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Regional insights into the relationship between metabolic associated steatotic liver disease and chronic kidney disease: a socioeconomic perspective on disease correlation

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Abstract

Background Studies exploring the correlation between Metabolic Dysfunction-Associated Steatotic Liver Disease (MASLD) and the increased risk of chronic kidney disease (CKD) from a country-specific perspective have been limited. This study addresses regional variations and the role of the Socio-Demographic Index (SDI) in this relationship.

Methods This analysis integrates MASLD and country-level CKD data from the Global Burden of Disease study 2021. To evaluate the relationships between MASLD and CKD incidence, mixed-effects linear regression models that account for country-level random effects were employed. This analysis was adjusted for median age, percentage of males, SDI, and metabolic risk factors.

Results The incidence of MASLD and CKD demonstrated a similar regional distribution, with the highest of MASLD and CKD occurring in North Africa and the Middle East. After adjusting for age, gender, systolic blood pressure, fasting plasma glucose, body mass index, and SDI, a higher incidence of MASLD was associated with an increased incidence of CKD ($p < 0.001$), with MASLD incidence accounting for 53.0% of the explained variance in CKD incidence. Additionally, SDI, demographic variables (median age, population of male) and metabolic risks (High SBP, FPG and BMI), were responsible for 10.4%, 6.3%, and 30.3% of the explained variance in CKD incidence, respectively. Different patterns emerged in this association according to SDI status. In low SDI countries, significant associations were observed between increasing MASLD incidence rates and higher CKD incidence ($p = 0.007$), whereas in high SDI countries, no significant associations were found between MASLD and CKD incidence ($p = 0.106$).

Conclusions Our findings reveal a geographical correlation between MASLD and CKD incidence, contingent upon socioeconomic factors. To effectively mitigate the global burden of MASLD and CKD, it is imperative to design and implement targeted public health strategies that consider the unique socioeconomic contexts of each region, thus fostering equitable health outcomes.

Keywords Metabolic Dysfunction-Associated Steatotic Liver Disease, Chronic kidney disease, Mixed-effects linear regression, Socioeconomic development index

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Introduction

Metabolic dysfunction-associated steatotic liver disease (MASLD), which affects approximately one-third of the global population [1, 2], while chronic kidney disease (CKD) is estimated to impact a similar proportion of the 8 billion people worldwide [3]. Both conditions pose significant global health challenges. Regional variations in MASLD and CKD, particularly health inequities linked to geography and the socioeconomic development, have been identified in various studies [4, 5]. The prevalence of CKD is significantly higher among both the general population and high-risk groups in low- and middle-income countries [6]. A significant portion of the burden of CKD, amounting to 63%, can be attributed to these regions [7]. Moreover, Danpanichkul et al. have reported an increasing burden of MASLD in low-income and lower-middle-income countries [4]. The lack of resources and inadequate political will to effectively address MASLD and CKD in these areas is particularly concerning. A global study revealed that approximately one-third of countries lack public policies against MASLD, indicating that their preparedness index score is zero [8, 9].

An expanding body of evidence supports the association between MASLD and an elevated risk of CKD [10–12]. However, no studies have investigated this correlation from a country-specific perspective. Our research emphasizes the Socioeconomic Development Index (SDI) as a critical metric of socioeconomic inequality, encompassing a comprehensive assessment of health, education, and income levels [13]. Given the regional variations in MASLD and CKD prevalence, along with health inequities related to the SDI, we hypothesize that the association between MASLD and CKD differs across countries with varying SDI levels, influenced by factors such as genetic background, disparities in kidney care, pollution, urbanization, and lifestyle changes. In this study, we employ ecological analyses to evaluate the global associations between MASLD and CKD at the national level. We aim to investigate cross-country health inequalities and examine the interactions between the SDI and the association between MASLD and CKD. By emphasizing the role of socioeconomic factors, our research aims to provide new insights into the complex relationship between MASLD and CKD across various regions of the globe, thereby informing public health initiatives and policy interventions.

Materials and methods

Study design and data sources

This study examined the correlation between the incidence of MASLD and CKD. For the purpose of this analysis, we utilized two different data sources. Country-level data on the proportion of males and the seven Global Burden of Disease (GBD) super regions were obtained from the 2021 GBD study. Detailed methodologies employed in the GBD analysis can be found in previously published works [2, 5, 13, 14]. In this analysis, we utilized the SDI as a measure of socioeconomic development, where higher values denote a greater degree of development [15]. Furthermore, we analyzed the summary exposure values of metabolic risk factors, which quantify cumulative exposure to various metabolic risks; higher values for each component indicate a greater impact on public health [16]. In addition to the GBD data, median age information for each country was obtained from the Central Intelligence Agency (CIA) [17].

Definition

CKD was defined as an estimated glomerular filtration rate (eGFR) of less than 60 ml/min/1.73 m2or an albumin-to-creatinine ratio exceeding 30 mg/g. This definition encompassed individuals with end-stage kidney disease who are undergoing dialysis or have received a kidney transplant [18]. The GBD 2021 re-extracted data from the European Dialysis and Transplant Association and the European Renal Association for the years 1998–2017. A new feature of GBD 2021 was the sex-split data by super-region for the dialysis, transplant, stage 3–5, stage 3, and stage 4 models. The global sex coefficient was employed by GBD 2021 to sex-split the data for the CKD stage 1–2 and CKD stage 5 models. MASLD was mapped to the term "total burden related to non-alcoholic fatty liver disease (NAFLD)" in the GBD 2021 framework [19]. This aggregate cause includes NAFLD, represented by the International Classification of Diseases (ICD-10) codes K75.81 and K76.0, which cover both steatotic and steatohepatitic forms of non-alcoholic metabolic liver disease [18–20]. The GBD conducted a systematic literature review that included studies utilizing ultrasound or other diagnostic imaging methods for diagnosis. Additionally, the review considered the proportion of the general population consuming less than 70 g of alcohol per week for females and less than 140 g for males to adjust the reported year-age-sex and location-specific prevalence rates to accurately reflect the prevalence of NAFLD in the general population [21]. The GBD 2021 included 11 new case series studies to improve the assessment of the aetiological fraction of cirrhosis [18].

Statistical analysis

The estimates released by the GBD 2021 were based on the average of 500 draws from the distribution of estimates, with 95% uncertainty intervals (UIs) calculated using the 2.5th and 97.5th percentile values, respectively. Mixed-effects linear regression (MELR) models were utilized to evaluate the associations between the incidence

of MASLD and CKD at the country level. This analysis was adjusted for median age, percentage of males, SDI, and metabolic risk factors, including high systolic blood pressure (SBP), body mass index (BMI), and fasting plasma glucose (FPG). MELR is particularly well-suited for this study due to its ability to account for both random effects, which capture country-specific variances, and fixed effects, which model general patterns. To account for heterogeneity among various countries and regions, we incorporated these as random effects. This approach enhances the robustness of our conclusions while effectively addressing national disparities [2, 22]. To determine the suitability of incorporating random effects, we assessed the fit of our MELR models both with and without these effects, utilizing the Akaike Information Criterion (AIC). The variance explained by the MELR was represented as (R^2) marginal (variance accounted for by the fixed effects) and (R^2) conditional (variance accounted for by the fixed effects and random effects) [23]. The glmm.hp package was utilized to compute the (R^2) values of MELR models. In the subgroup analysis, countries were categorized as high SDI (socioeconomically developed—above the median SDI) and low SDI (socioeconomically less developed).

The autoregressive integrated moving average (ARIMA) model is frequently employed in epidemiological and demographic studies to forecast trends by analyzing time series of historical data [24]. To select an appropriate model, the auto.arima() function from the forecast package was utilized. Quantile–Quantile (Q-Q), Autocorrelation Function (ACF), and Partial Autocorrelation Function (PACF) plots were employed to assess the residuals for normality. The model's residuals were verified as white noise using the Ljung-Box test. We fitted a Lorenz concentration curve to the observed cumulative relative distribution of populations, which were sorted based on their SDI and disease prevalence. This step involved calculating the cumulative incidence rates of CKD and MASLD across different SDI levels, thereby allowing us to visualize and understand the distribution of disease incidence relative to socioeconomic status. To quantify health inequalities, we numerically integrated the area under the Lorenz curve. This area represents the degree of inequality in health outcomes, allowing us to derive the health inequality concentration index. A concentration index value closer to zero indicates a more equitable distribution of health outcomes, while values approaching one signify substantial disparities. This illustrates how incidence rates are disproportionately influenced by socioeconomic factors, emphasizing the need to address these inequalities to improve overall public health [25]. Statistical significance was assessed using a two-sided p-value of less than 0.05. Data analysis was performed between September 1 and October 30, 2024, utilizing R version 4.4.1.

Results

Age-standardized incidence rates of CKD and MASLD

Globally, the age-standardized incidence rate of CKD per 100,000 population increased from 192.16 (95% UI: 178.69, 207.34) in 1990 to 233.56 (95% UI: 220.02, 247.24) in 2021 (Table 1). The number of new CKD cases rose from 7,790,705 (95% UI: 7,226,165, 8,402,568) in 1990 to 19,935,038 (95% UI: 18,702,793, 21,170,794) in 2021 (Supplementary Fig. 1). Similarly, the age-standardized incidence rate of MASLD per 100,000 population rose from 475.54 (95% UI: 432.59, 518.19) in 1990 to 593.28 (95% UI: 542.72, 643.70) in 2021 (Table 1). The number of new MASLD cases also increased, rising from 24,856,159 (95% UI: 22,579,697, 27,333,110) in 1990 to 48,353,272 (95% UI: 44,229,139, 52,358,017) in 2021 (Supplementary Fig. 1). In various GBD regions, both MASLD and CKD demonstrated an increase in age-standardized incidence rates over the same period (Table 1).

Age-standardized mortality and DALY Rates for CKD and MASLD

Additionally, the age-standardized mortality rate of CKD per 100,000 population increased from 14.86 (95% UI: 13.64, 16.38) in 1990 to 18.50 (95% UI: 16.72, 19.85) in 2021 (Table 1). Similarly, the age-standardized mortality rate of MASLD per 100,000 population rose from 1.53 (95% UI: 1.17, 1.97) in 1990 to 1.62 (95% UI: 1.27, 2.02) in 2021 (Table 1). Globally, the age-standardized DALY rate of CKD per 100,000 population increased from 479.85 (95% UI: 439.18, 523.79) in 1990 to 529.62 (95% UI: 486.25, 577.42) in 2021 (Table 1). Similarly, the age-standardized DALY rate of MASLD per 100,000 population rose from 40.20 (95% UI: 30.73, 52.23) in 1990 to 42.40 (95% UI: 33.60, 53.31) in 2021 (Table 1). The trend of age-standardized DALY rates exhibited variations across different GBD regions, particularly in high SDI and high-middle SDI regions (Table 1). Descriptive information regarding the epidemiological indices of MASLD and CKD across various socioeconomic indices is presented in Table 1.

Predicted age-standardized incidence rates of MASLD and CKD

The age-standardized incidence rate of CKD was predicted to increase by 3.6% between 2021 and 2031, reaching an estimated age-standardized incidence rate of 242.03 per 100,000 population in 2031(Supplementary Fig. 2A).The number of new CKD cases was expected to rise by 11.4% during the same period, resulting in approximately 22,210,614 new cases in

Table 1 Global and regional incidence, mortality, and DALYs of CKD and MASLD

Location	Measure	Chronic kidney disease		Metabolic dysfunction-associated steatotic liver disease (MASLD)	
		Age-standardized rate (1990)	Age-standardized rate (2021)	Age-standardized rate (1990)	Age-standardized rate (2021)
Global	Incidence	192.16 (178.69, 207.34)	233.56 (220.02, 247.24)	475.54 (432.59, 518.19)	593.28 (542.72, 643.70)
	Mortality	14.86 (13.64, 16.38)	18.50(16.72, 19.85)	1.53 (1.17, 1.97)	1.62 (1.27, 2.02)
	DALYs	479.85 (439.18, 523.79)	529.62 (486.25, 577.42)	40.20 (30.73, 52.23)	42.40 (33.60, 53.31)
Low SDI	Incidence	121.74 (112.82, 132.30)	155.00 (143.40, 167.34)	483.42 (440.22, 527.63)	553.74 (503.53, 605.08)
	Mortality	29.72 (26.31, 34.62)	29.43 (26.13, 33.80)	1.89 (1.34, 2.67)	1.74 (1.34, 2.23)
	DALYs	853.95 (760.14, 971.76)	791.80 (704.14, 909.10)	47.45 (34.47, 64.59)	42.89 (33.61, 55.57)
Low-middle SDI	Incidence	153.07 (141.43,166.40)	204.97 (189.81, 220.30)	520.74 (474.21, 566.64)	623.22 (569.62,676.23)
	Mortality	18.59 (16.43, 22.23)	23.08 (20.97, 26.31)	1.69 (1.21, 2.43)	1.87 (1.39, 2.41)
	DALYs	609.44 (545.07, 686.29)	686.98 (622.51, 765.20)	41.94 (30.32, 58.47)	47.65 (35.77, 61.75)
Middle SDI	Incidence	171.16 (157.68, 185.82)	232.96 (219.53, 246.12)	533.69 (485.35, 580.65)	656.97 (602.08, 712.86)
	Mortality	19.07 (17.39, 21.35)	20.89 (18.45, 22.67)	1.63 (1.25, 2.11)	1.78 (1.39, 2.21)
	DALYs	585.56 (531.8, 652.64)	596.45 (540.33, 650.48)	42.14 (32.23, 54.23)	45.53 (36.02, 56.74)
High-middle SDI	Incidence	160.44 (148.12, 174.09)	205.90 (194.10, 218.61)	478.36 (435.28, 522.10)	611.29 (557.97, 665.56)
	Mortality	11.36 (10.43, 12.65)	12.02 (10.68, 13.38)	1.47 (1.12, 1.86)	1.40 (1.09, 1.76)
	DALYs	360.84 (325.48, 401.54)	324.64 (293.58, 360.92)	37.79 (28.89, 48.32)	38.00 (29.71, 48.17)
High SDI	Incidence	252.30 (234.15, 272.41)	277.75 (260.70, 295.01)	342.72 (312.23, 373.46)	450.03 (412.20, 488.43)
	Mortality	9.22 (8.45, 9.62)	14.12 (12.30, 15.21)	1.43 (1.09, 1.84)	1.48 (1.15, 1.85)
	DALYs	277.64 (250.03, 303.24)	358.51 (324.74, 390.20)	38.39 (29.45, 49.78)	38.73 (30.51, 48.83)
High-income	Incidence	255.64 (236.68, 276.28)	274.77 (256.64, 293.20)	319.10 (290.57, 347.31)	385.98 (353.50, 418.49)
	Mortality	9.60 (8.74, 10.01)	13.92 (12.01, 15.07)	1.69 (1.28, 2.19)	1.51 (1.17, 1.90)
	DALYs	273.83 (246.67, 298.78)	337.23 (303.27, 367.67)	45.10 (34.19, 58.08)	39.01 (30.74, 48.82)
Central Europe, Eastern Europe, and Central Asia	Incidence	117.11 (107.87, 127.53)	198.15 (184.85, 212.14)	436.15 (399.70, 472.99)	506.16 (464.57, 549.08)
	Mortality	5.89 (5.68, 6.12)	7.76 (7.18, 8.42)	1.19 (0.89, 1.56)	2.41 (1.79, 3.17)
	DALYs	263.00 (237.20, 289.34)	278.71 (248.72, 313.99)	33.39 (24.91, 44.59)	77.38 (56.51, 104.92)
Latin America and Caribbean	Incidence	218.35 (201.94, 237.81)	326.68 (309.06, 344.40)	557.70 (510.43, 606.26)	645.85 (594.14, 700.24)
	Mortality	22.88 (21.82, 23.80)	30.72 (28.13, 33.50)	2.86 (2.09, 3.75)	3.41 (2.55, 4.42)
	DALYs	659.07 (623.93, 698.66)	836.80 (766.70, 916.03)	78.28 (56.68, 103.79)	92.88 (69.10, 121.33)
North Africa and Middle East	Incidence	255.33 (235.33, 278.00)	411.19 (385.40, 438.45)	849.02 (777.99, 920.82)	1037.64 (963.01, 1109.65)
	Mortality	31.22 (25.48, 47.04)	37.71 (32.73, 42.39)	2.64 (1.74, 4.06)	2.70 (1.93, 3.68)
	DALYs	759.90 (642.73, 1059.21)	846.64 (747.18, 948.02)	53.96 (37.45, 78.19)	58.97 (43.63, 79.78)
South Asia	Incidence	146.23 (134.74, 158.66)	177.65 (164.06, 192.03)	464.89 (421.18, 507.16)	564.19 (513.27, 615.45)
	Mortality	13.98 (12.14, 15.90)	16.45 (14.03, 19.25)	1.10 (0.78, 1.57)	1.30 (0.94, 1.73)
	DALYs	509.78 (449.63, 573.28)	540.57 (473.83, 620.42)	30.47 (21.52, 43.06)	33.75 (24.71, 44.57)
Southeast Asia, East Asia, and Oceania	Incidence	151.00 (138.33, 164.70)	184.99 (174.05, 195.93)	507.44 (461.04, 553.39)	621.12 (565.79, 677.03)
	Mortality	16.39 (14.67, 19.12)	15.28 (13.29, 17.22)	1.18 (0.90, 1.53)	1.07 (0.83, 1.32)
	DALYs	531.84 (476.56, 599.31)	462.97 (411.39, 515.98)	30.72 (23.39, 39.45)	26.37 (20.97, 32.30)
Sub-Saharan Africa	Incidence	121.56 (112.57, 131.78)	158.99 (146.90, 171.71)	497.70 (452.88, 543.97)	557.57 (507.44, 607.74)
	Mortality	35.84 (31.66, 40.72)	38.28 (34.69, 43.07)	2.39 (1.67, 3.43)	2.52 (1.96, 3.24)
	DALYs	974.40 (867.16, 1090.91)	957.14 (856.36, 1089.31)	58.82 (42.49, 81.47)	60.83 (47.08, 79.13)

2031 (Supplementary Fig. 2B). Similarly, the age-standardized incidence rate of MASLD was predicted to increase by 5.4% between 2021 and 2031, reaching an estimated age-standardized incidence rate of 625.29 per 100,000 population in 2031 (Supplementary Fig. 2A). The number of new MASLD cases was projected to increase by 16.1% over the same period, leading to approximately 56,133,126 new cases in 2031 (Supplementary Fig. 2B). Both males and females were projected to exhibit similar increasing trends in MASLD and CKD during the predicted period from 2021 to 2031 (Supplementary Fig. 2).

Cross-country health inequality in MASLD and CKD

Variations in age-standardized incidence rates and DALYs for MASLD and CKD among different countries were observed. Nevertheless, a relative similarity in trends between MASLD and CKD across countries was also noted (Fig. 1). At the national level, the age-standardized incidence rate of CKD ranged from 106.71 (95% UI: 97.77, 116.52) in the Republic of Uganda to 495.83 (95% UI: 465.09, 529.64) in the Kingdom of Saudi Arabia (Fig. 1A). In 2021, North Africa and the Middle East exhibited the highest age-standardized incidence rates of CKD and MASLD among the GBD regions (Table 1). The age-standardized incidence rate of MASLD ranged from 310.17 (95% UI: 284.58, 338.28) in the Republic of Finland to 1,188.57 (95% UI: 1,107.18, 1,268.67) in the Arab Republic of Egypt (Fig. 1B). The Lorenz curve analysis revealed significant socioeconomic disparities in the incidence rates of CKD and MASLD. In 2021, the concentration index for CKD incidence rates was 0.32 (95% CI: 0.31, 0.33) (Fig. 2), indicating a marked inequality in the distribution of CKD among different SDI levels. Similarly, the concentration index for MASLD was 0.27 (95% CI: 0.27, 0.28) (Fig. 2). These findings indicated that a higher burden of CKD and MASLD is disproportionately concentrated in countries with middle to high SDI levels, indicating critical areas for potential public health intervention and resource allocation.

Associations of MASLD and CKD using MELR models

Our adjusted models demonstrated significant associations between increasing incidence rates of MASLD and higher incidence rates of CKD ($\beta = 0.130$, SE = 0.036, $p < 0.001$). Furthermore, the increasing incidence rates of CKD were found to be associated with an elevated median age ($\beta = 1.330$, SE = 0.649, $p = 0.042$), higher SBP ($\beta = 0.092$, SE = 0.043, $p = 0.033$), and higher BMI ($\beta = 0.231$, SE = 0.068, $p < 0.001$) (Table 2). With a marginal R^2 of 0.40 and a conditional R^2 of 0.80, MASLD incidence was responsible for 53.0% of the explained variance in CKD incidence. Additionally, SDI, demographic variables (median age, population of male) and metabolic risks (High SBP, FPG and BMI), were responsible for 10.4%, 6.3%, and 30.3% of the explained variance in CKD incidence, respectively (Fig. 3).

Given the interaction effects between CKD incidence and the SDI, we subsequently conducted subgroup analyses based on SDI levels using MELR models with country-level random effects. In low SDI countries, significant associations were observed between increasing incidence rates of MASLD and higher incidence rates of CKD ($\beta = 0.129$, SE = 0.047, $p = 0.007$) (Table 2). In contrast, in high SDI countries, no significant associations were found between increasing incidence rates of MASLD and incidence rates of CKD ($\beta = 0.100$, SE = 0.060, $p = 0.106$) (Table 2).

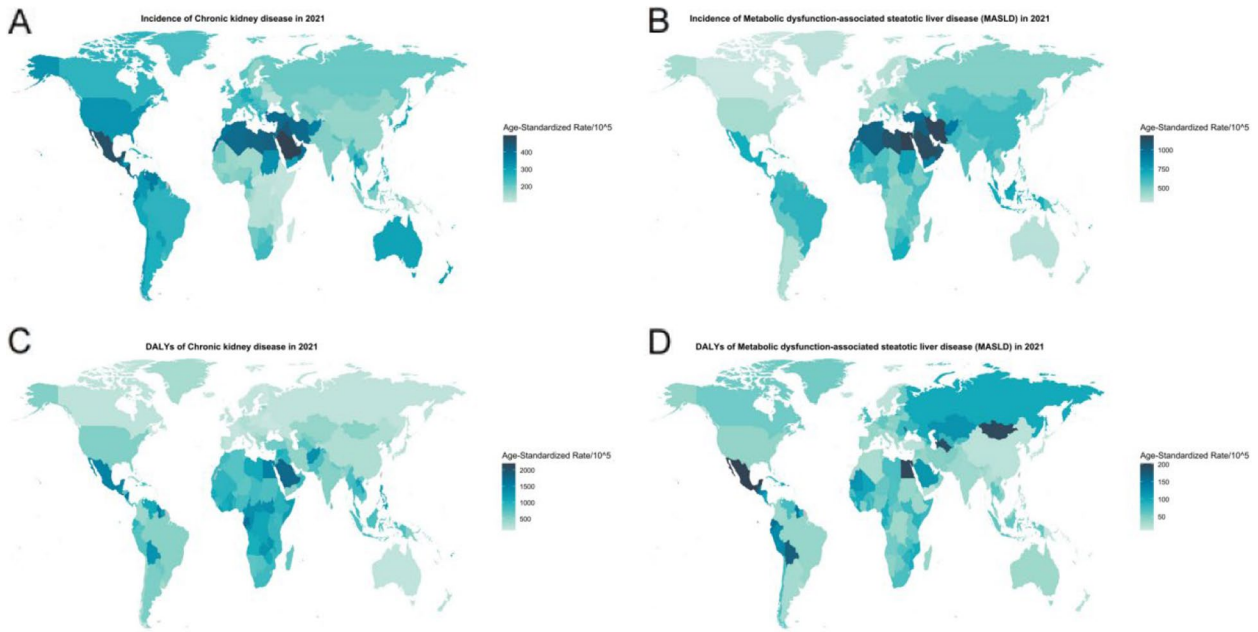

Fig. 1 Global heat map of incidence and DALYs of CKD and MASLD in 2021

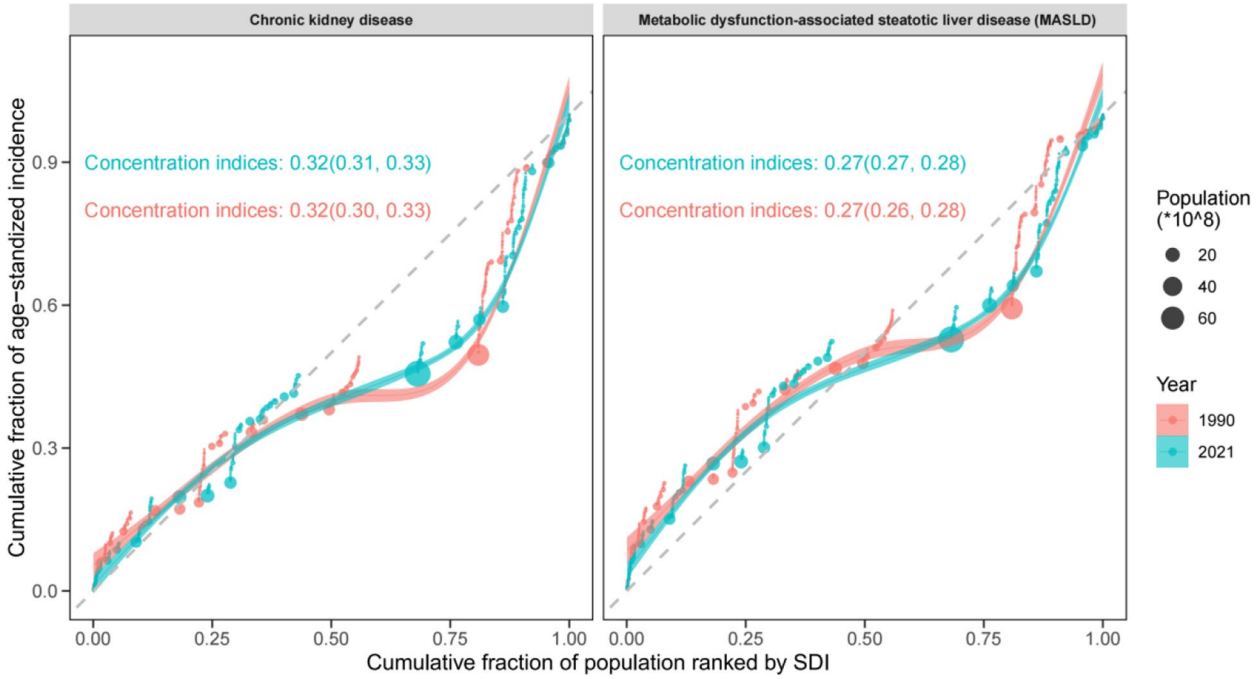

Fig. 2 Lorenz curves illustrating the relationship between incidence rates of CKD and MASLD (per 100,000 people) and the Socio-Demographic Index (SDI) for various countries in the years 1990 and 2021. The curves represent the distribution of CKD and MASLD incidence across different SDI levels. The line of equality (diagonal line) represents an ideal scenario where incidence rates are evenly distributed among different socio-demographic levels. The area between the Lorenz curve and this line indicates the degree of inequality in the incidence of CKD and MASLD—greater areas signify larger disparities. Additionally, the concentration indices shown on the figure quantitatively represent this inequality. Values closer to zero indicate a more equitable distribution across SDI levels, while higher values suggest a significant disparity, where countries with lower SDI levels may face a disproportionately higher burden of CKD and MASLD

Table 2 Associations of risk factors with CKD incidence at the country level using MELR model

	ALL countries			Low SDI countries			High SDI countries		
Characteristic	**Estimate (β)**	**SE**	***p* value**	**Estimate**	**SE**	***p* value**	**Estimate**	**SE**	***p* value**
MASLD incidence	0.130	0.036	P < 0.001	0.129	0.047	0.007	0.100	0.060	0.106
SDI	61.381	36.476	0.094	8.872	43.884	0.840	47.901	93.564	0.610
Demographic									
Median age	1.330	0.649	0.042	1.096	1.116	0.329	0.478	0.960	0.620
Population male	65.324	100.280	0.516	14.033	198.165	0.944	140.22	148.953	0.349
Metabolic risk									
High SBP	0.092	0.043	0.033	0.067	0.049	0.173	0.164	0.080	0.044
High FPG	−0.061	0.032	0.055	−0.103	0.035	0.004	0.051	0.068	0.448
High BMI	0.231	0.068	P < 0.001	0.307	0.074	P < 0.001	−0.0006	0.145	0.997

MASLD metabolic dysfunction-associated steatotic liver disease, *SBP* systolic blood pressure, *FPG* fasting plasma glucose, *BMI* body mass index

Statistical significance was determined as *p* value < 0.05

Discussion

This study provides a comprehensive analysis of the epidemiology and correlation between MASLD and CKD. To the best of our knowledge, this is the first study to address the association of the MASLD and CKD from the perspective of worldwide and it has yielded several findings that deserve attention from health policymakers and researchers. Our analysis from 1990 to 2021 revealed a significant global increase in the burden of MASLD and CKD, with projections indicating a concerning rise in new cases over the next decade. Furthermore, our examination of GBD data identified a correlation

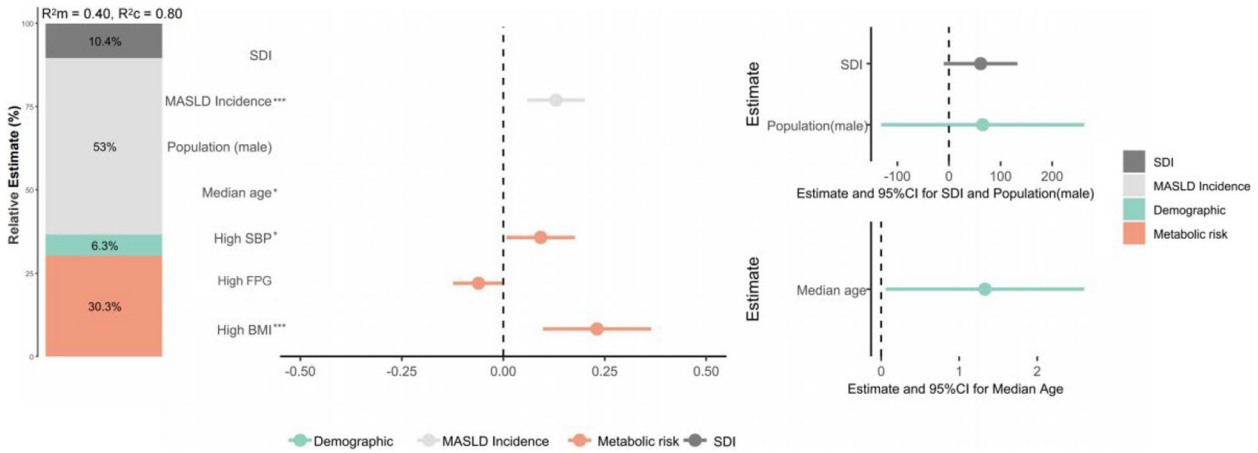

Fig. 3 Associations between the incidence of MASLD and CKD at the country level. The analysis employed mixed-effects linear regression models that included country-level random effects. Adjustments were made for median age, percentage of male population, systolic blood pressure (SBP), fasting plasma glucose (FPG), body mass index (BMI), and the Sociodemographic Index (SDI)

between higher incidences of MASLD and CKD, as well as a notable interaction effect between MASLD and CKD incidence concerning the SDI of the countries studied, suggesting that socioeconomic factors may influence this relationship. These findings carry important implications for policymakers confronting the global challenges posed by MASLD and CKD.

The significant rise in the age-standardized incidence rates of MASLD and CKD from 1990 to 2021 suggests a growing prevalence likely linked to several interrelated factors. One potential reason for this increase could be the global rise in risk factors associated with both diseases, including obesity, hypertension, and diabetes, all of which are known to directly influence renal and hepatic health [26–29]. As these trends continue, it is crucial to consider their implications for global health strategies, including the UN Sustainable Development Goals (SDGs), particularly Goal 3, which promotes better health and well-being, and Goal 10, which aims to reduce health inequalities. The rising incidence rates of MASLD and CKD underscore the necessity for initiatives that enhance health outcomes and address the social determinants of health, especially among underserved populations. Implementing integrated public health strategies focused on preventing and managing risk factors—such as promoting healthy lifestyles, improving access to healthcare, and increasing awareness about obesity, hypertension, and diabetes—will be vital for addressing the challenges presented by MASLD and CKD.

We observed a disparity in the incidence of MASLD and CKD across countries with varying SDI. Younossi et al. [30] conducted an analysis indicating that the prevalence of MASLD among individuals with Type 2 Diabetes in the Middle East and North Africa reached as high as 77.3%. This prevalence is significantly higher than that reported in global assessments [30]. Genetic variances among populations can result in differing susceptibilities to these diseases. Patients with MASLD bearing the PNPLA3 mutation genotype are at an elevated risk of renal impairment, as demonstrated by declines in eGFR and increased urinary protein levels [31, 32]. The PNPLA3 gene significantly influences susceptibility to MASLD in patients of Turkish descent [33]. Moreover, disparities in air pollution exposure related to varying socio-economic statuses and geographic regions can profoundly affect the onset and progression of MASLD and CKD [34–36]. Countries in North Africa and the Middle East exhibit some of the highest death rates worldwide attributable to air pollution exposure [37]. These findings have significant implications for policymakers regarding the implementation of genetic screening programs and early identification systems aimed at facilitating personalized healthcare strategies. Additionally, there is a need to enhance access to health resources for at-risk populations by increasing the availability of lifestyle modification programs and preventive healthcare services.

Numerous population-based studies have confirmed the association between MASLD and CKD [38, 39]. Our national-level analysis further corroborated the relationship between the increasing incidence of MASLD and CKD after controlling for demographic and metabolic factors. Notably, 53.0% of the variance in CKD incidence can be attributed to MASLD incidence. The SDI, demographic variables (median age and male population percentage), and metabolic risks (high SBP, FPG, and BMI) accounted for 10.4%, 6.3%, and 30.3% of the explained variance in CKD incidence, respectively. Residual confounding is likely the primary explanation for the

substantial unexplained variance, as the confounding factors considered at the country level were limited. Furthermore, the impact of MASLD is greater than that of these other factors, underscoring its critical role in the pathogenesis of CKD. Attention should be given to the relative size of this effect, especially when compared to other included factors, as there is no guarantee that the model captures all relevant variables. This consideration is particularly important in national-level studies, where many individual-level data points cannot be incorporated into the analysis.

MASLD can induce kidney injury through various biological pathways, including increased cytokine release, which leads to systemic inflammation and oxidative stress [40]. Additionally, components of the renin–angiotensin–aldosterone system (RAAS) derived from adipocytes stimulate the production of pro-inflammatory factors and contribute to insulin resistance. This condition can cause direct kidney damage and indirectly affect renal function by promoting atherosclerotic dyslipidemia [40]. The theory of the "gut-liver-kidney axis" has garnered significant attention. On the one hand, excessive caloric intake resulting from an imbalanced diet can disrupt intestinal flora, elevate levels of Gram-negative bacteria, lipopolysaccharides, nephrotoxins, and secondary bile acids, thereby promoting the onset and progression of both MASLD and CKD [41–43]. Conversely, short-chain fatty acids in the gut, such as acetic acid, sodium butyrate, and propionic acid, play a crucial role in energy provision and blood pressure regulation. These fatty acids are involved in liver fat synthesis, gluconeogenesis, and inflammatory responses. Reduced levels of short-chain fatty acids may lead to liver and kidney impairments, elevated blood pressure, and further deterioration of kidney function [41–43].

Furthermore, our subgroup analyses revealed that in low SDI countries, there was a significant positive association between increasing CKD incidence rates and higher MASLD incidence rates. Conversely, in high SDI countries, no significant correlation was observed. The findings suggested that the socioeconomic context played a critical role in the relationship between MASLD and CKD. In low SDI countries, several factors may contribute to the observed association. Firstly, access to healthcare services and disease management may be more limited in these regions. The 2023 Global Kidney Health Atlas reveals significant disparities in kidney care worldwide, with marked deficiencies identified by the World Health Organization across all health sectors, particularly in low-income and lower-middle-income countries [44–46]. Additionally, high pollution levels may exacerbate the burden on the kidneys, while a lack of medical resources in low-income countries can hinder adequate early diagnosis and treatment [16, 36, 47]. Alterations in the regulation and trafficking of essential minerals, such as calcium, phosphorus, and magnesium, may contribute to adverse kidney outcomes [48]. In countries with low SDI, where dietary deficiencies and limited healthcare access are prevalent, these mineral imbalances can be exacerbated, further complicating the management of both MASLD and CKD [49]. Understanding how mineral dysregulation interacts with these diseases could offer new insights into their pathophysiology and underscore the necessity for targeted interventions tailored to the distinct challenges encountered in various SDI contexts.

In countries with a high SDI, the lack of a significant association between MASLD and CKD incidence rates may be attributed to several factors. The nonsignificant outcomes might reflect either residual confounding or a genuine lack of association between MASLD incidence and CKD in countries with high SDI. Advanced healthcare systems and improved access to medical care facilitate better management and early detection of both conditions [44, 50, 51]. In these settings, patients with MASLD may receive proactive treatment that mitigates the risk of developing CKD, such as lifestyle counseling, diabetes management, and regular monitoring of liver function. It is also essential to consider that high SDI countries often have effective public health policies aimed at curbing obesity and promoting healthy lifestyle choices [52, 53]. These initiatives may reduce the overall incidence of metabolic disorders, thereby lowering the potential interaction between MASLD and CKD. However, as patient demographics and healthcare access continue to evolve in high SDI countries, future studies should continuously monitor these relationships to identify any emerging trends or shifts. The interrelationship between CKD and MASLD in this context emphasizes the necessity of integrated healthcare approaches to address these interconnected diseases.

The present study acknowledges several limitations. Firstly, the cross-sectional design limits the capacity to make causal inferences about the associations between the incidence of MASLD and CKD. Interpretations at the national level should be made cautiously to avoid ecological fallacy, a logical error that attributes group characteristics to individuals. This caution is imperative because the data utilized is aggregated at the country level rather than at the individual level. While we recognize the value of exploring regional nuances, our current model structure does not allow for further incorporation of random effects when analyzing these subgroup divisions. Furthermore, residual confounding remains a significant concern that may contribute to the substantial unexplained variance, potentially more so than the direct effects of MASLD, due to the limited

covariates at the country level included in this study. Additionally, variability in the diagnostic criteria for MASLD across regions may introduce potential biases in our findings. The reliance on the previous definition of NAFLD instead of the updated concept of MASLD represents another significant limitation that may undermine the precision and applicability of published findings. Nevertheless, recent data demonstrate strong concordance between NAFLD and MASLD despite definitional discrepancies, suggesting that the recent nomenclature changes have had minimal impact on the study's outcomes [54].

Conclusion

In summary, the increasing incidence rates of MASLD and CKD underscore the urgent need for targeted public health interventions that address both the socioeconomic and metabolic determinants of health. The relationship between MASLD and CKD is influenced by socioeconomic factors, which appear to modulate the interaction effects observed in our study. These findings highlight the necessity for customized public health strategies that tackle the unique challenges faced by different SDI groups. Further research is essential to elucidate the underlying mechanisms of these associations and their implications for clinical practice and public health policy.

Supplementary Information

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Supplementary Material 1

Supplementary Material 2

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Authors' contributions
Author Contributions: Jiang Bai have full access to all of the data in the study and take responsibility for the integrity of the data and the accuracy of the data analysis. Concept and design: Jiang Bai, Lijuan Zhang. Acquisition, analysis, or interpretation of data: Mingyan Zhang, Yifan Hao, Zhen Yi. Drafting of the manuscript: Jiang Bai, Lijuan Zhang. Critical review of the manuscript for important intellectual content: Mingyan Zhang, Yifan Hao, Zhen Yi Statistical analysis: Jiang Bai. Obtained funding: No Administrative, technical, or material support: Yun Zhou. Supervision: Yun Zhou.

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Data availability
The data sets from this study are available at https://vizhub.healthdata.org/gbd-results/. The comprehensive data set creation plan and underlying analytic code can be obtained from the first author, Jiang Bai, upon request.

Declarations

Ethics approval and consent to participate
Ethical approval was not required for this study in accordance with local/national guidelines. Written informed consent to participate in the study was not required in accordance with local/national guidelines. This study does not involve sensitive personal data, ethical issues, or breaches of policy.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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