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The global burden of childhood diarrheal diseases attributable to suboptimal breastfeeding from 1990 to 2021: an exploratory analysis of estimates from the global burden of disease study

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Abstract

Background Understanding the spatial and temporal patterns of the disease burden of childhood diarrhea attributable to suboptimal breastfeeding (including non-exclusive and discontinued breastfeeding) is crucial for global health policy and intervention strategies. This study aimed to comprehensively assess the global, regional, and national burden of childhood diarrheal diseases attributable to suboptimal breastfeeding in 204 countries and territories from 1990 to 2021.

Methods This study utilized data from the Global Burden of Diseases, Injuries, and Risk Factors Study (GBD) 2021 to estimate deaths, disability-adjusted life years (DALYs), age-standardized mortality rate (ASMR), and age-standardized DALY rate (ASDR) of childhood diarrheal diseases attributable to suboptimal breastfeeding. Suboptimal breastfeeding was assessed as a combination of non-exclusive breastfeeding and discontinued breastfeeding. And the average annual percentage change (AAPC) from 1990 to 2021 was calculated to determine long-term trends. Additionally, frontier analyses were conducted to evaluate the efficiency of different countries in reducing the disease burden relative to their socio-demographic index (SDI) levels.

Results By 2021, the global number of deaths and DALYs attributable to childhood diarrheal diseases due to suboptimal breastfeeding was 63,133 and 573,430, respectively. Between 1990 and 2021, the number of deaths and DALYs, as well as ASMR (AAPC: -5.40) and ASDR (AAPC: -5.38), declined by approximately 80%. However, significant disparities persist across regions. Low-SDI regions, particularly in Western Sub-Saharan Africa, continued to bear the highest disease burden. At the countries or territories level, Nigeria, India, and Chad recorded the highest number of deaths and DALYs, while Chad, South Sudan, and Lesotho exhibited the highest ASMR and ASDR values. Similar patterns were observed for non-exclusive and discontinued breastfeeding, with the greatest burden concentrated in resource-limited settings.

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Conclusion While the global burden of childhood diarrheal diseases attributable to suboptimal breastfeeding has significantly declined over the past three decades, the disease burden remains disproportionately high in less developed regions. These findings underscore the urgent need for targeted public health policies and interventions to promote exclusive and continued breastfeeding, especially in high-burden regions, to further reduce preventable childhood morbidity and mortality.

Keywords Diarrheal diseases, Breastfeeding, Disability-adjusted life year, Mortality, Global burden of disease

Background

In 2001, the World Health Organization (WHO) issued recommendations on breastfeeding, including three key components: timely initiation (within 1 h of birth), exclusive breastfeeding until six months of age, and continued breastfeeding until 24 months of age [1, 2]. Breastfeeding protects against diarrhea and respiratory infections, is consistently associated with higher cognitive performance in children and adolescents, and may have a protective effect against overweight and diabetes [3]. Research has shown that the polysaccharides in breast milk are part of the natural immune mechanism and are responsible for breast milk's protection of breastfed infants against diarrheal diseases [4]. In addition, breastfeeding reduces exposure to contaminated fluids and foods, helping to ensure adequate nutrition and, thus, non-specific immunity. Moreover, breastfeeding is the most cost-effective intervention to protect children from diarrhea and all causes of death [1]. Despite the well-documented benefits of breastfeeding for people, society and the planet, optimal breastfeeding is often challenged by multiple unfavorable socio-cultural barriers as well as sub-optimal policy design and program implementation. Based on solid evidence of short-term health benefits, WHO has set a target of 50% of infants being exclusively breastfed for the first 6 months of life [5]. However, only 38% of infants worldwide are exclusively breastfed within the first six months of life, far below the WHO goal [6]. Current evidence suggests that most women are not surrounded by a friendly and supportive environment for breastfeeding, partly because of a lack of social support, insufficient funding, unsatisfactory monitoring and enforcement of legislation, and limited institutional capacity to support and protect optimal breastfeeding practices [7].

Suboptimal breastfeeding includes non-exclusive and discontinued breastfeeding, with non-exclusive breastfeeding (children not exclusively breastfed if < 6 months of age) and discontinued breastfeeding (children who discontinue breastfed at 6–23 months) [8]. Suboptimal breastfeeding is associated with several adverse child health outcomes, including an increased incidence of diarrhea and pneumonia and increased mortality [8, 9, 10]. Worldwide, diarrheal diseases are the leading cause of death in children five years of age and under [11]. Despite the decline in mortality in recent years, diarrhea remains one of the leading preventable causes of child mortality. In addition to contributing to high mortality rates, recurrent or persistent diarrhea has serious long-term effects on growth, nutrition and cognition [12]. In recent years, several studies have focused on the burden of childhood diarrhea disease due to inappropriate breastfeeding using the Global Burden of Diseases, Injuries, and Risk Factors Study (GBD) database. However, they have been limited to the national level. A study has shown that more than half (56.5%) of late neonatal diarrhea deaths in Nigeria can be attributed to poor breastfeeding practices [13]. Moreover, another study showed that suboptimal breastfeeding is an associated factor in the cause of diarrhea-specific deaths in Indian children [14]. There are no studies that have systematically explored the global burden of childhood diarrheal diseases attributable to suboptimal breastfeeding at the global, regional and 204-country levels.

The GBD 2021 database is a comprehensive health data platform [15], which released updated data for 2021 in May 2024. The dataset covers 288 causes of death, 371 diseases and injuries, and 88 risk factors across 204 countries and territories, providing estimates of morbidity, mortality, and disability-adjusted life years (DALYs). This study presents an exploratory analysis of these estimates, focusing on global, regional, and national trends in the burden of childhood diarrheal diseases attributable to suboptimal breastfeeding. By analyzing indicators such as mortality and DALYs, this study aims to provide a clear picture of the distribution and trends of these diseases across different regions and countries. The findings contribute to a better understanding of the current disease burden and offer valuable data to inform future public health strategies and research directions. Identifying high-risk populations and regions will allow for the development of more targeted interventions to reduce the morbidity and mortality associated with childhood diarrheal diseases.

Methods

Data source

Data in this study were obtained from the GBD 2021 newly released dataset [16]. GBD 2021 estimates relevant indicators for 23 age groups from birth to 95 years and older: males, females, and all sexes combined; and 204 countries and territories grouped into 21 regions. The

GBD regions are geographically and epidemiologically similar countries and territories organized into super-regions based on cause-of-death patterns. GBD 2021 contains comprehensive estimates and integrated assessments of 371 diseases and 88 risk factors for 204 countries worldwide [17].

GBD divides all GBD risk factors into four levels and the sum of all risk factors. In GBD 2021, Suboptimal breastfeeding is the seventh-ranked level 3 risk factor in children under five years of age. It includes two level 4 risk factors: non-exclusive breastfeeding (including predominant, partial, and no breastfeeding in infants less than 6 months of age) and discontinued breastfeeding (among infants 6–23 months of age). Patients' ages were divided into four subgroups: <28 days, 1 – 5 months, 6 – 11 months and 12 – 23 months. The non-exclusive breastfeeding group is < 28 days and 1–5 months. The discontinued breastfeeding group was 6–11 months and 12–23 months.

Because the data of GBD 2021 is public, the Institutional Ethics Committee approved the exemption of this study as it does not need approval. The analytic process for this study complied with the Guidelines for Accurate and Transparent Health Estimates Reporting (GATHER) statements (***GATHER checklist***) [17].

Statistical analysis

We conducted an exploratory analysis using the estimates provided by the GBD 2021 database, which includes disease burden indicators such as deaths and DALYs, mortality rate, DALY rate, age-standardized mortality rate (ASMR), age-standardized DALY rate (ASDR), population attributable fractions (PAFs) and its 95% uncertainty interval (95% UI) (based on the 25th and 975th values across all 1000 draws). The AAPCs of ASMR and ASDR were then further calculated. DALY, defined as the total number of healthy years lost from onset to death [18], is a key parameter for assessing the burden of disease [19].

We calculated the average annual percentage change (AAPC) using Joinpoint software (National Cancer Institute, Rockville, MD, USA) to quantify the long-term trend of ASMR and ASDR from 1990 to 2021. The logarithmic age standardization index can be applied to the regression model: $\ln(y) = \alpha + \beta x + \varepsilon$, where Y represents the corresponding age standardization index and X represents the calendar year. AAPC is calculated as $100 \times (\exp(\beta)-1)$, and its 95% confidence interval (95% CI) can also be calculated from the model. Suppose the 95% confidence interval of the corresponding AAPC estimate is greater than 0. In that case, the age standardization index is considered to be on the rise; if the 95% confidence interval is less than 0, it will be on the decline, and if the 95% confidence interval includes 0, it will be stable [20]. In addition, to explore the impact of socio-demographic indices (SDI) on the burden of childhood diarrheal disease due to suboptimal breastfeeding, non-exclusive breastfeeding, and discontinued breastfeeding, associations were assessed at the national and regional levels using Spearman correlation analyses, taking into account the non-normal distribution of the corresponding variables. SDI is a comprehensive index that measures the per capita income, average years of education, and fertility rate of females under 25 [21]. It is closely related to health outcomes. SDI ranges from 0 to 1, where 0 represents the lowest level of development, and 1 represents the highest level [22]. In this study, according to the SDI value, 204 countries and regions are divided into five groups: high SDI, high-middle SDI, middle SDI, low-middle SDI and low SDI regions.

Frontier analysis evaluates the performance and efficiency of decision-making units (such as countries or regions) in transforming inputs into outputs [23]. In this study, data envelopment analysis and stochastic frontier analysis are used to construct an efficiency frontier representing best practices, and the performance of each decision-making unit is compared with this frontier to determine the efficiency level. In order to analyze the performance of different SDI levels, we divided 204 countries and regions in GBD research into five SDI categories: low, medium-low, medium-high and high SDI. We evaluated the performance of these countries and regions, and the lower limit of the ratio of ASMR and ASDR represents the lowest value each country or region can achieve according to its SDI level.

This study uses the R statistical software program (version 4.3.1) and the Joinpoint software program (version 5.2.0.0) to statistically analyze and visualize the data. P value < 0.05 is considered statistically significant.

Results

Burden of disease from childhood diarrheal diseases in 2021

Burden of disease attributable to suboptimal breastfeeding

Globally, the death number of childhood diarrhea diseases attributable to suboptimal breastfeeding in 2021 is 63,133 (95% UI: 45,947, 84,695); among females, 28,852 (95% UI: 21,488, 36,815) and males, 34,281(95% UI: 22,368, 50,155) (Table 1). The DALYs were 5,734,306 (95% UI: 4,195,272, 7,663,992) for females 2,625,763 (95% UI: 1,959,771, 3,339,561) and males 3,108,543 (95% UI: 2,036,363, 4,535,266) (Table S1).

It is clear that the number of deaths and the number of DALYs peaks at 1–5 months and that the rates of mortality and DALYs are also higher at 1–5 months than at several other ages. Males have a higher number of deaths, DALYs, mortality and DALYs rates than females (Fig. 1).

At the SDI regional level, the low SDI regions had the highest number of deaths(107,108) and DALYs

Table 1 Global death of childhood diarrheal diseases attributable to suboptimal breastfeeding in 1990 and 2021, and the temporal trend from 1990 to 2021

Characteristics	Sex	1990 Deaths (95%UI)	1990 ASMR/10^5 (95%UI)	1990 Age-standardized PAF, % (95%UI)	2021 Deaths (95%UI)	2021 ASMR/10^5 (95%UI)	2021 Age-standardized PAF, % (95%UI)	1990–2021 AAPC of ASMR (95%CI)
Suboptimal breastfeeding	Both	348,986 (265468, 436840)	5.53 (4.21, 6.92)	9.24 (6.64, 11.99)	63,133 (45947, 84695)	1.01 (0.74, 1.36)	6.69 (4.48, 9.49)	-5.40 (-5.52, -5.28)
	Male	187,896 (133757, 248447)	5.77 (4.1, 7.63)	8.96 (5.56, 12.36)	34,281 (22368, 50155)	1.07 (0.7, 1.56)	6.88 (3.95, 10.72)	-5.31 (-5.46, -5.16)
	Female	161,091 (118466, 202703)	5.28 (3.88, 6.65)	9.42 (6.44, 13.22)	28,852 (21488, 36815)	0.96 (0.71, 1.22)	6.67 (3.90, 10.34)	-5.48 (-5.65, -5.30)
Non-exclusive breastfeeding	Both	305,714 (230379, 385807)	4.84 (3.64, 6.1)	8.08 (5.80, 10.72)	54,770 (40513, 73076)	0.88 (0.65, 1.18)	5.82 (3.92, 8.32)	-5.44 (-5.58, -5.30)
	Male	165,416 (116642, 221075)	5.06 (3.57, 6.77)	7.87 (4.92, 10.93)	29,745 (19886, 43963)	0.93 (0.62, 1.37)	5.98 (3.57, 9.22)	-5.36 (-5.52, -5.20)
	Female	140,298 (103146, 176450)	4.59 (3.38, 5.77)	8.19 (5.66, 11.48)	25,025 (18608, 32128)	0.83 (0.62, 1.07)	5.80 (3.41, 9.05)	-5.48 (-5.65, -5.30)
Discontinued breastfeeding	Both	43,273 (15811, 76468)	0.7 (0.25, 1.23)	1.17 (0.41, 2.06)	8364 (2911, 14955)	0.13 (0.05, 0.24)	0.90(0.29, 1.72)	-5.26 (-5.38, -5.13)
	Male	22,480 (8159, 40930)	0.7 (0.26, 1.28)	1.09 (0.35, 2.03)	4536 (1520, 8471)	0.14 (0.05, 0.26)	0.87 (0.28, 1.60)	-5.13 (-5.28, -4.98)
	Female	20,793 (7593, 35850)	0.69 (0.25, 1.19)	1.24 (0.40, 2.16)	3827 (1323, 6795)	0.13 (0.04, 0.22)	0.87 (0.29, 1.61)	-5.37 (-5.48, -5.26)

ASMR, age-standardized mortality rate; PAF, population attributable fraction; UI, uncertainty interval; AAPC, average annual percentage change

(35253340.46), ASMR (2.29 per 100,000 people) and ASDR (206.81 per 100,000 people). Among the 21 GBD regions, Western Sub-Saharan Africa, South Asia and Eastern Sub-Saharan Africa ranked the top three concerning deaths and DALYs. However, the top three ASMRs or ASDRs occurred in Western Sub-Saharan Africa, the Caribbean and Southern Sub-Saharan Africa (Tables S2 - S3).

In terms of countries or territories, Nigeria ranked first in terms of deaths (16,884) and DALYs (152,2504.60), with Nigeria being followed by India and Chad (Fig. 2, Figure S1, Tables S4 - S5). Chad's ASMR (9.97 per 100,000 people) and ASDR (896.92 per 100,000 people) ranked first, followed by South Sudan and Lesotho (Fig. 2, Figure S1, Tables S6 - S7).

Burden of disease attributable to non-exclusive breastfeeding

The death number of childhood diarrhea diseases attributable to non-exclusive breastfeeding in 2021 is 54,770 (95% UI: 40,513, 73,076); among females, 25,025 (95% UI: 18,608, 32,128) and males, 29,745 (95% UI: 19,886, 43,963) (Table 1). The DALYs were 4,974,191 (95% UI: 3,683,234, 6,631,501) for females 2,277,139 (95% UI: 1,700,335, 2,915,395) and males 2,697,052 (95% UI: 1,810,396, 3,978,800) (Table S1).

1–5 months is the peak period for the number of deaths and DALYs, and rates of mortality and DALY are also higher at 1–5 months than at < 28 days (Fig. 1, Figure S2).

At the SDI regional level, the low SDI regions had the highest number of deaths (34,182) and DALYs (3089502.05), ASMR (2.00 per 100,000 people) and ASDR (180.76 per 100,000 people). Among the 21 GBD regions, Western Sub-Saharan Africa, South Asia and Eastern Sub-Saharan Africa ranked the top three concerning deaths and DALYs. However, the top three ASMRs or ASDRs occurred in Western Sub-Saharan Africa, Southern Sub-Saharan Africa and the Caribbean (Tables S8 - S9).

In terms of countries or territories, Nigeria also ranked first in the number of deaths (14,492) and DALYs (1308473.65), followed by India and Chad (Figures S3 - S4, Tables S10 - S11). Chad ranked first in ASMR (8.81 per 100,000 people) and ASDR (793.62 per 100,000 people), followed by South Sudan and Somalia (Figures S3 - S4, Tables S12 - S13).

Burden of disease attributable to discontinued breastfeeding

The death number of childhood diarrhea diseases attributable to discontinued breastfeeding in 2021 is 8,364 (95% UI: 2,911, 14,955); among females, 3,827 (95% UI: 1,323, 6,795) and males, 4,536 (95% UI: 1,520, 8,471) (Table 1). The DALYs were 760,114 (95% UI: 266,457,

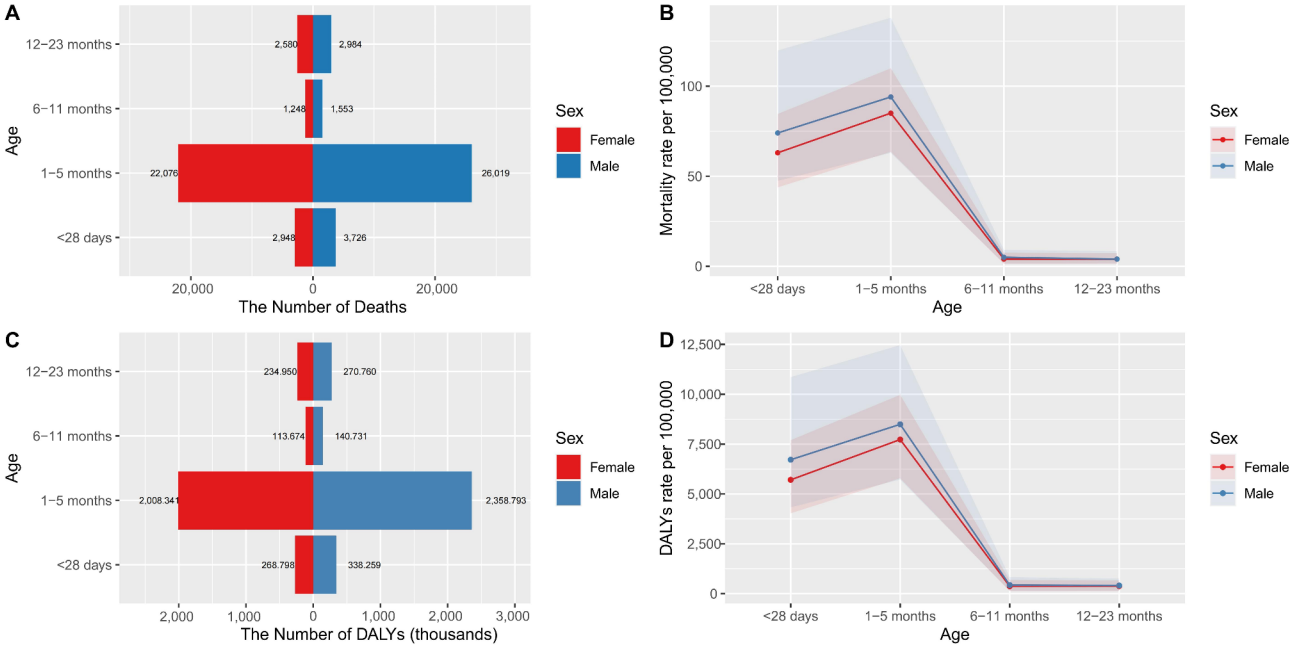

Fig. 1 Age-specific number of deaths (**A**), mortality rate (**B**), number of DALYs (**C**) and DALY rate (**D**) of children's diarrhea diseases attributable to suboptimal breastfeeding in 2021 by sex. DALY, disability-adjusted life year

1,362,626) for females 348,624 (95% UI: 120,891, 616,359) and for males 411,490 (95% UI: 138,388, 765,210) (Table S1).

12–23 months was the peak for the number of deaths and DALYs, whereas there was no significant difference in mortality and DALY rate between 6 and 11 months and 12–23 months (Fig. 1, Figure S5).

At the SDI regional level, the low SDI regions had the highest number of deaths (4,865) and DALYs (435838.40), ASMR (0.29 per 100,000 people) and ASDR (26.05 per 100,000 people) attributable to discontinued breastfeeding. Among the 21 GBD regions, Western Sub-Saharan Africa, South Asia and Eastern Sub-Saharan Africa ranked the top three in terms of deaths and DALYs attributable to discontinued breastfeeding. However, the top three ASMRs or ASDRs occurred in Southern Sub-Saharan Africa, Western Sub-Saharan Africa and the Caribbean (Tables S14 - S15).

In terms of countries or territories, Nigeria also ranked first in the number of deaths (2,392) and DALYs (214030.95), followed by India and Pakistan (Figures S6 - S7, Tables S16 - S17). Chad ranked first in ASMR (1.16 per 100,000 people) and ASDR (103.30 per 100,000 people), followed by Lesotho and Haiti (Figures S6 - S7, Tables S18 - S19).

Changing pattern of burden of disease from childhood diarrheal diseases from 1990 to 2021

Changing pattern of burden of disease attributable to suboptimal breastfeeding

The global number of deaths attributable to suboptimal breastfeeding decreased from 348,986 (95% UI: 265,468, 436840) in 1990 to 63,133 (95% UI: 45,947, 84,695) in 2021. The ASMR decreased from [5.53 (95% UI: 4.21,6.92) per 100,000 people] in 1990 to [1.01 (95% UI: 0.74,1.36) per 100,000 people] in 2021. The AAPC of ASMR was – 5.40 (95% CI: -5.52, -5.28) (Table 1; Fig. 3). The number of DALYs and ASDR also declined from 1990 to 2021, with an AAPC of ASDR of -5.38 (95% CI: -5.51, -5.26) (Table S1, Fig. 3).

At the SDI region level, ASMR and ASDR declined in all regions. High-middle SDI regions had the fastest decreases in ASMR and ASDR, with AAPCs of -7.56 (95% CI: -7.73, -7.38) and – 7.41 (95% CI: -7.6, -7.22), respectively (Tables S2 - S3).

At the GBD region level, both ASMR and ASDR declined in 21 GBD regions. Tropical Latin America had the fastest decrease in ASMR or ASDR, with AAPCs of -12.32 (95% CI: -12.94, -11.7) and – 12.14 (95% CI: -12.64, -11.63), respectively (Tables S2 - S3).

At the countries or territories level, the fastest reduction in ASMR or ASDR was in Kazakhstan, with AAPCs of -12.86 (95% CI: -14.34, -11.36) and – 12.69 (95% CI: -14.12, -11.25), respectively (Tables S20 - S21, Fig. 2, Figure S1). The AAPCs of ASMR and ASDR for 204 countries are shown in Table S26.

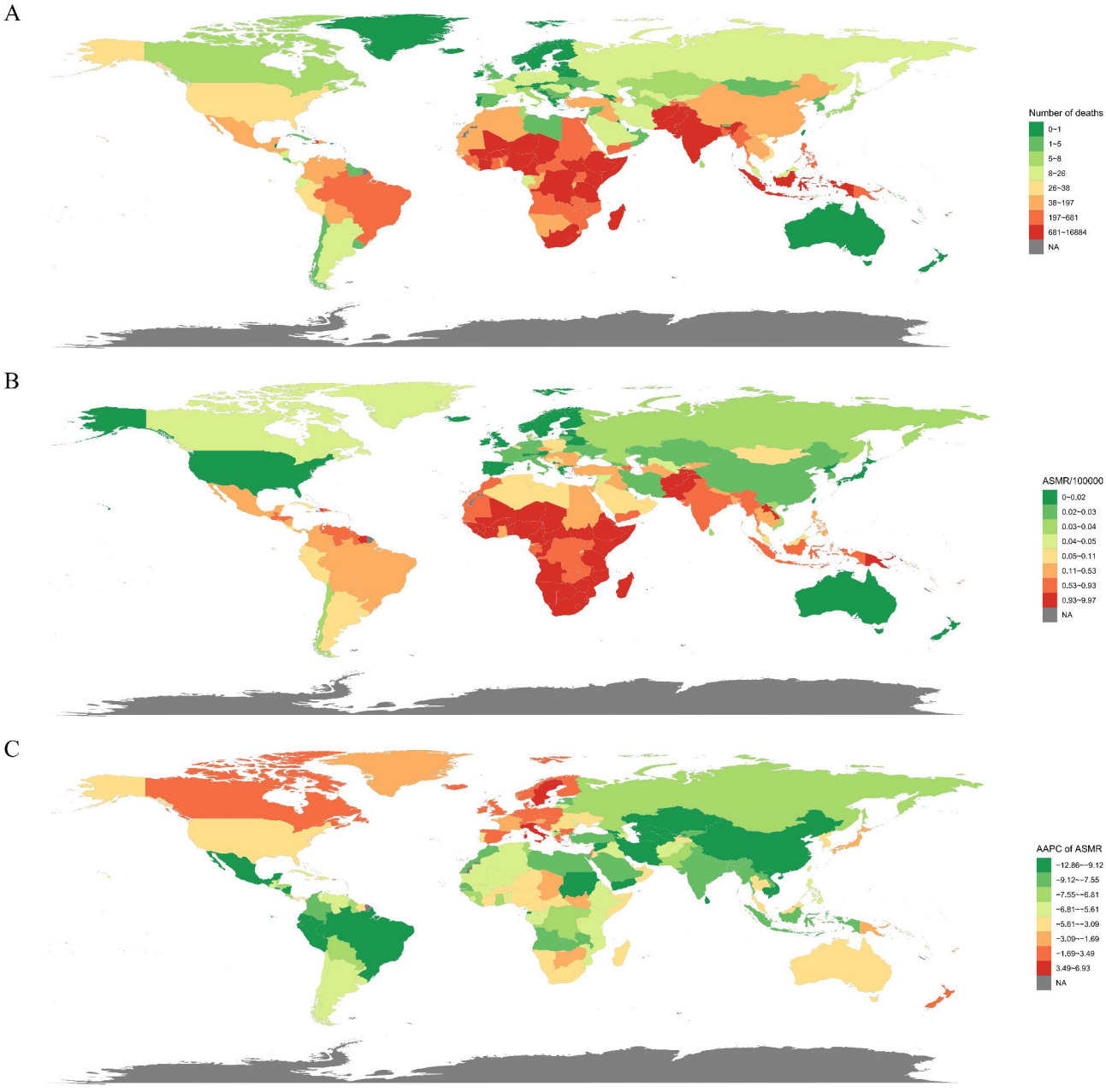

Fig. 2 Global male and female mortality burden for childhood diarrheal diseases attributable to suboptimal breastfeeding. (**A**) Number of deaths in 2021. (**B**) ASMR in 2021. (**C**) AAPC of ASMR from 1990 to 2021. Lower values are represented by greener colors and higher values by redder colors. The data has been divided into eight equal ranges (quantiles) based on their values. ASMR, age-standardized mortality rate; AAPC, average annual percentage change

Changing pattern of burden of disease attributable to non-exclusive breastfeeding

The global number of deaths attributable to non-exclusive breastfeeding declined from 305,714 (95% UI: 230,379, 385,807) in 1990 to 54,770 (95% UI: 40,513, 73,076) in 2021. The ASMR declined from [4.84 (95% UI: 3.64,6.1) per 100,000 people] in 1990 to [0.88(95% UI: 0.65,1.18) per 100,000 people] in 2021. The AAPC of ASMR was − 5.44 (95% CI: -5.58, -5.30) (Table 1, Figure S8). DALYs and ASDR also declined from 1990 to 2021, with AAPC of ASDR of -5.44 (-5.58, -5.30) (Table S1, Figure S8).

At the SDI region level, ASMR and ASDR declined in all regions. Low-middle SDI regions experienced the fastest declines in ASMR and ASDR, with AAPCs of -7.24 (95% CI: -7.59, -6.9) and − 7.21 (95% CI: -7.55, -6.87), respectively (Tables S8 - S9).

At the GBD region level, Tropical Latin America had the fastest declines in ASMR and ASDR, with AAPCs

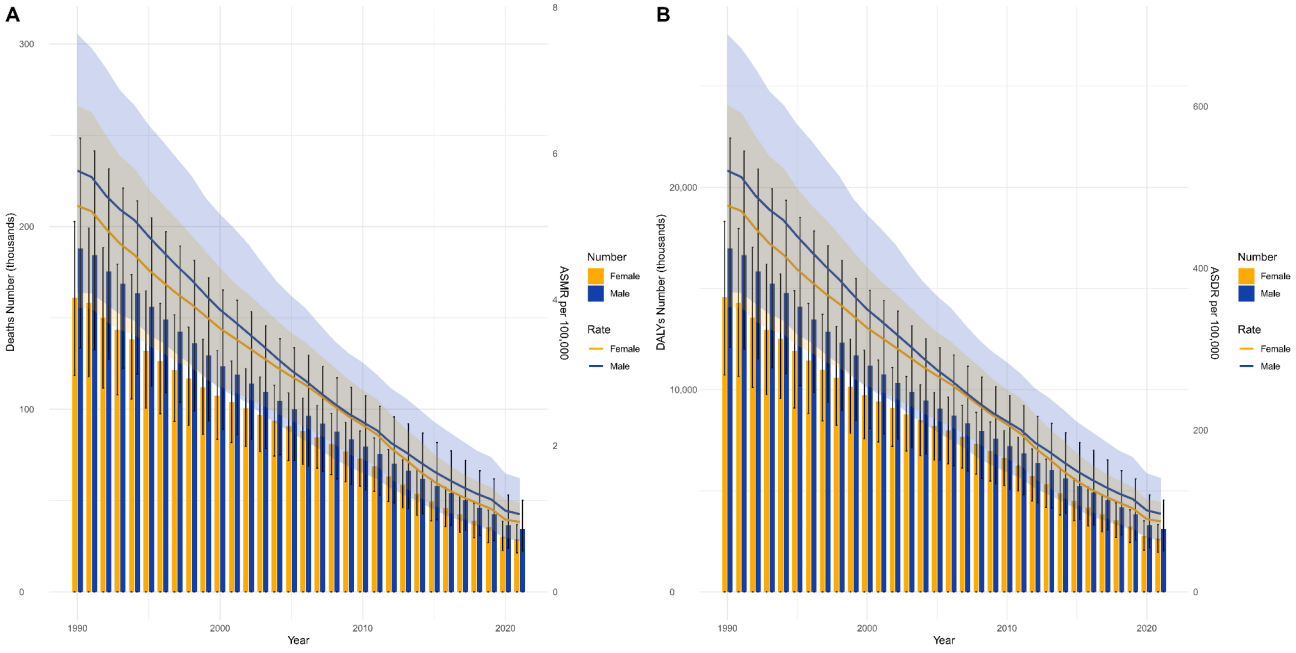

Fig. 3 Trends in the number of deaths, the number of DALYs, ASMR and ASDR of childhood diarrheal diseases attributable to suboptimal breastfeeding by sex from 1990 to 2021. (**A**) The number of deaths and ASMR; (**B**) The number of DALYs and ASDR. DALY, disability-adjusted life year; ASMR, age-standardized mortality rate; ASDR, age-standardized disability-adjusted life year rate;

of -12.51 (95% CI: -13.16, -11.85) and – 12.48 (95% CI: -13.13, -11.83), respectively (Tables S8 - S9).

At the countries or territories level, the fastest decline in ASMR or ASDR was in Kazakhstan, with AAPCs of -12.95 (95% CI: -14.15, -11.72) and – 12.78 (95% CI: -13.95, -11.59) (Tables S22 - S23, Figures S3 - S4). The AAPCs of ASMR and ASDR for 204 countries are shown in Table S27.

Changing pattern of burden of disease attributable to discontinued breastfeeding

Global deaths attributable to discontinued breastfeeding declined from 43,273 (95% UI: 15,811, 76,468) in 1990 to 8,364 (95% UI: 2,911, 14,955) in 2021. ASMR declined from [0.7 (95% UI: 0.25,1.23) per 100,000 people] in 1990 to [0.13 (95% UI: 0.05, 0.24) per 100,000 people] in 2021. The AAPC of ASMR was – 5.26 (95% CI: -5.38, -5.13) (Table 1, Figure S9). The number of DALYs and ASDR also declined from 1990 to 2021, with an AAPC of ASDR of -5.38 (95% CI: -5.51, -5.26) (Table S1, Figure S9).

At the SDI region level, ASMR and ASDR declined in all regions. High-middle SDI regions had the fastest decreases in ASMR and ASDR, with AAPCs of -9 (95% CI:-9.36, -8.63) and – 8.63 (95% CI: -8.89, -8.38), respectively (Tables S14 - S15).

At the GBD region level, both ASMR and ASDR declined in 21 GBD regions. East Asia had the fastest decrease in ASMR or ASDR, with AAPCs of -12.76 (95% CI: -13.27, -12.25) and – 12.44 (95% CI: -12.87, -12), respectively (Tables S14 - S15).

At the countries or territories level, the fastest reduction in ASMR or ASDR was in Uzbekistan, with AAPCs of -12.9 (95% CI: -16.1, -9.58) and – 12.86 (95% CI: -15.97, -9.64), respectively (Tables S24 - S25, Figures S6 - S7). The AAPCs of ASMR and ASDR for 204 countries are shown in Table S28.

PAF of the childhood diarrheal diseases

PAF of the childhood diarrheal diseases attributable to suboptimal breastfeeding

PAFs in ASMR for childhood diarrheal diseases attributable to suboptimal breastfeeding varied considerably by region or age group. Globally, the PAF was 6.69 (95% UI: 4.48, 9.49). At the SDI region level, the highest PAF was 7.47 (95% UI: 5.41, 10.47) in the High-middle SDI region; at the GBD region level, higher PAF values were found mainly in the Caribbean, Central Asia and Eastern Europe.

In the 0–2 year age group, the highest PAF percentage was 47.51 (95% UI: 38.87, 55.62) for 1–5 months, much higher than in several other age groups (Table 2).

PAF of the childhood diarrheal diseases attributable to non-exclusive breastfeeding

Globally, the PAF in ASMR was 5.82 (95% UI: 3.92, 8.32). At the SDI region level, the highest PAF was 6.33 (95% UI: 4.69, 8.84) in the High-middle SDI region; at the GBD region level, high PAF values were mainly found in the Caribbean, Central Asia and Eastern Europe.

Table 2 Population attributable fraction of childhood diarrhea diseases in age-standardized mortality rate attributable to suboptimal breastfeeding, non-exclusive breastfeeding and discontinued breastfeeding by region and age for both sexes in 2021

Characteristics	PAF, % (95%UI)		
	Suboptimal breastfeeding	Non-exclusive breastfeeding	Discontinued breastfeeding
Global	6.69 (4.48, 9.49)	5.82 (3.92, 8.32)	1.44 (0.53, 2.53)
5 SDI Regions			
High SDI	2.6 (2.06, 3.24)	2.17 (1.77, 2.68)	0.42 (0.17, 0.66)
High-middle SDI	7.47 (5.41, 10.47)	6.33 (4.69, 8.84)	1.14 (0.4, 2.04)
Middle SDI	5.27 (3.32, 8.34)	4.38 (2.85, 7.08)	0.89 (0.27, 1.66)
Low-middle SDI	2.53 (1.42, 4.11)	2.19 (1.24, 3.64)	0.34 (0.1, 0.66)
Low SDI	3.41 (1.98, 5.13)	2.98 (1.76, 4.51)	0.43 (0.13, 0.88)
21 GBD Regions			
Andean Latin America	5.56 (3.35, 8.23)	4.25 (2.48, 6.42)	1.31 (0.43, 2.43)
Australasia	2.06 (1.44, 2.77)	1.39 (1.04, 1.82)	0.67 (0.25, 1.11)
Caribbean	19.09 (13.86, 24.52)	16.24 (11.39, 21.59)	2.85 (1.05, 4.91)
Central Asia	17.04 (12.81, 21.07)	13.52 (10.08, 17.35)	3.51 (1.35, 5.99)
Central Europe	9.92 (7.96, 11.84)	8.43 (6.83, 10.02)	1.49 (0.58, 2.35)
Central Latin America	6.03 (4.23, 7.72)	4.15 (3.29, 5.22)	1.88 (0.65, 3.16)
Central Sub-Saharan Africa	3.13 (1.47, 5.96)	2.78 (1.31, 5.33)	0.35 (0.1, 0.81)
East Asia	10.44 (6.18, 14.8)	8.43 (5.14, 11.91)	2.01 (0.64, 3.72)
Eastern Europe	15.27 (12.62, 17.79)	11.83 (10.31, 13.44)	3.44 (1.42, 5.48)
Eastern Sub-Saharan Africa	2.87 (1.69, 4.7)	2.53 (1.53, 4.23)	0.34 (0.11, 0.71)
High-income Asia Pacific	2.89 (2.06, 3.94)	2.33 (1.69, 3.11)	0.56 (0.22, 0.96)
High-income North America	1.61 (1.29, 2)	1.43 (1.15, 1.76)	0.18 (0.07, 0.3)
North Africa and Middle East	13.49 (9.28, 18.07)	11.69 (8.07, 16.01)	1.8 (0.58, 3.11)
Oceania	2.96 (1.52, 5.18)	2.01 (0.95, 3.71)	0.96 (0.27, 2)
South Asia	1.62 (0.84, 2.89)	1.43 (0.75, 2.54)	0.19 (0.05, 0.41)
Southeast Asia	4.39 (2.58, 7.6)	3.85 (2.3, 6.91)	0.54 (0.16, 1.15)
Southern Latin America	4.52 (3.29, 5.83)	3.66 (2.68, 4.65)	0.86 (0.32, 1.43)
Southern Sub-Saharan Africa	6.98 (4.57, 10.85)	5.77 (3.76, 8.97)	1.21 (0.4, 2.39)
Tropical Latin America	5.32 (3.94, 6.9)	4.3 (3.25, 5.45)	1.02 (0.38, 1.67)
Western Europe	2.31 (1.77, 2.93)	1.87 (1.47, 2.37)	0.44 (0.17, 0.71)
Western Sub-Saharan Africa	6.02 (3.8, 8.69)	5.2 (3.34, 7.63)	0.82 (0.26, 1.55)
Age			
< 28 days	27.28 (22.06, 32.43)	27.28 (22.06, 32.43)	NA
1–5 months	47.51 (38.87, 55.62)	47.51 (38.87, 55.62)	NA
6–11 months	3.17 (1.14, 5.42)	NA	3.17 (1.14, 5.42)
12–23 months	8.33 (3.11, 13.89)	NA	8.33 (3.11, 13.89)

GBD, Global Burden of Diseases, Injuries, and Risk Factors Study; PAF, population attributable fraction; SDI, socio-demographic index; UI, uncertainty interval

In the 0–6 months age group, the highest percentage of PAF was 47.51 (95% UI: 38.87, 55.62) for 1–5 months (Table 2).

PAF of the childhood diarrheal diseases attributable to discontinued breastfeeding

Globally, the PAF in ASMR was 1.44 (95% UI: 0.53, 2.53). At the SDI region level, the highest PAF was 1.14 (95% UI: 0.4, 2.04) in the High-middle SDI region, and at the GBD region level, the top three PAF values were Central Asia, Eastern Europe, and the Caribbean.

In the 6–23 month age group, the higher PAF percentage was 8.33 (95% UI: 3.11, 13.89) for 12–23 months (Table 2).

The changing patterns at different SDI levels

At the level of the 21 GBD regions, the ASMR and ASDR of childhood diarrheal diseases attributable to suboptimal breastfeeding declines sharply as the SDI rises, then rises gradually at an SDI of about 0.45–0.52, and then continues to decline, stabilizing at a level close to 0. At the level of the 204 countries, there is a gradual decline in ASMR and ASDR with the rise in SDI in 2021 (Fig. 4, ***Figure S10***). ASMR and ASDR for childhood diarrheal diseases attributable to non-exclusive and discontinued breastfeeding show similar trends (Figures S11 - S14).

Frontier analysis of ASMR and ASDR

Frontier analyses show that the burden of childhood diarrheal diseases attributable to suboptimal breastfeeding,

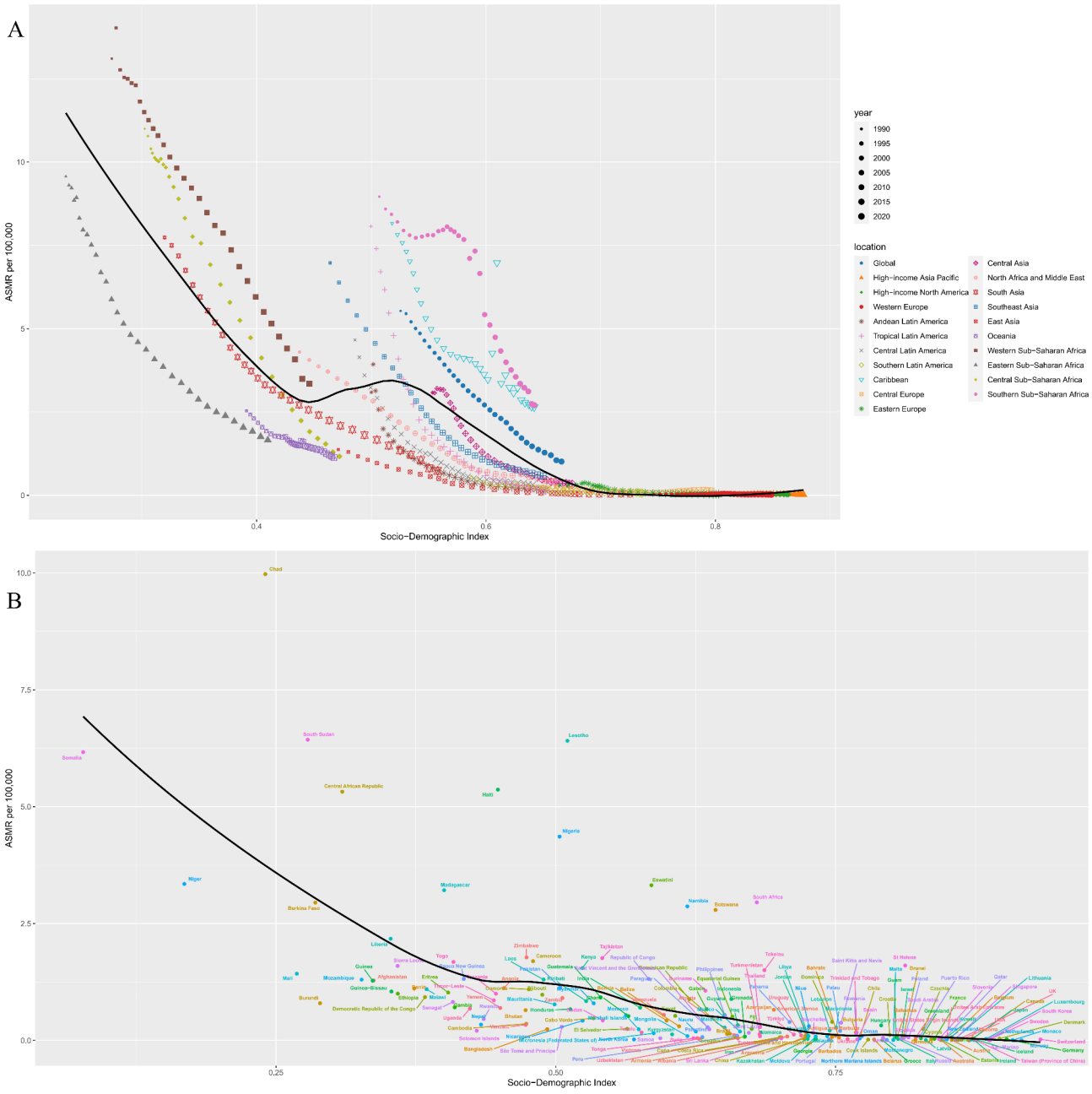

Fig. 4 Distribution of ASMR for childhood diarrheal diseases attributable to suboptimal breastfeeding across different socio-demographic index levels. (**A**) Global and 21 Global Burden of Disease regions from 1990 to 2021; (**B**) 204 countries and territories in 2021. ASMR, age-standardized mortality rate; SDI, Socio-demographic Index

non-exclusive breastfeeding and discontinued breastfeeding in most countries is on a downward trend from 1990 to 2021 (Fig. 5, Figures S15-S16). Differences in the disease burden across countries decrease as SDI levels increase, with less developed countries having a high potential to reduce the burden and developed countries having a low potential to reduce the burden. The analysis highlights the 15 worst-performing countries globally, the five best-performing countries in low SDI regions and the five worst-performing countries in high SDI regions.

Discussion

In this study, the global burden of diarrheal diseases attributable to suboptimal breastfeeding, including non-exclusive breastfeeding and discontinued breastfeeding, and its temporal and spatial trends were systematically quantified and compared. From 1990 to 2021, the three risk factors of suboptimal breastfeeding, non-exclusive breastfeeding and discontinued breastfeeding led to the same trend of disease burden, and their influence on the world gradually decreased, manifested in the gradual

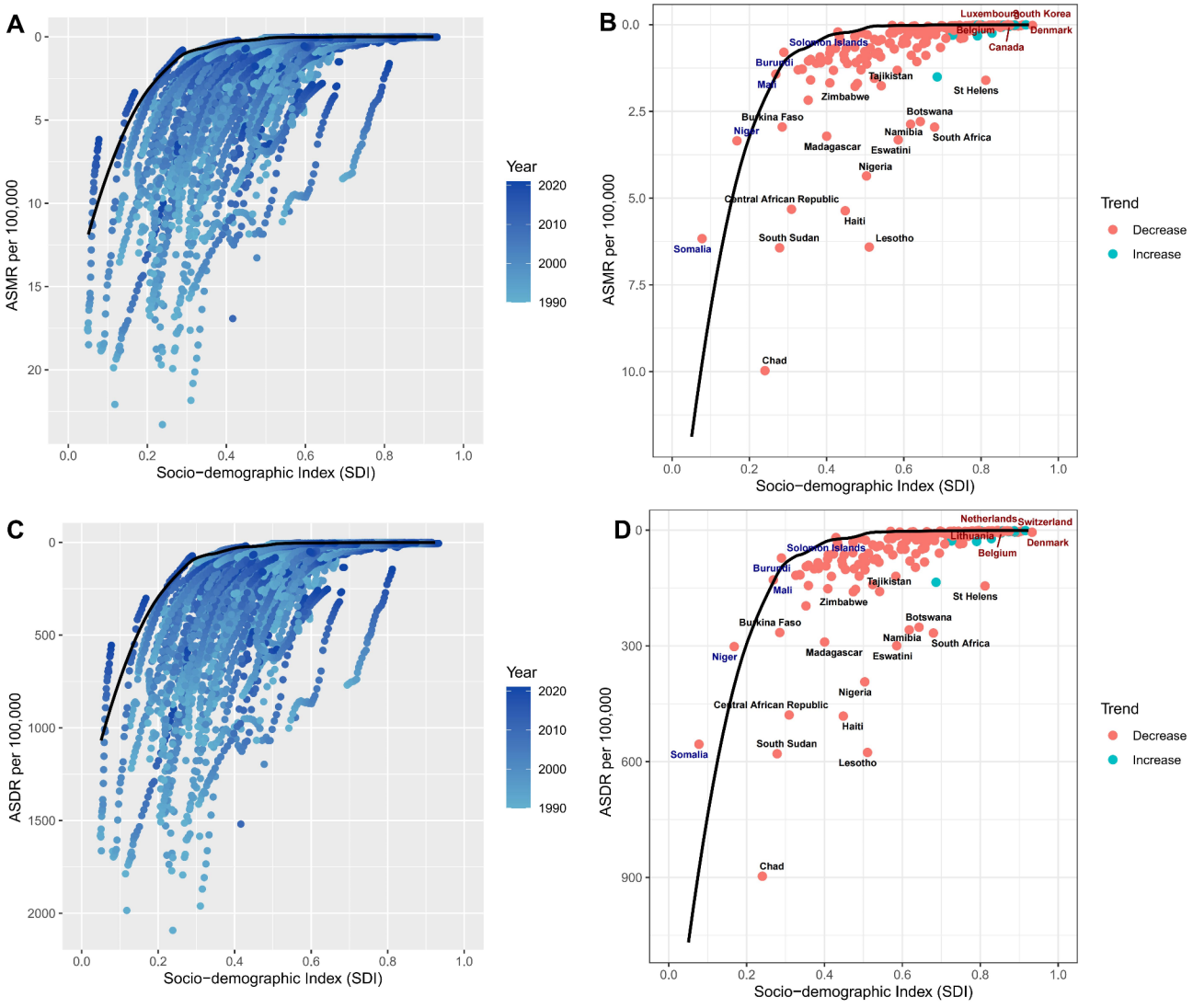

Fig. 5 Results of frontier analysis for ASMR and ASDR of childhood diarrheal diseases attributable to suboptimal breastfeeding. Black lines represent the lower limits of age-standardized rate achievable at different SDI levels, with points representing different countries and regions. The 15 countries and regions with the most significant effective differences globally are labelled in black font, the 5 countries and regions with the most minor effective differences among low SDI countries are labelled in blue font, and the 5 countries and regions with the most significant effective differences among high SDI countries are labelled in red font. In panels B and D, blue dots indicate countries and regions with decreased age-standardized rates from 1990 to 2021, while red dots indicate those with increased age-standardized rates. (**A**) and (**B**): Frontier analysis for ASMR; (**C**) and (**D**): Frontier analysis for ASDR. ASMR, age-standardized mortality rate; ASDR, age-standardized disability-adjusted life year rate

reduction of PAF. The burden attributable to suboptimal breastfeeding varies greatly due to the age and gender differences of patients and regional differences. The burden attributable to different types of suboptimal breastfeeding is also very different.

Breast milk is rich in antimicrobial substances that prevent early infections, including immunoglobulins, complement proteins, lysozyme, lactoferrin and oligosaccharides [24]. Breast milk bacteria may also have an immediate and long-term role in reducing the incidence and severity of bacterial infections in breastfed infants through various mechanisms [25].

Of course, as diarrheal diseases can be caused by a variety of pathogens—including bacteria, viruses, and protozoa—the specific mechanisms by which breastfeeding prevents diarrhea may vary. One key protective mechanism is the presence of fucosylated oligosaccharides in human milk, which prevent pathogens such as Campylobacter, E. coli, caliciviruses, and rotavirus from binding to gut receptors, thus inhibiting infection [4, 26]. Rotavirus, a major cause of childhood diarrhea, is particularly well protected against by lactadherin, a sialylated glycoprotein found in breast milk that directly binds to the virus and prevents it from infecting the gastrointestinal tract [27].

Research has demonstrated that breastfeeding offers protection against Giardia infections through the transfer of secretory IgA, an immune molecule that prevents symptomatic infections [28]. Another important aspect is the influence of breastfeeding on the infant's gut microbiota. Breastfed infants typically have a gut microbiota dominated by beneficial bacteria such as Bifidobacterium and Lactobacillus, which are known to inhibit pathogen colonization. In contrast, formula-fed infants tend to have a microbiota more similar to that of adults, which may promote the growth of harmful bacteria [29, 30].

Furthermore, studies such as that by Kaila et al. [31] show that the intake of Lactobacillus can induce colonization of the gut and help prevent rotavirus-related diarrhea. Therefore, breastfeeding not only provides passive immunity through antibodies but also plays an essential role in modulating the infant's gut microbiota and enhancing overall immune protection, significantly reducing the risk of diarrheal diseases caused by various pathogens.

Breastfeeding has long been reported to reduce morbidity and mortality from childhood diarrheal diseases [32, 33, 34]. A meta-analysis showed that non-exclusive breastfeeding led to an increased risk of diarrhea deaths in infants aged 0–5 months and that discontinued led to a disproportionately high risk of diarrhea deaths in infants aged 6–23 months [9]. In recent years, many studies have focused on the association between sub-breastfeeding and childhood diarrheal diseases in less developed countries. For example, a study from Pakistan showed that exclusive breastfeeding of infants under 6 months of age reduced the incidence of diarrheal disease [35]. A study from Ethiopia also showed that exclusive breastfeeding reduced the incidence of diarrheal disease in infants aged 0–5 months [36]. Another study from a Ugandan population showed that non-breastfeeding was a risk factor for diarrheal diseases in children and that male children were more likely to suffer from diarrheal diseases than females [37].

Our results suggest that the burden of childhood diarrheal diseases is higher with a lower SDI in 204 countries and at the regional level in 2021. Nigeria, India and Chad have the top three deaths. Nigeria, India and Chad had the top three numbers of deaths and DALYs. Chad, South Sudan and Lesotho have the top three ASMRs and ASDRs. These countries are underdeveloped and, except India, are African countries.

In our frontier analysis, for low SDI countries, we observed that countries with the smallest effective differences included Somalia, Niger, Mali, Burundi, and Solomon Islands. These countries exhibited relatively small variations in disease burden and breastfeeding practices, suggesting that they are relatively efficient in reducing disease burden given their low SDI. However, due to their still relatively high ASMR and ASDR, there remains a pressing need for further improvements in healthcare infrastructure and public health policies to address these issues. Other low SDI countries also have significant potential for reducing disease burden, indicating that targeted interventions could lead to substantial improvements.

For low SDI countries that are struggling with managing childhood diarrheal diseases and promoting exclusive breastfeeding, Niger offers an important example of successful interventions. In Sub-Saharan African countries, Chad has the lowest rate of early initiation of breastfeeding within the first hour of birth, at just 23.0%. Nigeria also shows a relatively low rate of 33.2%. In contrast, Niger performs better, with an early initiation rate of 52.9% [38]. These differences highlight the varying effectiveness of breastfeeding promotion programs and the need for tailored interventions to improve maternal and child health outcomes in these countries.

On the other hand, for high SDI countries, countries with the largest effective differences included Luxembourg, South Korea, Denmark, Belgium, and others. Despite being wealthy and highly developed nations, these countries show relatively low efficiency in reducing the burden of childhood diarrheal diseases and promoting exclusive breastfeeding. The large effective differences in these countries suggest that even in high SDI regions, national policies, healthcare systems, and cultural factors play significant roles in either facilitating or hindering optimal health outcomes.

Most of the 15 countries with the largest global effective variance in the frontier analysis belong to Africa. Most African countries are estimated to need to meet the WHO's global nutrition target of 50% exclusive breastfeeding by 2025 [39]. In 2017, Northern Nigeria and the entire Chad region had one of Africa's lowest exclusive breastfeeding rates. Most of Somalia and large parts of southeastern Niger were also in the lowest decile of exclusive breastfeeding rates in Africa in 2000 and 2017 [39].

In Africa, mothers' early breast milk (colostrum) is considered acidic and indigestible and is discarded and replaced with water, formula or animal milk, thus making breastfeeding difficult. The early introduction of water and porridge is a common practice across the continent, inhibiting the practice of exclusive breastfeeding and exposing infants to disease and nutritional risks from pathogens [7, 39, 40]. This is one of the reasons for the high burden of childhood diarrheal diseases in many parts of Africa. At the same time, numerous regions in Africa are low SDI regions with relatively limited medical resources, lower socio-economic status and lower disease awareness, whereas regions with high SDI tend to have more advanced research methods and healthcare systems

that are better able to diagnose and treat diseases; thus, the burden of disease may be relatively low in high SDI regions, whereas the burden of diarrheal disease is higher in low SDI regions [41].

Certainly, the challenges are not limited to Africa. In Asia, countries like India and Pakistan continue to have high absolute burdens of childhood diarrheal diseases despite the overall decline in disease burden in recent years. This is partly due to their large populations and partly due to cultural factors. For example, in certain regions of India, cultural beliefs discourage the use of colostrum [42], and in some areas, older mothers believe that colostrum is harmful to infants [43]. Additionally, there is significant inequality in access to maternal and child healthcare services across different states in India [44, 45]. These cultural and social barriers contribute to the high disease burden in these regions.

In addition, Haiti, located in the Caribbean, faces significant challenges despite the general recognition among women of the importance of breastfeeding for child health. Due to poverty, natural disasters, and other factors, they encounter social, cultural, and economic barriers that lead to low breastfeeding rates and a high burden of childhood diarrheal diseases [46, 47].

The global burden of childhood diarrheal disease attributable to suboptimal breastfeeding has declined from 1990 to 2021. However, the burden of disease in less developed countries and regions should not be underestimated, with particular attention to children aged 1–5 months who are not exclusively breastfed. Moreover, in Southern Sub-Saharan Africa, Western Sub-Saharan Africa and the Caribbean, or countries with a high disease burden, such as Chad, India and Nigeria, there is a need to develop systems to promote breastfeeding to achieve the WHO goals.

Our study has some limitations. First, the estimation results depend on the existing data sources, and the accuracy of GBD data depends on the quality of existing data in various countries. Data reporting and predictability of childhood diarrheal diseases may need to be improved in 204 countries, leading to potential inaccuracies [19]. Secondly, it should be noted that the GBD data source does not cover all people or regions; Therefore, the research results only represent the general situation of a specific region. Third, publication bias related to relative risk may also be another limitation. Fourthly, considering the influence of breastfeeding on diarrhea in developing communities, not including other breastfeeding indicators (such as starting breastfeeding on time) may also be one of the study's limitations.

Conclusion

This study provides key data on childhood diarrheal diseases attributable to suboptimal breastfeeding, with significant implications for global public health. Although the burden has decreased in recent decades, it remains a major challenge. To further mitigate its impact, policies to promote breastfeeding and reduce the disease burden should be developed based on the geographical distribution and epidemiological characteristics of the disease burden. In addition, policymakers should focus on low SDI countries, fostering positive societal attitudes toward breastfeeding, mainstreaming breastfeeding into preventive programs for both children and women, regulating the breastmilk substitutes industry, scaling up breastfeeding interventions, and removing structural and social barriers to women's breastfeeding abilities.

Abbreviations

AAPC	Average annual percentage change
ASDR	Age-standardized DALY rate
ASMR	Age-standardized mortality rate
CI	Confidence interval
DALY	Disability-adjusted life year
GBD	Global Burden of Diseases, Injuries, and Risk Factors Study
PAF	Population attributable fraction
SDI	Socio-demographic indices
UI	Uncertainty interval
WHO	World Health Organization

Supplementary Information

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Supplementary Material 1

Supplementary Material 2

Supplementary Material 3

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Author contributions

SW involved in conceptualization, design, data extraction, statistical analysis, language editing, and original manuscript writing. TZ involved in data extraction and statistical analysis, checked the analysis, and made a significant contribution. KXW and DML reviewed the study's design and the review the draft manuscript and made a significant contribution. XYC involved in data interpretation, data curation, article review, and validation, critical revision for intellectual substance, and article review. The authors approved the final version of the manuscript.

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Data availability

The data used in this paper were obtained from free database downloads and have been described explicitly in the text. Further inquiries can be directed to the corresponding author.

Declarations

Ethics approval and consent to participate
There was no need to get informed consent or ethical approval for this study again because all of the data were taken from published sources, and the informed consent and approval were received.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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