Association between household fuel types and undernutrition status of adults and children under 5 years in 14 low and middle income countries

Jing Li1,5, Xin Xu1,5, Jin Li2,3, Dan Li2,3, Qiyong Liu4 and Haibin Xue2,3,∗

1 Weifang Medical University, Weifang 261053 Shandong Province, People’s Republic of China
2 Weifang People’s Hospital, Weifang 261000 Shandong Province, People’s Republic of China
3 The First Affiliated Hospital of Weifang Medical University, Weifang 261000 Shandong Province, People’s Republic of China
4 National Institute for Communicable Disease Control and Prevention, Chinese Center for Disease Control and Prevention, Beijing, People’s Republic of China
5 Jing Li and Xin Xu contributed equally to this manuscript.
∗ Author to whom any correspondence should be addressed.

E-mail: haibin_xue@163.com

Keywords: biomass fuel, household air pollution, underweight, stunting, wasting, body mass index

Supplementary material for this article is available online

Abstract

Polluting biomass fuel use has adverse effects on human health, but there are limited studies exploring the association between biomass fuel use and undernutrition in adult and child population. The study aims to investigate the association between biomass fuel use and undernutrition status of adults and children under 5 years of age in low and middle income countries (LMICs). Data were from the Demographic and Health Surveys in 14 LMICs. The main exposure variable was type of fuel the household mainly used for cooking. Linear regression models and Modified Poisson regression models with robust error variance in consideration of complex survey design were used to estimate the association between type of fuel used for cooking and the outcomes of interest. Personal and household data were collected by questionnaire, and anthropometry data were collected by measurement with a standardised protocol. A total of 532,987 households were included in the analysis, and the majority of households (63.9%) used high polluting fuels. For women, use of high polluting fuels lead to a 0.66 kg m$^{-2}$ (95% CI: −0.74, −0.58) decrease in BMI and a 10% (95% CI: 7%, 13%) higher risk of underweight. For men, high polluting fuels lead to a 0.63 kg m$^{-2}$ (95% CI: −0.88, −0.38) decrease in BMI and a 11% (95% CI: 5%, 18%) higher risk of underweight. For children, high polluting fuels resulted in a 0.16 (95% CI: −0.20, −0.11), 0.17 (95% CI: −0.22, −0.11), and 0.09 (95% CI: −0.14, −0.04) unit decrease in weight-for-age, height-for-age, and weight-for-height z scores, respectively; high polluting fuel use can lead to a 10% (95% CI: 3%, 18%) higher risk of underweight and a 13% (95% CI: 7%, 19%) higher risk of stunting, respectively. Effective interventions should be adopted by policymakers to accelerate the transition of polluting fuels to cleaner energy in LMICs.

1. Introduction

World Health Organization (WHO) estimates that approximately 3 billion people worldwide use polluting fuels such as coal, kerosene, wood, charcoal, crop waste, or animal dung in inefficient stoves (2018). Inefficient cooking and heating with these polluting fuels in homes with poor ventilation are a major source of household air pollution (HAP) exposure in low and middle income countries (LMICs) (Balmes 2019). According to the Global Burden of Disease Study 2019, HAP from solid fuel use was among the top ten risk factors for disease and ranked as the second environmental risk factor for global disability-adjusted life-years (DALYs) (GBD 2019 Risk Factors Collaborators 2020), leading to 1.8 million deaths and 60.9 million DALYs in 2017 (Lee et al 2020). Additionally, the burden attributed to HAP in LMICs was overwhelmingly higher than that in high-income countries (60.8 million compared with 0.09
millions (Lee et al. 2020). The inefficient burning and combustion-generated substances have well-documented adverse effects on human health: particulates, such as PM\(_{10}\) and PM\(_{2.5}\); inorganic gaseous compounds, such as sulphur dioxide (SO\(_2\)) and carbon monoxide (CO); hydrocarbons, such as polycyclic aromatic hydrocarbons (PAHs); oxygenated organic compounds, such as benzene and formaldehyde; and cilia toxic respiratory irritants, such as acrolein and cresols (Guerico et al. 2021). Accumulating evidence has consistently demonstrated that polluting biomass fuel use can lead to a broad range of respiratory and cardiovascular conditions in both adult and child population (Bellows et al. 2020, Dai et al. 2021, Mortimer et al. 2020). For example, a recent meta-analysis, including 15.5 million participants from 123 countries, reported that HAP was positively associated with asthma (relative risk (RR)): 1.23, 95% confidence interval (CI): 1.11, 1.36), acute respiratory infection in both adults (RR: 1.53, 95%CI: 1.22, 1.93) and children (RR: 1.39, 95%CI: 1.29, 1.49), chronic obstructive pulmonary disease (RR: 1.70, 95%CI: 1.47, 1.97), cerebrovascular disease (RR:1.09, 95%CI: 1.04, 1.14), and ischemic heart disease (RR:1.10, 95%CI: 1.09–1.11) (Lee et al. 2020).

Undernutrition includes deficiencies of essential vitamins and minerals, underweight, and childhood stunting and wasting (Popkin et al. 2020). Undernutrition is now still a public health issue, especially under the context of the double burden of malnutrition in LMICs, which is the coexistence of undernutrition and overweight/obesity (Popkin et al. 2020). Adult underweight and child underweight, stunting, and wasting are widespread and prevalent indicators of undernutrition (Local Burden of Disease Child Growth Failure Collaborators 2020, Victora et al. 2021). This is because the prevalence of them are relatively high in LMICs, the anthropometry data are easy to obtain, and the indicators are comparable across regions (Local Burden of Disease Child Growth Failure Collaborators 2020, Victora et al. 2021). Globally, 462 million adults are underweight, while 144 million and 47 million children under 5 years of age are stunted and wasted, respectively, and most of them are in LMICs (World Health Organization 2020). Undernutrition among adults, especially reproductive age women, represents a serious problem not only for their own health, but also for the health and nutrition of their offspring. For example, lower pre-pregnancy body mass index (BMI) is associated with increased risks of adverse maternal and child outcomes, such as placental abruption, low birth weight, poor intellectual development, and poor intellectual, physical and mental development (Hung and Hsieh 2016, Li et al. 2018). Childhood undernutrition is linked with severe short-term (e.g. delayed motor and cognitive development), medium-term (e.g. poorer school performances), and long-term consequences (e.g. abnormal metabolic status and increased risk of noncommunicable chronic diseases in adulthood) (Grillo et al. 2016, De Lucia Rolfe et al. 2018, Hock et al. 2018).

Current evidence supports an association between smoking and lower weight of adults (Hu et al. 2018), and there is also suggestive evidence linking ambient air pollution and environmental tobacco smoke (ETS) exposure with undernutrition of children (Spears et al. 2019, Islam et al. 2021). The combustion of the above-mentioned polluting fuels is qualitatively similar to the burning of tobacco in terms of emissions of particulate matter and gases, and the mechanisms by which smoke from polluting fuels causes adverse health effects in human subjects are likely similar (Balmes 2019). However, there are only limited studies exploring the association between biomass fuel use and undernutrition status of adults or children, and their data are all from single country (Amegah et al. 2020, Islam et al. 2021, Lamichhane et al. 2020, Liang et al. 2020). They reported that using unclean fuel was significantly associated with an increased risk of stunting in Chinese (odds ratio (OR): 1.34, 95%CI: 1.07, 1.68), Nepalese (for year 2011, OR: 1.50, 95%CI: 1.04, 2.18; for years 2006, 2011, and 2016, OR: 1.48, 95%CI: 1.16, 1.89), and Indian (for years 2005–06, OR: 1.05, 95%CI: 1.03, 1.06; for years 2015–16, OR: 1.16, 95%CI: 1.13, 1.19) children, respectively (Baliatti and Datta 2017, Dadras and Chapman 2017, Islam et al. 2021, Lamichhane et al. 2020, Liang et al. 2020). In addition, Lamichhane et al. found that HAP was significantly associated with an increased risk of underweight in Nepalese children (OR: 1.35, 95%CI: 1.02, 1.79), and Amegah et al. found using unclean fuel resulted in 0.81 kg m\(^{-2}\) (95%CI: 0.29, 1.33) reduction in BMI of children. In addition, the results of their study also showed that biomass fuel use was positively associated with asthma (relative risk (RR): 1.70, 95%CI: 1.47, 1.97), cerebrovascular disease (RR:1.09, 95%CI: 1.04, 1.14), and ischemic heart disease (RR:1.10, 95%CI: 1.09–1.11) (Lee et al. 2020).

Therefore, this study will investigate the association between biomass fuel use and undernutrition status of adults and children under 5 years of age from multiple LMICs. Moreover, we will further stratify the exposure of biomass fuel by cooking place. Our study should be a significant addition to the literature on the environmental determinants of undernutrition status of both adult and child population, and possibly provide solid evidence on policy interventions for improving indoor air quality and subsequently promoting population health in LMICs.
2. Materials and methods

2.1. Study design and data sources
We used standard Demographic and Health Surveys (DHS) data which is in public domain and it can be accessed at https://dhsprogram.com/. The DHS are nationally representative, repeated cross-sectional household surveys conducted in LMICs, collecting detailed nutrition and health information on children (aged 0–59 months), women and men (aged 15–49 years) in selected households using a multi-stage stratified cluster sampling design. Detailed information on the DHS has been described elsewhere (Corsi et al 2012). Surveys across countries used similar sampling design, standardised questionnaires, and measurement tools, to allow cross-country comparisons. We obtained permission to use these data for this study from the DHS Program. Informed consent was obtained from participants prior to the survey. No further approval was required for this study since the data were completely anonymized and available in the public domain.

Anthropometry data for men was not routinely collected as part of the standard DHS, but was available only in selected countries by randomly selecting a subset of households for measurement. These selected countries were Ethiopia, Ghana, India, Lesotho, Liberia, Maldives, Namibia, Nepal, Sao Tome and Principe, Sierra Leone, South Africa, Swaziland, Uganda, and Zimbabwe, and surveys were conducted between 2006 and 2016. Therefore, for this study, we included and pooled all these 14 DHS surveys where anthropometry data for children, women, and men were all available. Weight and height for women, men, and children were measured by trained personnel during the survey with a standardised protocol. The eligibility criteria were: men (1) who were aged 18–49 years and alive at the time of the survey, and (2) with weight and height measures in biologically plausible value ranges; women (1) who were aged 18–49 years, alive, and not pregnant at the time of the survey, and (2) with weight and height measures in biologically plausible value ranges; children (1) who were aged 0–59 months and alive at the time of the survey, (2) and with weight- and height/length-related anthropometry z scores in biologically plausible value ranges. The detailed information regarding the biologically implausible measures is in the following 2.3 Outcomes section.

2.2. Exposures
The main exposure variable of interest was type of fuel the household mainly used for cooking. In each survey, the specific question asked was, 'What type of fuel does your household mainly use?'. For this analysis, the cooking fuel used was categorized into high polluting fuels (electricity, liquid petroleum gas, natural gas and biogas) (Sreeramareddy et al 2011). We further stratify the fuel exposure by cooking place: cooking in the house and cooking in a separate building or outdoors. Some previous studies used solid fuel as their exposure variables of interest (Kleimola et al 2015, Khan et al 2017, Liang et al 2020). For comparison, we conducted a supplementary analysis by categorizing type of fuel into solid fuels (kerosene excluded from the high polluting fuel group) and low polluting fuels.

2.3. Outcomes
For adults, BMI and underweight were the outcomes of interest. Adult BMI was calculated as weight in kilograms divided by the square of height in meters (kg m$^{-2}$). Biologically implausible values were height <100.0 cm or >250.0 cm, weight <30.0 kg or >250.0 kg (Lartey et al 2019). BMI was categorized according to standard international guidelines developed by the WHO: underweight (BMI of <18.5 kg m$^{-2}$), normal weight (BMI of 18.5–24.9 kg m$^{-2}$) and overweight including obesity (BMI $\geq$ 25.0 kg m$^{-2}$), hereinafter denoted as ‘overweight’. The Asian cut-point for overweight of BMI $\geq$ 23.0 kg m$^{-2}$ was also evaluated for participants from India, Maldives, and Nepal (WHO Expert Consultation 2004).

For children under five, anthropometry z scores and undernutrition indicators (underweight, stunting, and wasting) were the outcomes of interest. Anthropometry z scores, including weight-for-age z score (WAZ), height-for-age z score (HAZ), and weight-for-height z score (WHZ), were calculated by comparing the child’s measurements with the median value in the reference population from the WHO child growth standards (2009). Underweight was defined as a WAZ $<-2$ standard deviations (SDs) of the median, stunting as HAZ $<-2$ SDS, and wasting as WHZ $<-2$ SDS (2009). HAZ $>6$ SDs above or below and WAZ and WHZ as $>5$ SDS above or below the median of the reference population were considered to be biologically implausible (World Health Organization 2009).

2.4. Covariates
Covariates for adult analysis were age, education level, marital status, occupation (not working, non-manual, manual, and agricultural), smoking (in last 24 h), ETS exposure in the house, household wealth quintile (1st quintile: poorest to 5th quintile: richest, within each country), residence (urban or rural), the gross domestic product (GDP) per capita on purchasing power parity (PPP, current international dollar) in the year of the survey, survey year, and country fixed effects. The DHS categorized occupations following a coding scheme based on the ILO International Standard Classification of Occupations (Croft 1988).
Trevor and Allen 2018, International Labour Organization 2020). Wealth quintile for each household were provided by the DHS by evaluating standard household assets and durables, which is a relative index and a reliable proxy for household economic level (Giles et al 2015). ETS exposure was categorized by the frequency of a household member smoking inside the house (daily, weekly, monthly or less, and never). GDP per capita on PPP of a country is an index of GDP per person adjusted for living costs and inflation. We used this indicator for each country, corresponding to the survey year as reported by the World Bank (http://databank.worldbank.org/data/indicator/). Covariates for child analysis were age, sex, multiple birth (yes or no), birth order, birth interval, parental BMI, parental occupation, parental smoking, ETS exposure in the house, household wealth quintile, residence, GDP per capita on PPP, survey year, and country fixed effects.

2.5. Statistical analysis
We included strata, cluster, and sampling weights provided by the DHS in estimating prevalence of undernutrition indicators and in regression models to ensure that the estimates were representative in pooled analyses. In the pooled dataset, sampling weights were rescaled proportionally according to population size of each country at the year of survey (Li et al 2020b). Linear regression models in consideration of complex survey design were used to estimate the unadjusted and adjusted association between type of fuel used for cooking, and adult BMI and child anthropometry z scores (WAZ, HAZ, and WHZ). The results were expressed as regression coefficients ($\beta$) with their corresponding 95% confidence intervals (CIs). Modified Poisson regression models with robust error variance in consideration of complex survey design were used to estimate the unadjusted and adjusted association between type of fuel used for cooking, and adult BMI and child underweight, stunting, and wasting (Yelland et al 2011). The results were expressed as prevalence ratios (PRs) with 95% CIs.

In all regression models, participants who were exposed to low pollution fuels served as a reference group. Because of the disproportionate missingness of ETS, adult occupation and smoking across surveys, and also attempting to test the influence of smoking and ETS on adult outcomes and the influence of parental BMI, smoking and ETS on child outcomes, we built several adjusted regression models for adults (models 2 and 3) and children (models 2, 3, and 4), respectively. For adults and children, model 1 was the unadjusted model. For adults, model 2 adjusted for participants’ age, education level, marital status, household wealth quintile, residence, the GDP per capita on PPP in the year of the survey, survey year, and country fixed effects; model 3 additionally adjusted for participants’ occupation, smoking, and ETS exposure in the house. For children, model 2 adjusted for participants’ age, sex, multiple birth, birth order, birth interval, household wealth quintile, residence, the GDP per capita on PPP in the year of the survey, survey year, and country fixed effects; model 3 additionally adjusted for participants’ parental BMI, and parental occupation; model 4 additionally adjusted for participants’ parental smoking, and ETS exposure in the house.

All statistical analyses were performed using SAS version 9.4. All statistical tests were 2-tailed, and P<0.05 was considered statistically significant.

3. Results

3.1. Sample characteristics
A total of 532,987 households were included in the analysis, and the number of included women, men, and children were 646,758, 138,507, and 71,725, respectively. Table 1 and figure S1 (available online at stacks.iop.org/ERL/16/054079/mmedia) presents the characteristics of the included households and children, respectively. The majority of households (63.9%) used high polluting fuels, and only 13.8% of households cooked in a separate building and 8.6% cooked outdoors. Mean BMI of women and men in this study was 22.3 kg $m^{-2}$ (SD: 6.3) and 22.1 kg $m^{-2}$ (SD: 8.2), and the weighted prevalence of underweight of women and men was 18.7% and 14.5%, respectively. Mean WAZ, HAZ, and WHZ of children under five in this study was $−1.18$ (SD:

| Table 1. Characteristics of the included households. |
|----------------------------------------------------|
| Characteristics                  | n     | Percentage, % |
|----------------------------------|-------|---------------|
| Total                            | 532987| 100.0         |
| Type of fuel                     |       |               |
| Low pollution                    | 192549| 36.1          |
| High pollution                   | 340438| 63.9          |
| Cooking place                    |       |               |
| In a separate building           | 73414 | 13.8          |
| In the house                     | 413778| 77.6          |
| Outdoors                         | 45795 | 8.6           |
| Wealth quintile, within country  |       |               |
| First, poorest                   | 110646| 20.8          |
| Second                           | 114674| 21.5          |
| Third                            | 109998| 20.6          |
| Fourth                           | 101912| 19.1          |
| Fifth, richest                   | 95757 | 18.0          |
| Location                         |       |               |
| Urban                            | 156055| 29.3          |
| Rural                            | 376932| 70.7          |
| Environmental tobacco smoke in the house |       |               |
| Never                            | 292572| 54.9          |
| Monthly or less                  | 33216 | 6.2           |
| Weekly                           | 45536 | 8.5           |
| Daily                            | 158775| 29.8          |
| Missing                          | 2888  | 0.5           |
Table 2. Characteristics of the included women and men.

| Characteristics                  | Women   | Men     |
|----------------------------------|---------|---------|
|                                  | n       | Percentage, % | n       | Percentage, % |
| Total                            | 646,758 | 100.0    | 138,507 | 100.0         |
| Age, years                       |         |          |         |               |
| ~24                              | 171,695 | 26.5     | 38,562  | 27.8          |
| 25 ~ 34                          | 218,028 | 33.7     | 46,455  | 33.5          |
| 35 ~                            | 257,035 | 39.7     | 53,490  | 38.6          |
| Education                        |         |          |         |               |
| None                             | 197,595 | 30.6     | 19,296  | 13.9          |
| Primary                          | 95,477  | 14.8     | 26,152  | 18.9          |
| Secondary or higher              | 353,686 | 54.7     | 93,059  | 67.2          |
| Marital Status                   |         |          |         |               |
| Married                          | 500,428 | 77.4     | 89,231  | 64.4          |
| Never married/widowed/divorced   | 146,330 | 22.6     | 49,276  | 35.6          |
| Weight status                    |         |          |         |               |
| Body mass index                  | 22.3a   | 6.3b     | 22.1a   | 8.2b          |
| Underweight                      | 118,834 | 18.7c    | 19,894  | 14.5c         |
| Normal weight                    | 385,665 | 57.4c    | 94,258  | 66.7c         |
| Overweight or obesity            | 142,259 | 24.0c    | 24,355  | 18.8c         |
| Occupation                       |         |          |         |               |
| Not working                      | 92,805  | 14.3     | 21,756  | 15.7          |
| Non-manual                       | 27,154  | 4.2      | 35,037  | 25.3          |
| Manual                           | 13,500  | 2.1      | 35,991  | 26.0          |
| Agricultural                     | 28,613  | 4.4      | 42,997  | 31.0          |
| Missing                          | 484,686 | 74.9     | 272,6   | 2.0           |
| Smoking (in last 24 h)           |         |          |         |               |
| No                               | 639,546 | 98.9     | 115,413 | 83.3          |
| Yes                              | 3908    | 0.6      | 22,573  | 16.3          |
| Missing                          | 3304    | 0.5      | 521     | 0.4           |

*Mean of body mass index.

b Standard deviation of body mass index.

c Weighted prevalence.

1.28), −1.34 (SD: 1.65) and −0.58 (SD: 1.41), and the weighted prevalence of underweight, stunting, and wasting was 25.3%, 34.2% and 14.0%, respectively. Weighted prevalence of undernutrition indicators for each country were listed in table S1.

3.2. Cooking fuel and risk of adult underweight

In adjusted models (model 2), use of high polluting fuels resulted in a 0.66 kg m⁻² (95% CI: −0.74, −0.58) decrease in BMI and a 10% (95% CI: 7%, 13%) higher risk of underweight of women. The adjusted associations by cooking place showed similar patterns with the aforementioned results, and in model 3 additionally adjustment for smoking, ETS exposure and occupation, the results were predominantly unchanged (table 4).

In adjusted models (model 2), use of high polluting fuels resulted in a 0.63 kg m⁻² (95% CI: −0.88, −0.38) decrease in BMI and a 11% (95% CI: 5%, 18%) higher risk of underweight of men. The adjusted associations by cooking place showed similar patterns with the aforementioned results, but only indoor use of high polluting fuels was statistically significant associated with higher risk of underweight in model 3 (table 4).

3.3. Cooking fuel and risk of child undernutrition

In adjusted models (model 2), use of high polluting fuels resulted in a 0.16 unit (95% CI: −0.20, −0.11) decrease in WAZ, a 0.17 unit (95% CI: −0.22, −0.11) decrease in HAZ, and a 0.09 unit (95% CI: −0.14, −0.04) decrease in WHZ in children. The adjusted associations by cooking place showed similar patterns with the aforementioned results. In models 3 and 4 additionally adjustment for parental BMI, parental occupation, parental smoking, and ETS exposure, results were also similar, except for the non-significant association between high polluting fuel use in a separate building or outdoors and HAZ in model 4 (table 5).

In adjusted models (model 2), use of high polluting fuels resulted in a 10% (95% CI: 3%, 18%) higher risk of underweight and a 13% (95% CI: 7%, 19%) higher risk of stunting in children. In models 3 and 4, only indoor use of high polluting fuels was statistically significant associated with higher risks of underweight (PR = 1.09, 95% CI: 1.01, 1.16) and stunting (PR = 1.07, 95% CI: 1.00, 1.16), respectively. There were no statistically significant associations between high polluting fuel exposure and risk of wasting in all adjusted models (models 2, 3, and 4) (table 5).
Table 3. Characteristics of the included children under five years of age.

| Characteristics                  | n     | Percentage, % |
|----------------------------------|-------|---------------|
| Total                            | 71 725| 100.0         |
| Sex                              |       |               |
| Male                             | 36 586| 51.0          |
| Female                           | 35 139| 49.0          |
| Multiple birth                   |       |               |
| No                               | 70 369| 98.1          |
| Yes                              | 1356  | 1.9           |
| Birth order                      |       |               |
| First                            | 21 327| 29.7          |
| Second                           | 18 946| 26.4          |
| Third                            | 12 014| 16.8          |
| Fourth                           | 7357  | 10.3          |
| ⩾ Fifth                          | 12 081| 16.8          |
| Birth interval                   |       |               |
| First child                      | 21 327| 29.7          |
| ⩽ 23 months                     | 10 831| 15.1          |
| 24–47 months                    | 25 495| 35.5          |
| ⩾ 48 months                     | 14 072| 19.6          |
| Malnutrition indicators          |       |               |
| Weight for age z-score           | −1.18 | 1.28          |
| Height for age z-score           | −1.34 | 1.65          |
| Weight for height z-score        | −0.58 | 1.41          |
| Underweight                     | 18 087| 25.2          |
| Stunting                        | 24 459| 34.1          |
| Wasting                         | 10 109| 14.1          |
| Maternal weight status           |       |               |
| Under weight                     | 12 526| 17.5          |
| Normal weight                   | 44 491| 62.0          |
| Overweight or Obese             | 14 591| 20.3          |
| Missing                          | 117   | 0.2           |
| Paternal weight status           |       |               |
| Under weight                     | 10 335| 14.4          |
| Normal weight                   | 34 434| 48.0          |
| Overweight or Obese             | 8327  | 11.6          |
| Missing                          | 18 629| 26.0          |
| Maternal occupation             |       |               |
| Not working                      | 43 094| 60.1          |
| Non-manual                      | 8705  | 12.1          |
| Manual                           | 4793  | 6.7           |
| Agricultural                    | 13 770| 19.2          |
| Missing                          | 1363  | 1.9           |
| Paternal occupation             |       |               |
| Not working                      | 3523  | 4.9           |
| Non-manual                      | 20 164| 28.1          |
| Manual                           | 21 198| 29.6          |
| Agricultural                    | 24 500| 34.2          |
| Missing                          | 2340  | 3.3           |
| Maternal smoking (in last 24 h)  |       |               |
| No                               | 69 007| 96.2          |
| Yes                              | 507   | 0.7           |
| Missing                          | 2211  | 3.1           |
| Paternal smoking (in last 24 h)  |       |               |
| No                               | 40 767| 56.8          |
| Yes                              | 7414  | 10.3          |
| Missing                          | 23 544| 32.8          |

*Mean of z score.

*Standard deviation of z score.

*Weighted prevalence.

In a supplementary analysis categorizing type of fuel into solid fuels and low polluting fuels, we found similar results with the above findings (Tables S2 and S3). Using Asian cut-point for overweight of BMI ⩾ 23.0 kg m\(^{-2}\) also showed similar results (data not shown).

4. Discussion

This study provides a comprehensive understanding of the association between high polluting fuel exposure and undernutrition indicators for women, men, and children in LMICs. Using household survey data from 14 countries, we found high polluting fuel exposure was associated with increased risk of undernutrition for adults and children, and the adverse effect of indoor cooking with high polluting fuels tended to be more pronounced.

This study revealed that the majority of household members in LMICs were exposed to high polluting fuels, and most of them were exposed to an environment of indoor cooking. According to International Energy Agency, the total number of people worldwide lacking access to clean fuels and technologies will remain largely unchanged by 2030 if no effective policy was implemented (2017). Therefore, the impact of polluting fuel exposure on health and well-being has become a noteworthy global health concern, particularly in LMICs (Shupler et al 2019).

Most previous research studied the adverse effects of polluting fuel exposure on adult health outcomes, but most of them focused on lung function (Devien et al 2018), respiratory diseases (Devien et al 2018, Li et al 2019), or mortality (Yu et al 2018, 2020). Only one study from Ghana reported that polluting fuel exposure was associated with decreased BMI of women (Amegah et al 2020), which was consistent with our findings.

Some other studies focused on the impact of polluting fuel exposure on children as they were regarded as a more susceptible population. This is because children, especially those in younger age, spend more time in the house and breathe more air per minute than adults, and their respiratory and immune systems are not fully developed (Islam et al 2021). In these studies, adverse effects of polluting fuel exposure were mainly focused on respiratory disease (Khan et al 2017, Budhathoki et al 2020), birth outcomes (Sreeramareddy et al 2011, Khan et al 2017), and mortality (Kleimola et al 2015, Khan et al 2017, Naz et al 2017, Owili et al 2017, Nisha et al 2018). Only a few studies explored the association between biomass fuel use and undernutrition status of children, and they reported inconsistent results (Balietti and Datta 2017, Dadras and Chapman 2017, Amegah et al 2020).
Table 4. Linear regression coefficients ($\beta$) for body mass index (BMI) and prevalence ratios (PR) for underweight for high polluting fuel exposure compared with low polluting fuel exposure for women and men.

| Samples | Outcomes | Groups                  | Model 1    | Model 2    | Model 3    |
|---------|----------|-------------------------|------------|------------|------------|
|         |          | $\beta$/PR (95%CI)      | $P$-value  | $\beta$/PR (95%CI) | $P$-value  | $\beta$/PR (95%CI) | $P$-value  |
| Women   | BMI      | Total                   | -2.53 (-2.59, -2.47) | <0.001 | -0.66 (-0.74, -0.58) | <0.001 | -0.65 (-0.70, -0.59) | <0.001 |
|         |          | High polluting fuel     | -2.75 (-2.81, -2.69) | <0.001 | -0.68 (-0.75, -0.62) | <0.001 | -0.68 (-0.74, -0.62) | <0.001 |
|         |          | In the house            | -2.13 (-2.30, -1.95) | <0.001 | -0.59 (-0.85, -0.33) | <0.001 | -0.55 (-0.69, -0.40) | <0.001 |
|         |          | Total                   | 1.55 (1.52, 1.59)   | <0.001 | 1.10 (1.07, 1.13)   | <0.001 | 1.16 (1.10, 1.22)   | <0.001 |
|         |          | High polluting fuel     | 1.62 (1.58, 1.66)   | <0.001 | 1.08 (1.05, 1.11)   | <0.001 | 1.11 (1.05, 1.17)   | <0.001 |
|         |          | In the house            | 1.43 (1.34, 1.52)   | <0.001 | 1.19 (1.11, 1.28)   | <0.001 | 1.28 (1.11, 1.47)   | 0.001  |
| Men     | BMI      | Total                   | -2.06 (-2.21, -1.92) | <0.001 | -0.63 (-0.88, -0.38) | <0.001 | -0.62 (-0.79, -0.46) | <0.001 |
|         |          | High polluting fuel     | -2.22 (-2.35, -2.08) | <0.001 | -0.51 (-0.66, -0.35) | <0.001 | -0.51 (-0.64, -0.37) | <0.001 |
|         |          | In the house            | -2.10 (-2.38, -1.62) | <0.001 | -1.12 (-1.92, -0.32) | 0.006  | -1.16 (-1.25, -1.06) | <0.001 |
|         |          | Total                   | 1.37 (1.30, 1.44)   | <0.001 | 1.11 (1.05, 1.18)   | <0.001 | 1.08 (1.01, 1.14)   | 0.018  |
|         |          | High polluting fuel     | 1.56 (1.48, 1.65)   | <0.001 | 1.23 (1.05, 1.44)   | 0.009  | 1.20 (1.02, 1.40)   | 0.027  |
|         |          | In the house            | 1.18 (1.04, 1.34)   | 0.009  | 1.07 (1.00, 1.14)   | 0.064  | 1.04 (0.97, 1.11)   | 0.309  |

Low polluting fuels included electricity, liquid petroleum gas, natural gas, and biogas, and served as a reference group. High polluting fuels included wood, straw, animal dung, agricultural crop, kerosene, coal, and charcoal.

Model 1 was the unadjusted model.

Model 2 adjusted for participants’ age, education level, marital status, household wealth quintile, residence, the GDP per capita on PPP (current international dollar) in the year of the survey, survey year, and country fixed effects.

Model 3 adjusted for variables from model 2 and participants’ occupation, smoking, and ETS exposure in the house.
Table 5. Linear regression coefficients ($\beta$) for anthropometry z scores and prevalence ratios (PR) for underweight, stunting, and wasting for high polluting fuel exposure compared with low polluting fuel exposure for children under five years of age.

| Outcomes                  | Groups                               | Model 1          | Model 2          | Model 3          | Model 4          |
|---------------------------|--------------------------------------|------------------|------------------|------------------|------------------|
| Weight-for-age z score    | Total                                | $\beta$ (95%CI)  | $P$-value        | $\beta$ (95%CI)  | $P$-value        | $\beta$ (95%CI)  | $P$-value        |
|                           | High polluting fuel                  | $-0.26 (-0.30, -0.22)$ | $< 0.001$       | $-0.16 (-0.20, -0.11)$ | $< 0.001$       | $-0.13 (-0.15, -0.11)$ | $< 0.001$       |
|                           | In the house                         | $-0.51 (-0.56, -0.47)$ | $< 0.001$       | $-0.13 (-0.18, -0.07)$ | $< 0.001$       | $-0.10 (-0.12, -0.08)$ | $< 0.001$       |
|                           | In a separate building or outdoors   | $-0.12 (-0.20, -0.04)$ | 0.002           | $-0.20 (-0.30, -0.10)$ | $< 0.001$       | $-0.14 (-0.21, -0.08)$ | $< 0.001$       |
|                           | Total                                | $-0.49 (-0.54, -0.44)$ | $< 0.001$       | $-0.17 (-0.22, -0.11)$ | $< 0.001$       | $-0.14 (-0.16, -0.12)$ | $< 0.001$       |
|                           | High polluting fuel                  | $-0.62 (-0.68, -0.57)$ | $< 0.001$       | $-0.14 (-0.21, -0.07)$ | $< 0.001$       | $-0.12 (-0.14, -0.10)$ | $< 0.001$       |
|                           | Cooking place                        |                  | 0.002           |                  |                  |                  |                  |
|                           | In the house                         | $-0.37 (-0.47, -0.28)$ | $< 0.001$       | $-0.16 (-0.29, -0.03)$ | 0.013           | $-0.08 (-0.14, -0.01)$ | 0.023           |
|                           | In a separate building or outdoors   |                  | 0.002           |                  |                  |                  |                  |
|                           | Total                                | $0.04 (0.00, 0.08)$ | 0.059           | $-0.09 (-0.14, -0.04)$ | $< 0.001$       | $-0.06 (-0.08, -0.04)$ | $< 0.001$       |
|                           | High polluting fuel                  |                  | 0.059           |                  |                  |                  |                  |
|                           | Cooking place                        |                  |                  |                  |                  |                  |                  |
|                           | In the house                         | $-0.21 (-0.26, -0.16)$ | $< 0.001$       | $-0.07 (-0.13, -0.01)$ | 0.023           | $-0.05 (-0.07, -0.03)$ | $< 0.001$       |
|                           | In a separate building or outdoors   | $0.15 (0.07, 0.23)$ | $< 0.001$       | $-0.15 (-0.26, -0.05)$ | 0.005           | $-0.14 (-0.21, -0.07)$ | $< 0.001$       |
|                           | Total                                |                  | 0.002           |                  |                  |                  |                  |
| Weight-for-height z score | High polluting fuel                  | $1.37 (1.30, 1.44)$ | $< 0.001$       | $1.10 (1.03, 1.18)$ | 0.003           | $1.05 (0.97, 1.12)$ | 0.224           |
|                           | Cooking place                        |                  | 0.002           |                  |                  |                  |                  |
|                           | In the house                         | $1.73 (1.64, 1.83)$ | $< 0.001$       | $1.12 (1.04, 1.21)$ | 0.002           | $1.09 (1.00, 1.18)$ | 0.041           |
|                           | In a separate building or outdoors   | $1.13 (0.98, 1.31)$ | 0.100           | $1.07 (0.89, 1.29)$ | 0.448           | $1.03 (0.86, 1.23)$ | 0.736           |
| Underweight               | High polluting fuel                  |                  | 0.002           |                  |                  |                  |                  |
|                           | Cooking place                        |                  | 0.002           |                  |                  |                  |                  |
|                           | In the house                         |                  | 0.002           |                  |                  |                  |                  |
|                           | In a separate building or outdoors   |                  | 0.002           |                  |                  |                  |                  |

(Continued.)
| Outcomes | Groups                      | Model 1          | Model 2          | Model 3          | Model 4          |
|----------|-----------------------------|------------------|------------------|------------------|------------------|
|          |                             | $\beta$/PR (95%CI) | $P$-value        | $\beta$/PR (95%CI) | $P$-value        | $\beta$/PR (95%CI) | $P$-value        |
| Stunting | Total                       |                  |                  |                  |                  |
|          | High polluting fuel         | 1.58 (1.51, 1.66) | $< 0.001$        | 1.13 (1.07, 1.19) | $< 0.001$        | 1.09 (1.02, 1.16) | 0.007            | 1.08 (1.01, 1.16) | 0.017            |
|          | Cooking place               |                  |                  |                  |                  |
|          | In the house                | 1.74 (1.66, 1.83) | $< 0.001$        | 1.09 (1.02, 1.16) | 0.009            | 1.07 (1.00, 1.15) | 0.065            | 1.07 (1.00, 1.16) | 0.045            |
|          | In a separate building or outdoors | 1.57 (1.39, 1.77) | $< 0.001$        | 1.18 (1.02, 1.37) | 0.023            | 1.13 (0.95, 1.34) | 0.167            | 1.13 (0.94, 1.35) | 0.193            |
| Wasting  | High polluting fuel         | 0.94 (0.87, 1.01) | 0.077            | 1.02 (0.94, 1.11) | 0.651            | 1.01 (0.92, 1.12) | 0.771            | 1.00 (0.91, 1.11) | 0.954            |
|          | Cooking place               |                  |                  |                  |                  |
|          | In the house                | 1.18 (1.09, 1.27) | $< 0.001$        | 1.03 (0.94, 1.13) | 0.552            | 0.99 (0.90, 1.09) | 0.804            | 1.00 (0.90, 1.10) | 0.926            |
|          | In a separate building or outdoors | 0.89 (0.75, 1.05) | 0.159            | 1.08 (0.86, 1.35) | 0.509            | 1.01 (0.81, 1.26) | 0.926            | 1.00 (0.80, 1.26) | 0.969            |

Low polluting fuels included electricity, liquid petroleum gas, natural gas, and biogas, and served as a reference group. High polluting fuels included wood, straw, animal dung, agricultural crop, kerosene, coal, and charcoal.

Model 1 was the unadjusted model.

Model 2 adjusted for participants’ age, sex, multiple birth, birth order, birth interval, household wealth quintile, residence, the GDP per capita on PPP (current international dollar) in the year of the survey, survey year, and country fixed effects.

Model 3 adjusted for variables from model 2 and participants’ parental BMI, and parental occupation.

Model 4 adjusted for variables from model 3 and participants’ parental smoking, and ETS exposure in the house.
Islam et al (2021), Lamichhane et al (2020), Liang et al (2020). Studies from China, India, and Nepal found significant associations between polluting fuel or solid fuel exposure and lower child anthropometry z scores or higher risk of undernutrition, which were in line with our findings (Baillet and Datta 2017, Dadras and Chapman 2017, Islam et al 2021, Lamichhane et al 2020, Liang et al 2020). By contrast, a study from Swaziland did not identify such associations, which may be attributed to its limited sample size (Machisa et al 2013).

The mechanisms by which polluting fuel exposure causes undernutrition of adults and children are still not well understood, but it is believed to be involved in inefficient burning and combustion-generated gases, toxic pollutants, and particulate matter (PM) pathogenic processes. For example, carbon monoxide (CO) is one of the common gases emitted from inefficient burning of fuel and it was found to be a trigger of weight reduction of obese mice (Hosick et al 2014). This procedure was via elevated metabolism from upregulation of mitochondrial biogenesis and mitochondrial uncoupling causing alterations in morphology of the epidermal fat depot and adipocyte number (Hosick et al 2014). Another possible mechanism was related with interference DNA damages by toxic pollutants such as PAHs, and increased urinary PAH metabolite concentrations were found in children and adolescents from households with indoor heating or cooking (Murawski et al 2020). Moreover, a cohort study has confirmed that exposure to elevated levels of PAHs is associated with reduced fetal and child growth (Tang et al 2006). In addition, previous studies have shown that maternal ambient PM exposure, such as PM$_{2.5}$ and PM$_{10}$, was associated with increased risks of preterm birth and low birth weight, and these two adverse pregnancy outcomes were subsequently risk factors for childhood undernutrition (Li et al 2020a). Therefore, offspring from mothers exposed to combustion-generated PM during pregnancy are at increased risk of growth failure. It is of note that high polluting fuel exposure was still associated with indicators of child undernutrition after adjustment for parental BMI. Parental BMI was considered as a proxy for the shared environment, dietary, genetic, and economic status (Perkins et al 2016), thus this adjusted association might reflect the independent effects of polluting fuel exposure on child growth. Several other indirect pathways are also possible. HAP might cause frequent episodes of febrile respiratory illness, which would subsequently lead to elevated metabolic requirements, anorexia and less food intake, accelerated catabolism (Sinharoy et al 2020). These body responses can result in an unbalanced nutrient status, and hence to growth retardation (Sinharoy et al 2020). Then, households would allocate incomes to health-care expenses related to infections instead of food and nutrition (Sinharoy et al 2020). Furthermore, Sola et al conducted an exploratory review, and they proposed several hypotheses that people who are short of adequate and appropriate household fuel may have to alter their cooking and eating habits by reducing the meal frequency, switching to diets that require less cooking time, and undercooking their food (Sola et al 2016). Through these practices, the quantity, quality and nutritional value of the food consumed would be affected, and finally result in inadequate nutrients intake (Sola et al 2016).

To the best of our knowledge, this is the first and largest study examining the association between high polluting fuel exposure and multiple undernutrition indicators for women, men, and children in LMICs. The uniform protocols, scientific sampling methodology, and standardized questionnaires made the results accurate and reliable. This study has several limitations. First, causal inference is difficult to draw in this study because of its cross-sectional design. Therefore, our results should be interpreted with caution. Second, undernutrition is a consequence of complicated environmental, dietary, and genetic factors, but the secondary nature of the data impeded us from including some variables of interest and detailed information of exposure. For example, variables for daily nutrient intakes and adequacy, the type of cooking building, the length of time that participants had spent in their households, and the extent of their exposure to fuel were not available. Third, anthropometry data was not routinely collected for men in most DHS surveys, thus only 11 surveys from Africa and three from Asia were included, making the generalizability of our findings limited.

5. Conclusions

In conclusion, indoor high polluting fuel exposure was associated with increased risk of adult underweight and child underweight and stunting. It is fair to expect that the transition of high polluting fuels toward clean fuels for cooking in LMICs will present beneficial gains for both adult and child population health. Effective interventions should be adopted by policymakers to accelerate the transition of polluting fuels to cleaner energy and reduce the health burden. Our study also suggests that indoor cooking tends to make larger impact on child growth. Therefore, if a complete change cannot be achieved in a short period of time, at least more awareness is needed for parents to keep their children stay away from the kitchen while cooking.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://dhsprogram.com/.
Acknowledgments

The authors are grateful to The U.S. Agency for International Development (USAID) for providing the valuable DHS data.

Funding

The research has received funding from: Key Research and Development Plan of Shandong Province (No. 2019GSF111067), Shandong Provincial Social Science Planning Research Project (No. 18CQXJ18), Shandong Medical and Health Technology Development Plan (No. 2017WS703), Teaching Reform and Research Project of Weifang Medical College (No. 2018YB013), National Steering Committee of Medical Professional Degree Postgraduate Education Project (No. C-YX20190301-04), Medical Education Research Project of Medical education Branch of Chinese Medical Association and Medical Education Professional Committee of Chinese Association of Higher Education (No. 2018A-N02079), and Health Standard Assessment Project of Chinese Center for Disease Control and Prevention (No. 20270418).

Authorship contribution statement

Jing Li: Conceptualization, Formal analysis, Methodology, Resources, Writing—original draft.

Xin Xu: Data curation, Resources, Validation, Writing—original draft.

Jin Li: Data curation, Methodology, Resources, Writing—original draft.

Dan Li: Data curation, Methodology, Resources, Writing—review & editing.

Qiuyong Liu: Formal analysis, Software, Validation, Writing-review & editing.

Haibin Xue: Conceptualization, Data curation, Methodology, Project administration, Resources, Supervision, Writing-review & editing.

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Amegah A K, Boachie J, Nâyhi S and Jaakkola J J K 2020 Association of biomass fuel use with reduced body weight of adult Ghanaian women J. Expo. Sci. Environ. Epidemiol. 30 670–9

Baliatti A and Datta S 2017 The impact of indoor solid fuel use on the stunting of Indian children (available at: www.ancabalietti.net/wp-content/uploads/2017/04/Datta_Baliatti_March2017.pdf) (Accessed 13 March 2021)

Balmes J R 2019 Household air pollution from domestic combustion of solid fuels and health J. Allergy Clin. Immunol. 143 1979–87

Bellows A L, Spiegelman D, Du S and Jaacks L M 2020 The association of cooking fuel use, dietary intake, and blood pressure among rural women in China Int. J. Environ. Res. Public Health 17 5516

Budhathoki S S et al 2020 The association of childhood pneumonia with household air pollution in nepal: evidence from Nepal demographic health surveys Matern. Child Health J. 24 48–56

Corsi D J, Neuman M, Finlay J E and Subramanian S V 2012 Demographic and health surveys: a profile Int. J. Epidemiol. 41 1602–13

Croft Trevor N A M J M and Allen C K 2018 Guide to DHS Statistics (Rockville, MD: ICF).

Dadras O and Chapman R S 2017 Biomass fuel smoke and stunting in early childhood: findings from a national survey Nepal J. Health. Res. 31 57–15

Dai X et al 2021 Exposure to household air pollution over 10 years is related to asthma and lung function decline Eur. Respir. J. 57 2000602

De Lucia Rolfe E et al 2018 Associations of stunting in early childhood with cardiometabolic risk factors in adulthood PLoS One 13 e0192196

Devien L et al 2018 Sources of household air pollution: the association with lung function and respiratory symptoms in middle-aged adult Environ. Res. 164 140–8

GBD 2019 Risk Factors Collaborators 2020 Global burden of 87 risk factors in 204 countries and territories, 1990–2019: a systematic analysis for the Global Burden of Disease Study 2019 Lancet 396 1223–49

Giles C L, Whirrow M J, Davies M J, Davies C E, Rumbold A R and Moore V M 2015 Growth trajectories in early childhood, their relationship with antenatal and postnatal factors, and development of obesity by age 9 years: results from an Australian birth cohort study Int. J. Obes. 39 1049–56

Grillo L P, Gigante D P, Horta B L and De Barros F C 2016 Childhood stunting and the metabolic syndrome components in young adults from a Brazilian birth cohort study Eur. J. Clin. Nutr. 70 548–53

Guercio V et al 2021 Exposure to indoor and outdoor air pollution from solid fuel combustion and respiratory outcomes in children in developed countries: a systematic review and meta-analysis Sci. Total Environ. 755 142187

Hock R S et al 2018 Childhood malnutrition and maltreatment are linked with personality disorder symptoms in adulthood: results from a Barbados lifespan cohort Psychiatry Res. 269 501–8

Hosick P A et al 2014 Chronic carbon monoxide treatment attenuates development of obesity and remodels adipocytes in mice fed a high-fat diet Int. J. Obes. 38 132–9

Hu Y et al 2018 Smoking cessation, weight change, type 2 diabetes, and mortality New. Engl. J. Med. 379 623–32

Hung T H and Hsieh T T 2016 Prepregnatastional body mass index, gestational weight gain, and risks for adverse pregnancy outcomes among Taiwanese women: a retrospective cohort study Taiwan J. Obstet. Gynecol. 55 575–81

International Energy Agency 2017 Energy Access Outlook 2017 (available at: https://webstore.iea.org/weo-2017-special-report-energy-access-outlook) (Accessed 18 October 2020)

International Labour Organization 2008 International Standard Classification of Occupations (available at: www.ilo.org/public/english/bureau/stat/isco/isco08/) (Accessed 28 November 2020)

Islam S, Rana M J and Mohanty S K 2021 Cooking, smoking, and stunting: effects of household air pollution sources on childhood growth in India Indoor Air 31 229–49

Khan M N, Nurs C Z B, Mozifzul Islam M, Islam M R and Rahman M M 2017 Household air pollution from cooking and risk of adverse health and birth outcomes in Bangladesh: a nationwide population-based study Environ. Health 16 57
Kleimola L, Patel A B, Borkar J A and Hibberd P L 2015
Consequences of household air pollution on child survival:
evidence from demographic and health surveys in 47
countries Int. J. Occup. Environ. Health 21 294–302

Lamichhane D K, Leen J H and Kim H C 2020 Household air
pollution and caste-ethnic differences in undernutrition
among children in Nepal Arch. Environ. Occup. Health
75 435–44

Larrey S T et al 2019 Rapidly increasing prevalence of overweight
and obesity in older Ghanaian adults from 2007–2015;
evidence from WHO-SAGE Waves 1 & 2 PLoS One
14 e0215045

Lee K K et al 2020 Adverse health effects associated with
household air pollution: a systematic review, meta-analysis,
and burden estimation study Lancet Glob. Health 8 e1427–34

Li C et al 2018 Effect of maternal pre-pregnancy underweight and
average gestational weight gain on physical growth and
intellectual development of early school-aged children Sci.
Rep. 8 12014

Li C et al 2020a Maternal exposure to air pollution and the risk of
low birth weight: a meta-analysis of cohort studies Environ.
Res. 190 109970

Li J et al 2019 Solid fuel use and incident COPD in Chinese adults:
findings from the China Kadoorie Biobank Environ. Health
Perspect. 127 37008

Li Z, Kim R, Vollmer S and Subramanian S V 2020b Factors
associated with child stunting, wasting, and underweight in
35 low- and middle-income countries JAMA Netw. Open
3 e203386

Liang W et al 2020 Association of solid fuel use with risk of
stunting in children living in China Indoor Air 30 264–74

Local Burden of Disease Child Growth Failure Collaborators 2020
Mapping child growth failure across low- and
middle-income countries Nature 577 231–4

Machisa M, Wichmann J and Nyasulu P S 2013 Biomass fuel use
for household cooking in Swaziland: is there an association
with anaemia and stunting in children aged 6–36 months?
Trans. R. Soc. Trop. Med. Hyg. 107 535–44

Mortimer K et al 2020 Pneumonia and exposure to household air
pollution in children under the age of 5 years in rural
Malawi: findings from the cooking and pneumonia study
Chest 158 501–11

Murawski A et al 2020 Poly cyclic aromatic hydrocarbons (PAH) in
urine of children and adolescents in Germany—human
biomonitoring results of the German Environmental Survey
2014–2017 (GerESV) Int. J. Hyg. Environ. Health
226 113491

Nas S, Page A and Agho K E 2017 Household air pollution from
use of cooking fuel and under-five mortality: the role of
breastfeeding status and kitchen location in Pakistan PLoS
One 12 e0175256

Nisha M K, Alam A and Raynes-Greenow C 2018 Variations in
perinatal mortality associated with different polluting fuel
types and kitchen location in Bangladesh Int. J. Occup.
Environ. Health 24 47–54

Owili P O, Muga M A, Pan W C and Kuo H W 2017 Cooking fuel
and risk of under-five mortality in 23 Sub-Saharan African
countries: a population-based study Int. J. Environ. Health
Res. 27 191–204

Perkins J M, Subramanian S V, Davey Smith G and Özaltin E 2016
Adult height, nutrition, and population health Nutr. Rev.
74 149–65

Popkin B M, Corvalan C and Grummer-Strawn L M 2020
Dynamics of the double burden of malnutrition and the
changing nutrition reality Lancet 395 65–74

Shupler M et al 2019 Household, community, sub-national and
country-level predictors of primary cooking fuel switching
in nine countries from the PURE study Environ. Res. Lett.
14 085006

Sinharoy S S, Clasen T and Martorell R 2020 Air pollution and
stunting: a missing link? Lancet Glob. Health 8 e472–5

Sola P, Ochieng C, Yila J and Iyama M 2016 Links between energy
access and food security in sub Saharan Africa: an
exploratory review Food Sec. 8 635–42

Spears D, Dey S, Chowdhury S, Scovonick N, Vyas S and Apte J
2019 The association of early-life exposure to ambient
PM(2.5) and later-childhood height-for-age in India: an
observational study Environ. Health 18 62

Sreeramarreddy C T, Shidhaye R R and Sathiyakumar N 2011
Association between biomass fuel use and maternal report
of child size at birth—an analysis of 2005–06 India
Demographic Health Survey data BMC Public. Health
11 403

Tang D, Li T Y, Liu J J, Chen Y H, Qu L and Perera F 2006
PAH-DNA adducts in cord blood and fetal and child
development in a Chinese cohort Environ. Health Perspect.
114 1297–300

Victora C G, Christian P, Vidaletti L P, Gatica-Dominguez G,
Menon P and Black R E 2021 Revisiting maternal and child
undernutrition in low-income and middle-income
countries: variable progress towards an unfinished agenda
Lancet (https://doi.org/10.1016/s0140-6736(21)00394-9)

WHO Expert Consultation 2004 Appropriate body-mass index
for Asian populations and its implications for policy and
intervention strategies Lancet 363 157–63

World Health Organization 2009 The WHO child growth
standards (available at: www.who.int/childgrowth/en/)
(Accessed 1 June 2020)

World Health Organization 2018 Household air pollution and
health (available at: www.who.int/news-room/fact-sheets/
detail/household-air-pollution-and-health) (Accessed 18
October 2020)

World Health Organization 2020 Malnutrition (available at:
www.who.int/news-room/fact-sheets/detail/malnutrition)
(Accessed 18 October 2020)

Yelland L N, Saltar A B and Ryan P 2011 Performance of the
modified Poisson regression approach for estimating relative
risks from clustered prospective data Am. J. Epidemiol.
174 984–92

Yu K et al 2018 Association of solid fuel use with risk of
cardiovascular and all-cause mortality in rural China JAMA
319 1551–61

Yu K et al 2020 Cooking fuels and risk of all-cause and
cardiopulmonary mortality in urban China: a prospective
cohort study Lancet Glob. Health 8 e430–9