

RESEARCH

Open Access



The long-term effects of adverse childhood experiences on adult health and behaviors: mediating role of socioeconomic inequality

Yanling Shu^{1,2†}, Zheng Zhang^{3†}, Hengyu Wang^{4†}, Chunling Wang⁵, Linfei Dou⁶, Wenhua Wang^{7,8}, Lei Zhang^{7,8}, Jianing Bi⁹ and Mingyang Wu^{6*}

Abstract

Background Despite extensive research into the health effects of adverse childhood experiences (ACEs), there remains a need for nationally representative data to assess the associations between ACEs and both adult health and behaviors, focusing on the mediating role of socioeconomic inequality.

Method Using data from the 2019–2022 Behavioral Risk Factor Surveillance System (BRFSS) ($N=249,186$ adults), ACE exposure was categorized into five groups (0, 1, 2, 3, and 4 or more ACEs). Socioeconomic inequality was assessed based on income levels. Binary logistic regression was employed to quantify the associations of ACEs/socioeconomic inequality with adult health and behaviors. Mediation models were used to evaluate the mediating effect of socioeconomic inequality on the relationships of continuous ACE scores with adult health and behaviors.

Results Each unit increase in ACE score was associated with a 4–34% increase in the odds of adverse health outcomes or unhealthy behaviors. Compared to participants with no ACE exposure, those with ≥ 4 ACEs exhibited a higher likelihood of experiencing asthma, arthritis, cancer, cardiovascular disease (CVD), chronic obstructive pulmonary disease (COPD), diabetes, disability, depression, more days of poor physical and mental health, and engagement in drinking, smoking and high-risk HIV behavior, with odds ratios ranging from 1.26 (95% CI: 1.22–1.31) for diabetes to 4.87 (95% CI: 4.72–5.02) for depression. Socioeconomic inequality mediated more than 5% of associations between ACE scores and diabetes, disability, COPD, and CVD.

Conclusions This study reveals a broad spectrum of negative health impacts associated with ACE exposure, with socioeconomic inequality demonstrating a significant mediating effect on these associations. The findings emphasize the need for public health interventions targeting both ACEs and socioeconomic inequality to alleviate the burden of chronic diseases and improve adult health conditions.

Keywords Adverse childhood experiences, Socioeconomic inequality, Mental health, Physical health, Behaviors

[†]Yanling Shu, Zheng Zhang and Hengyu Wang contributed equally to this work.

*Correspondence:
Mingyang Wu
mingyangwu@csu.edu.cn

Full list of author information is available at the end of the article



© The Author(s) 2025. **Open Access** This article is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License, which permits any non-commercial use, sharing, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if you modified the licensed material. You do not have permission under this licence to share adapted material derived from this article or parts of it. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by-nc-nd/4.0/>.

Introduction

Adverse childhood experiences (ACEs) are defined as long-term and repeated potentially traumatic events that occur before the age of 18 [1]. These experiences encompass various forms of maltreatment and abuse (emotional, physical, sexual), neglect (psychological, physical), and household dysfunctions (parental mental illness, substance abuse, domestic violence, divorce or separation, and parental incarceration) [1, 2, 3]. In the United States, ACEs affect millions of children each year. Data from the Behavioral Risk Factor Surveillance System (BRFSS) collected between 2019 and 2020 indicate that a significant proportion (63%) of American adults experienced at least one ACE during childhood, with 22% reporting four or more ACEs [4]. This widespread prevalence of ACEs contributes to a substantial economic burden associated with adult health conditions, estimated to cost the U.S. economy approximately \$14.1 trillion annually [4]. The past few years have witnessed burgeoning interest in ACEs given their profound and lasting effects on health outcomes throughout the lifespan. Emerging research has consistently shown that individuals with a higher number of ACEs are more likely to engage in risk behaviors, such as tobacco use and binge drinking, and are at an increased risk of developing mental health disorders, cardiovascular disease (CVD), diabetes, cancer, and even premature death [5, 6, 7]. Despite the extensive literature examining the health effects of ACEs, there remains a need for comprehensive and systematic evaluations using nationally representative data. Furthermore, the underlying mechanisms through which ACEs influence these long-term health effects are not yet fully understood, highlighting the need for further investigation.

Socioeconomic inequalities have long constituted a significant public health challenge, disproportionately affecting individuals with lower socioeconomic status (SES) compared to those with higher SES [8]. Previous research has consistently highlighted substantial disparities in health outcomes linked to SES, with individuals from lower SES backgrounds experiencing a higher prevalence of health issues, including infectious diseases, CVD, diabetes, mental health disorders, and cancer [9, 10, 11]. These health issues are influenced by SES through various pathways, such as education level, lifestyle choices, environmental factors, chronic disease management, and access to healthcare services. Besides, emerging evidence has underscored the role of ACEs as a key contributor to socioeconomic inequalities in health [12]. Children exposed to ACEs often exhibit dysfunction in the cerebral cortex, which can impair their ability for self-regulation, emotional management, and stress coping [13]. These neurobiological changes may perpetuate socioeconomic disparities into adulthood, as individuals with a history of ACEs are more likely to encounter

challenges in education, employment, and economic stability [14]. Based on the above research background, it is reasonable to hypothesize that SES may mediate the relationship between ACEs and health outcomes. Currently, several limited studies have explored the mediating role of SES in the relationship between ACEs and health risks. For example, it has been reported that SES partially or fully mediates the associations between ACEs and a range of health-related outcomes, including tobacco use, binge drinking, obesity, and depression [15]. Furthermore, current evidence suggests that educational attainment and income level can mediate the associations of ACEs with late-life depressive symptoms and unhealthy dietary habits [16, 17]. Despite these advancements, there is still a lack of comprehensive research based on nationally representative data examining how socioeconomic inequality mediates the relationships of ACEs with various health-related behaviors, physical health conditions, and mental health outcomes.

Therefore, this study aimed to explore the associations of ACEs with adult health and behaviors, and to determine whether these associations were mediated by socioeconomic status. The findings may help policymakers better identify high-risk populations and inform the development of targeted preventive strategies to address socioeconomic inequalities and reduce the disease burden associated with ACEs.

Methods

Data source and study sample

This cross-sectional study utilized data from the BRFSS spanning from 2019 to 2022. Coordinated by the Centers for Disease Control and Prevention (CDC), the BRFSS is conducted by state health departments through random-digit dialing to both landline and cellular telephones. The survey employs a complex sampling design, adjusting respondent data to known age, race, ethnicity, and gender ratios within the state. The primary goal of the BRFSS is to collect data on health-related risk behaviors, chronic health conditions, and the utilization of preventive services among non-institutionalized adults (≥ 18 years old) in the United States. Since this study used publicly available data, it was deemed exempt from institutional review board approval.

A total of 1,704,051 individuals participated in the BRFSS 2019–2022 life history survey. Initially, participants with missing or invalid values for ACEs and income status were excluded from the study. Subsequently, additional exclusions were made for participants lacking complete data on age, gender, race, marital status, education, body mass index (BMI), and physical activity status. Ultimately, 249,186 individuals were involved in the final analysis. Separate databases were created for each health outcome, with participants lacking data on a specific

health outcome excluded from the corresponding database. The number of participants included in each health outcome analysis is shown in Fig. 1.

Adverse childhood experiences

The BRFSS ACE module consists of 11 items, which are detailed in eTable 1 (Supplementary Content). These items were grouped into eight categories of adverse experiences: three types of abuse (physical, emotional, and sexual) and five types of household challenges (household member substance misuse, parental incarceration, mental illness, parental divorce, and witnessing intimate partner violence). All questions pertained to experiences occurring before the participants reached 18 years of age. The ACE score, ranging from 0 to 8, was calculated by summing the reported ACEs, reflecting the level of exposure to ACEs. Participants were subsequently categorized into five groups based on their total ACE scores: 0, 1, 2, 3, and 4 or more ACEs, consistent with previous studies using the BRFSS database to define ACE thresholds and score distributions [7, 18]. The BRFSS ACE measure

demonstrated good internal consistency, with a Cronbach's alpha coefficient of 0.80.

Socioeconomic inequality

Income level of participants was used to represent socioeconomic inequality in the study. Household income data from all sources were collected through the BRFSS survey and categorized into the following income brackets: <\$10,000, \$10,000–\$14,999, \$15,000–\$19,999, \$20,000–\$24,999, \$25,000–\$34,999, \$35,000–\$49,999, \$50,000–\$74,999, and ≥\$75,000. Based on the per capita income of the United States and a previous study [19], participants with an income of less than \$25,000 were classified as the low-income group.

Covariates

Basic socio-demographic characteristics, including age, gender (male or female), race (White and other), marital status (married, divorced, widowed, separated, never married, and a member of an unmarried couple), and education (did not graduate high school, graduated high school, attended college or technical school,

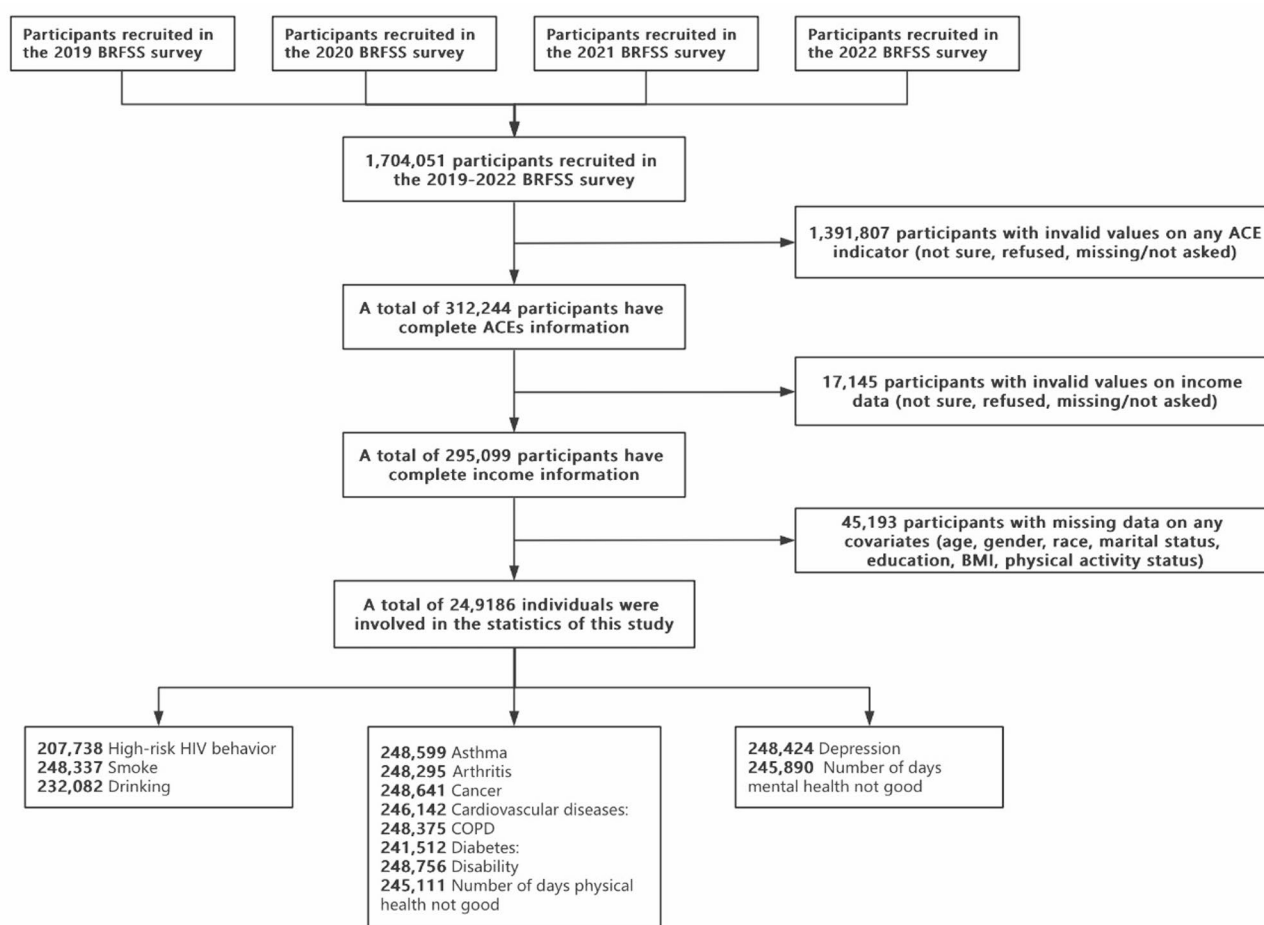


Fig. 1 Flowchart of screening study participants (inclusion and exclusion criteria)

and graduated from college or technical school), were collected through telephone interviews conducted by trained staff. The BMI was calculated by dividing weight in kilograms by height in meters squared. Age and BMI were analyzed as both continuous and categorical variables, with age divided into three groups (18–44, 45–64, and 65–80 years), and BMI categorized into three classes: $<25.0 \text{ kg/m}^2$ (normal), $25.0\text{--}29.9 \text{ kg/m}^2$ (overweight), and $\geq 30.0 \text{ kg/m}^2$ (obese). Low physical activity was defined as self-reporting no physical activity or exercise other than normal work in the previous 30 days.

Outcome variables

Physical and mental health conditions

Physical and mental health conditions were assessed through self-reported disease diagnoses and the days of poor physical/mental health. Physical health conditions encompass CVD (heart attacks/myocardial infarction, angina/coronary heart disease, and stroke), chronic obstructive pulmonary disease (COPD), asthma, arthritis, cancer, diabetes, and disability. Besides, the number of days in the previous month during which participants reported poor physical health due to illnesses or injuries was considered as days of poor physical health condition. Mental health conditions were assessed based on self-reported depression, as well as the number of days in the past 30 days when participants experienced poor mental health, including episodes of stress, depression, and emotional difficulties.

High-risk behaviors

Smoking status was characterized as current smoker or non-current smoker, according to the information provided in the tobacco use section. Drinking was classified based on the responses in the alcohol use section, focusing on adults who reported consuming at least one alcoholic drink in the last 30 days. High-risk human immunodeficiency virus (HIV) behavior was assessed through self-reported HIV risk. Participants were classified as engaging in high-risk HIV behavior if they reported any of the following behaviors (Yes/No): (1) having injected any drug other than those prescribed in the past year; (2) having been treated for a sexually transmitted disease in the past year; (3) having given or received money or drugs in exchange for sex in the past year; (4) having engaged in anal sex without a condom in the past year; (5) having had four or more sex partners in the past year [7]. Participants were not required to specify which behaviors applied to them.

Statistical analysis

Categorical variables were presented as counts (percentages). Continuous variables in this study were normally distributed and were therefore expressed as means (SDs).

Chi-square tests were used for categorical variables, while an analysis of variance (ANOVA) was conducted for continuous variables to assess group differences. Binary logistic regression models were utilized to calculate odds ratios (ORs) and 95% confidence intervals (CIs) to examine the associations of ACEs/income with physical/mental health conditions (including CVD, COPD, asthma, arthritis, cancer, diabetes, disability, and depression) and high-risk behaviors (including smoking, drinking, and HIV-risk behavior). Linear regression models were also employed to calculate β coefficients and 95% CIs to evaluate the relationship between ACEs/income and the days of poor physical/mental health. Specifically, the cumulative ACE score was included in the models to estimate the impact of each unit increase in ACE score on physical/mental health and high-risk behaviors. Participants were categorized into five groups based on their ACE scores, and the regression models were applied to compare the effects of different levels of ACE exposure on health outcomes. Trend testing was conducted to assess the statistical significance of the likelihood of an increase or decrease in the odds of outcome variables for each level of ACE exposure or income increase.

A mediation effect model was implemented using the ‘mediation’ package in R software to investigate the potential mediating role of socioeconomic inequality in the relationship between ACEs and health outcomes. In particular, logistic regression models were conducted to examine the relationship between ACE scores and low-income ($X \rightarrow M$), controlling for covariates. Subsequently, either logistic regression or linear regression models were used to explore the associations between low income and health outcomes ($M \rightarrow Y$). Upon establishing that a significant relationship exists between these variables, further analysis was carried out to investigate the mediating effect of low income on the relationship between ACE exposure and adverse health outcomes or high-risk behaviors. This mediation model employed a quasi-Bayesian Monte Carlo method with 1000 simulations for stability. The average causal mediation effect (ACME) quantifies the indirect impact of socioeconomic inequality (as a mediator) on the relationships of ACEs (as exposure) with health outcomes and high-risk behaviors (as outcomes). The average direct effect (ADE) represents the direct influence of the exposure on the outcome. The proportion mediated by socioeconomic inequality was calculated by dividing the ACME by the total effect (ACME + ADE) [20]. Additionally, sensitivity analyses were conducted by including income as a continuous variable in the mediation models.

The significance level was set at $P < 0.05$. All statistical analyses were performed using R 4.0.2.

Results

Table 1 presents the baseline characteristics of the study population. Among the 249,186 participants, the majority were female (52.24%) and white (79.62%). Over half of the participants were married (53.86%), and 39.39% of the participants graduated from college or technical school. In terms of ACEs, 62.32% of participants reported having experienced at least one ACE, with 16.28% reporting four or more ACEs. Emotional abuse was the most prevalent among the eight types of ACEs. Overall, higher ACE scores correlated with higher BMI and lower levels of physical activity engagement. Compared to participants with no ACE exposure, those with four or more ACEs were more likely to have lower levels of education (college or technical school: 42.98% vs. 30.70%; $P < 0.001$) and report higher rates of divorce (11.03% vs. 17.92%; $P < 0.001$). Besides, high ACE exposure (ACE score ≥ 4) was significantly linked to an increasing trend in the prevalence of various high-risk behaviors, and physical and mental disorders, including smoking, high-risk HIV behavior, COPD, asthma, arthritis, disability, and depression. Furthermore, participants with four or more ACEs reported more self-perceived poor physical health days (mean: 9.96 vs. 7.82; $P < 0.001$) and poor mental health days (mean: 10.60 vs. 6.01; $P < 0.001$) compared to those with no ACE exposure. Participants with ACEs also exhibited significant socioeconomic inequality. Specifically, those in the high ACE exposure group were more likely to have low incomes (income $< \$10k$: 5.63% vs. 2.62%; $P < 0.001$).

Table 2 presents the correlations between ACEs and high-risk behaviors, as well as the influence of income on these behaviors. Significant associations were observed between ACEs and high-risk behaviors, with higher ACE scores being associated with higher rates of drinking ($OR = 1.04$; 95% CI : 1.04–1.05), smoking ($OR = 1.23$; 95% CI : 1.22–1.23), and engagement in high-risk HIV behavior ($OR = 1.26$; 95% CI : 1.25–1.27). Compared to participants with no ACEs, those with high ACE scores (ACE score ≥ 4) demonstrated a nearly threefold increase in the likelihood of smoking ($OR = 2.87$; 95% CI : 2.79–2.94) and a nearly fourfold increase in the likelihood of engaging in high-risk HIV behavior ($OR = 3.99$; 95% CI : 3.72–4.30). Besides, smoking behavior was significantly associated with income, with individuals in the lower income group (income $< \$10k$) being 47% ($OR = 1.47$; 95% CI : 1.40–1.55) more likely to smoke compared to those in the higher income group (income $\geq \$75k$).

Table 3 shows the associations between ACEs and mental health, as well as the influence of income on mental health. A significant association was found between ACEs and depression, with each unit increase in ACE score corresponding to a 34% increase in the likelihood of depression ($OR = 1.34$; 95% CI : 1.34–1.35). Participants

with high ACE exposure (ACE score ≥ 4) exhibited nearly five times higher odds of depression ($OR = 4.87$; 95% CI : 4.72–5.02) compared to those with no ACE exposure. The linear regression model further indicated that each point increase in ACE score was associated with a 0.93-day increase ($\beta = 0.93$; 95% CI : 0.92–0.95) in self-reported poor mental health days per month. Furthermore, income was strongly linked to mental health. Individuals with low income (income $< \$10k$) exhibited significantly higher odds of depression ($OR = 2.88$; 95% CI : 2.72–3.05) and reported more mentally unhealthy days per month ($\beta = 4.35$; 95% CI : 4.17–4.54) compared to those with higher income (income $\geq \$75k$).

Table 4 presents the correlations between ACEs and physical health, as well as the influence of income on physical health. Compared to participants with no ACE exposure, participants with four or more ACEs exhibited a higher likelihood of suffering from various physical diseases (including asthma, arthritis, cancer, CVD, COPD, diabetes, and disability) and reported more days of poor physical health condition. Moreover, participants with low income (income $< \$10k$) had significantly higher odds of experiencing asthma, arthritis, cancer, CVD, COPD, diabetes, disability, and a greater number of days with poor physical health compared to those with higher income (income $\geq \$75k$). Furthermore, the associations of the variables involved in the regression models with high-risk behaviors, mental health, and physical health are shown in the supplementary content (eTables 3, 4 and 5).

Based on the observed associations between ACEs, income, and the aforementioned adverse outcomes, a mediation analysis was conducted to determine whether socioeconomic inequality mediated the relationship between ACEs and health/behavior (Table 5). After adjusting for covariates, it was found that ACEs directly influenced all high-risk behaviors, as well as adverse physical and mental health conditions examined in this study. The mediating role of socioeconomic inequality was evident for most adverse health outcomes, except for cancer and high-risk HIV behavior. Specifically, the proportion of the total effect mediated by socioeconomic inequality exceeded 5% for diabetes (6.87%), disability (6.17%), COPD (5.38%), CVD (5.02%), and days of poor physical health condition (5.83%). Furthermore, the results remained robust when income was treated as a continuous mediator variable (eTable 6).

Discussion

Our study revealed that the accumulation of ACEs was associated with an increased likelihood of experiencing negative health outcomes, which encompassed physical and mental illnesses, adverse behaviors, as well as days of poor physical/mental health. Furthermore, our findings

Table 1 Characteristics of the study populations according to ACE score groups

Characteristics	Total participants	ACE scores					P values
		0 ACE	1 ACE	2 ACEs	3 ACEs	≥ 4 ACEs	
Age, mean (SD)	55.95 (17.09)	59.98 (16.33)	56.76 (16.95)	54.7 (16.88)	52.66 (16.79)	48.3 (16.26)	< 0.001
18-44y	67,600 (27.13)	18,407 (19.60)	14,885 (25.48)	9733 (28.66)	7300 (32.67)	17,275 (42.59)	
45-64y	88,083 (35.35)	30,680 (32.67)	20,435 (34.97)	12,734 (37.50)	8568 (38.34)	15,666 (38.63)	
65-80y	93,503 (37.52)	44,809 (47.72)	23,109 (39.55)	11,489 (33.83)	6478 (28.99)	7618 (18.78)	
Gender, n (%)							< 0.001
Male	119,003 (47.76)	46,040 (49.03)	29,394 (50.31)	16,531 (48.68)	10,447 (46.75)	16,591 (40.91)	
Female	130,183 (52.24)	47,856 (50.97)	29,035 (49.69)	17,425 (51.32)	11,899 (53.25)	23,968 (59.09)	
White ethnicity or race, n (%)	198,413 (79.62)	77,588 (82.63)	46,392 (79.40)	26,680 (78.57)	17,225 (77.08)	30,528 (75.27)	< 0.001
Marital status, n (%)							< 0.001
Married	134,209 (53.86)	55,120 (58.70)	31,986 (54.74)	17,856 (52.59)	11,091 (49.63)	18,156 (44.76)	
Divorced	34,129 (13.70)	10,354 (11.03)	7770 (13.30)	5075 (14.95)	3660 (16.38)	7270 (17.92)	
Widowed	29,559 (11.86)	14,335 (15.27)	7012 (12.00)	3410 (10.04)	1972 (8.82)	2830 (6.98)	
Separated	4792 (1.92)	1230 (1.31)	1010 (1.73)	657 (1.93)	547 (2.45)	1348 (3.32)	
Never married	38,214 (15.34)	10,998 (11.71)	8958 (15.33)	5729 (16.87)	4089 (18.30)	8440 (20.81)	
A member of an unmarried couple	8283 (3.32)	1859 (1.98)	1693 (2.90)	1229 (3.62)	987 (4.42)	2515 (6.20)	
BMI, mean (SD)	28.77 (6.49)	28.26 (6.01)	28.7 (6.33)	28.99 (6.62)	29.26 (6.85)	29.59 (7.30)	< 0.001
<25 kg/m ²	6174 (2.51)	1591 (1.71)	1349 (2.34)	968 (2.89)	697 (3.18)	1569 (3.95)	
25-29.9 kg/m ²	152,238 (61.92)	61,535 (66.09)	36,228 (62.82)	20,102 (60.10)	12,667 (57.71)	21,706 (54.68)	
≥30 kg/m ²	87,464 (35.57)	29,982 (32.20)	20,096 (34.84)	12,378 (37.01)	8586 (39.12)	16,422 (41.37)	
Education, n (%)							< 0.001
Did not graduate high school	14,070 (5.65)	4694 (5.00)	3127 (5.35)	1849 (5.45)	1280 (5.73)	3120 (7.69)	
Graduated high school	64,705 (25.97)	23,809 (25.36)	15,122 (25.88)	8675 (25.55)	5817 (26.03)	11,282 (27.82)	
Attended college or technical school	72,252 (29.00)	25,036 (26.66)	16,442 (28.14)	10,065 (29.64)	7004 (31.34)	13,705 (33.79)	
Graduated from college or technical school	98,159 (39.39)	40,357 (42.98)	23,738 (40.63)	13,367 (39.37)	8245 (36.90)	12,452 (30.70)	
Income, n (%)							< 0.001
< 10k	8420 (3.38)	2464 (2.62)	1723 (2.95)	1128 (3.32)	823 (3.68)	2282 (5.63)	
10-15k	9982 (4.01)	3146 (3.35)	2127 (3.64)	1305 (3.84)	1046 (4.68)	2358 (5.81)	
15-20k	14,644 (5.88)	4882 (5.20)	3316 (5.68)	1961 (5.78)	1417 (6.34)	3068 (7.56)	
20-25k	19,737 (7.92)	6950 (7.40)	4526 (7.75)	2556 (7.53)	1808 (8.09)	3897 (9.61)	
25-35k	27,121 (10.88)	9891 (10.53)	6260 (10.71)	3735 (11.00)	2507 (11.22)	4728 (11.66)	
35-50k	35,803 (14.37)	13,603 (14.49)	8401 (14.38)	4858 (14.31)	3199 (14.32)	5742 (14.16)	
50-75k	42,288 (16.97)	16,444 (17.51)	9986 (17.09)	5742 (16.91)	3685 (16.49)	6431 (15.86)	
≥ 75k	91,191 (36.60)	36,516 (38.89)	22,090 (37.81)	12,671 (37.32)	7861 (35.18)	12,053 (29.72)	
Low physical activity, n (%)	62,202 (24.96)	23,127 (24.63)	14,504 (24.82)	8351 (24.59)	5590 (25.02)	10,630 (26.21)	< 0.001
CVD, n (%)	30,870 (12.39)	11,842 (12.61)	7223 (12.36)	4209 (12.40)	2707 (12.11)	4889 (12.06)	0.039
COPD, n (%)	21,735 (8.75)	6327 (6.76)	4684 (8.04)	3084 (9.11)	2327 (10.45)	5313 (13.16)	< 0.001
Asthma, n (%)	33,617 (13.52)	9381 (10.01)	7122 (12.21)	4794 (14.16)	3694 (16.59)	8626 (21.34)	< 0.001
Arthritis, n (%)	87,573 (35.27)	31,697 (33.87)	20,248 (34.77)	12,092 (35.73)	8122 (36.48)	15,414 (38.19)	< 0.001
Cancer, n (%)	26,302 (10.58)	10,773 (11.50)	6259 (10.73)	3405 (10.05)	2132 (9.57)	3733 (9.23)	< 0.001
Diabetes, n (%)	35,960 (14.89)	13,962 (15.29)	8347 (14.71)	4967 (15.10)	3208 (14.87)	5476 (14.04)	< 0.001
Disability, n (%)	17,958 (7.22)	4681 (4.99)	3356 (5.75)	2348 (6.93)	1979 (8.87)	5594 (13.83)	< 0.001
Days of poor physical health condition (SD)	4.09 (8.62)	3.23 (7.82)	3.76 (8.30)	4.24 (8.69)	4.85 (9.21)	6 (9.96)	< 0.001
Depression, n (%)	48,905 (19.69)	9562 (10.21)	9082 (15.58)	7622 (22.51)	6235 (28.03)	16,404 (40.65)	< 0.001
Days of poor mental health condition (SD)	3.94 (8.04)	2.14 (6.01)	3.11 (7.08)	4.35 (8.23)	5.49 (9.06)	8.11 (10.60)	< 0.001
Drinking, n (%)	129,220 (55.68)	45,973 (52.61)	31,134 (57.02)	18,406 (58.04)	12,181 (58.50)	21,526 (57.32)	< 0.001
Smoking, n (%)	106,909 (43.05)	33,231 (35.52)	24,349 (41.83)	15,456 (45.67)	10,890 (48.90)	22,983 (56.80)	< 0.001
High-risk HIV behavior, n (%)	8478 (4.08)	1197 (1.53)	1453 (2.98)	1353 (4.79)	1133 (6.09)	3342 (9.84)	< 0.001

Note: Data are presented as mean (SD) or n (%). ACEs, adverse childhood experiences; SD, standard deviation; BMI, body mass index; CVD, cardiovascular diseases; COPD, chronic obstructive pulmonary disease

a: Chi-square test for categorical variables to assess the disparities between groups

b: Analysis of variance for continuous variables to assess the disparities between groups

Table 2 Associations of ACEs and income with high-risk behaviors

Exposures	OR (95% CI)		
	Drinking	Smoking	High-risk HIV behavior
ACEs^a			
Each unit increase	1.04 (1.04, 1.05)**	1.23 (1.22, 1.23)**	1.26 (1.25, 1.27)**
0 ACE	Reference	Reference	Reference
1 ACE	1.19 (1.16, 1.21)**	1.38 (1.35, 1.41)**	1.57 (1.45, 1.70)**
2 ACEs	1.22 (1.19, 1.26)**	1.69 (1.64, 1.73)**	2.36 (2.18, 2.56)**
3 ACEs	1.26 (1.22, 1.30)**	1.98 (1.92, 2.04)**	2.78 (2.55, 3.03)**
≥ 4 ACEs	1.26 (1.22, 1.29)**	2.87 (2.79, 2.94)**	3.99 (3.72, 4.30)**
P for trend	< 0.001	< 0.001	< 0.001
Income^b			
< 10k	0.31 (0.29, 0.32)**	1.47 (1.40, 1.55)**	0.98 (0.88, 1.10)
10-15k	0.28 (0.26, 0.29)**	1.47 (1.49, 1.54)**	0.92 (0.81, 1.03)
15-20k	0.34 (0.32, 0.35)**	1.39 (1.33, 1.44)**	0.96 (0.87, 1.06)
20-25k	0.39 (0.37, 0.40)**	1.34 (1.30, 1.39)**	0.92 (0.84, 1.01)
25-35k	0.49 (0.48, 0.51)**	1.26 (1.22, 1.30)**	0.96 (0.88, 1.04)
35-50k	0.58 (0.56, 0.60)**	1.23 (1.20, 1.27)**	0.89 (0.82, 0.96)*
50-75k	0.70 (0.68, 0.72)**	1.18 (1.15, 1.21)**	0.93 (0.86, 1.00)
≥ 75k	Reference	Reference	Reference
P for trend	< 0.001	< 0.001	0.427

Note: ACEs, adverse childhood experiences

a: Adjusted for age, gender, race, marital status, BMI, education, physical activity and income

b: Adjusted for age, gender, race, marital status, BMI, education, physical activity and ACE score

***P* < 0.001

**P* < 0.01

Table 3 Associations of ACEs and income with mental health outcomes

Exposures	OR (95% CI)	
	Depressive,	Days of poor mental
	OR (95% CI)	health condition, β (95%CI)
ACEs^a		
Each unit increase	1.34 (1.34, 1.35)**	0.93 (0.92, 0.95)**
0 ACE	Reference	Reference
1 ACE	1.58 (1.53, 1.63)**	0.70 (0.62, 0.78)**
2 ACEs	2.41 (2.32, 2.49)**	1.73 (1.63, 1.82)**
3 ACEs	3.08 (2.96, 3.20)**	2.61 (2.50, 2.73)**
≥ 4 ACEs	4.87 (4.72, 5.02)**	4.63 (4.53, 4.72)**
P for trend	< 0.001	< 0.001
Income^b		
< 10k	2.88 (2.72, 3.05)**	4.35 (4.17, 4.54)**
10-15k	2.64 (2.50, 2.78)**	3.55 (3.38, 3.72)**
15-20k	2.13 (2.04, 2.24)**	2.61 (2.46, 2.75)**
20-25k	1.82 (1.74, 1.90)**	2.01 (1.88, 2.14)**
25-35k	1.60 (1.54, 1.67)**	1.39 (1.28, 1.50)**
35-50k	1.31 (1.26, 1.36)**	0.79 (0.69, 0.88)**
50-75k	1.22 (1.18, 1.26)**	0.56 (0.47, 0.65)**
≥ 75k	Reference	Reference
P for trend	< 0.001	< 0.001

Note: ACEs, adverse childhood experiences

a: Adjusted for age, gender, race, marital status, BMI, education, physical activity and income

b: Adjusted for age, gender, race, marital status, BMI, education, physical activity and ACE score

***P* < 0.001

**P* < 0.01

suggested that socioeconomic inequality served as a risk factor for adverse health outcomes and might mediate the health risks associated with ACEs, suggesting that socioeconomic inequality plays a crucial role in the associations between ACEs and both health conditions and high-risk behaviors.

Utilizing a large sample size, our study found that approximately 62.32% of participants reported one or more ACEs, aligning with the high prevalence observed in other regions and populations. Besides, this research contributed to a deeper understanding of the impacts of ACEs on broader health and behavior. Consistent with our findings, previous studies have demonstrated that adults who experienced ACEs were more likely to engage in health-risk behaviors, such as poor dietary habits, [17] substance abuse, [21] and non-suicidal self-injury [22]. Recent cross-sectional studies have also shown that ACEs have a pervasive effect on multiple bodily systems, including the cardiovascular, respiratory, digestive, and nervous systems, even at relatively low levels of exposure. Furthermore, ACEs have been identified as predictors of several mental health disorders, including anxiety, attention-deficit hyperactivity disorder, and substance use disorder [23, 24]. Importantly, these health consequences may become evident in early adulthood, further highlighting the long-term impact of ACEs on individuals' well-being [25]. Beyond the significant health burden, ACEs also impose substantial financial costs. A 2021

Table 4 Associations of ACEs and income with physical health

Exposures	OR (95% CI)							β (95% CI)
	Asthma	Arthritis	Cancer	CVD	COPD	Diabetes	Disability	Days of poor physical health condition
ACEs^a								
Each unit increases	1.14 (1.13, 1.15)**	1.16 (1.16, 1.17)**	1.08 (1.07, 1.09)**	1.13 (1.12, 1.14)	1.22 (1.21, 1.23)**	1.05 (1.04, 1.06)**	1.25 (1.24, 1.26)**	0.53 (0.51, 0.55)**
0 ACE	Reference	Reference	Reference	Reference	Reference	Reference	Reference	Reference
1 ACE	1.20 (1.16, 1.24)**	1.23 (1.20, 1.26)**	1.08 (1.04, 1.11)**	1.12 (1.09, 1.16)	1.33 (1.28, 1.39)**	1.02 (0.99, 1.05)**	1.18 (1.13, 1.24)**	0.59 (0.50, 0.67)**
2 ACEs	1.37 (1.32, 1.43)**	1.42 (1.38, 1.47)**	1.11 (1.07, 1.16)**	1.27 (1.22, 1.33)	1.64 (1.57, 1.72)**	1.13 (1.09, 1.17)**	1.48 (1.40, 1.56)**	1.10 (1.00, 1.20)**
3 ACEs	1.59 (1.52, 1.66)**	1.62 (1.56, 1.68)**	1.17 (1.11, 1.23)**	1.38 (1.32, 1.45)	1.99 (1.89, 2.10)**	1.17 (1.12, 1.22)**	1.90 (1.80, 2.02)**	1.67 (1.55, 1.78)**
≥ 4 ACEs	1.98 (1.91, 2.05)**	2.16 (2.10, 2.22)**	1.42 (1.36, 1.48)**	1.77 (1.70, 1.84)	2.84 (2.72, 2.97)**	1.26 (1.22, 1.31)**	3.03 (2.89, 3.17)**	2.67 (2.57, 2.77)**
P for trend	< 0.001		< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
Income^b								
< 10k	1.78 (1.67, 1.89)**	2.07 (1.96, 2.19)**	1.14 (1.05, 1.24)*	2.83 (2.63, 3.04)**	4.16 (3.86, 4.48)**	2.09 (1.96, 2.24)**	8.13 (7.52, 8.78)**	5.94 (5.74, 6.13)**
10-15k	1.66 (1.56, 1.76)**	1.95 (1.86, 2.06)**	1.11 (1.04, 1.20)*	2.58 (2.42, 2.75)**	3.89 (3.64, 4.17)**	2.10 (1.98, 2.24)**	6.78 (6.29, 7.30)**	5.39 (5.21, 5.58)**
15-20k	1.46 (1.38, 1.54)**	1.60 (1.53, 1.67)**	1.07 (1.01, 1.14)	2.20 (2.08, 2.33)**	3.02 (2.83, 3.22)**	1.77 (1.67, 1.87)**	5.09 (4.74, 5.46)**	3.80 (3.65, 3.96)**
20-25k	1.30 (1.24, 1.37)**	1.40 (1.34, 1.45)**	1.04 (0.99, 1.10)	1.88 (1.79, 1.99)**	2.59 (2.44, 2.75)**	1.65 (1.57, 1.74)**	4.02 (3.76, 4.30)**	2.79 (2.65, 2.92)**
25-35k	1.17 (1.12, 1.22)**	1.30 (1.26, 1.35)**	1.06 (1.01, 1.12)	1.63 (1.55, 1.71)**	2.14 (2.03, 2.27)**	1.46 (1.39, 1.52)**	3.06 (2.87, 3.27)**	1.76 (1.64, 1.88)**
35-50k	1.06 (1.02, 1.10)*	1.16 (1.13, 1.20)**	1.04 (0.99, 1.08)	1.38 (1.32, 1.44)**	1.80 (1.71, 1.90)**	1.32 (1.27, 1.38)**	2.14 (2.00, 2.28)**	1.01 (0.90, 1.11)**
50-75k	1.02 (0.98, 1.06)	1.14 (1.11, 1.17)**	1.04 (1.00, 1.09)	1.22 (1.17, 1.27)**	1.45 (1.38, 1.53)**	1.26 (1.21, 1.31)**	1.56 (1.46, 1.67)**	0.52 (0.43, 0.62)**
≥ 75k	Reference	Reference	Reference	Reference	Reference	Reference	Reference	Reference
P for trend	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001

Note: ACEs, adverse childhood experiences; CVD, cardiovascular diseases; COPD, chronic obstructive pulmonary disease

a: Adjusted for age, gender, race, marital status, BMI, education, physical activity and income

b: Adjusted for age, gender, race, marital status, BMI, education, physical activity and ACE score

** $P < 0.001$

* $P < 0.01$

meta-analysis conducted across 28 European countries revealed that ACEs contributed to significant economic burdens for all surveyed nations, ranging from US\$1 billion in Montenegro to \$129.4 billion in Germany [26]. Similarly, a 2019 report indicated that the economic costs attributed to ACEs represented approximately 2.7% of GDP in Europe and 3.5% in North America [27].

The present study also highlighted the role of ACEs in exacerbating socioeconomic inequality. The association between ACEs and socioeconomic factors is a complex public health issue that remains not yet fully understood. Firstly, there is an ongoing debate about whether poverty should be classified as an ACE. Secondly, socioeconomic inequality has been identified as a significant risk factor for the occurrence of ACEs, with the prevalence of ACEs increasing substantially along the household income

gradient [28, 29]. For example, a prospective cohort study based on data from the Avon Longitudinal Study of Parents and Children found that individuals from lower socioeconomic backgrounds were more likely to experience multiple ACEs compared with those from higher socioeconomic backgrounds [30]. Thirdly, ACEs may profoundly impact an individual's future socioeconomic status by affecting their educational attainment, employment stability, and social achievements [31]. In our study, we observed that individuals with higher ACE exposure were more likely to experience lower income levels and reduced educational attainment in adulthood compared to those with fewer ACEs. These findings are consistent with previous research by Zielinski et al., which revealed that adults who experienced physical or emotional abuse or severe neglect in childhood were more than twice as

Table 5 Low income (< 25k) partially mediates the relationship between ACE scores (continuous variable) and high-risk behaviors, physical health and mental health

Outcomes	β (95% CI)			Mediation proportion (%) (95% CI)
	Total effect	Direct effect	Indirect effect	
Physical health				
Asthma	0.0134 (0.0130, 0.0140)**	0.0131 (0.0126, 0.0137)**	0.0003 (0.0003, 0.0005)**	2.27 (2.28, 2.45)**
Arthritis	0.0281 (0.0272, 0.0289)**	0.0274 (0.0267, 0.0284)**	0.0007 (0.0006, 0.0008)**	2.55 (1.97, 2.99)**
Cancer	0.0064 (0.0058, 0.0071)**	0.0064 (0.0058, 0.0071)**	0.0000 (0.0000, 0.0000)	0.48 (-0.06, 1.08)
CVD	0.0113 (0.0106, 0.0119)**	0.0107 (0.0101, 0.0113)**	0.0006 (0.0002, 0.0004)**	5.02 (3.79, 6.20)**
COPD	0.0132 (0.0126, 0.0135)**	0.0125 (0.0121, 0.0129)**	0.0004 (0.0004, 0.0007)**	5.38 (3.45, 5.38)**
Diabetes	0.0060 (0.0054, 0.0068)**	0.0056 (0.0049, 0.0063)**	0.0004 (0.0004, 0.0006)**	6.87 (5.94, 9.73)**
Disability	0.0115 (0.0112, 0.0119)**	0.0108 (0.0105, 0.0111)**	0.0007 (0.0006, 0.0009)**	6.17 (4.98, 7.58)**
Days of poor physical health condition	0.5739 (0.5546, 0.5934) **	0.5404 (0.5216, 0.5577) **	0.0335 (0.0274, 0.0404) **	5.83 (4.78, 7.06) **
Mental health				
Depression	0.0345 (0.0341, 0.0351)**	0.0338 (0.0333, 0.0344)**	0.0007 (0.0006, 0.0009)**	1.91 (1.76, 2.63)**
Days of poor mental health condition	0.9612 (0.9415, 0.9798) **	0.9387 (0.9194, 0.9568) **	0.0225 (0.0183, 0.0273) **	2.33 (1.90, 2.86) **
High-risk behavior				
Drinking	0.0067 (0.0054, 0.0077)**	0.0082 (0.0071, 0.0093)**	-0.0014 (-0.0020, -0.0013)**	-21.17 (-33.65, -18.04)**
Smoking	0.0449 (0.0440, 0.0458)**	0.0445 (0.0435, 0.0454)**	0.0005 (0.0003, 0.0005)**	1.02 (0.72, 1.19)**
High-risk HIV behavior	0.0058 (0.0056, 0.0060)**	0.0058 (0.0056, 0.0060)**	0.0000 (0.0000, 0.0000)	0.03 (-0.33, 0.28)

Note: ACEs, adverse childhood experiences; CVD, cardiovascular diseases; COPD, chronic obstructive pulmonary disease

All models adjusted for age, gender, race, marital status, BMI, education and physical activity

** $P < 0.001$; * $P < 0.01$

likely to fall below the federal poverty level in adulthood and to reside in households within the lowest income quartile [32]. Furthermore, our study demonstrated the significant health effect of socioeconomic inequality. Our study further revealed a clear income gradient in the prevalence of nearly all examined adverse health outcomes, with individuals in the lowest income group having an eightfold greater risk of disability compared to those in the highest income group.

Given the contribution of ACEs to socioeconomic inequality and the well-documented association between socioeconomic inequality and adverse health outcomes, [33, 34] it is highly conceivable that socioeconomic inequality may mediate the relationship between ACEs and health outcomes. A study conducted in the United States indicated that 15–20% of the associations between ACEs and outcomes such as tobacco use, binge drinking, obesity, depression, and self-reported health status could be attributed to socioeconomic conditions [15]. Similarly, a study conducted in Japan revealed that SES, measured by self-reported educational attainment and annual household income, mediated 10.1% of the association between ACEs and late-life depressive symptoms [16]. Furthermore, Nagata et al. demonstrated that college educational attainment mediated the relationship between ACEs and unhealthy dietary habits. Specifically, the percentage of the total effect mediated by college educational attainment was 22.69% for high fast-food consumption and 22.94% for sugary beverages, respectively

[17]. The findings of the present study aligned with these limited previous studies and offer a more comprehensive analysis of how socioeconomic inequality mediates the relationship between ACEs and various health outcomes, particularly CVD, COPD, diabetes, and disability. However, socioeconomic inequality in this study was primarily assessed through income. Other socioeconomic factors, such as education and occupation, may also have the impact of ACEs on health outcomes. This highlights the need for further research to explore these factors and refine our understanding of the underlying mechanisms.

The mechanisms underlying the health effects of ACEs are still incompletely understood. Previous research has primarily focused on toxic stress, which arises from prolonged and repeated exposure to significant adversity during the critical developmental period of childhood [35, 36]. This chronic exposure can lead to the activation of the hypothalamic-pituitary-adrenal (HPA) axis, triggering a toxic stress response [35]. This response is characterized by the release of elevated levels of cortisol into the bloodstream, which in turn induces chronic inflammation by increasing the production of reactive oxygen species, C-reactive protein, and cytokines, [37, 38] thereby ultimately impacting physical and mental health. Furthermore, the present study emphasized that socioeconomic inequality might serve as a critical mechanism through which ACEs exerted health effects. Specifically, ACEs can impair the development of crucial brain regions such as the hippocampus, frontal lobe, and

amygdala [39]. These neurological alterations manifest as persistent cognitive impairments and emotional dysregulation, [13] which may subsequently impede educational achievement, professional advancement, and the accumulation of financial resources. Ultimately, this cascade of effects contributes to the perpetuation of socioeconomic disparities across the lifespan, further exacerbating the long-term adverse impacts on health [40].

Nevertheless, it is essential to acknowledge the limitations of this study. Firstly, the cross-sectional study design limits the ability to establish causal relationships between ACEs and health outcomes. Secondly, the study only utilized income to measure socioeconomic inequality, potentially overlooking other factors such as education, employment, assets, and other socioeconomic variables, which may also mediate the health effects of ACEs. Thirdly, the reliance on self-reported data for collecting information on ACEs, high-risk behaviors, and adverse physical and mental outcomes may introduce recall bias. Fourthly, this study did not assess certain temporal aspects of ACEs, such as severity, age of onset, and cumulative exposure, which could significantly influence the likelihood of disease diagnoses. Fifthly, although we adjusted for various personal demographic and lifestyle variables, residual or unmeasured confounding factors could still impact the outcomes. Finally, while our primary focus was on mediation analyses based on existing theoretical frameworks, we recognized that socioeconomic inequality might not only act as a mediator but also serve as a potential moderator in the relationships between ACEs and adult health outcomes. Specifically, socioeconomic factors such as income, education, and access to resources could amplify or attenuate the effects of ACEs, depending on the level of inequality. Individuals from lower socioeconomic backgrounds may experience more severe or prolonged effects of ACEs due to limited access to healthcare, education, and social support, whereas those from higher socioeconomic backgrounds may have more resources to buffer the negative impacts of ACEs. Future research should explicitly explore both the mediating and moderating roles of socioeconomic inequality to provide a more nuanced understanding of how these factors intersect and influence the long-term effects of ACEs on adult health and behaviors.

Given the global prevalence of ACEs, compounded by the ongoing repercussions of armed conflicts, climate change, and forced migration, ACEs will remain a significant public health concern in the future. The present study highlighted the importance of addressing ACEs as a critical factor influencing adult health and behaviors, and offered a fresh perspective for researchers, clinicians, psychotherapists, public health specialists, and decision-makers working to mitigate the long-term impacts of ACEs, as well as informing practices in areas such

as medical services, psychotherapy, psychiatry, social services, and public health policy. Furthermore, this research suggested that socioeconomic inequality was a significant mediator in the relationship between ACEs and health outcomes. Targeted interventions addressing socioeconomic inequality may help reduce the exposure effect of ACEs, especially among vulnerable populations.

Conclusion

This large-scale, population-based, cross-sectional study revealed a high prevalence of ACEs among adults. Exposure to high levels of ACEs was associated with a wide range of negative health outcomes, with socioeconomic inequality playing a key role in mediating these associations. These findings emphasize the need for public health strategies that addressed ACEs and socioeconomic inequality to reduce the long-term burden of chronic diseases and promote better health across the lifespan.

Abbreviations

ACE	Adverse childhood experience
BRFSS	Behavioral Risk Factor Surveillance System
CVD	Cardiovascular disease
COPD	Chronic obstructive pulmonary disease
SES	Socioeconomic status
HIV	Human immunodeficiency virus
BMI	Body mass index
ADE	Average direct effect
ACME	Average causal mediation effect
SD	Standard deviation
OR	Odds ratio
CI	Confidence interval
HPA	Hypothalamic-pituitary-adrenal

Supplementary Information

The online version contains supplementary material available at <https://doi.org/10.1186/s12889-025-23192-3>.

Supplementary Material 1

Acknowledgements

We are grateful to all participants, data managers, and clinical administrative staff involved in this study.

Author contributions

S.Y.L. and Z.Z. wrote the main manuscript text, S.Y.L., Z.Z., W.H.Y., W.C.L., D.L.F., W.W.H., Z.L., and B.J.N. made substantial contributions to the acquisition, analysis, interpretation of data; W.H.Y. and W.M.Y. have drafted the work or substantively revised it.

Funding

The study was funded through grants from the Natural Science Foundation of Hunan Province (2023JJ40801), the Changsha Municipal Natural Science Foundation (kq2208302), and the Natural Science Basic Research Program of Shaanxi Province (2024JC-YBQN-0943).

Data availability

Further information on the BRFSS data and access to the data can be found at: <https://www.cdc.gov/brfss/>.

Declarations

Ethics approval and consent to participate

This study was deemed exempt from institutional review board approval and followed the guidelines of the Declaration of Helsinki. Informed consent was obtained from all the participants.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

Author details

¹Ministry of Education Key Laboratory of Environment and Health, State Key Laboratory of Environmental Health (Incubating), School of Public Health, Tongji Medical College, Huazhong University of Science and Technology, No.13 Hangkong Road, Wuhan 430030, China

²Department of Maternal and Child Health, School of Public Health, Tongji Medical College, Huazhong University of Science and Technology, No.13 Hangkong Road, Wuhan 430030, China

³Xiangya School of Medicine, Central South University, No.172, Tongzipo Road, Changsha 410013, China

⁴Department of Clinical Microbiology and Immunology, College of Pharmacy and Laboratory Medicine Science, Army Medical University, Gaotanyan Street No.30, Shapingba District, Chongqing 400038, China

⁵Affiliated Rehabilitation Hospital of Nanchang University, Nanchang, China

⁶Department of Maternal and Child Health, Xiangya School of Public Health, Central South University, No.172 Tongzipo Road, Changsha 410013, China

⁷Shaanxi Medical Association, Xi'an, China

⁸Shaanxi Provincial Health Industry Association Service Center, Xi'an, China

⁹Department of Health Statistics, School of Public Health, China Medical University, Shenyang, China

Received: 11 December 2024 / Accepted: 15 May 2025

Published online: 27 May 2025

References

1. Finkelhor D, Shattuck A, Turner H, Hamby S. Improving the adverse childhood experiences study scale. *JAMA Pediatr.* 2013;167:70–5. <https://doi.org/10.1001/jamapediatrics.2013.420>.
2. Evans GW, Kim P. Childhood poverty and health: cumulative risk exposure and stress dysregulation. *Psychol Sci.* 2007;18:953–7. <https://doi.org/10.1111/j.1467-9280.2007.02008.x>.
3. Felitti VJ, Anda RF, Nordenberg D, Williamson DF, Spitz AM, Edwards V, Koss MP, Marks JS. Relationship of childhood abuse and household dysfunction to many of the leading causes of death in adults. The adverse childhood experiences (ACE) study. *Am J Prev Med.* 1998;14:245–58. [https://doi.org/10.1016/s0749-3797\(98\)00017-8](https://doi.org/10.1016/s0749-3797(98)00017-8).
4. Peterson C, Aslam MV, Niolon PH, Bacon S, Bellis MA, Mercy JA, Florence C. Economic burden of health conditions associated with adverse childhood experiences among US adults. *JAMA Netw Open.* 2023;6:e2346323. <https://doi.org/10.1001/jamanetworkopen.2023.46323>.
5. Fujiwara T. Impact of adverse childhood experience on physical and mental health: A life-course epidemiology perspective. *Psychiatry Clin Neurosci.* 2022;76:544–51. <https://doi.org/10.1111/pcn.13464>.
6. Lin WH, Chiao C. The relationship between adverse childhood experience and heavy smoking in emerging adulthood: the role of not in education, employment, or training status. *J Adolesc Health.* 2022;70:155–62. <https://doi.org/10.1016/j.jadohealth.2021.07.022>.
7. Campbell JA, Walker RJ, Egede LE. Associations between adverse childhood experiences, High-Risk behaviors, and morbidity in adulthood. *Am J Prev Med.* 2016;50:344–52. <https://doi.org/10.1016/j.amepre.2015.07.022>.
8. Hosseinpoor AR, Stewart Williams JA, Itani L, Chatterji S. Socioeconomic inequality in domains of health: results from the world health surveys. *BMC Public Health.* 2012;12:198. <https://doi.org/10.1186/1471-2458-12-198>.
9. Ye X, Wang Y, Zou Y, Tu J, Tang W, Yu R, Yang S, Huang P. Associations of socio-economic status with infectious diseases mediated by lifestyle, environmental pollution and chronic comorbidities: a comprehensive evaluation based on UK biobank. *Infect Dis Poverty.* 2023;12:5. <https://doi.org/10.1186/s4024-9-023-01056-5>.
10. Amini-Rarani M, Vahedi S, Borjali M, Nosratabadi M. Socioeconomic inequality in congenital heart diseases in Iran. *Int J Equity Health.* 2021;20:251. <https://doi.org/10.1186/s12939-021-01591-3>.
11. Bono F, Matranga D. Socioeconomic inequality in non-communicable diseases in Europe between 2004 and 2015: evidence from the SHARE survey. *Eur J Public Health.* 2019;29:105–10. <https://doi.org/10.1093/eurpub/cky165>.
12. Jaffee SR, Ambler A, Merrick M, Goldman-Mellor S, Odgers CL, Fisher HL, Danese A, Arseneault L. Childhood maltreatment predicts poor economic and educational outcomes in the transition to adulthood. *Am J Public Health.* 2018;108:1142–7. <https://doi.org/10.2105/ajph.2018.304587>.
13. Shonkoff JP, Garner AS. The lifelong effects of early childhood adversity and toxic stress. *Pediatrics.* 2012;129:e232–246. <https://doi.org/10.1542/peds.2011-2663>.
14. Björkenstam E, Helgesson M, Mittendorfer-Rutz E. Childhood adversity and risk of later labor market marginalization in young employees in Sweden. *Eur J Public Health.* 2023;33:264–71. <https://doi.org/10.1093/eurpub/ckad019>.
15. Font SA, Maguire-Jack K. Pathways from childhood abuse and other adversities to adult health risks: the role of adult socioeconomic conditions. *Child Abuse Negl.* 2016;51:390–9. <https://doi.org/10.1016/j.chiabu.2015.05.013>.
16. Yazawa A, Shiba K, Inoue Y, Okuzono SS, Inoue K, Kondo N, Kondo K, Kawachi I. Early childhood adversity and late-life depressive symptoms: unpacking mediation and interaction by adult socioeconomic status. *Soc Psychiatry Psychiatr Epidemiol.* 2022;57:1147–56. <https://doi.org/10.1007/s00127-022-02241-x>.
17. Testa A, Zhang L, Jackson DB, Ganson KT, Raney JH, Nagata JM. Adverse childhood experiences and unhealthy dietary behaviours in adulthood. *Public Health Nutr.* 2024;27:e40. <https://doi.org/10.1017/s1368980024000144>.
18. Guinn AS, Ports KA, Ford DC, Breiding M, Merrick MT. Associations between adverse childhood experiences and acquired brain injury, including traumatic brain injuries, among adults: 2014 BRFSS North Carolina. *Inj Prev.* 2019;25:514–20. <https://doi.org/10.1136/injuryprev-2018-042927>.
19. Keeler C, Max W, Yao T, Wang Y, Zhang X, Sung HY. Smoking behavior in Low- and High-Income adults immediately following California proposition 56 tobacco tax increase. *Am J Public Health.* 2020;110:868–70. <https://doi.org/10.2105/ajph.2020.305615>.
20. Valeri L, Vanderweele TJ. Mediation analysis allowing for exposure-mediator interactions and causal interpretation: theoretical assumptions and implementation with SAS and SPSS macros. *Psychol Methods.* 2013;18:137–50. <https://doi.org/10.1037/a0031034>.
21. Beatty A, Shepard E, Bickford E, Weyandt L. Adverse childhood experiences and prescription stimulant use in adults: A systematic review. *Pharm (Basel).* 2024;12. <https://doi.org/10.3390/pharmacy12020052>.
22. Zhang L, Wang W, Chen Y, Abudoula A, Wang X, Yuan X, Luo Y, Wu M, Ma L. Adverse childhood experiences, unhealthy lifestyle, and nonsuicidal self-injury: findings from six universities in Shaanxi Province, China. *Front Public Health.* 2023;11:1199882. <https://doi.org/10.3389/fpubh.2023.1199882>.
23. Bomysoad RN, Francis LA. Adverse childhood experiences and mental health conditions among adolescents. *J Adolesc Health.* 2020;67:868–70. <https://doi.org/10.1016/j.jadohealth.2020.04.013>.
24. Tzouvara V, Kupdere P, Wilson K, Matthews L, Simpson A, Foye U. Adverse childhood experiences, mental health, and social functioning: A scoping review of the literature. *Child Abuse Negl.* 2023;139:106092. <https://doi.org/10.1016/j.chiabu.2023.106092>.
25. Zhang Z, Wang W, Yuan X, Wang X, Luo Y, Dou L, Zhang L, Wu M. Adverse childhood experiences and subsequent physical and mental health among young adults: results from six universities in China. *Psychiatry Res.* 2024;335:115832. <https://doi.org/10.1016/j.psychres.2024.115832>.
26. Hughes K, Ford K, Bellis MA, Glendinning F, Harrison E, Passmore J. Health and financial costs of adverse childhood experiences in 28 European countries: a systematic review and meta-analysis. *Lancet Public Health.* 2021;6:e848–57. [https://doi.org/10.1016/s2468-2667\(21\)00232-2](https://doi.org/10.1016/s2468-2667(21)00232-2).
27. Bellis MA, Hughes K, Ford K, Ramos Rodriguez G, Sethi D, Passmore J. Life course health consequences and associated annual costs of adverse childhood experiences across Europe and North America: a systematic review and meta-analysis. *Lancet Public Health.* 2019;4:e517–28. [https://doi.org/10.1016/s2468-2667\(19\)30145-8](https://doi.org/10.1016/s2468-2667(19)30145-8).

28. Halfon N, Larson K, Son J, Lu M, Bethell C. Income inequality and the differential effect of adverse childhood experiences in US children. *Acad Pediatr*. 2017;17:S70–8. <https://doi.org/10.1016/j.acap.2016.11.007>.
29. Freisthler B, Merritt DH, LaScala EA. Understanding the ecology of child maltreatment: a review of the literature and directions for future research. *Child Maltreat*. 2006;11:263–80. <https://doi.org/10.1177/1077559506289524>.
30. Houtepen LC, Heron J, Suderman MJ, Fraser A, Chittleborough CR, Howe LD. Associations of adverse childhood experiences with educational attainment and adolescent health and the role of family and socioeconomic factors: A prospective cohort study in the UK. *PLoS Med*. 2020;17:e1003031. <https://doi.org/10.1371/journal.pmed.1003031>.
31. Black MM, Pérez-Escamilla R, Rao SF. Integrating nutrition and child development interventions: scientific basis, evidence of impact, and implementation considerations. *Adv Nutr*. 2015;6:852–9. <https://doi.org/10.3945/an.115.010348>.
32. Zielinski DS. Child maltreatment and adult socioeconomic well-being. *Child Abuse Negl*. 2009;33:666–78. <https://doi.org/10.1016/j.chiabu.2009.09.001>.
33. Pearlin LI, Schieman S, Fazio EM, Meersman SC. Stress, health, and the life course: some conceptual perspectives. *J Health Soc Behav*. 2005;46:205–19. <https://doi.org/10.1177/002214650504600206>.
34. Cohen S, Janicki-Deverts D, Chen E, Matthews KA. Childhood socioeconomic status and adult health. *Ann NY Acad Sci*. 2010;1186:37–55. <https://doi.org/10.1111/j.1749-6632.2009.05334.x>.
35. Dempster KS, O'Leary DD, MacNeil AJ, Hodges GJ, Wade TJ. Linking the hemodynamic consequences of adverse childhood experiences to an altered HPA axis and acute stress response. *Brain Behav Immun*. 2021;93:254–63. <https://doi.org/10.1016/j.bbi.2020.12.018>.
36. Danese A, McEwen BS. Adverse childhood experiences, allostasis, allostatic load, and age-related disease. *Physiol Behav*. 2012;106:29–39. <https://doi.org/10.1016/j.physbeh.2011.08.019>.
37. Iob E, Lacey R, Steptoe A. The long-term association of adverse childhood experiences with C-reactive protein and hair cortisol: cumulative risk versus dimensions of adversity. *Brain Behav Immun*. 2020;87:318–28. <https://doi.org/10.1016/j.bbi.2019.12.019>.
38. Kuhlman KR, Horn SR, Chiang JJ, Bower JE. Early life adversity exposure and circulating markers of inflammation in children and adolescents: A systematic review and meta-analysis. *Brain Behav Immun*. 2020;86:30–42. <https://doi.org/10.1016/j.bbi.2019.04.028>.
39. McLaughlin KA, Weissman D, Bitrán D. Childhood adversity and neural development: A systematic review. *Annu Rev Dev Psychol*. 2019;1:277–312. <https://doi.org/10.1146/annurev-devpsych-121318-084950>.
40. Wang J, Geng L. Effects of socioeconomic status on physical and psychological health: lifestyle as a mediator. *Int J Environ Res Public Health*. 2019;16. <https://doi.org/10.3390/ijerph16020281>.

Publisher's note

Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.