs) and years lived with a disability (YLDs) due to prevalent cases of disease or health condition in the population [14].

The SDI is a composite indicator of the degree of social development that combines lagging income per capita, the average educational attainment of individuals aged 15 and over, and the total fertility rates of females under the age of 25 [15], expressed on a scale of 0 (least developed) to 1 (most developed). The 204 countries and territories were divided into five SDI groups: low SDI, low-middle SDI, middle SDI, high-middle SDI, and high SDI.

Table 1 Age-standardized incidence and DALYs of KC in people aged 65 years and older between 1990 and 2021 at the global and regional levels, and their AAPC from 1990 to 2021

Characteristics	Incidence						DALYs					
	Cases in 1990	Age-standardized rate in 1990 (per 100,000)	Cases in 2021	Age-standardized rate in 2021 (per 100,000)	AAPC (95% CI)	*P* value	Cases in 1990	Age-standardized rate in 1990 (per 100,000)	Cases in 2021	Age-standardized rate in 2021 (per 100,000)	AAPC (95% CI)	*P* value
Global	70,003 (66115–72896)	21.73 (20.38–22.69)	203,022 (184450–214928)	26.74 (24.20-28.35)	0.67 (0.57 to 0.76)	< 0.001	779,889 (740807–810600)	239.95 (226.54-250.03)	1,826,969 (1675419–1937528)	240.05 (219.31-254.88)	0.00 (-0.07 to 0.07)	0.97
Sex												
Female	29,946 (27472–31821)	16.23 (14.81–17.28)	75,536 (65430–82175)	18.00 (15.59–19.58)	0.33 (0.24 to 0.43)	< 0.001	318,904 (294983–336890)	172.40 (158.64-182.54)	645,536 (565402–699991)	153.61 (134.52-166.57)	-0.37 (-0.45 to -0.29)	< 0.001
Male	40,057 (38225–41597)	29.40 (27.87–30.60)	127,486 (117291–135659)	37.68 (34.46–40.16)	0.80 (0.72 to 0.87)	< 0.001	460,986 (440439–479193)	332.64 (316.02-346.49)	1,181,432 (1095756–1257769)	347.76 (320.64-370.76)	0.15 (0.06 to 0.23)	0.001
Age												
65 to 69	22,278 (21574–22958)	18.02 (17.45–18.57)	54,937 (52135–57500)	19.92 (18.90-20.85)	0.32 (0.19 to 0.46)	< 0.001	278,302 (269303–286545)	225.15 (217.87-231.81)	543,685 (516355–571289)	197.10 (187.19-207.11)	-0.44 (-0.58 to -0.29)	< 0.001
70 to 74	17,915 (17123–18592)	21.16 (20.23–21.96)	54,391 (50939–56899)	26.42 (24.75–27.64)	0.74 (0.58 to 0.91)	< 0.001	198,652 (190833–206219)	234.64 (225.41-243.58)	479,753 (452619–503897)	233.07 (219.89–244.80)	-0.02 (-0.18 to 0.13)	0.774
75 to 79	15,942 (15158–16562)	25.90 (24.62–26.91)	40,041 (36610–42120)	30.36 (27.76–31.94)	0.49 (0.40 to 0.59)	< 0.001	164,695 (156898–170876)	267.56 (254.89–277.60)	335,774 (310304–354168)	254.60 (235.28-268.54)	-0.18 (-0.27 to -0.10)	< 0.001
80 to 84	9010 (8114–9523)	25.47 (22.94–26.92)	28,751 (24630–30922)	32.83 (28.12–35.31)	0.82 (0.70 to 0.94)	< 0.001	89,799 (82110–94681)	253.84 (232.11-267.64)	242,477 (211653–260301)	276.85 (241.66–297.20)	0.27 (0.15 to 0.39)	< 0.001
85 to 89	3736 (3236–4020)	24.72 (21.42–26.60)	17,081 (14031–18729)	37.36 (30.69–40.96)	1.39 (1.16 to 1.61)	< 0.001	35,948 (31494–38522)	237.89 (208.41-254.92)	143,669 (120257–156966)	314.23 (263.02-343.31)	0.92 (0.73 to 1.11)	< 0.001
90 to 94	931 (764–1023)	21.74 (17.84–23.88)	6094 (4830–6774)	34.06 (27.00-37.86)	1.50 (1.32 to 1.69)	< 0.001	10,342 (8539–11318)	241.35 (199.26-264.12)	63,589 (50905–70266)	355.46 (284.55-392.78)	1.30 (1.09 to 1.50)	< 0.001
95 plus	191 (144–217)	18.79 (14.19–21.34)	1727 (1274–1985)	31.68 (23.37–36.42)	1.71 (1.37 to 2.05)	< 0.001	2151 (1631–2440)	211.29 (160.17-239.66)	18,022 (13326–20642)	330.65 (244.50-378.73)	1.47 (1.15 to 1.79)	< 0.001
SDI												
Low SDI	709 (593–830)	4.37 (3.62–5.14)	2103 (1631–2563)	5.79 (4.49–7.07)	0.94 (0.83 to 1.05)	< 0.001	13,599 (11433–15906)	80.28 (66.98–94.31)	35,658 (27558–43402)	95.31 (73.71-116.14)	0.57 (0.49 to 0.65)	< 0.001
Low-middle SDI	1712 (1514–1916)	3.91 (3.43–4.39)	7414 (6781–8065)	6.52 (5.94–7.10)	1.69 (1.59 to 1.79)	< 0.001	30,163 (26736–33775)	66.66 (58.78–74.88)	112,663 (103124–122279)	97.40 (88.92-105.78)	1.25 (1.16 to 1.35)	< 0.001
Middle SDI	4983 (4628–5321)	6.71 (6.21–7.18)	26,386 (23550–29366)	11.64 (10.35–12.97)	1.78 (1.60 to 1.97)	< 0.001	78,784 (73330–83819)	102.76 (95.33-109.52)	315,444 (283843–348247)	138.00 (123.71-152.58)	0.96 (0.81 to 1.12)	< 0.001

Table 1 (continued)

Characteristics	Incidence						DALYs					
	Cases in 1990	Age-standardized rate in 1990 (per 100,000)	Cases in 2021	Age-standardized rate in 2021 (per 100,000)	AAPC (95% CI)	*P* value	Cases in 1990	Age-standardized rate in 1990 (per 100,000)	Cases in 2021	Age-standardized rate in 2021 (per 100,000)	AAPC (95% CI)	*P* value
High-middle SDI	18,743 (17649–19729)	22.48 (21.07–23.69)	58,610 (53314–63086)	32.08 (29.12–34.55)	1.18 (1.00 to 1.36)	< 0.001	227,462 (214962–238729)	270.95 (255.13-284.79)	540,275 (493830–580750)	295.09 (269.17-317.33)	0.32 (0.20 to 0.44)	< 0.001
High SDI	43,762 (40947–45948)	41.80 (39.07–43.92)	108,264 (96928–115535)	52.38 (47.19–55.75)	0.69 (0.55 to 0.84)	< 0.001	428,602 (403388–449581)	410.33 (385.66-430.62)	820,317 (737682–877300)	395.26 (357.89-421.62)	-0.14 (-0.25 to -0.02)	0.02
Region												
Andean Latin America	195 (163–232)	12.24 (10.23–14.55)	934 (712–1221)	18.63 (14.22–24.37)	1.39 (0.88 to 1.90)	< 0.001	3368 (2841–3976)	208.78 (175.84-246.58)	12,727 (9792–16592)	253.36 (194.91-330.32)	0.63 (0.15 to 1.11)	0.01
Australasia	831 (708–961)	37.07 (31.54–42.88)	2495 (2018–2997)	47.32 (38.33–56.86)	0.73 (0.55 to 0.92)	< 0.001	9353 (7978–10900)	416.21 (354.48-485.11)	19,380 (15780–23083)	366.54 (299.01-436.54)	-0.51 (-0.65 to -0.37)	< 0.001
Caribbean	244 (219–271)	10.81 (9.68–12.01)	698 (596–805)	14.69 (12.53–16.93)	1.07 (0.90 to 1.24)	< 0.001	3690 (3335–4070)	162.24 (146.35–179.20)	8893 (7614–10222)	187.25 (160.39-215.22)	0.51 (0.35 to 0.67)	< 0.001
Central Asia	409 (356–480)	11.63 (10.11–13.67)	1089 (954–1223)	17.95 (15.74–20.14)	1.44 (1.05 to 1.83)	< 0.001	6287 (5509–7368)	178.62 (156.39-209.46)	15,482 (13531–17426)	251.27 (219.87-282.65)	1.09 (0.68 to 1.50)	< 0.001
Central Europe	3940 (3686–4204)	29.74 (27.76–31.78)	11,023 (9881–12163)	49.32 (44.20-54.41)	1.68 (1.53 to 1.84)	< 0.001	56,319 (52944–59828)	421.58 (395.40-448.36)	123,137 (111330–134280)	550.84 (498.04-600.69)	0.88 (0.82 to 0.94)	< 0.001
Central Latin America	817 (774–856)	12.83 (12.13–13.46)	4333 (3860–4818)	20.45 (18.21–22.73)	1.45 (1.39 to 1.51)	< 0.001	13,475 (12824–14059)	208.43 (197.96–217.70)	59,684 (53399–66422)	280.32 (250.75-311.86)	0.97 (0.64 to 1.31)	< 0.001
Central Sub-Saharan Africa	60 (40–92)	4.18 (2.65–6.51)	169 (100–270)	4.95 (2.88–7.96)	0.55 (0.46 to 0.64)	< 0.001	1168 (776–1786)	76.04 (48.66-117.94)	3004 (1789–4853)	84.31 (49.25-136.71)	0.35 (0.27 to 0.42)	< 0.001
East Asia	4800 (4168–5386)	7.96 (6.89–8.96)	30,550 (25166–36272)	15.47 (12.74–18.35)	2.18 (1.81 to 2.55)	< 0.001	70,627 (61256–79414)	112.96 (97.84-127.14)	284,610 (234067–338608)	144.49 (118.85-171.77)	0.80 (0.45 to 1.14)	< 0.001
Eastern Europe	6551 (6086–7021)	27.49 (25.52–29.48)	16,290 (14881–17703)	48.50 (44.30-52.69)	1.93 (1.42 to 2.44)	< 0.001	80,929 (75345–86652)	339.69 (316.04-363.83)	162,553 (147879–177072)	481.66 (438.31-524.55)	1.20 (0.93 to 1.47)	< 0.001
Eastern Sub-Saharan Africa	368 (295–442)	6.79 (5.43–8.18)	1078 (777–1361)	9.29 (6.72–11.71)	1.03 (0.95 to 1.11)	< 0.001	7116 (5709–8577)	125.72 (100.61-151.75)	18,513 (13289–23541)	154.41 (111.24-196.12)	0.68 (0.62 to 0.74)	< 0.001
High-income Asia Pacific	3113 (2843–3352)	17.90 (16.29–19.30)	14,138 (11926–15744)	28.84 (24.74–31.97)	1.50 (1.20 to 1.81)	< 0.001	36,606 (34190–38282)	209.92 (195.24–219.90)	125,837 (107775–137283)	254.79 (222.52-276.17)	0.58 (0.18 to 0.98)	0.005
High-income North America	19,436 (18042–20351)	56.23 (52.17–58.89)	42,308 (38009–44848)	66.00 (59.30-69.95)	0.51 (0.32 to 0.69)	< 0.001	146,002 (136529–152903)	423.77 (396.03-443.93)	257,718 (232909–273619)	401.00 (362.70-425.51)	-0.20 (-0.36 to -0.04)	0.017

Table 1 (continued)

Characteristics	Incidence						DALYs					
	Cases in 1990	Age-standardized rate in 1990 (per 100,000)	Cases in 2021	Age-standardized rate in 2021 (per 100,000)	AAPC (95% CI)	*P* value	Cases in 1990	Age-standardized rate in 1990 (per 100,000)	Cases in 2021	Age-standardized rate in 2021 (per 100,000)	AAPC (95% CI)	*P* value
North Africa and Middle East	876 (742–1032)	7.32 (6.14–8.68)	4501 (3852–5310)	13.37 (11.41–15.80)	1.99 (1.88 to 2.10)	< 0.001	14,132 (12012–16478)	114.55 (96.58-134.58)	52,342 (45076–61740)	154.69 (132.88-182.65)	1.00 (0.86 to 1.13)	< 0.001
Oceania	5 (3–8)	2.89 (1.79–4.26)	15 (9–22)	3.18 (1.96–4.78)	0.29 (0.04 to 0.53)	0.02	78 (48–118)	41.49 (25.22-62.00)	212 (127–329)	44.68 (26.78–68.89)	0.22 (0.05 to 0.39)	0.009
South Asia	1294 (1114–1479)	3.22 (2.76–3.71)	6594 (5857–7334)	5.54 (4.91–6.17)	1.79 (1.54 to 2.04)	< 0.001	24,053 (20697–27454)	57.74 (49.45–66.26)	102,478 (91073–113855)	84.45 (74.96–93.91)	1.27 (0.98 to 1.56)	< 0.001
Southeast Asia	1114 (943–1273)	6.04 (5.10–6.91)	4583 (3954–5275)	9.00 (7.73–10.39)	1.30 (1.15 to 1.45)	< 0.001	15,903 (13545–18105)	84.58 (71.92–96.48)	55,166 (47932–63263)	106.98 (92.56-122.92)	0.75 (0.60 to 0.90)	< 0.001
Southern Latin America	1313 (1124–1519)	31.67 (27.08–36.67)	4280 (3628–4989)	52.83 (44.77–61.59)	1.70 (1.23 to 2.16)	< 0.001	18,380 (15851–21212)	441.20 (379.93–509.50)	45,427 (38804–52520)	560.64 (478.81-648.26)	0.80 (0.39 to 1.20)	< 0.001
Southern Sub-Saharan Africa	129 (100–157)	6.33 (4.92–7.68)	459 (408–509)	10.53 (9.34–11.68)	1.63 (1.33 to 1.92)	< 0.001	2173 (1689–2636)	103.66 (80.71-125.76)	7150 (6365–7922)	159.81 (141.90-177.24)	1.38 (1.08 to 1.68)	< 0.001
Tropical Latin America	670 (616–720)	9.48 (8.66–10.20)	3824 (3415–4165)	17.25 (15.37–18.81)	1.95 (1.49 to 2.42)	< 0.001	11,209 (10362–11993)	154.98 (142.57-166.09)	52,909 (47662–57297)	237.53 (213.53-257.42)	1.49 (1.02 to 1.97)	< 0.001
Western Europe	23,657 (21768–25440)	42.09 (38.70-45.28)	53,065 (46414–58300)	57.40 (50.73–62.81)	1.02 (0.87 to 1.17)	< 0.001	255,738 (236820–273270)	457.17 (422.98-488.74)	409,873 (362285–447587)	440.29 (393.31-478.76)	-0.10 (-0.20 to -0.01)	0.029
Western Sub-Saharan Africa	180 (147–214)	2.78 (2.28–3.30)	595 (502–689)	4.52 (3.84–5.22)	1.57 (1.50 to 1.64)	< 0.001	3283 (2700–3899)	48.94 (40.28–58.09)	9874 (8317–11459)	73.07 (61.82–84.55)	1.29 (1.22 to 1.36)	< 0.001

KC kidney cancer; *AAPC* average annual percentage change; *DALYs* disability-adjusted life years; *SDI* socio-demographic index

Risk factors

We calculated and reported DALYs and mortality for KC that were attributable to smoking, high BMI, and occupational exposure to trichloroethylene (established most detailed risk factors with available data in GBD). Current smokers are defined as individuals who currently use any tobacco product on a daily or occasional basis, while former smokers are those who have stopped using all smoking tobacco products for at least 6 months. High BMI is defined as a BMI greater than 20–23 kg/m^2 for individuals aged 20 years and older. Occupational exposure to trichloroethylene is defined as the percentage of individuals (≥ 15 years) who have been exposed to trichloroethylene at various intensity levels [16].

DisMod-MR 2.1 and spatiotemporal Gaussian process regression were used to quantify the impact of these risk factors. The estimate of GBD risk factors is based on a comparative risk assessment framework, consisting of six steps: (1) identifying the inclusion of risk-outcome pairs; (2) estimation of relative risk as functional exposure; (3) estimation of exposures for each risk by age, sex, location, and year; (4) identification of the theoretical minimum risk exposure level (TMREL) and the counterfactual exposure; (5) estimation of attributable burden and population attributable fractions (PAFs); (6) estimation of the DALYs and mortality attributable to various combinations of risk factors. Detailed descriptions and basic methods of each step are provided elsewhere [17].

Statistical analysis

We uesd direct standardization method to calculate the corresponding age-standardized rate (ASR) of age groups by "ageadjust.direct" function of package "epitools" within R software [18–20]. The age-standardized incidence rate (ASIR), age-standardized prevalence rate (ASPR), age-standardized mortality rate (ASMR), and age-standardized DALYs rate (ASDR) (per 100,000 people, respectively) for KC were calculated using the world standard population reported in GBD 2021 as a reference [21]. The calculation formula is as follows:

$$\text{Age-standardized rate} = \frac{\sum_{i=1}^{A} a_i w_i}{\sum_{i=1}^{A} w_i}$$

For the formula: where a_i is the age-specific rate in the ith age group, w_i is the weight in the same age subgroup of the chosen reference standard population (in which i denotes the ith age class), and A is the total number of age groups.

In this study, the annual percent change (APC) and average annual percentage change (AAPC) were calculated using the joinpoint regression analysis model, which is commonly applied to assess the time trend of disease burden in epidemiological studies. We selected a log-linear model (ln y = xb) to analyze the trends of ASIR, ASPR, ASMR, and ASDR. The grid search method was employed to determine the number and location of join points, with a maximum of 5 join points allowed. The Monte Carlo permutation test was used to select the optimal number of join points [22]. The specific calculation method has been described in previous study [23]. If AAPC or APC and their 95% confidence intervals (CI) are both > 0 (or both < 0), the corresponding trend is considered to be an upward (or downward) trend. The calculation formula is as follows:

$$\text{AAPC} = \left\{ \exp\left(\frac{\sum w_i b_i}{\sum w_i} \right) - 1 \right\} \times 100$$

For the formula: b_i is the slope coefficient for the ith segment with i indexing the segments in the desired range of years and w_i is the length of each segment in the range of years.

The Bayesian age-period-cohort (BAPC) model was used to project the burden of KC to 2040. A notable advantage of the BAPC model is its use of the Integrated Nested Laplacian Approximation (INLA) method, which approximates the edge posterior distribution and helps avoid some of the mixing and convergence problems associated with traditional Bayesian methods of Markov Chain Monte Carlo sampling [24]. Due to its comprehensive coverage and ability to capture temporal trends, the BAPC model has been widely validated and applied in epidemiological research, particularly in studies involving age-structured population data and complex cohort effects [24].

In addition, we present findings based on the respective SDI values across all GBD regions and 204 countries and territories. Correlations between age-standardized rate and SDI were examined using Pearson correlation analysis. Joinpoint regression analysis was performed using the Joinpoint Regression Program [25]. All statistical analyses and data visualization were performed using the R (version 4.3.3). A two-sided P value < 0.05 was considered statistically significant.

Results

Global trends

Globally, incident cases of KC in adults aged 65 years and older increased from 70,003 in 1990 to 203,022 in 2021, an increase of 190.02% (Table 1, Table S1). During the same period, the ASIR increased from 21.73 per 100,000 people to 26.74 per 100,000 people (AAPC = 0.67%, 95%CI: 0.57–0.76%) (Table 1). Additionally, the proportion of incident cases of KC in the older adults (≥ 65 years) relative to the overall number of incident cases has continued to rise (Figure S1). The upward trend in ASIR of KC among people aged 65 years and older was noticeable from 1990 to 2021 compared to the overall age of population with KC (Figure S2). Joinpoint regression analysis indicated an increase in ASIR from 1990 to 2015, followed by a decline from 2015 to 2021 (APC = -0.61%) (Fig. 1, Table S2).

The cases of DALYs for KC among those aged ≥ 65 years increased from 779,889 in 1990 to 1,826,969 in 2021, and the ASDR increased from 239.95 per 100,000 people to 240.05 per 100,000 people (Table 1). Similarly, the cases of prevalence and mortality increased by 239.25% and 150.50%, respectively (Table S1). During this period, the corresponding ASPR (AAPC = 1.24%, 95%CI: 1.14–1.34%) and ASMR (AAPC = 0.13%, 95%CI: 0.05–0.22%) also showed upward trends (Table S3).

Global trends by sex

From 1990 to 2021, the ASIR among adults aged 65 years and older increased globally in both males (from 29.40 per 100,000 people to 37.68 per 100,000 people, AAPC = 0.80%, 95%CI: 0.72–0.87%) and females (from 16.23 per 100,000 people to 18.00 per 100,000 people, AAPC = 0.33%, 95%CI: 0.24–0.43%) (Table 1). In the older population, KC was predominantly more common in males, with 1.34 times more cases than in females (40,057 vs. 29,946) in 1990 and 1.69 times more cases (127,486 vs. 75,536) in 2021 (Table 1). Across all age subgroups ≥ 65 years, males consistently had higher ASIR than females between 1990 and 2021 (Figure S3).

Similarly, males aged 65 years and older had higher ASPR (137.84 per 100,000 people vs. 71.44 per 100,000 people), ASMR (21.11 per 100,000 people vs. 9.43 per 100,000 people), and ASDR (347.76 per 100,000 people vs. 153.61 per 100,000 people) than females in 2021 (Table 1, Table S3). These sex difference remained the same regardless of changes in age and SDI, with males having a higher disease burden than females (Fig. 2, Figure S3, and S4). From 1990 to 2021, the ASPR (AAPC = 1.46%, 95%CI: 1.35–1.56%), ASMR (AAPC = 0.28%, 95%CI: 0.19–0.37%), and ASDR (AAPC = 0.15%, 95%CI: 0.06–0.23%) in males increased, while females experienced an increase in ASPR (AAPC = 0.83%, 95%CI: 0.67–0.99%) and a decrease in ASMR (AAPC = -0.21%, 95%CI: -0.30% to -0.12%) and ASDR (AAPC = -0.37%, 95%CI: -0.45% to -0.29%) (Table 1, Table S3).

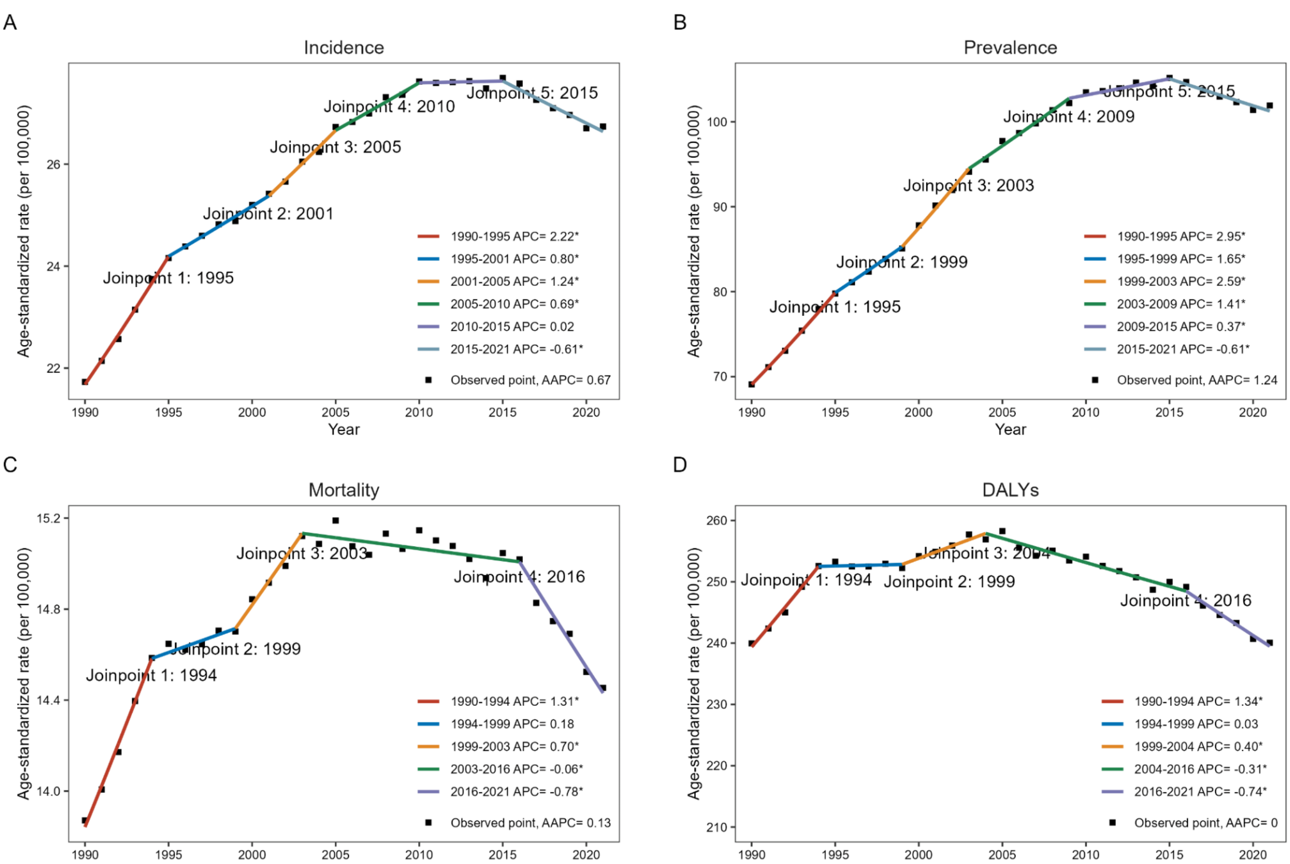

Fig. 1 Joinpoint regression analysis of KC in people aged 65 years and older from 1990 to 2021 at the global level. (**A**) Age-standardized incidence trends; (**B**) Age-standardized prevalence trends; (**C**) Age-standardized mortality trends; (**D**) Age-standardized DALYs trends. *KC* kidney cancer; *APC* annual percentage change; *AAPC* average annual percentage change; *DALYs* disability-adjusted life years

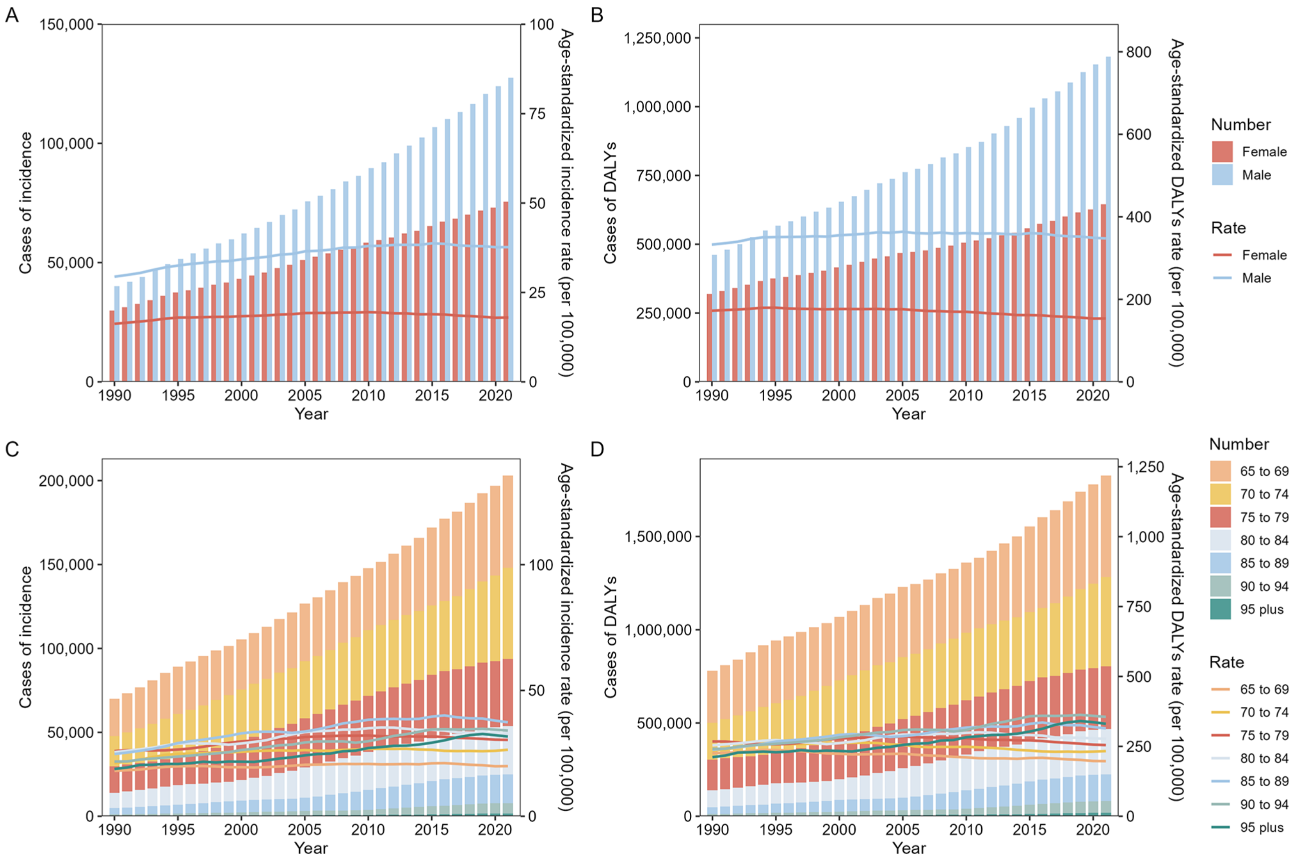

Fig. 2 Incidence and DALYs of KC in people aged 65 years and older from 1990 to 2021 at the global level. (**A**) Cases and age-standardized incidence by sex; (**B**) Cases and age-standardized DALYs by sex; (**C**) Cases and age-standardized incidence by age; (**D**) Cases and age-standardized DALYs by age. *KC* kidney cancer; *DALYs* disability-adjusted life years

Global trends by age subgroup

Globally, the incident cases of KC tripled between 1990 and 2021 in every age subgroup of people aged 65 years and older (65–69 years: from 22,278 to 54,937; 70–74 years: from 17,915 to 54,391; 75–79 years: from 15,942 to 40,041; 80–84 years: from 9010 to 28,751), and even more than four-fold in the ≥ 85 age groups (85–89 years: from 3736 to 17,081; 90–94 years: from 931 to 6094; ≥95 years: from 191 to 1727) (Table 1). In both 1990 and 2021, the incident cases decreased with age in the older population. In addition, the ASIR of KC increased significantly in all age subgroups during 1990–2021, especially in the 95 plus group (AAPC = 1.71%, 95%CI: 1.37–2.05%) (Table 1).

Among the older adults, the global ASPR of KC increased at varying rates across different age subgroups, with the most significant increase occurring in the 85–89 years group (AAPC = 2.16%, 95%CI: 1.86–2.45%), rising from 24.83 per 100,000 people in 1990 to 47.78 per 100,000 people in 2021 (Table S3). Notably, the ASDR and ASMR decreased in the age subgroups under 80 years, while both metrics increased in those aged 80 and older, with the most substantial increase occurring in people over 95 years (AAPC: 1.47% for ASDR and 1.51% for ASMR) (Table 1, Fig. 2, Table S3, Figure S5).

Global trends by SDI

From 1990 to 2021, the ASIR of KC among people aged 65 years and older increased in all SDI subgroups, especially in countries with middle SDI (AAPC = 1.78%, 95%CI: 1.60–1.97%), while the increase was minimal in countries with high SDI (AAPC = 0.69%, 95%CI: 0.55–0.84%) (Table 1). Regardless of SDI level, the increase in ASIR in people aged ≥ 65 years was consistently higher than in the general population (Figure S2, Figure S6). In 2021, with the increase in the country's SDI level, the ASIR (5.79 per 100,000 people for low SDI region vs. 52.38 per 100,000 people for high SDI region), ASPR (10.22 per 100,000 people for low SDI region vs. 232.85 per 100,000 people for high SDI region), ASMR (5.41 per 100,000 people for low SDI region vs. 23.57 per 100,000 people for high SDI region) and ASDR (95.31 per 100,000 people for low SDI region vs. 395.26 per 100,000 people for high SDI region) all showed an upward trend (Table 1, Table S3).

The ASPR rose in all SDI subgroups from 1990 to 2021, with the most substantial increase in countries with middle SDI (AAPC = 3.14%, 95%CI: 2.97–3.32%) (Table S3). In all SDI subgroups, the ASMR of KC increased among older adults (≥ 65 years), particularly in countries with low-middle SDI (AAPC = 1.28%, 95%CI: 1.16–1.39%). The increase was smallest and not statistically significant in countries with high SDI (AAPC = 0.06%, 95%CI: -0.05–0.17%, $P = 0.267$) (Table S3). Notably, from 1990 to 2021, countries with high SDI exhibited a downward trend in ASDR (AAPC = -0.14%, 95%CI: -0.25% to -0.02%), while all other SDI subgroups showed significant increases (Table 1, Figure S4).

Regional trends

From 1990 to 2021, the ASIR of KC among older adults (≥ 65 years) showed an upward trend in all 21 regions. During this period, the fastest increase in ASIR for older adults was observed in East Asia (AAPC = 2.18%, 95%CI: 1.81–2.55%), while Oceania (AAPC = 0.29%, 95%CI: 0.04–0.53%) exhibited the slightest upward trend (Table 1). In 2021, the highest ASIR of KC for people aged ≥ 65 years was observed in High-income North America (66.00 per 100,000 people), while Oceania had the lowest ASIR (3.18 per 100,000 people), with the same trend observed across sex (Table 1, Figure S7).

During 1990–2021, the ASDR for KC among people aged ≥ 65 increased in most regions, except for Australasia (AAPC = -0.51%, 95%CI: -0.65% to -0.37%), High-income North America (AAPC = -0.20%, 95%CI: -0.36% to -0.04%), and Western Europe (AAPC = -0.10%, 95%CI: -0.20% to -0.01%), where downward trends were observed. The ASDR rose most dramatically in Tropical Latin America (AAPC = 1.49%, 95%CI: 1.02–1.97%) (Table 1). In 2021, Southern Latin America showed the highest ASDR (560.64 per 100,000 people), High-income North America had the highest ASPR (331.31 per 100,000 people), and Central Europe experienced the highest ASMR (31.24 per 100,000 people). In contrast, Oceania had the lowest ASDR (44.68 per 100,000 people), ASPR (7.20 per 100,000 people), and ASMR (2.64 per 100,000 people) (Table 1, Table S3, Figure S7). Between 1990 and 2021, the ASPR for KC among people aged ≥ 65 years increased across regions, with East Asia showing the fastest growth (AAPC = 4.22%, 95%CI: 3.90–4.55%). In addition, except for Australasia (AAPC = -0.29%, 95%CI: -0.42% to -0.16%) and High-income North America (AAPC = -0.02%, 95%CI: -0.20–0.17%), ASMR increased in all regions (Table S3).

National trends

From 1990 to 2021, the incident cases of KC among people aged 65 years and older increased in all countries and territories. The ASIR increased in almost all countries and territories, with 12 countries showing a decline. More than half of these regions with declining ASIR were high and high-middle SDI countries (Fig. 3, Table S4, Table S5, Figure S8). During this period, the highest increases in ASIR (AAPC = 11.51%, 95%CI: 10.59–12.43%), ASPR (AAPC = 12.30%, 95%CI: 11.83–12.78%), ASMR (AAPC = 11.08%, 95%CI: 10.11–12.07%), and ASDR (AAPC = 10.99%, 95%CI: 9.98–12.01%) were observed in Cabo Verde, while the most significant decreases of ASIR (AAPC = -3.25%, 95%CI: -4.53% to -1.94%), ASPR (AAPC = -2.29%, 95%CI: -3.51% to -1.06%), ASMR (AAPC = -4.05%, 95%CI: -5.34% to -2.74%), and ASDR (AAPC = -4.06%, 95%CI: -5.32% to -2.77%) were recorded in Sri Lanka (Fig. 3, Figure S8, Table S5, Table S6). In 2021, Czechia showed the highest ASIR (92.25 per 100,000 people) and ASDR (819.88 per 100,000 people) (Table S5). The national prevalence and mortality for people aged 65 years and older and associated AAPC from 1990 to 2021 were presented in Tables S5, Figures S8, and S9.

Trends between SDI and KC

Our results showed that ASIR, ASDR and SDI were positively correlated at the global and regional levels (ASIR-SDI: $R = 0.81$, ASDR-SDI: $R = 0.78$, all $P < 0.001$) (Fig. 4). Specifically, as the SDI increased, the ASIR showed a brief decline when the SDI value was less than 0.367, increased within the range of 0.367 to 0.811, and then declined again. Similarly, the ASDR exhibited a brief decline when the SDI value was less than 0.376, increased within the range of 0.376 to 0.755, and then declined again. The ASIR in High-income North America and Southern Latin America was higher than expected based on the SDI value over the observation period. In contrast, the ASIR in High-income Asia Pacific was below expectation for its SDI level. Similarly, ASDR in Southern Latin America was higher than expected based on SDI value over the observation period, while ASDR in High-income Asia Pacific was lower than expected at its SDI level, and the ASDR of Eastern Europe was also higher than expected (Fig. 4).

The relationships between ASIR, ASDR and SDI across 204 countries and territories showed an initial rise, peaking at SDI of 0.913 and 0.861 respectively, and subsequently a downward trend (ASIR-SDI: $R = 0.70$, ASDR-SDI: $R = 0.65$, all $P < 0.001$) (Fig. 4). Figure S10 provides an overview of the associations between ASPR, ASMR and SDI in KC among people aged 65 years and older at global, regional, and national levels.

Risk factors

Smoking and high BMI were the main risk factors for KC related DALYs and mortality, while the contribution of occupational exposure to trichloroethylene was relatively

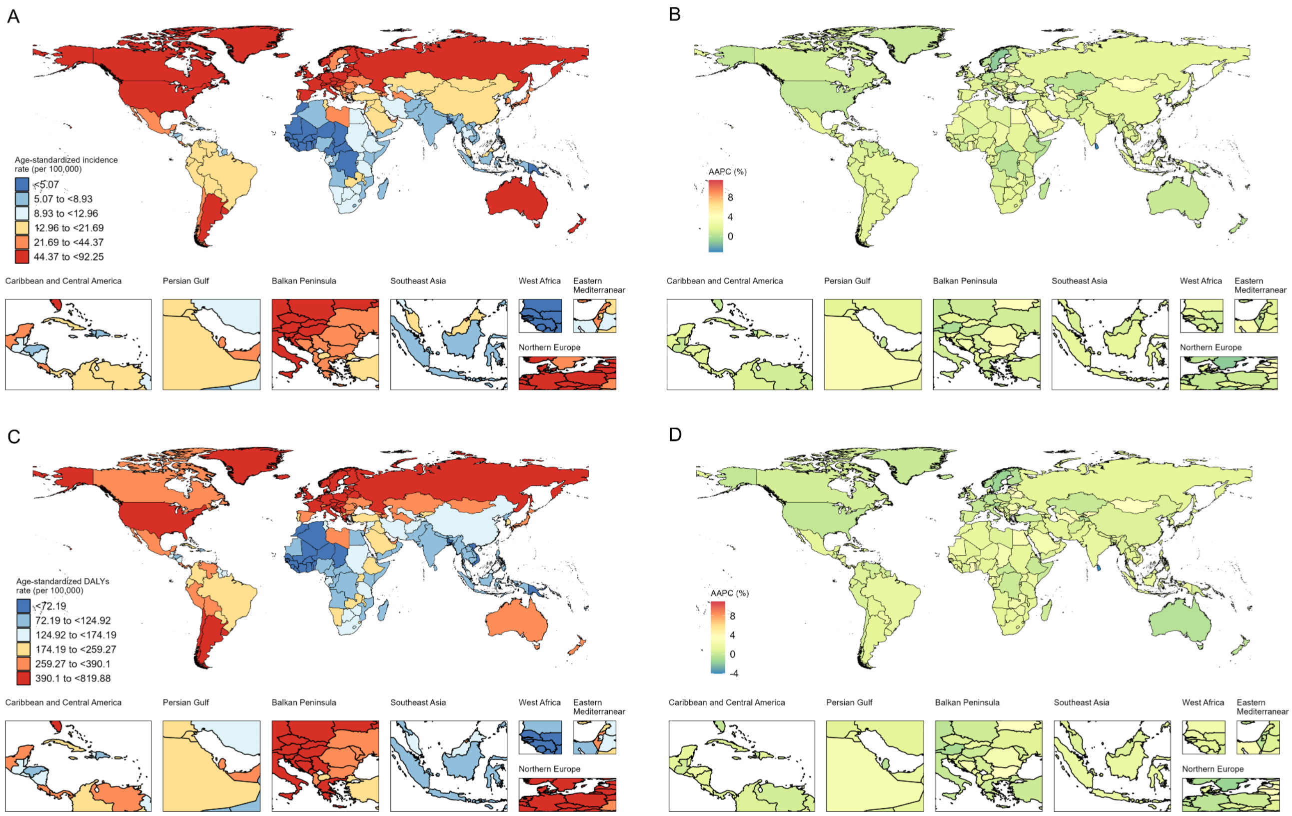

Fig. 3 Age-standardized incidence and DALYs of KC in people aged 65 years and older in 204 countries and territories(**A**) Age-standardized incidence in 2021; (**B**) AAPC in age-standardized incidence from 1990 to 2021; (**C**) Age-standardized DALYs in 2021; (**D**) AAPC in age-standardized DALYs from 1990 to 2021. *DALYs* disability-adjusted life-years; *KC* kidney cancer; *AAPC* average annual percentage change

small. In 2021, the ASDR and ASMR for KC were 25.85 and 1.46 per 100,000 people due to smoking, 48.98 and 2.87 per 100,000 people due to high BMI, and 0.08 and 0.004 per 100,000 people due to occupational exposure to trichloroethylene (Table 2). From 1990 to 2021, the ASDR of KC attributed to high BMI (AAPC = 0.66%, 95%CI: 0.60–0.72%) and occupational exposure to trichloroethylene (AAPC = 1.73%, 95%CI: 1.65–1.80%) exhibited an upward trend, whereas the ASDR of KC due to smoking demonstrated a downward trend (AAPC = -0.69%, 95%CI: -0.75% to -0.63%). In 2021, smoking (ASDR = 45.89 per 100,000 people) and high BMI (ASDR = 88.99 per 100,000 people) contributed the most to the DALYs for KC in countries with high SDI. Notably, between 1990 and 2021, countries with high SDI experienced the most rapid decline in ASDR (AAPC = -0.96%, 95%CI: -1.08% to -0.84%) attributable to smoking, while the slowest increase in ASDR (AAPC = 0.48%, 95%CI: 0.39–0.57%) attributable to high BMI were also observed in high SDI countries (Table 2).

During the same time, high BMI (AAPC = 0.80%, 95%CI: 0.70–0.90%) and occupational exposure to trichloroethylene (AAPC = 1.74%, 95%CI: 1.67–1.81%) contributed to an upward trend in ASMR globally, while smoking contributed to a downward trend (AAPC = -0.56%, 95%CI: -0.63% to -0.50%). In countries with high SDI, smoking experienced the most significant reduction in ASMR (AAPC = -0.78, 95%CI: -0.89% to -0.67%) from 1990 to 2021, and high BMI had the highest ASMR (2.54 per 100,000 people) in 2021 (Table 2).

Global disease burden prediction for KC to 2040

Using the BAPC model, we projected the global burden of KC for individuals aged 65 years and older from 2022 to 2040. The results suggest a continuing decline in the global burden of KC among both males and females, indicating a favorable trend (Fig. 5). The ASIR, ASPR, ASMR, and ASDR are estimated to fall to 22.52, 82.52, 11.81, and 192.15 per 100,000 people by 2040, respectively (Table S7 and S8). Specifically, by sex, the decline in males will be greater.

Discussion

To the best of our knowledge, this study represents the first comprehensive assessment of the burden for KC and associated risk factors in people aged 65 years and older from 1990 to 2021, along with projections through 2040. Our findings found that the ASIR for KC increased from 1990 to 2021, while the ASDR remained stable. Furthermore, the global burden of KC is projected to decline

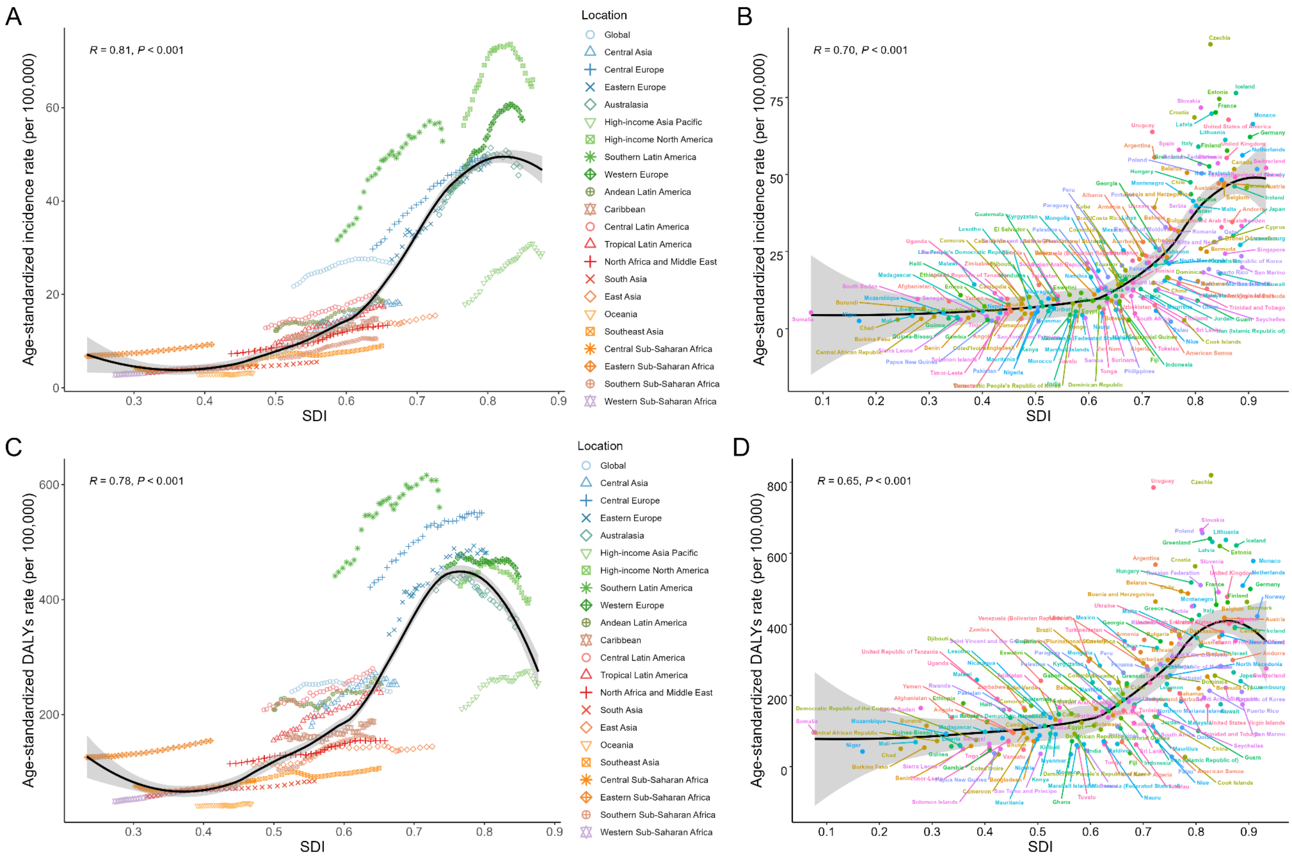

Fig. 4 Global, regional, and national levels of KC in people aged 65 years and older by SDI. (**A**) Age-standardized incidence from 1990 to 2021 at the global and 21 regions levels; (**B**) Age-standardized incidence in 2021 in 204 countries and territories; (**C**) Age-standardized DALYs from 1990 to 2021 at the global and 21 regions levels; (**D**) Age-standardized DALYs in 2021 in 204 countries and territories. For each region, points from left to right depict estimates from each year from 1990 to 2021. Expected trends based on SDI and disease age-standardized rates in all locations were shown as the black line. *KC* kidney cancer; *SDI* socio-demographic index; *DALYs* disability-adjusted life-years

through 2040. In the stratified analysis, the burden of KC was significantly higher in males than in females, with ASIR peaking in the 85 to 89 age group in 2021. The burden of KC is also more pronounced in countries with high SDI, with substantial inter-country variations. Moreover, our study showed a significant positive correlation between SDI values and KC burden. Our findings regarding the older population differ from those previously published in GBD 2019 concerning the general population's KC [26, 27]. The GBD 2019 results indicated that High-income North America had the most incident cases in 2019, and East Asia had the largest increase in ASMR between 1990 and 2019. In our study, Western Europe had the highest incident cases in 2021, and Tropical Latin America had the largest increase in ASMR for KC between 1990 and 2021. These findings contribute to a more comprehensive understanding of the increased global burden of KC by focusing on trends in older patients (≥ 65 years). These results hold significant implications for both health practice and future research.

From 1990 to 2021, the global ASIR, ASPR, and ASMR for people aged 65 years and older showed an upward trend, although ASDR remained largely unchanged. Much of the increase in incidence can be attributed to increased life expectancy and population growth [28], as KC is typically diagnosed in individuals aged 60 to 70 years [29]. In addition, over the past decades, advances and widespread use of abdominal cross-sectional imaging have also led to an increase in the number of incidental diagnoses of KC, which has resulted in an increase in the incidence [27, 30]. The shift from traditional to industrial diets, greater exposure to environmental pollutants, and lifestyle alterations such as reduced physical activity can all lead to an elevated risk of chronic kidney diseases, which in turn leads to the development of KC [31–33].

Our study revealed that across different age groups, the KC burden is consistently higher in males than in females. Smoking, alcohol consumption, obesity, and unhealthy lifestyle habits are known risk factors for the occurrence and progression of KC [34–36]. Males are generally exposed to these risk factors for a longer duration, making them more likely to develop KC. For example, the global smoking rate was estimated at 32.6% for males and 6.5% for females in 2020 [32]. Previous study

Table 2 Main risk factors for age-standardized DALYs and mortality of KC in people aged 65 years and older between 1990 and 2021, and their AAPC from 1990 to 2021

Risk factors by SDI	Age-standardized DALYs (per 100,000) (95% UI)		AAPC (95% CI)	*P* value	Age-standardized mortality (per 100,000) (95% UI)		AAPC (95% CI)	*P* value
	1990	2021			1990	2021		
Smoking								
Global	31.99 (19.71–45.97)	25.85 (15.12–37.81)	-0.69 (-0.75 to -0.63)	< 0.001	1.74 (1.05–2.52)	1.46 (0.83–2.17)	-0.56 (-0.63 to -0.50)	< 0.001
Low SDI	3.28 (1.85–4.87)	3.14 (1.75–4.74)	-0.11 (-0.20 to -0.03)	0.011	0.18 (0.10–0.27)	0.18 (0.10–0.27)	-0.09 (-0.24 to 0.06)	0.234
Low-middle SDI	6.87 (4.20–9.82)	7.42 (4.54–10.66)	0.30 (0.18 to 0.41)	< 0.001	0.38 (0.23–0.55)	0.42 (0.25–0.60)	0.30 (0.13 to 0.48)	0.001
Middle SDI	12.19 (7.76–17.03)	13.82 (8.44–19.58)	0.40 (0.12 to 0.67)	0.004	0.69 (0.44–0.97)	0.79 (0.48–1.12)	0.42 (0.15 to 0.70)	0.002
High-middle SDI	33.84 (21.14–47.72)	34.58 (20.93–49.10)	0.11 (-0.03 to 0.25)	0.128	1.79 (1.11–2.55)	1.86 (1.11–2.68)	0.18 (0.03 to 0.33)	0.022
High SDI	61.45 (37.20-89.04)	45.89 (25.77–70.68)	-0.96 (-1.08 to -0.84)	< 0.001	3.22 (1.92–4.73)	2.54 (1.39–3.98)	-0.78 (-0.89 to -0.67)	< 0.001
High body mass index								
Global	39.81 (15.45–65.10)	48.98 (19.67–79.56)	0.66 (0.60 to 0.72)	< 0.001	2.24 (0.87–3.68)	2.87 (1.14–4.69)	0.80 (0.70 to 0.90)	< 0.001
Low SDI	4.18 (1.54–6.79)	8.37 (2.95–14.08)	2.28 (2.23 to 2.33)	< 0.001	0.22 (0.08–0.36)	0.46 (0.16–0.77)	2.36 (2.26 to 2.46)	< 0.001
Low-middle SDI	5.20 (1.96–8.37)	13.11 (5.14–21.53)	3.05 (2.91 to 3.20)	< 0.001	0.29 (0.11–0.46)	0.72 (0.28–1.19)	3.04 (2.87 to 3.22)	< 0.001
Middle SDI	10.49 (4.00-17.11)	23.22 (9.36–38.57)	2.62 (2.57 to 2.67)	< 0.001	0.60 (0.23–0.98)	1.31 (0.53–2.19)	2.59 (2.54 to 2.65)	< 0.001
High-middle SDI	46.56 (18.16–76.15)	64.72 (25.82–104.70)	1.09 (0.89 to 1.29)	< 0.001	2.54 (0.98–4.16)	3.67 (1.45–5.97)	1.22 (1.04 to 1.40)	< 0.001
High SDI	76.21 (29.60-124.72)	88.99 (36.17-143.43)	0.48 (0.39 to 0.57)	< 0.001	4.16 (1.61–6.82)	5.11 (2.04–8.27)	0.65 (0.48 to 0.82)	< 0.001
Occupational exposure to trichloroethylene								
Global	0.05 (0.01–0.09)	0.08 (0.02–0.14)	1.73 (1.65 to 1.80)	< 0.001	0.002 (0.000-0.004)	0.004 (0.001–0.007)	1.74 (1.67 to 1.81)	< 0.001
Low SDI	0.02 (0.00-0.04)	0.03 (0.01–0.06)	1.58 (1.47 to 1.68)	< 0.001	0.001 (0.000-0.002)	0.002 (0.000-0.003)	1.64 (1.54 to 1.75)	< 0.001
Low-middle SDI	0.02 (0.00-0.04)	0.05 (0.01–0.08)	2.61 (2.50 to 2.72)	< 0.001	0.001 (0.000-0.002)	0.002 (0.000-0.004)	2.64 (2.54 to 2.75)	< 0.001
Middle SDI	0.04 (0.01–0.08)	0.09 (0.02–0.16)	2.32 (2.08 to 2.55)	< 0.001	0.002 (0.000-0.004)	0.004 (0.001–0.008)	2.32 (2.19 to 2.45)	< 0.001
High-middle SDI	0.05 (0.01–0.10)	0.10 (0.02–0.19)	2.05 (1.94 to 2.16)	< 0.001	0.002 (0.001–0.005)	0.005 (0.001–0.009)	2.04 (1.94 to 2.13)	< 0.001
High SDI	0.06 (0.01–0.11)	0.08 (0.02–0.14)	0.73 (0.60 to 0.86)	< 0.001	0.003 (0.001–0.005)	0.004 (0.001–0.007)	0.80 (0.67 to 0.93)	< 0.001

KC kidney cancer; *AAPC* average annual percentage change; *DALYs* disability-adjusted life years; *SDI* socio-demographic index

has also shown that males tend to have a higher BMI than females [3]. Additionally, industries with higher male participation may be more likely to expose individuals to occupational hazards associated with urinary cancer [37]. The report indicated that the occupational exposure to trichloroethylene of males is about twice that of females [38], and males also have a higher prevalence in jobs with such exposure [39].

We found that from 1990 to 2021, the ASIR and ASPR of KC increased across all age subgroups among people aged 65 years and older. The increase in urinary disorders with age is usually attributed to the accumulation of genetic mutations, hormonal changes, and lifestyle factors over time [16]. Over these decades, likely due to screening efforts, early diagnosis, and improved treatment and its availability, the 65 to 79 age groups saw a decline in ASDR and ASMR, indicating improved life expectancy in these populations. However, in the 80 years and older age groups, the ASDR and ASMR continued to increase, potentially due to mechanisms such as cellular aging, stress responses, and declines in immune function [9]. The heavy KC burden of older adults has significant social and economic implications worldwide,

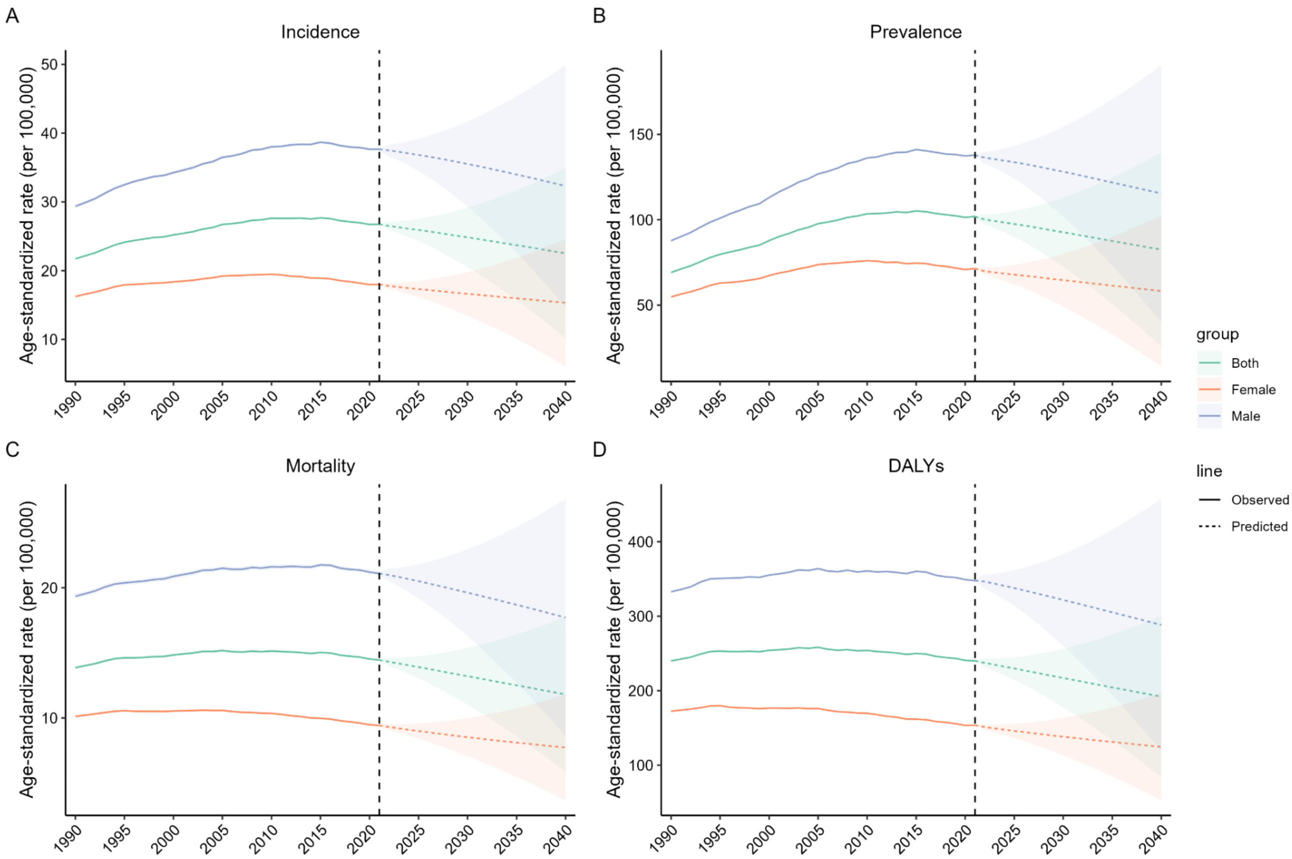

Fig. 5 The temporal trends of age-standardized rates of KC in people aged 65 years and older between 1990 and 2040 at the global level. (**A**) Age-standardized incidence; (**B**) Age-standardized prevalence; (**C**) Age-standardized mortality; (**D**) Age-standardized DALYs. The colorful shadow denotes the 95% highest density interval of prediction values. The predictive mean value is shown as a colorful dashed line. The vertical dashed line indicates where the prediction starts. *KC* kidney cancer; *DALYs* disability-adjusted life years

necessitating adaptive policies and strategies to ensure the well-being of older populations.

As countries become more developed, the burden of KC tends to increase. In 2021, High-income North America and Western Europe had the highest ASIR, while Southern Latin America and Central Europe had the highest ASDR. The disease burden of KC increased with the level of SDI, which highlights the impact of different SDI regions on disease prevention and management strategies. Although our study confirmed a positive correlation between SDI and KC burden, the association varied across levels of development. The burden of KC among older adults in High-income Asia Pacific was substantially lower than expected based on its SDI, while Southern Latin America showed a higher burden than expected, consistent with previous findings on trends in BMI [40]. Several factors may explain why countries with higher SDI experience a greater burden of KC. In developed countries with faster development and higher productivity, the prevalence of risk factors for KC, including smoking, obesity, hypertension, and physical inactivity, is generally higher [41]. Another explanation could be cross-sectional imaging techniques are more common in high SDI and high-income countries, which may lead to an increase in the incidental discovery of small kidney masses [42], with more than half of cases likely to be discovered incidentally according to the report [43]. Additionally, population aging, driven by increased life expectancy, is an important reason for the high incidence of KC in countries with high SDI.

At the national level, Czechia exhibited the highest ASIR and ASDR in 2021, possibly due to factors such as arsenic exposure, high prevalence of smoking and obesity [43]. This study found that while the ASIR of KC continued to rise in most countries, 12 countries, primarily in high SDI and high-middle SDI regions, showed a decrease in ASIR. In general, countries with high SDI values tend to have adequate medical resources, a higher willingness among the population to undergo routine medical examinations, and the support of relatively prosperous economic conditions and effective health promotion. These factors contribute to the decline in the burden of KC.

Between 1990 and 2021, smoking and high BMI were the main drivers of KC among people aged 65 years and older. Smoking significantly increases the risk of KC incidence and mortality [44]. Fortunately, "smoke-free" campaigns in some countries have led to a decline in smoking rates over the past decade [45, 46]. The decline was greater in high-income countries compared to low-income countries [32], which may explain our findings that the largest decreases in ASMR and ASDR of smoking-related KC were observed in high SDI region. Therefore, it is crucial to emphasize smoking cessation to the public as a means to reduce the burden of KC as much as possible. Countries with higher SDI tend to have a higher burden of KC caused by high BMI, which may be related to the higher proportion of overweight people in these countries [47]. From 1990 to 2021, the high BMI-related KC burden increased significantly in regions with lower SDI. This could be due to the gradual improvement of living conditions and the abundance of food supply over time, combined with a lack of awareness about the risks associated with high BMI in these regions [47]. Therefore, lifestyle management for individuals at high risk for KC, particularly maintaining a healthy weight through regular exercise and a balanced diet, is strongly recommended.

Since 2015, ASIR and ASPR of KC among people aged 65 years and older have declined, with a corresponding decline in ASDR and ASMR occurring a year later. This phenomenon can be attributed to heightened health consciousness and enhanced lifestyle practices, which have led to a degree of control over the risk factors associated with KC. In addition, recent advances in medical diagnostic technology have made it easier to diagnose KC at an earlier stage. Early diagnosis improves the possibility of timely intervention, which helps reduce mortality. We predict that this favorable trend will continue from 2022 to 2040 for both males and females.

Given the projected decline in burden by 2040, emphasis should be placed on sustaining advances in medical technology and lifestyle interventions, particularly in regions experiencing the highest current burden. To address the disparities in KC burden highlighted by the study, a multi-faceted approach is recommended. This includes improving healthcare access by strengthening medical infrastructure in low SDI region and optimizing resource allocation in high SDI region. Targeting males and high SDI region should be prioritized to reduce KC-specific risk factors and improve early detection and treatment [16]. The government should implement timely national obesity prevention and management to stop the increase of obesity and KC cases, carry out large-scale tobacco control interventions, such as increasing tobacco taxes, enhancing mass media campaigns and strengthening education [48], improving public awareness of KC risk factors and early symptoms, and promote regular screening for early detection. Finally, long-term planning and policy advocacy are needed to sustain the projected decline in KC burden by 2040 and address emerging risk factors.

Future research should explore more molecular mechanisms underlying gender disparities in KC, as understanding these biological differences could lead to more targeted and effective therapies. Additionally, studies are needed to evaluate the impact of emerging diagnostic technologies in low SDI settings, where resource limitations may affect their implementation and effectiveness. Further investigation into the role of environmental and occupational risk factors, particularly in rapidly industrializing regions, could help identify new prevention strategies. Finally, longitudinal studies tracking the long-term outcomes of lifestyle interventions and early detection programs are essential to refine global KC control strategies and ensure equitable health outcomes across diverse populations.

Our study acknowledges several limitations. First, the availability and completeness of data, particularly in low-income countries, may be insufficient, leading to differences in estimation accuracy. Second, despite the use of rigorous statistical methods, variations in health information systems and reporting mechanisms across regions may affect the accuracy of the results. For example, the potential underreporting of KC cases is due to sparse data and the absence of comprehensive cancer registries in most low- or middle-income countries, while the number of cases in high SDI countries is increased due to incidental diagnosis. Finally, there is typically a 3-year delay in data collection, which means trends in KC burden over the last three years may differ from our projections, leading to slight deviations in the subsequent forecasts.

Conclusions

In conclusion, the global ASIR of KC aged 65 years and older increased from 1990 to 2021, while the ASDR remained stable. The burden of KC is expected to decline through 2040. Overall, the burden of KC is higher in countries with high SDI, and among males. As population aging accelerates worldwide, it is critical to be aware of the increasing potential burden of KC. This study advocates urgent response strategies that focus on older populations and patients with KC, rationalize the allocation of health resources, and provide targeted guidelines to address disparities. Attributable risk factor analysis highlights smoking and high BMI as the leading factors to KC related DALYs and mortality among older adults. Policymakers must address the growing burden of KC by promoting healthy lifestyles, dietary habits, and reducing smoking to reduce future disease burden.

List of Abbreviations

KC	Kidney cancer
GBD	Global burden of disease
BMI	Body mass index
DALYs	Disability-adjusted life years
SDI	Socio-demographic index
UI	Uncertainty interval
ASIR	Age-standardized incidence rate
ASPR	Age-standardized prevalence rate
ASMR	Age-standardized mortality rate
ASDR	Age-standardized DALYs rate
APC	Annual percent change
AAPC	Average annual percentage change
CI	Confidence interval
BAPC	Bayesian age-period-cohort
ASR	Age-standardized rate

Supplementary Information

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Supplementary Material 1

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Author contributions
NZ, HJB, and ZYZ conceived the study. NZ accessed and acquired the raw data, performed the primary analysis, prepared tables and figures. NZ, HJB and ZYZ drafted the first manuscript and contributed to the interpretation of the data. BFY and HZ critically reviewed results and provided valuable inputs on revision. JBL and GPZ supervised the study and provided critical revisions and suggestions. All authors reviewed the article, read the final manuscript and approved the submission.

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Data availability
Data used in the analyses can be obtained from the Global Health Data Exchange Global Burden of Disease Results Tool (https://ghdx.healthdata.org/gbd-2021).

Declarations

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

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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