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Clean Cooking Access and Sex Differences in Household Air Pollution Mortality Across Countries

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ABSTRACT: Access to clean cooking could coincide with lower household air pollution (HAP) mortality, but cooking roles alone cannot predict sex differences in attributable mortality. This study matched 2021 World Health Organization age-standardized, all-cause HAP-attributable mortality rates by sex to World Bank clean-cooking access estimates. Paired rates, female–male differences and ratios, correlations, and adjusted regressions were examined across countries. In 180 countries, mean female and male rates were 51.39 and 61.36 per 100,000, respectively. The mean female-minus-male difference was -9.97 (95% confidence interval [CI], -12.82 to -7.13). Male rates were higher in 104 countries, female rates in 21, and both were zero in 55. Access correlated inversely with female (Spearman $\rho = -0.980$) and male mortality ($\rho = -0.977$). In 175 complete cases, a 10-percentage-point higher access level was associated with 14.94 fewer female deaths per 100,000 (95% CI, 13.66–16.22 fewer) and 17.74 fewer male deaths (95% CI, 15.89–19.59 fewer) after adjustment. The female-by-access interaction was $+0.273$ per access point (95% CI, 0.181–0.366), indicating a less negative female slope. These ecological associations cannot establish an intervention effect: clean-cooking access and modeled HAP mortality share household-energy inputs, and countries at universal access often have zero modeled mortality.

1. INTRODUCTION

Polluting cooking fuels and inefficient stoves generate fine particulate matter and other contaminants within and around households. The World Health Organization (WHO) estimated 2.9 million deaths attributable to HAP in 2021 and identifies cardiovascular, respiratory and malignant diseases among the modeled outcomes (WHO, 2025). Expansion of clean cooking is central to Sustainable Development Goal (SDG) 7, while reducing air-pollution mortality relates to SDG 3. Household use of unprocessed biomass also entails fuel collection and local environmental pressures (WHO, 2025; IEA et al., 2025).

Cooking and fuel collection often place women near household emissions for longer periods (WHO, 2025). However, the sex distribution of age-standardized attributable mortality also reflects baseline disease rates and modeled exposure–response relationships (WHO, 2026a). Greater exposure near a stove therefore does not establish a higher female all-cause attributable mortality rate. Global burden estimates document substantial HAP-attributable disease, while exposure estimates differ by fuel type and urban or rural setting (GBD 2021 HAP Collaborators, 2025; Mohajeri et al., 2023). Country-level associations cannot isolate the effect of a cooking intervention.

This study examined whether national clean-cooking access was associated with female and male age-standardized HAP-attributable mortality in 2021 and with the female–male difference. Paired sex differences and associations adjusted for GDP per capita and urbanization were also assessed.

2. MATERIALS AND METHODS

2.1. Study design

This ecological, cross-sectional secondary-data study used countries as the units of analysis. The observation year was 2021, the latest year in the WHO HAP burden series available for this indicator at extraction (WHO, 2026a). Inference refers to countries, not individuals.

2.2. Data sources

WHO Global Health Observatory OData indicator AIR_52, “Household air pollution attributable death rate (per 100 000 population, age-standardized),” supplied the outcomes. The analytic filter was TimeDim=2021, SpatialDimType=COUNTRY, Dim2=GHECAUSE_GHE000000 (all causes), and Dim1=SEX_FMLE or SEX_MLE. NumericValue was used in place of the rounded display string. WHO's uncertainty bounds were retained in the dataset but were not propagated through the country-comparison tests. The outcome is a comparative-risk-assessment estimate rather than a count of directly attributed deaths (WHO, 2026a).

World Bank World Development Indicators supplied EG.CFT.ACCS.ZS (percentage primarily using clean cooking fuels and technologies) (World Bank, 2026a), NY.GDP.PCAP.CD (GDP per capita, current US dollars), and SP.URB.TOTL.IN.ZS (urban population percentage) (World Bank, 2026b). World Bank metadata supplied names, ISO3 codes, regions, and income categories. Clean-cooking estimates draw on the WHO Global Household Energy Database and a hierarchical model; high-income countries can be assumed to have universal access (World Bank, 2026a; Stoner et al., 2020). Table 1 gives definitions and sources. Original API responses and access dates accompany the study.

Table 1. Variable definitions and sources.

Variable	Definition and unit	Code/source
Female/male HAP mortality	All-cause, sex-specific, age-standardized attributable death rate per 100,000	WHO GH0 AIR_52, 2021; GHECAUSE_GHE000000
Clean-cooking access	Population primarily using clean fuels and technologies, %	World Bank EG.CFT.ACCS.ZS, 2021
GDP per capita	Current US\$; natural log in models	World Bank NY.GDP.PCAP.CD, 2021
Urban population	Percentage of total population	World Bank SP.URB.TOTL.IN.ZS, 2021
Female–male gap / ratio	Female minus male rate / female divided by male rate if male >0	Derived from WHO NumericValue

2.3. Country selection and study period

All 217 non-aggregate World Bank country/economy entries were considered and matched to WHO records by ISO3 code. Among 181 economies with sex-specific WHO estimates, Puerto Rico lacked a cooking-access value; 180 entered the primary analysis. Across the 217 entries, 36 lacked a matched WHO rate and 28 lacked access data, with overlap between those groups. Five primary-sample countries lacked GDP per capita (Cuba, Eritrea, Democratic People's Republic of Korea, South Sudan, and Yemen), leaving 175 adjusted-model complete cases. Urbanization was complete in the primary sample. Missing values were not imputed; the accompanying audit lists each exclusion.

2.4. Study variables

Female and male outcomes were age-standardized HAP-attributable death rates per 100,000. Exposure was clean-cooking access on a 0–100 percentage-point scale. GDP per capita was natural-log transformed because of its right-skewed distribution. Urbanization remained on its original percentage scale. Smoking prevalence was omitted because comparable sex-specific coverage was insufficient for this parsimonious country-level analysis.

2.5. Construction of female–male measures

For each country, the absolute gap was female minus male mortality; positive values indicate higher female rates. The female-to-male ratio was calculated only where the male rate was greater than zero. At a zero male rate, the ratio is undefined, including when both rates are zero; no pseudocount was added. These definitions were applied directly to the unrounded WHO numeric rates.

2.6. Statistical analysis

Descriptive statistics were calculated across countries without population weighting. Means, medians, standard deviations, quartiles, and ranges were reported. A paired t-test, 95% t interval, and Cohen's d_z summarized within-country sex differences. The difference distribution was strongly non-normal (Shapiro–Wilk $p=8.42 \times 10^{-16}$), so a Wilcoxon signed-rank test was also reported. Spearman correlation was primary for skewed variables with boundary values; Pearson correlation was supplementary.

Separate ordinary least-squares models regressed each sex-specific rate on cooking access, $\ln(\text{GDP per capita})$, and urbanization, with HC3 robust standard errors. A pooled country–sex model included a female indicator, access, their interaction, and the covariates; standard errors were clustered by country. An additional model used the female-minus-male gap as its outcome. Diagnostics included Breusch–Pagan and residual Shapiro–Wilk tests, variance inflation factors (VIF), and Cook's distances. Sensitivity analyses removed countries above Cook's $D>4/n$ in either sex model and separately restricted access to $<95\%$. Two-sided p-values are reported without multiple-testing adjustment for exploratory secondary comparisons. Reproducible NumPy and SciPy code, numeric outputs, and transformations are supplied.

2.7. Ethical considerations

All data are aggregated, publicly accessible country-level estimates. There were no individual records, recruitment, or intervention; institutional review was not sought for this secondary analysis.

3. RESULTS AND DISCUSSION

3.1. Study sample and descriptive findings

The primary sample comprised 180 countries; 175 had complete covariates for adjusted models. Male mean mortality exceeded female mean mortality, and both distributions were right-skewed (Table 2). In 55 countries, both rates were zero and recorded cooking access was 100%. This concentration at the boundary contributes to the strong observed associations. The female-to-male ratio was defined in 125 countries.

Table 2. Descriptive statistics for the primary sample.

Variable	n	Mean (SD)	Median (Q1–Q3)	Minimum–maximum
Female rate / 100,000	180	51.39 (61.89)	15.00 (0–102.61)	0–227.42
Male rate / 100,000	180	61.36 (74.46)	20.10 (0–124.12)	0–290.01
Clean cooking, %	180	67.69 (37.72)	89.10 (32.93–100)	0–100
Female minus male rate	180	−9.97 (19.34)	−0.92 (−13.53–0)	−102.36–32.93
Female-to-male ratio	125	0.834 (0.171)	0.822 (0.713–0.928)	0.454–1.292
GDP per capita, US\$	175	15,803.77 (22,932.94)	5,274.61 (2,253.29–18,833.07)	264.17–134,965.82
Urban population, %	180	58.71 (22.03)	60.19 (40.57–74.95)	14.44–100

3.2. Regional patterns

Country-weighted mean rates were highest in the WHO Africa region (113.17 per 100,000 for females and 133.55 for males). They were lowest in Europe (6.89 and 8.77, respectively). The median female-minus-male gap was most negative in Africa,

followed by the Western Pacific; medians were zero in Europe and the Eastern Mediterranean (Table 5). These are descriptive summaries of included countries, not population-weighted WHO regional estimates.

Table 5. Descriptive WHO regional patterns in the 180-country sample. Country-weighted means, not WHO population-weighted regional estimates.

WHO region	n	Mean female rate	Mean male rate	Median female-minus-male gap
Africa	47	113.17	133.55	-16.35
Americas	33	16.56	17.39	-0.65
Eastern Mediterranean	19	40.29	43.05	0.00
Europe	49	6.89	8.77	0.00
South-East Asia	10	71.69	84.97	-9.49
Western Pacific	22	71.10	95.28	-12.53

3.3. Sex differences in HAP mortality

The mean female-minus-male rate was -9.97 per 100,000 (95% CI, -12.82 to -7.13). The paired t-test and Wilcoxon test both indicated a difference (Table 3). Male rates were higher in 104 countries, female rates in 21, and both rates were zero in 55. The direction varied by country: Haiti had the largest positive gap and Kiribati the largest negative gap. Figure 1 shows the paired rates; the accompanying ranked-country plot gives all gaps.

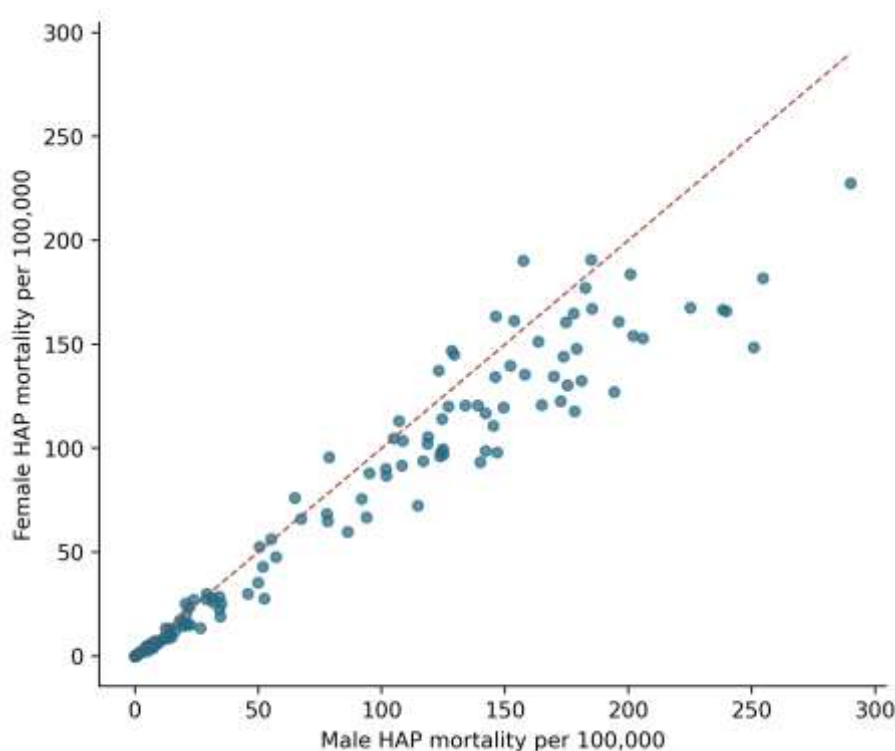


Figure 1. Female versus male age-standardized HAP-attributable mortality rate (per 100,000) in 180 countries; dashed line is equality.

3.4. Clean-cooking access and mortality

Clean-cooking access had a strong inverse correlation with both female and male modeled rates (Table 3; Figure 2A–B). In adjusted models, 10 percentage points higher access corresponded to 14.94 fewer female and 17.74 fewer male deaths per

100,000 (Table 4). These associations are partly expected because the exposure and modeled outcomes share household-energy inputs. They do not estimate the effect of increasing access.

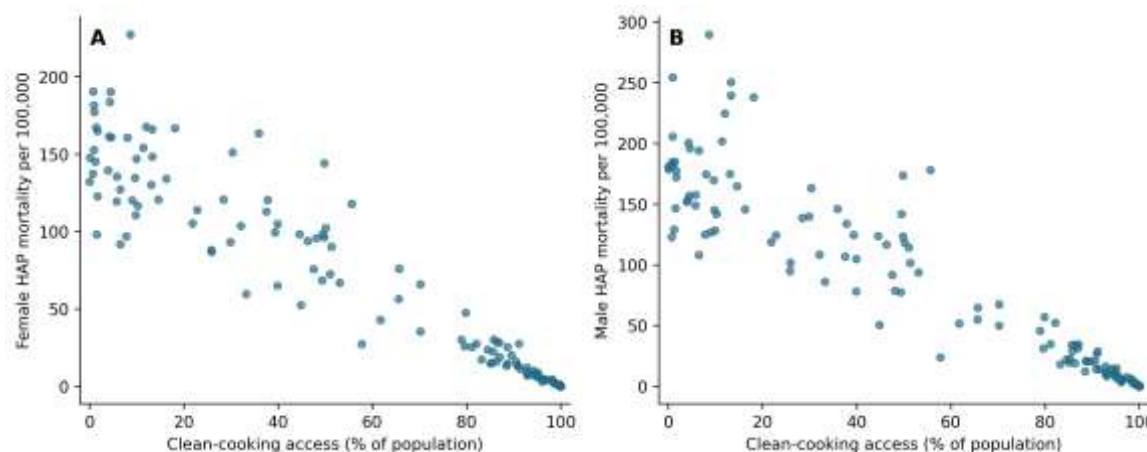


Figure 2. Clean-cooking access versus age-standardized HAP-attributable mortality in 180 countries: (A) female and (B) male rates.

3.5. Female–male mortality gap and clean-cooking access

The absolute female-minus-male gap moved toward zero as access increased (Spearman $\rho=0.604$; Table 3; Figure 3). The ratio showed a weaker negative association among countries with a nonzero male rate. Ratios omit the 55 countries with zero male rates and become unstable when denominators are small. The absolute gap is therefore easier to interpret for this sample.

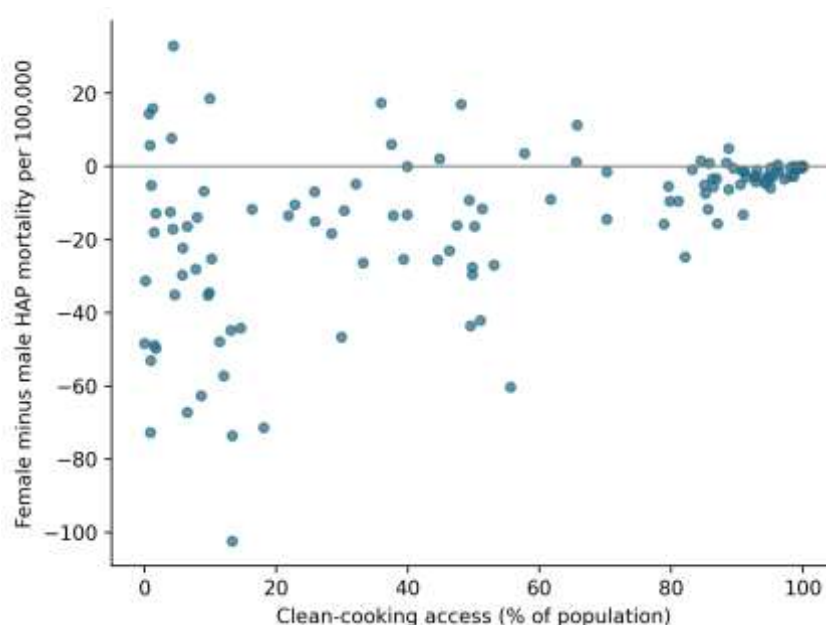


Figure 3. Clean-cooking access versus female-minus-male age-standardized HAP-attributable mortality in 180 countries; horizontal line is zero.

Table 3. Paired comparison and correlations with clean-cooking access.

Comparison	n	Estimate	p
Female minus male, paired t-test	180	-9.97; 95% CI -12.82 to -7.13; dz=-0.516	7.82×10^{-11}
Female minus male, Wilcoxon	180	W=980	3.17×10^{-13}
Female rate, Spearman ρ	180	-0.980	5.75×10^{-127}
Male rate, Spearman ρ	180	-0.977	1.98×10^{-121}
Female-minus-male gap, Spearman ρ	180	0.604	2.66×10^{-19}
Female-to-male ratio, Spearman ρ	125	-0.208	0.0202

3.6. Multivariable findings and diagnostics

Access retained negative coefficients for both sexes after adjustment (Table 4). GDP per capita and urbanization were not independently associated with either rate at conventional significance levels in these models. The female-by-access interaction was +0.273 per percentage point (95% CI, 0.181–0.366), indicating a less negative female slope. A separate gap model showed the same general pattern. The high model R^2 values should be interpreted in light of the shared inputs and the zero-rate boundary.

Table 4. Adjusted associations in 175 countries. HC3 robust intervals for separate and gap models; country-clustered intervals for pooled interaction.

Outcome / term	Coefficient per unit	95% CI	p	R ²
Female rate: cooking access	-1.494	-1.622 to -1.366	2.25×10^{-54}	0.918
Female rate: ln GDP per capita	-2.376	-5.532 to 0.781	0.139	
Female rate: urbanization	-0.018	-0.174 to 0.138	0.816	
Male rate: cooking access	-1.774	-1.959 to -1.589	7.76×10^{-44}	0.888
Male rate: ln GDP per capita	-1.457	-5.917 to 3.003	0.520	
Male rate: urbanization	-0.075	-0.320 to 0.170	0.546	
Gap: cooking access	0.280	0.148 to 0.412	4.57×10^{-5}	0.296
Pooled: female $\times$ cooking access	0.273	0.181 to 0.366	2.53×10^{-8}	0.901

Heteroskedasticity tests supported use of robust standard errors, and residual distributions were non-normal. The largest VIF was 3.08. Twenty-one countries exceeded Cook's $D > 4/n$ in at least one sex model. Removing them, or restricting the sample

to access below 95%, left the access slopes negative. Neither sensitivity analysis removes the dependence between the two modeled indicators.

3.7. Interpretation and comparison with previous research

Higher mean male attributable mortality does not negate the greater cooking-related exposure experienced by many women. WHO's all-cause attributable rates combine sex-specific disease burden with exposure and relative-risk models; they do not measure time spent cooking (WHO, 2026a). The GBD 2021 analysis likewise separates exposure from attributable outcomes (GBD 2021 HAP Collaborators, 2025). Modeled urban–rural and fuel-type exposure differences also show why national access is an imperfect proxy for individual exposure (Mohajeri et al., 2023).

The very high access–mortality correlations are partly built into the estimates. WHO's HAP burden model uses household-energy exposure estimates, and the World Bank access series draws on the WHO household-energy database (WHO, 2026a; World Bank, 2026a; Stoner et al., 2020). Shared inputs create statistical dependence; small p-values do not provide independent epidemiological confirmation. Universal-access assumptions and 55 paired zeros strengthen the pattern. The sensitivity checks did not remove the association, but they do not resolve this dependence.

3.8. Public-health and natural-resource implications

Cleaner household energy can reduce smoke exposure, while reduced reliance on inefficient solid-fuel combustion may also affect fuel collection and local resource use (WHO, 2025; IEA et al., 2025). The country patterns can guide closer study of places with low access and high modeled burden. They cannot quantify deaths prevented by a specific intervention or its sex-specific benefits. Future studies should measure fuel stacking, personal exposure, baseline health, and outcomes over time.

3.9. Strengths and limitations

The analysis included all matchable economies, used ISO3 joins and paired sex comparisons, and provides source files, a country audit, and sensitivity results. It remains an ecological cross-section, subject to unmeasured smoking, occupational and ambient exposures and variation in baseline disease rates. Five countries lacked GDP data. WHO mortality uncertainty was not propagated into regression intervals, which condition on published point estimates. Most importantly, the exposure and outcome share household-energy model inputs. Universal-access assumptions, zero modeled rates, and bounded access can exaggerate correlations; no association here establishes causality.

4. CONCLUSION

In 2021, the mean age-standardized HAP-attributable mortality rate was higher for males than females among 180 matched countries, although 21 countries had higher female rates. Countries with greater clean-cooking access had markedly lower modeled mortality in both sexes and a less negative female-minus-male gap. These ecological patterns are influenced by shared modeling inputs and ceiling and floor effects. Independent exposure and longitudinal outcome data are needed to assess sex-specific consequences of clean-cooking expansion.

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