Nutrition impacts of non-solid cooking fuel adoption on under-five children in developing countries[1]

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Abstract
This paper seeks to examine the nutrition impacts of using non-solid cooking fuel on under-five children in developing countries. We draw on data of more than 1.12 million children in 62 developing countries from the Demographic and Health Surveys (DHS). Results from both FE and IV estimates show that using non-solid cooking fuel significantly improves the nutrition outcomes of under-five children. Compared with their peers from households mainly using solid fuel, children from households mainly using non-solid fuel exhibit a lower probability of being stunting (by 5.9 percentage points) and underweight (by 1.2 percentage points). The possible mechanisms underlying these relationships can be improved indoor air quality and induced reduction in children's respiratory symptoms, benefits on maternal health, and reduction in maternal time spent on fuel collection or cooking. Heterogenous analyses suggest that the nutrition benefits of using non-solid cooking fuel are more prominent among boys, children above three years old, and those from households of lower social economic status, rural areas and southeast Asia.

Keywords: non-solid cooking fuel, nutrition benefits, under-five children, developing countries

1. Introduction

The latest statistics show that a significant number of children under five across the world suffer from malnutrition, especially those in developing countries (Liu *et al.* 2019; Qin *et al.* 2019). For example, FAO (2021) estimates that in 2020,149.2 million and 45.4 million under-five children were stunted and wasting, respectively. WHO (2021) reports the prevalence of anemia in children aged 6-59 months as high as 42%. Nearly three-quarters of the world's stunted children live in central and southern Asia (37%) and sub-Saharan Africa (37%). To achieve the SDG target of ending all forms of malnutrition by 2030 and the internationally agreed target of a 40% reduction in the number of stunted under-five children by 2025 (WHO 2017), it is urgent to understand the causes of malnutrition among children under five in developing countries and explore possible measures to fight against it.

Exposure to air pollution, among others, has been blamed for generating long-lasting damage to the nutrition and health outcomes of children. On the one hand, recent studies have found that

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outdoor air pollution increases infant mortality rate and the prevalence of respiratory disease and stunting, including PM2.5 (Kurata *et al.* 2020; Balietti *et al.* 2022), CO (Knittel *et al.* 2016), NO2 (Knibbs *et al.* 2018), burning organic matter (Rosales-Rueda and Triyana 2019) and car pollution (Alexander and Schwandt 2022). On the other hand, household air pollution (HAP) has attracted increasing attention as individuals spend more time indoors nowadays (Kurata *et al.* 2020). A number of studies have shown that exposure to dirty cooking fuels or cigarette smoke harm childhood wellbeing in the form of higher infant mortality rate, lower birth weight, and more respiratory illnesses (Simon 2016; Cesur *et al.* 2018; Imelda 2020; Kurata *et al.* 2020; McGeary *et al.* 2020; Afridi *et al.* 2021).

HAP induced by exposure to solid cooking fuel poses a great threat to children's nutrition and health. It has been revealed that HAP from solid fuels (e.g. woods, agricultural residues, dungs, charcoals, and coals) is the leading environmental risk factor for attributable deaths, ranking the fourth among all the mortality risk factors for children aged 0-9 years in 1990-2019 (Murray *et al.* 2020). Theoretically speaking, there might be two potential causal pathways through which solid fuel affects children's nutrition. One pathway comes from the direct damage from pollutant discharge. Solid fuel emits more PM2.5, CO and NOx than other cleaner fuels (Imelda 2020; González-Martín *et al.* 2021; Somanathan *et al.* 2022). Children aged under five, whose immune systems and lungs are not yet fully developed, are more susceptible to these pollutants (Schwartz 2004). The other pathway is that solid fuel might harm children's nutrition outcomes by decreasing the wellbeing of their mothers, such as their health (Baumgartner *et al.* 2011; Amegah *et al.* 2020; James *et al.* 2020). Moreoever, some other studies have revealed that reliance on solid fuels forces mothers in developing countries to spend more than one hour per day gathering fuels (Rehfuess and WHO 2006) and spend more time on cooking (Imelda 2020), which might squeeze out their parenting time.

Despite its threat to children's health and nutrition, developing countries are far from completing the transition from solid to non-solid cooking fuel. Statistics show that 2.8 billion people, mostly of whom concentrate in developing countries, are exposed to HAP from using solid cooking fuels (Bonjour *et al.* 2013). In Africa and southeast Asia, more than 60% of households cook with solid fuels (Bonjour *et al.* 2013). Such being the case, a natural question arises: to what extent would the shift by households depending on solid fuel to cleaner non-solid fuels benefit children's nutrition in the developing world? More specifically, is it beneficial to use non-solid cooking fuels for the nutrition outcomes of under-five children?

In this paper, we seek to answer this question by examining whether households' adoption of non-solid cooking fuel helps to improve the nutrition outcomes of under-five children in developing countries. We address the potential selection biases by employing the instrumental variable (IV) approach. Specifically, we take the leave-one-out approach leveraging the prevalence of non-solid fuel usage in the area where the household lives, which plausibly provides exogenous variations in households' adoption of non-solid cooking fuels. We draw on data from the Demographic and Health Surveys (DHS) that offers three helpful features facilitating our identification strategy. First, DHS is a nationally representative survey, spanning from the 1980s to the 2010s and covering nearly half of the worlds' developing countries, with a large sample size of more than one million under five children. This feature makes our study representative of developing countries and cross-country comparisons possible. Second, DHS randomly selects sample households within each primary sampling unit (PSU) in each country, which allows us to construct the instrumental variable at the PSU level. Finally, the rich information that DHS collected through household, women's and men's questionnaires enables us to address contextual confounding by controlling for a set of covariates at the child, parent and household levels.

Our results show that households' adoption of non-solid cooking fuel significantly reduces the prevalence of some indicators of malnutrition among under-five children in developing countries. Specifically, compared with their peers from households using solid cooking fuel, under-five children from households using non-solid cooking fuel are less likely to be stunted (by 5.9 percentage points, pp) and underweight (by 1.2 pp), but there is no significant difference in terms of wasting and anemia. We also find that using non-solid fuels brings health benefits to mothers as measured by lower probability of being underweight (by 3.5 pp) and higher BMI (by 0.913 points). However, it also increases mothers' likelihood of being overweight (by 3.9 pp). We also provide evidence that the benefits of households' adoption of non-solid fuel can be driven by improving indoor air quality, reducing children's respiratory symptoms and reducing mothers' time spent on fuel collection or cooking. Finally, our results reveal heterogenous effects of using non-solid fuels with boys, children above 3 years old, those from households of lower social economic status, rural areas, and southeast Asia benefiting more from using non-solid fuels than their counterparts.

This study contributes to the literature in three ways. First, we add to a growing economic literature on the effects of air pollution on children's nutrition or health outcomes (Knittel *et al.* 2016; Knibbs *et al.* 2018; Rosales-Rueda and Triyana 2019; Kurata *et al.* 2020; Balietti *et al.* 2022; Alexander and Schwandt 2022). While previous studies mostly focus on effects of outdoor air pollution, our estimates highlight the nutrition benefits of transition to cleaner cooking fuel and provide some insights relevant to policies to reduce household air pollution. Second, our findings fill in the gaps in the literature focusing on the damage of using solid fuel by revealing its causal effects on wasting, underweight, and anemia. While the literature correlating cooking fuel type and child nutrition dates back to Mishra and Retherford (2007), most studies have not addressed the endogenous sorting in households' adoption of cleaner cooking fuel. Some exceptions include Balietti and Datta (2017) and Kurata *et al.* (2020), which only discussed the effects on stunting or HAZ. To the best of our knowledge, this paper is the first attempt to document, with a casual interpretation, that households' adoption of non-solid fuels improves children's multiple nutrition outcomes. Finally, this study is the first of which we are aware that comparing the nutrition impacts of using non-solid fuels across developing countries spanning as many as six regions of the world.

The remainder of this paper is organized as follows. Section 2 introduces the sample and the data, followed by an empirical framework in Section 3. Section 4 presents our empirical findings. The final section concludes.

2. Data and methods

2.1. Survey and sample

The Demographic and Health Survey

Our analyses draw on data from the Demographic and Health Survey (DHS). The DHS program was initiated by the United States Agency for International Development (USAID) in 1984 to improve the global understanding of health and population trends in the developing world. The sample countries are primarily those that have received USAID assistance. However, several non-USAID-supported countries have also participated in the survey with funding from UNICEF, UNFPA, and the World Bank (Croft *et al.* 2018).

DHS adopted a two-stage probability-proportional-to-size (PPS) sampling strategy to select the study sample. In the first stage, the primary sampling units (PSU), typically the census enumeration areas of the country, were selected and formed the survey clusters. Secondly, within each sample cluster, 25-30 households were randomly selected from a complete household roster, and all the children aged 0-59 months in the households were surveyed. To date, eight phases of the survey have been conducted on a five-year basis. By the time of this study, data for the first seven phases are publicly available, covering 92 developing countries.

It is worth noting that each survey phase of DHS shares the following three characteristics. First, the surveys across different countries during the same phase generally use the same questionnaire. Secondly, due to the large number of participating countries, different countries might complete the same phase in different years. Taking the fourth phase between 1997 and 2003 for example, while Zimbabwe conducted the survey in 1999, Niger did so in 2001. Finally, as the frequency and continuation of DHS depends on the country's discretion (Corsi *et al.* 2012), not all sample countries have participated in all survey phases so far. In fact, out of the 92 countries from the first seven survey phases, only 3 (3%) countries have participated in all the eight phases, while 19 (21%) have participated in only one phase, and 47 (51%) two to five phases.

Study sample

Following a three-step procedure, we identified the subsample from DHS for the purpose of our study. In the first step, we excluded data from the first three phases as the question on cooking fuel type was not asked until the phase-four survey and afterward, which left us with 62 countries. In the second step, we kept the households who have under-five children at the time of the survey and answered the question "What type of fuel does your household mainly use for cooking?". In the final step, we further excluded those households who responded "No food cooked in the household" to this question. After this process, we are left with 1,128,085 under-five children from 770,395 households in 62 developing countries, which become our study sample. The source for the DHS data and the procedure we took to assemble and clean the DHS dataset used in this paper are presented in Appendix I. As shown in Table 1, the 62 sample countries come from six of the ten regions across the world, including two from southeast Asia, six from south Asia, six from west Asia, nine from Latin America, four from north Africa, and 35 from sub-Saharan Africa, covering 38% of all the developing countries (163) of the world.

[*Table 1 about here*]

During each phase of surveys, a set of questionnaires were administered to the head, women and men of the household. For the purpose of this study, we draw on information from three modules in each phase of the survey. The first module is the household questionnaire where a series of information about household characteristics was collected, including the types of cooking fuel, kitchen, floor, wall, toilet and drinking water, availability of electricity, and the name of the household head. The second module is the woman's questionnaire, where we draw on information about the nutrition outcomes of children (including stunting, wasting, underweight, and anemia) and their mothers (including BMI score, underweight, overweight and anemia). This module also provides us with rich information on the demographic and health characteristics of children (including gender, age in months, number of siblings, birth weight, birth order, and status of vaccination) as well as their mothers (including age, years of schooling, marital status, whether the mother works and smokes, number of antenatal visits). Finally, we draw on information about the age and years of schooling of the mother's partner from the men's questionnaire.

2.2 Variables

Non-solid cooking fuel. Following the definition by Rehfuess and WHO (2006), we classify a household as using non-solid cooking fuel if their main type of cooking fuel is electricity, natural gas, biogas, LPG or kerosene. In contrast, if a household's main type of cooking fuel is coal/lignite, charcoal, wood, straw/shrub/grass, agricultural crops or animal dung, we classify them as using solid cooking fuel. Based on this classification, we create a dummy variable that takes the value of one if a household uses non-solid cooking fuel and zero otherwise.

Nutrition indicators of children. We focus on four nutrition indicators of children that are commonly used in the literature: stunting, underweight, wasting and anemia (Mishra and Retherford 2007; Kyu *et al.* 2010; Machisa *et al.* 2013; Ahmed *et al.* 2021; Amadu *et al.* 2021). Referring to the WHO growth reference data for children aged 0-5 years (WHO 2006), DHS calculated the Height-for-age Z-score (HAZ), Weight-for-age Z-score (WAZ) and Weight-for-height Z-score (WHZ) for each child based on their height, weight, age and gender. Following the child growth standards of WHO (2006), a child with a HAZ less than minus two is defined as "Stunting", with a WAZ less than minus two defined as "Underweight", and with a WHZ less than minus two defined as "Wasting". Following WHO (2021), children aged 6 to 59 months are defined as "Anemia" if their altitude-adjusted hemoglobin is less than 110 g/L.

Health indicators of mothers. We focus on four health indicators of children's mothers provided in DHS. The first one is BMI score. The next two indicators are generated from BMI score. One is a dummy variable called "Underweight" that takes the value of one if the BMI score is less than 18.5 and zero otherwise. The other is also a dummy variable called "Overweight" that takes the value of one if the BMI score is above 25 and zero otherwise. The last indicator is anemia, which takes the value of one if the altitude-adjusted hemoglobin of the non-pregnant (pregnant) mother is less than 120 (110) g/L and zero otherwise (WHO 2006).

Covariates. Following the literature, we control for characteristics at the child, parent, and household levels that might affect the nutrition outcomes of children (Mishra and Retherford 2007; Imelda 2020; Kurata *et al.* 2020; Afridi *et al.* 2021; Amadu *et al.* 2021). Specifically, we control for six covariates at the child level (including gender, age in months, number of siblings, birth weight, whether the child is the first child, and whether he/she has received basic vaccinations), eight covariates at the parent level (including age, years of schooling of the mother and her partner, whether the mother works and smokes, number of antenatal visits by the mother, marital status of parents). We also take into account five covariates at the household level, including whether the household lives in rural areas, whether the household head is female, access to the improved toilet (e.g., flush toilet, pit latrine with slab, and ventilated improved pit latrine), access to clean water (e.g., protected tube wells, water piped into the dwelling and public taps) and access to electricity.

2.3. Descriptive statistics

Our data show that of the 770,395 sample households with children under five, 30% use mainly non-solid fuel for cooking (Table 2, Panel B). On average, a sample household has 1.5 under-five children, with almost two-thirds (64%) of sample households having only one, 29% having two, and 7% haveing more than two. At the child level, 28% of the 1,128,085 sample children live in households that use mainly non-solid cooking fuels.

Descriptive statistics also suggest that households' adoption of non-solid fuels varies greatly by regions and by countries. As shown in Figures 1 and 2, households in north Africa exhibit the highest adoption (91%), followed by those in west Asia (77%), with their peers in southeast Asia being the lowest (less than 9%). At the country level, the proportion of households using non-solid cooking fuel ranges from 0% in Liberia to 100% in Jordan. In fact, only 8 out of the 62 sample developing countries have more than 80% of their households using non-solid cooking fuel. Another point worthy of noting is that the share of households using non-solid cooking fuel in most developing countries, especially in Latin American and African countries, has stagnated since 1998. Only several Asian countries witnessed significant progress in households' adoption of non-solid cooking fuel, such as Armenia (from 62% in 2000 to 97% in 2015) and Cambodia (from 2% in 2000 to 19% in 2014).

[*Table 2 about here*]

[*Figures 1 and 2 about here*]

Our sample children seem lag far behind the global average (Table 2, Panel A) with obvious variations across regions (Figure 3) in terms of nutrition outcomes, and some of them suffer from respiratory symptoms. Our data show that 36% (11%) of them are stunted (wasted), which is significantly higher than the global average of 23% (8%) in 2016 (FAO 2017). Meanwhile, 22% of the sample children are underweight. The prevalence of anemia is 56%, compared to the global average of 42% in 2020 (WHO 2021). By regions, under-five children in southeast Asia, south Asia, south Asia, and sub-Saharan Africa exhibit the highest probability of being stunted (47%), wasted (19%), underweight (35%) and anemic (64%), respectively. In contrast, their peers in Latin America are the least likely to be wasted (2%), whereas those in west Asia are the least likely to be stunted (20%), underweight (7%) and anemic (32%). Taken together, while under-five children in the sample developing countries lag far behind the global average in their nutrition outcomes, those in west Asia and Latin America perform relatively better than their peers in southeast and south Asia, and sub-Saharan Africa. In the meantime, 24% and 22% sample children had a cough or fever in the two weeks before the interview.

[*Figure 3 about here*]

When it comes to the health outcomes of mothers of the sample children, the picture is also concerning, especially in southeast Asia and north Africa. The mean BMI score of mothers is 22.7, ranging from the lowest mean of 20.9 in southeast Asia to the highest of 26.4 in north Africa. Moreover, 14% and 17% of mothers are underweight and overweight, respectively. Nearly a third of mothers (33%) suffer from anemia, which is almost the same as the global average of 33% in 2016 (FAO 2017). Figure 4 further reveals the non-negligible variation by regions in maternal health outcomes. Specifically, mothers in south Asia exhibit the highest likelihood of being underweight (25%) and anemic (40%). In contrast, their peers in Latin America are the least likely to be underweight (3%) or anemic (22%). The prevalence of overweight among sample mothers is 33% in north Africa, more than four times that in southeast Asia (8%).

[*Figure 4 about here*]

Results from descriptive statistics also suggest an apparent negative correlation between household non-solid cooking fuel adoption and malnutrition among under-five children. When we aggregate samples by country and survey year to construct the proportion of households that adopted non-solid cooking fuel and the prevalence of child malnutrition, then plot the correlation coefficients between the two and weight them by the number of sample children in each country and each survey year, it appears an obvious correlation: the higher the proportions of households adopted non-solid cooking fuel, the lower the prevalence of stunting, wasting, underweight and anemia among under-five children (Figure 5).

[*Figure 5 about here*]

2.4 Empirical specification

To examine the causal effects of using non-solid cooking fuel on children's nutrition outcomes, we have to address the endogeneity of "Selection on unobservables". Specifically, if certain unobservable parental- or household-characteristics are significantly correlated with both the adoption of non-solid cooking fuel and the nutrition outcomes of under-five children, we might end up observing a significant relationship between households' adoption of non-solid cooking fuel and children's nutrition outcomes even though no causal relationship actually exists. In this section, we try to address this problem through a two-step approach. In the first step, we employ a fixed-effects model to eliminate the influences of time-invariant, subnational region-invariant and time-region-invariant unobservable confounding factors as follows,

$$Y_{icdt} = \alpha + \beta Non\_solid_{icdt} + \boldsymbol{Z}^{'}_{icdt}\boldsymbol{\gamma} + \eta_d + \alpha_t + \delta_{ct} + \varepsilon_{icdt} \tag{1}$$

Where Y_{icdt} denotes the nutrition outcomes of child *i* at sub-national region *d* from region c of the world in the survey year *t*. Non_solid_{icdt} denotes a dummy variable that takes the value of one if a child lives in a household mainly using non-solid fuel for cooking and zero otherwise. $\boldsymbol{Z}^{'}_{icdt}$ denotes a set of covariates at the child, parent and household levels, which we introduced above. η_d, α_t and δ_{ct} denotes the sub-national region, survey year, and region-survey year fixed effects, which we use to control for time-invariant geographic and social features by sub-national regions, region-invariant but time-varying confounding factors, and time-varying economic and social characteristics of different regions of the world, respectively. Standard errors are clustered at the sub-national region level.

In the second step, we capture the exogenous variations in households' adoption of non-solid cooking fuel to further address the "Selection on unobservables". Taking advantage of the random sampling within each PSU of DHS, we follow previous studies (e.g., Balietti and Datta (2017) and Kurata *et al.* (2020), among others) and use the availability of non-solid cooking fuel as an instrumental variable (IV) for household's adoption of it. The IV is measured by the ratio of the number of households using non-solid cooking fuels in PSU *p* excluding household *h* over the total number of households (N_p) in PSU *p* minus one.

$$Proportion_{hp} = \frac{\sum_{k \neq h} Non\_solid_{kp}}{N_p - 1} \tag{2}$$

With the IV constructed, we employ the following two-step least squares (2SLS) approach:

Stage 1: $$\widehat{Non\_solid}_{icdt} = \alpha + \beta Proportion_{hp} + \boldsymbol{Z}^{'}_{icdt}\boldsymbol{\gamma} + \eta_d + \alpha_t + \delta_{ct} + \epsilon_{icdt} \tag{3}$$

Stage 2: $$\mathrm{Y}_{icdt} = \alpha + \beta \widehat{Non\_solid}_{icdt} + \boldsymbol{Z}^{'}_{icdt}\boldsymbol{\gamma} + \eta_d + \alpha_t + \delta_{ct} + \sigma_{icdt} \tag{4}$$

Where $Proportion_{hp}$ denotes the IV, and the rest is the same as in Equation (1) above[2].

The proportion of children living in households from the same PSU that use mainly non-solid

[2] It is shown in Figure A1 that more than 50% of the sample villages not having any households using non-solid fuel. Also, after regressing the share of non-solid fuel in PSU on village fixed effects and plotting the distribution of residuals in Panel B of Figure A1, it shows that the distribution of residuals is approximately normal.

cooking fuel is considered a valid instrument for households' adoption of non-solid cooking fuel from two perspectives. On the one hand, the adoption of non-solid cooking fuel by fellow households within the same PSU can significantly predict the use of non-solid cooking fuel in the sample household under discussion. As shown in Panel B of Table 3, the IV significantly predicts households' adoption of non-solid cooking fuels with sufficiently large Cragg-Donald F statistics (more than 61,000), suggesting that our estimation does not suffer from a weak IV problem.

On the other hand, we provide some evidence lessening the concern of the violation of the IV exclusion assumption. Although the share of clean (or non-clean) fuel in PSU has been widely exploited to construct IV for households' endogenous adoption of clean (or non-clean) fuel (Balietti and Datta (2017), Kurata *et al.* (2020), among others), there are potential concerns over the validity of the IV. First and foremost, the IV at the village level may reflect other characteristics of the village, which may affect children's nutrition outcomes. For example, the share of non-solid fuel in PSU may reflect the availability of infrastructure in villages, as the use of non-solid fuel, such as natural gas or LPG, relies on well-developed gas pipelines or marketing networks, and the availability of infrastructure would affect children's nutrition through other channels. In response to this concern, we focus on children from villages with at least one household using non-solid fuel (their IV is greater than zero) and reran the IV regressions. Results in Table A3 show that in these villages with energy infrastructure, IV remains to be a significant predictor of households' adoption of non-solid fuels. This finding provides the first piece of evidence that the IV does not violate the exclusion assumption.

Second, there is another concern that the IV might reflect social economic status of the village. For example, children from more developed villages might be more likely to have access to cleaner cooking fuels while also have better nutrition outcomes than their peers from less-developed villages. To address this concern, we perform a falsification test by following Di Falco *et al.* (2011), Alem *et al.* (2015), and Chen *et al.* (2020). Specifically, we test whether our IV has predictive power for nutrition outcomes of the subsample from households using solid fuel. The results in Table A4 show that in most cases, the IV estimates using subsamples are insignificant, except for the stunting with a small coefficient of 0.03, suggesting that even if our IV does have some direct effect on children's nutrition, it would be almost negligible.

Last but not the least, there is concern that neighbors' adoption of non-solid fuel might help improve the outdoor air quality, thus improving children's nutrition outcomes. To deal with this concern, we turn to the environmental literature and find out that even if such potential impact exists, it would be relatively small for the following reasons. On the one hand, indoor pollutant levels are typically twice higher as that in the outdoors, and people spend 80-90% of their life in increasingly air-tight buildings (González-Martín *et al.* 2021). Moreover, it is relatively difficult for under-five children to move to the outdoor area without the company of their caregivers. On the other hand, there are multiple sources of outdoor air pollution, such as industry and energy supply, transport, dust, waste management, agricultural practices and household energy (WHO 2021). Households' adoption of solid fuel is just one of them. Taken together, the concern raised at the beginning of this paragraph might not be a problem.

3. Results and discussion

3.1. Main results

Consistent with results from descriptive analyses, our regression results show that households' adoption of non-solid cooking fuel has a statistically significant and negative impact on the prevalence of malnutrition among under-five children. As presented in Panel A of Table 3, results from both FE and IV show that households' adoption of non-solid cooking fuel is associated with lower probability of under-five children being stunted (by 4.1-5.9 pp) or underweight (by 1.2-2.1 pp), but has no significant impact on the probability of being anemic. When it comes to wasting, while results from FE suggest a 0.4 pp reduction in the probability, the estimate from IV is not significant.

[*Table 3 about here*]

We compare our main estimates above to those from relevant public health literature to put them into context. As for the impacts on stunting, our results are generally consistent with previous findings revealing a positive association between exposure to biomass or solid cooking fuel and childhood stunting (Mishra and Retherford 2007; Dadras and Chapman 2017; Liang *et al.* 2020; Upadhyay *et al.* 2021; Amadu *et al.* 2021; Caleyachetty *et al.* 2022). In fact, our IV estimate of a 5.9 pp reduction in the probability of being stunted is similar to those found in India (6.5 pp) by Balietti and Datta (2017). Furthermore, evidence from 31 countries in sub-Saharan Africa also suggests that using clean fuel (including electricity, LPG, and natural gas) is associated with a lower prevalence of being wasted and underweight. In contrast, Machisa *et al.* (2013), Kim *et al.* (2017) and Schwinger *et al.* (2022) found a weak association between solid or biomass fuel adoption and stunting of under-three or under-two children. Kurata *et al.* (2020) did not find any significant impact of households' adoption of non-solid cooking fuel on the probability of being stunted among under-five children in Bangladesh. As for the impacts on anemia, our results are consistent with Machisa *et al.* (2013) that observed no significant association between biomass fuel use and childhood anemia. In contrast, several studies (Mishra and Retherford 2007; Kyu *et al.* 2010; Amadu *et al.* 2021) observed a positive correlation between biomass fuel use and child anemia.

3.2. Potential mechanisms

So far, our results have shown that households' adoption of non-solid cooking fuel helps reduce the prevalence of stunting and underweight among under-five children. Why is it like this? A close examination of the literature reveals at least two potential causal pathways underlying such research findings. One is by improving household air quality (Imelda 2020), which can benefit children's nutrition directly. Evidence from the public health literature suggests that air pollution leads to repeated episodes of febrile respiratory illness, inducing more active immune activities and altering the metabolism of key nutrients, leading to nutritional imbalance that will impair children's nutrition (Dewey and Mayers 2011; Sinharoy *et al.* 2020; Li *et al.* 2021). The other is by promoting the wellbeing of mothers, such as improving mother's health (Amegah *et al.* 2020; James *et al.* 2020) or reducing their time spent on collecting fuel/cooking (Afridi *et al.* 2021; Akter and Pratap 2022). Although DHS does not collect information on air quality at the household level or time spent on collecting fuels or cooking by mothers, DHS collects information on children's respiratory symptoms (such as cough and fever) and mothers' health (such as BMI index). Moreover, we are also fortunate to get information on the time spent on collecting fuels in 13 African countries from a WHO report (Hutton *et al.* 2006). Thus, in this subsection, we draw on information from various sources, including evidence from environmental studies, information on the respiratory symptoms of children, health and time use of mothers, to explore potential mechanisms.

First and foremost, evidence from exposure studies suggests that switching from solid cooking fuel to the non-solid one can help reduce PM2.5 and CO emissions, which in turn reduces the prevalence of malnutrition. In fact, a credible measurement of household air quality using minute-by-minute data in rural India reveals that the level of PM2.5 pollutants can rise up to 1000 ug/m3 during meal preparations in the household using solid fuel, which is 40 times greater than the safe limit (25 ug/m3) (Somanathan *et al.* 2022). There is also evidence that switching from solid cooking fuel to LPG is associated with a reduction of 295 ug/m3 in PM2.5 and 23.8 ppm in CO, and switching to an induction cooker further leads to a reduction of 200-450 ug/m3 in PM2.5 pollutants (Imelda 2020; Somanathan *et al.* 2022). Furthermore, it has been documented that the decrease in PM2.5 concentration by one standard deviation helps reduce the prevalence of stunting by five pp, and a decrease in CO by 1 μg/m3 helps reduce the standard deviation of the wasting prevalence by 3 pp (Balietti *et al.* 2022).

The literature cited above has provided supporting evidence that households' transition to non-solid cooking fuel can benefit children's nutrition by reducing indoor air pollution directly. Such being the case, we would expect to see reducions in respiratory symptoms among children. Evidence from public health literature suggests that respiratory symptoms, like fever, can lead to nutritional imbalances and impair children's nutrition (Dewey and Mayers 2011; Sinharoy *et al.* 2020; Li *et al.* 2021). To test this mechanism, we further examine the effect of households' adoption of non-solid cooking fuel on children's likelihood of respiratory symptoms over the past two weeks. Results from the FE model show that households' adoption of non-solid cooking fuel is significantly associated with a lower probability of cough (by 0.4 pp) and fever (by 0.5 pp) over the past two weeks among under-five children (Table 4). However, results from the IV approach do not come out significant, which might have something to do with the the way we measure respiratory symptoms. According to Kurata *et al.* (2020), the effects of non-solid cooking fuels are cumulative, but DHS only reports respiratory symptoms within only two weeks. Taken together, these findings provide weak evidence in support of the direct mechanism that the use of non-solid fuels can benefit children's nutrition by improving indoor air quality and reducing their respiratory symptoms.

[Table 4 about here]

When exploring the other potential pathway, we do find evidence that the benefits of households' using non-solid cooking fuel on under-five children's nutrition outcomes might also come from improved maternal health. As shown in Table 5, households' adoption of non-solid cooking fuel improves maternal BMI score by 0.913 points (almost 4% higher than the sample average) and reduces their likelihood of being underweight by 3.5 pp. These findings are consistent with the those of Amegah *et al.* (2020). However, our results also suggest households' adoption of non-solid cooking fuel increases the likelihood of being overweight among mothers of under-five children, but not on their likelihood of being anemic. Moreover, evidence from the public health literature further suggests that burning biomass fuels is a risk factor for respiratory symptoms, pneumonia (James *et al.* 2020), and elevated blood pressure (Baumgartner *et al.* 2011) for women.

[Table 5 about here]

Furthermore, results from secondary data also suggest that households' adoption of non-solid cooking fuel can help to reduce the time that mothers spend on collecting fuel. It has been well documented that mothers in developing countries spend a lot of time collecting solid fuels, such as firewood, dung cake, and so on, which can be as high as 1.4 hours in India (Parikh 2009) and 1.5 hours on average in sub-Saharan Africa (Rehfuess and WHO 2006) per day. There is also evidence that households' adoption of non-solid cooking fuels can significantly help alleviate mothers from the long-time burden of gathering fuel (Afridi *et al.* 2021; Akter and Pratap 2022). In the case of this study, although DHS does not collect information on maternal time spent on collecting fuel, we obtain the average time that women spent on collecting fuels in 13 African countries between 1990 and 2003 from a WHO report (Hutton *et al.* 2006). Among these countries, ten of them have participated in the DHS survey, including Burkina Faso, Ethiopia, Ghana, Kenya, Malawi, Namibia, Nigeria, Uganda, Zambia and Zimbabwe. When we plot the use of non-solid fuel in these countries (from the DHS data) against the time mothers spend on collecting fuels (from the WHO report), and find that the higher the proportion of households using non-solid fuels, the lower the average time that women spent gathering fuel in these countries (Figure 6). In sum, such a finding provides suggestive evidence for our second potential mechanism.

Finally, households' adoption of non-solid fuels might free maternal labor by shortening cooking time. It has been shown that clean fuel such as LPG burns more efficiently and leads to less time that mothers spent on cooking (Imelda 2020). For instance, Akter and Pratap (2022) reported that adopters of LPG save 15 minutes of cooking time per day than non-adopters. It is worth noting that there is recent evidence that the LPG adoption leads to an increase in women's working hours (Verma and Imelda, 2022). It remains unclear whether mothers would use the time saved from collecting fuels or cooking on parenting children, which might benefit children's nutrition outcomes. This might be an interesting topic for future studies.

3.3. Heterogeneity in nutrition impacts of non-solid cooking fuel on under-five children

By child and household characteristics

So far, we have shown the nutrition benefits of households' using non-solid cooking fuel on under-five children, is it possible that the impacts vary by sub-groups of children? To answer this question, we conduct heterogenous analyses by children's gender (girl/boy), age (above/below three years old), region of residence (rural/urban), and household socioeconomic status (high/low, mothers have finished junior high school or above equal "high"). We introduce the aforementioned dummy variables into Equations 1-4 separately and interact it with the dummy variable indicating households' adoption of non-solid cooking fuel before we reran the regressions.

[*Table 6 about here*]

Results from heterogeneous effects on children's nutrition outcomes show three informative patterns as follows (Table 6). First, we find that boys benefit more from households' adoption of non-solid cooking fuel than girls (Panel A, Table 6). As to stunting, both boys and girls benefit from household's adoption of non-solid cooking fuel, with the former benefiting more than the latter. This finding is in contrast to those of Imelda (2020) and Kurata *et al.* (2020) that find girls benefits more than boys. As to wasting and underweight, we find that only boys benefit from households' adoption of non-solid cooking fuel. One possible explanation for the gender heterogeneity might be that boys are more vulnerable to air pollution than girls because of their lower respiratory volumes and narrower peripheral airways in early childhood (Clougherty 2010).

Second, children aged above three years old tend to benefit more from households' adoption of non-solid cooking fuel than their younger peers in terms of stunting, underweight and anemia (Panel B), but less in terms of wasting. One possible explanation is that the older children are more likely to participate in cooking in the kitchen and help with collecting cooking fuel, such as firewood, dung, and so on than their younger peers (Rehfuess and WHO 2006). In this case, transition into cleaner cooking fuel can protect the older children from fuel collection and cooking activities and make them breathe fewer pollutants. This finding is consistent with that of Machisa *et al.* (2013). However, Kim *et al.* (2017) and Schwinger *et al.* (2022) find that solid or biomass fuel is uncorrelated with the prevalence of stunting of under-three children.

Finally, children from rural areas and households of lower socioeconomic status benefit more from households' adoption of non-solid cooking fuel in terms of stunting, wasting and underweight, but not in anemia (Panels C and D). These findings are consistent with those of Mishra and Retherford (2007) and Amadu *et al.* (2021), which imply that greater equity in the access to non-solid cooking fuel might be an inclusive option to help reduce socioeconomic disparities in the nutrition outcomes of children.

By regions

Results from heterogeneous analyses also suggest nutrition impacts of households' adoption of non-solid cooking fuel vary by regions (Table 7). We find that in four out of the six regions, households' adoption of non-solid cooking helps to improve child nutrition outcomes. Among the four regions, under-five children in southeast Asia benefit the most from households' adoption of non-solid cooking fuel, with 12.5, 12.1 and 16.4 pp lower probability of being stunted, underweight and anemic induced by households' adoption of non-solid cooking fuel, respectively. In contrast, we do not find any evidence that households' adoption of non-solid cooking fuels is associated with improvement in nutrition outcomes among under-five children in west Asia and sub-Saharan Africa. In fact, as far as sub-Saharan Africa is concerned, the prevalence of anemia among under-five children from households using non-solid cooking fuel appears to be higher than their peers from households using solid cooking fuel. One possible explanation for the lack of benefits might be the inadequate supply of energy infrastructure in sub-Saharan countries, these countries have the lowest access levels to electricity and modern cooking fuels in the world (Prasad 2011). Also, kerosene is the most common modern cooking fuel in sub-Saharan Africa, while its inadequate combustion can lead to black carbon emissions, which would also damage health outcomes (Curto *et al.* 2019).

[*Table 7 about here*]

4. Conclusion

In this paper, we have examined whether households' adoption of non-solid cooking fuel would benefit children's nutrition outcomes in developing countries. Drawing on a cross-country dataset covering 1,128,085 under-five children from 62 countries in six regions of the world, we took fixed effects and instrumental variable approaches and found that households' adoption of non-solid fuel reduces the prevalence of stunting and underweight among under-five children. We also provide empirical evidence that improvement in mother's health is one potential mechanism underlying these research findings, along with suggestive evidence of improvement in household air quality, reduction in respiratory symptoms of children, reduction in fuel collection or cooking time of mothers. Results from heterogeneous analyses show that the beneficial effects of household's adoption of non-solid cooking fuel are more pronounced among boys, children above three years old, those from rural areas, households of lower socioeconomic status and southeast Asia. Last but not the least, we find consistent evidence that households' adoption of non-solid cooking fuel exerts nutrition benefits on under-five children in developing countries in four out of the six regions, with the exception of west Asia and sub-Saharan Africa.

We acknowledge four limitations of our study. First, as DHS only collected information about the type of cooking fuel used at the time of the survey, we are not able to disentangle the adoption of non-solid cooking fuel before and after birth, whose effects on children's nutrition or health might differ a lot (Imelda 2020). Second, while the DHS survey asked about the type of fuel mainly used in the households, it did not ask any about the frequency and quantity of households' adoption of cooking fuels. Such being the case, we are able to measure whether a household uses non-solid cooking fuels or not, but not their intensity or the use of multiple types of cooking fuels. Considering that some households may use both solid and non-solid fuels for cooking purposes, and the intensity of cooking fuel use may differ among households, future studies on this topic with more detailed information are necessary. Third, due to data constraints, the effects on household air pollutants and maternal time spent on fuel collection and cooking cannot be identified in this study. Thus, we are not able to identify which underlying mechanism might dominate. Finally, the survival bias might lead to the underestimation of our results. Given the positive association between unclean cooking fuel and infant mortality rate (Imelda 2020; Odo *et al.* 2021), our estimates can be interpreted as a lower bound of the actual benefits of households' adoption of non-solid cooking fuel.

Despite the limitations, our findings shed some light on relevant policies that seek to promote household energy conversion and improve children's nutrition in at least four aspects. First, given the beneficial effects of adopting non-solid cooking fuel on children's nutrition outcomes, especially for those from disadvantaged groups, a set of concerted policy tools are needed to facilitate the transition from solid to non-solid cooking fuels by households in developing countries, such as providing financial subsidy, reducing the perceived cost of clean fuels and raising awareness about the damage of using solid fuels. Besides, we find that boys, children aged above three years old, and those from rural areas and households of lower socioeconomic status benefit more from households' adoption of non-solid cooking fuel, which implies that more supports should be given to children living in disadvantaged household and rural areas, and those from undeveloped countries. Also, it is necessary to avoid children under five years old, whether girls or boys, participating in cooking activities associated with solid fuels and fuel gathering activities. Moreover, our findings from mechanism analyses imply that practical measures should be adopted to protect mothers from indoor air pollution caused by the combustion of solid fuel, improve maternal health, and save their time spent on fuel gathering and cooking. Finally, our consistent evidence about the benefits of using non-solid cooking fuels on the nutrition outcomes of under-five children in most developing countries calls for concerted efforts by stakeholders worldwide to facilitate the transition to cleaner household cooking fuels.

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Table 1 Population coverage survey frequency for the 62 sample countries

Region	Number of countries surveyed	Survey countries	Survey years	Observations
Southeast Asia (EAP)	2	Cambodia, Timor-Leste	2000, 2005, 2009, 2010, 2014	25,213
West Asia (ECA)	6	Albania, Armenia, Azerbaijan, Kyrgyz Republic Moldova, Tajikistan	2000, 2005, 2006, 2008, 2010, 2012, 2015	20,477
Latin America (LAC)	9	Bolivia, Colombia, Dominican Republic, Guatemala Guyana, Haiti, Honduras, Nicaragua, Peru	2000, 2001, 2002, 2003, 2005, 2007, 2008, 2009, 2010, 2011, 2012, 2013, 2014	190,025
North Africa (MNA)	4	Egypt, Jordan, Morocco, Yemen	2000, 2002, 2003, 2005, 2007, 2009, 2012, 2013	73,924
South Asia (SAS)	6	Bangladesh, India, Maldives, Myanmar, Nepal, Pakistan	1998, 2001, 2004, 2006, 2007, 2009, 2011, 2012, 2014, 2015, 2016	329,533
Sub-Saharan Africa (SSA)	35	Benin, Burkina Faso, Burundi, Cameroon, Chad, Comoros, Congo, Congo Democratic Re.., Cote d'Ivoire, Ethiopia, Gabon, Gambia, Ghana, Guinea, Kenya, Lesotho, Liberia, Madagascar, Malawi, Mali, Mozambique, Namibia, Niger, Nigeria, Rwanda, Sao Tome and Principe, Senegal, Sierra Leone, South Africa, Swaziland, Tanzania, Togo, Uganda, Zambia, Zimbabwe	1999, 2000, 2001, 2003, 2004, 2005, 2006, 2007, 2008, 2009, 2010, 2011, 2012, 2013, 2014, 2015, 2016	488,913
Total	62		1998-2016	1,128,085

Data source: The Demographic and Health Surveys (DHS).

Table 2 Descriptive statistics

	Observations	Mean	SD	Min	Max
Panel A: Dependent Variables					
Nutrition outcomes of children					
Stunting (1=yes)	991,224	0.357	0.479	0	1
Wasting (1=yes)	1,038,900	0.108	0.310	0	1
Underweight (1=yes)	1,072,518	0.223	0.417	0	1
Anemia (1=yes)	572,387	0.560	0.496	0	1
Rspiratory symptoms of children					
Cough (1=yes)	1,120,145	0.241	0.427	0	1
Fever (1=yes)	1,112,125	0.220	0.414	0	1
Health outcomes of mothers					
Maternal BMI index	960,847	22.660	4.442	12.02	60
Maternal Underweight (1=yes)	960,847	0.140	0.347	0	1
Maternal Overweight (1=yes)	960,847	0.170	0.375	0	1
Maternal Anemia (1=yes)	663,063	0.329	0.470	0	1
Panel B: Household and Parental Characteristics					
Non-solid cooking fuel (1=yes)	770,395	0.296	0.457	0	1
HHs live in rural areas (1=yes)	770,395	0.664	0.472	0	1
Head of household is female (1=yes)	770,395	0.167	0.373	0	1
HHs with improved toilet (1=yes)	770,395	0.310	0.461	0	1
HHs with clean water (1=yes)	770,395	0.681	0.462	0	1
HHs with electricity (1=yes)	770,395	0.559	0.490	0	1
Mother's age (years)	770,395	28.461	6.683	16	49
Partner's age (years)	770,395	34.678	7.739	15	62
Mother's years of schooling (years)	770,395	5.631	4.853	0	18
Partner's years of schooling (years)	770,395	6.531	4.372	0	18
Parents married (1=yes)	770,395	0.770	0.421	0	1
Mother at work (1=yes)	770,395	0.407	0.491	0	1
Mother smoke (1=yes)	770,395	0.046	0.209	0	1
No. of antenatal visits during pregnancy	770,395	4.300	3.861	0	95
Panel C: Individual Characteristics					
Girl (1=yes)	1,128,085	0.490	0.500	0	1
Age in months	1,128,085	28.570	17.200	0	59.99
Number of siblings	1,128,085	2.411	2.252	0	11
First birth (1=yes)	1,128,085	0.274	0.446	0	1
Birth weight (kg)	1,128,085	3.069	0.573	1.55	5.22
Vaccination (1=yes)	1,128,085	0.298	0.425	0	1

Data source: The Demographic and Health Surveys (DHS).

Table 3 Effects of non-solid cooking fuel on nutrition outcomes of under-five children

	Stunting		Wasting		Underweight		Anemia	
	FE	IV	FE	IV	FE	IV	FE	IV
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Panel A: FE or IV Estimates								
Non-solid cooking fuel	-0.041***	-0.059***	-0.004**	-0.001	-0.021***	-0.012**	-0.001	0.008
	(0.003)	(0.006)	(0.002)	(0.004)	(0.003)	(0.006)	(0.004)	(0.008)
Sub-national region FEs	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FEs	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
*Region*Year FEs*	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Constant	0.756***		0.264***		0.575***		0.980***	
	(0.011)		(0.008)		(0.013)		(0.010)	
Observations	991,224	991,224	1,038,900	1,038,900	1,072,518	1,072,518	572,387	572,387
R-squared	0.114	0.051	0.074	0.013	0.140	0.033	0.160	0.063
Panel B: First-stage estimation (Outcome: Non-solid cooking fuel)								
Share of non-solid fuel in PSU		0.897***		0.898***		0.898***		0.917***
		(0.008)		(0.007)		(0.007)		(0.008)
Cragg-Donald Wald F statistic		6.1e+05		6.5e+05		6.7e+05		3.6e+05

Notes: (1) The odd columns report estimates from the FE model, the even columns report estimates from the IV model. (2) All the columns include sub-national region fixed effects, survey year fixed effects, the interactions of region fixed effects and survey year fixed effects. (3) Standard errors clustered at the sub-national region level are reported in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Table 4 Effects of non-solid cooking fuel on respiratory symptoms of under-five children

	Cough				Fever			
	FE	IV	FE	IV	FE	IV	FE	IV
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Panel A: FE or IV Estimates								
Non-solid cooking fuel	-0.005**	-0.006	-0.004**	-0.005	-0.005**	-0.007	-0.005**	-0.005
	(0.002)	(0.004)	(0.002)	(0.005)	(0.002)	(0.004)	(0.002)	(0.005)
Sub-national region FEs	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FEs	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
*Region*Year FEs*	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Month FEs	No	No	Yes	Yes	No	No	Yes	Yes
Constant	0.286***		0.327***		0.286***		0.327***	
	(0.006)		(0.006)		(0.006)		(0.006)	
Observations	1,112,125	1,112,125	1,120,145	1,120,145	1,112,125	1,112,125	1,120,145	1,120,145
R-squared	0.062	0.006	0.093	0.005	0.063	0.006	0.093	0.005
Panel B: First-stage estimation (Outcome: Non-solid cooking fuel)								
Share of non-solid fuel in PSU		0.898***		0.898***		0.898***		0.898***
		(0.008)		(0.008)		(0.008)		(0.008)
Cragg-Donald Wald F statistic		6.9e+05		6.9e+05		6.9e+05		6.9e+05

Notes: (1) The odd columns report estimates from the FE model, the even columns report estimates from the IV model. (2) All the columns include sub-national region fixed effects, survey year fixed effects, the interactions of region fixed effects and survey year fixed effects, and month fixed effects are further added in column (3), (4), (7) and (8). (3) Standard errors clustered at the sub-national region level are reported in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Table 5 Effects of non-solid cooking fuel on maternal health

	Maternal BMI		Maternal Underweight		Maternal Overweight		Maternal Anamia	
	FE	IV	FE	IV	FE	IV	FE	IV
	(1)	(2)	(1)	(2)	(5)	(6)	(7)	(8)
Panel A: FE or IV Estimates								
Non-solid cooking fuel	0.644***	0.913***	-0.034***	-0.035***	0.033***	0.039***	-0.004	-0.003
	(0.048)	(0.093)	(0.005)	(0.008)	(0.004)	(0.007)	(0.003)	(0.006)
Sub-national region FEs	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FEs	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Region*Year FEs	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	960,847	960,847	960,847	960,847	960,847	960,847	663,063	663,063
R-squared	0.308	0.085	0.118	0.016	0.108	0.025	0.050	0.002
Panel B: First-stage estimation (Outcome: Non-solid cooking fuel)								
Share of non-solid fuel in PSU		0.898***		0.898***		0.898***		0.917***
		(0.008)		(0.008)		(0.008)		(0.007)
Cragg-Donald Wald F statistic		6.0e+05		6.0e+05		6.0e+05		4.2e+05

Notes: (1) The odd columns report estimates from the FE model, the even columns report estimates from the IV model. (2) All the columns include sub-national region fixed effects, survey year fixed effects, the interactions of region fixed effects and survey year fixed effects. (3) Control variables include rural, girl, age in months, number of siblings, first birth, birth weight, vaccination, mother's age, partner's age, mother's years of schooling, partner's years of schooling, parents are married, mother at work, mother smoke, no. of antenatal visits, HHs live in rural areas, head of household is female, HHs with improved toilet, HHs with clean water, HHs with electricity. (4) Standard errors clustered at the sub-national region level are reported in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Table 6 Heterogeneous analyses by gender, age, region and family SES

	Stunting		Wasting		Underweight		Anemia	
	FE	IV	FE	IV	FE	IV	FE	IV
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Panel A: by Gender								
Non-solid cooking fuel	-0.047***	-0.066***	-0.007***	-0.004	-0.025***	-0.019***	-0.002	0.007
	(0.003)	(0.006)	(0.002)	(0.005)	(0.003)	(0.006)	(0.004)	(0.009)
Non-solid cooking fuel*Girl	0.011***	0.016***	0.005***	0.007***	0.010***	0.014***	0.003	0.002
	(0.002)	(0.003)	(0.001)	(0.002)	(0.002)	(0.002)	(0.003)	(0.004)
Covariates	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Sub-national region FEs	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FEs	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Region*Year FEs	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	991,224	991,224	1,038,900	1,038,900	1,072,518	1,072,518	572,387	572,387
R^2	0.115	0.051	0.074	0.013	0.140	0.033	0.160	0.063
Panel B: by Age								
Non-solid cooking fuel	0.001	-0.002	-0.015***	-0.014***	-0.009**	0.005	0.006	0.017*
	(0.003)	(0.006)	(0.002)	(0.004)	(0.004)	(0.006)	(0.004)	(0.009)
Non-solid cooking fuel*Age above three	-0.116***	-0.143***	0.028***	0.033***	-0.032***	-0.044***	-0.015***	-0.021***
	(0.005)	(0.005)	(0.002)	(0.002)	(0.003)	(0.004)	(0.005)	(0.006)
Covariates	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Sub-national region FEs	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FEs	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

*Region*Year FEs*	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	991,224	991,224	1,038,900	1,038,900	1,072,518	1,072,518	572,387	572,387
R^2	0.117	0.054	0.075	0.013	0.140	0.034	0.160	0.063
Panel C: by Region								
Non-solid cooking fuel	-0.029***	-0.042***	0.002	0.005	-0.002	0.006	0.003	0.011
	(0.004)	(0.007)	(0.002)	(0.004)	(0.003)	(0.006)	(0.004)	(0.008)
Non-solid cooking fuel*Rural	-0.026***	-0.045***	-0.013***	-0.017***	-0.038***	-0.049***	-0.006	-0.009
	(0.004)	(0.006)	(0.002)	(0.003)	(0.003)	(0.005)	(0.005)	(0.009)
Covariates	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Sub-national region FEs	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FEs	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
*Region*Year FEs*	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	991,224	991,224	1,038,900	1,038,900	1,072,518	1,072,518	572,387	572,387
R^2	0.115	0.051	0.074	0.013	0.140	0.034	0.160	0.063
Panel D: by Family SES								
Non-solid cooking fuel	-0.050***	-0.072***	-0.009***	-0.008	-0.038***	-0.037***	-0.000	0.008
	(0.004)	(0.007)	(0.002)	(0.005)	(0.004)	(0.006)	(0.004)	(0.010)
Non-solid cooking fuel*High SES	0.017***	0.026***	0.010***	0.013***	0.035***	0.048***	-0.001	-0.001
	(0.005)	(0.006)	(0.002)	(0.003)	(0.004)	(0.004)	(0.004)	(0.006)
Covariates	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Sub-national region FEs	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FEs	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
*Region*Year FEs*	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	991,224	991,224	1,038,900	1,038,900	1,072,518	1,072,518	572,387	572,387
R^2	0.115	0.051	0.074	0.013	0.140	0.034	0.160	0.063

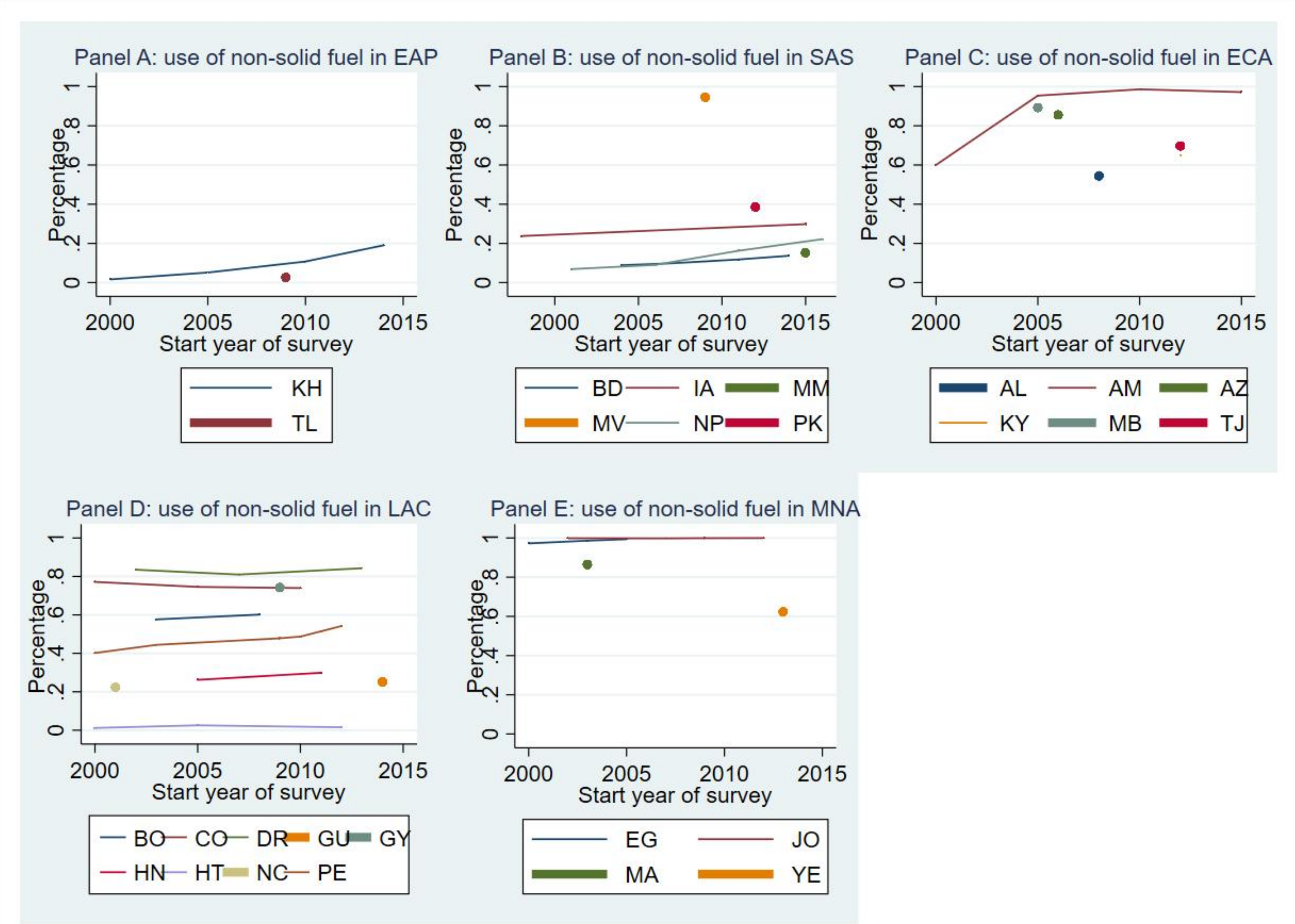
Notes: (1) The odd columns report estimates from the FE model, the even columns report estimates from the IV model. (2) All the columns include sub-national region fixed effects, survey year fixed effects, the interactions of region fixed effects and survey year fixed effects. (3) Control variables include rural, girl, age in months, number of siblings, first birth, birth weight, vaccination, mother's age, partner's age, mother's years of schooling, partner's years of schooling, parents are married, mother at work, mother smoke, no. of antenatal visits, HHs live in rural areas, head of household is female, HHs with improved toilet, HHs with clean water, HHs with electricity. (4) Standard errors clustered at the sub-national region level are reported in parentheses. *** p < 0.01, ** p < 0.05, * p < 0.1.

Table 7 Heterogeneous analyses by regions

	Stunting		Wasting		Underweight		Anemia	
	FE	IV	FE	IV	FE	IV	FE	IV
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Panel A: Southeast Asia								
Non-solid cooking fuel	-0.072***	-0.125***	0.008	0.017	-0.057***	-0.121***	-0.082***	-0.164***
	(0.015)	(0.028)	(0.007)	(0.013)	(0.012)	(0.018)	(0.017)	(0.035)
Observations	21,719	21,719	23,126	23,126	24,210	24,210	14,245	14,245
R^2	0.115	0.058	0.053	0.007	0.106	0.059	0.137	0.099
Panel B: West Asia								
Non-solid cooking fuel	-0.012	-0.014	0.001	0.005	-0.002	-0.007	-0.018	-0.012
	(0.010)	(0.027)	(0.007)	(0.012)	(0.009)	(0.020)	(0.014)	(0.027)
Observations	17,867	17,867	18,955	18,955	19,682	19,682	11,672	11,672
R^2	0.059	0.024	0.032	0.013	0.054	0.020	0.150	0.074
Panel C: Latin America								
Non-solid cooking fuel	-0.058***	-0.097***	0.001	0.001	-0.007***	-0.009**	-0.019**	-0.039**
	(0.006)	(0.013)	(0.001)	(0.002)	(0.002)	(0.004)	(0.007)	(0.016)
Observations	163,309	163,309	178,638	178,638	180,694	180,694	82,913	82,913
R^2	0.180	0.100	0.019	0.005	0.059	0.033	0.167	0.120
Panel D: North Africa								
Non-solid cooking fuel	-0.037**	-0.096***	-0.027**	-0.052***	-0.050***	-0.106***	-0.006	-0.029
	(0.014)	(0.022)	(0.011)	(0.015)	(0.011)	(0.018)	(0.020)	(0.033)
Observations	62,587	62,587	68,642	68,642	70,724	70,724	26,935	26,935
R^2	0.115	0.013	0.061	0.009	0.199	0.011	0.204	0.053
Panel E: South Asia								
Non-solid cooking fuel	-0.041***	-0.058***	-0.008**	-0.009	-0.035***	-0.039***	-0.007	-0.009
	(0.004)	(0.007)	(0.003)	(0.010)	(0.004)	(0.011)	(0.005)	(0.012)
Observations	306,859	306,859	307,077	307,077	317,570	317,570	223,583	223,583
R^2	0.086	0.061	0.034	0.016	0.088	0.056	0.106	0.051
Panel F: Sub-Saharan Africa								
Non-solid cooking fuel	-0.013***	-0.017	0.005	0.011	0.004	0.013	0.017**	0.040***
	(0.005)	(0.011)	(0.004)	(0.008)	(0.005)	(0.010)	(0.009)	(0.015)
Observations	418,883	418,883	442,462	442,462	459,638	459,638	213,039	213,039
R^2	0.091	0.043	0.050	0.016	0.085	0.027	0.146	0.058
Covariates	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Sub-national region FEs	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FEs	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
*Region*Year FEs*	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Notes: (1) The odd columns report estimates from the FE model, the even columns report estimates from the IV model. (2) All the columns include sub-national region fixed effects, survey year fixed effects, the interactions of region fixed effects and survey year fixed effects. (3) Control variables include rural, girl, age in months, number of siblings, first birth, birth weight, vaccination, mother's age, partner's age, mother's years of schooling, partner's years of schooling, parents are married, mother at work, mother smoke, no. of antenatal visits, HHs live in rural areas, head of household is female, HHs with improved toilet, HHs with clean water, HHs with electricity. (4) Standard errors clustered at the sub-national region level are reported in parentheses. *** p < 0.01, ** p < 0.05, * p < 0.1.

Figure 1 Proportion of households using non-solid cooking fuel in the sample countries outside the sub-Saharan Africa



Notes: The subgraphs represent the non-solid cooking fuel use of countries from southeast Asia, south Asia, west Asia, Latin America and north Africa separately.

Figure 2 Proportion of households using non-solid cooking fuel in the sample countries in sub-Saharan Africa (SSA)

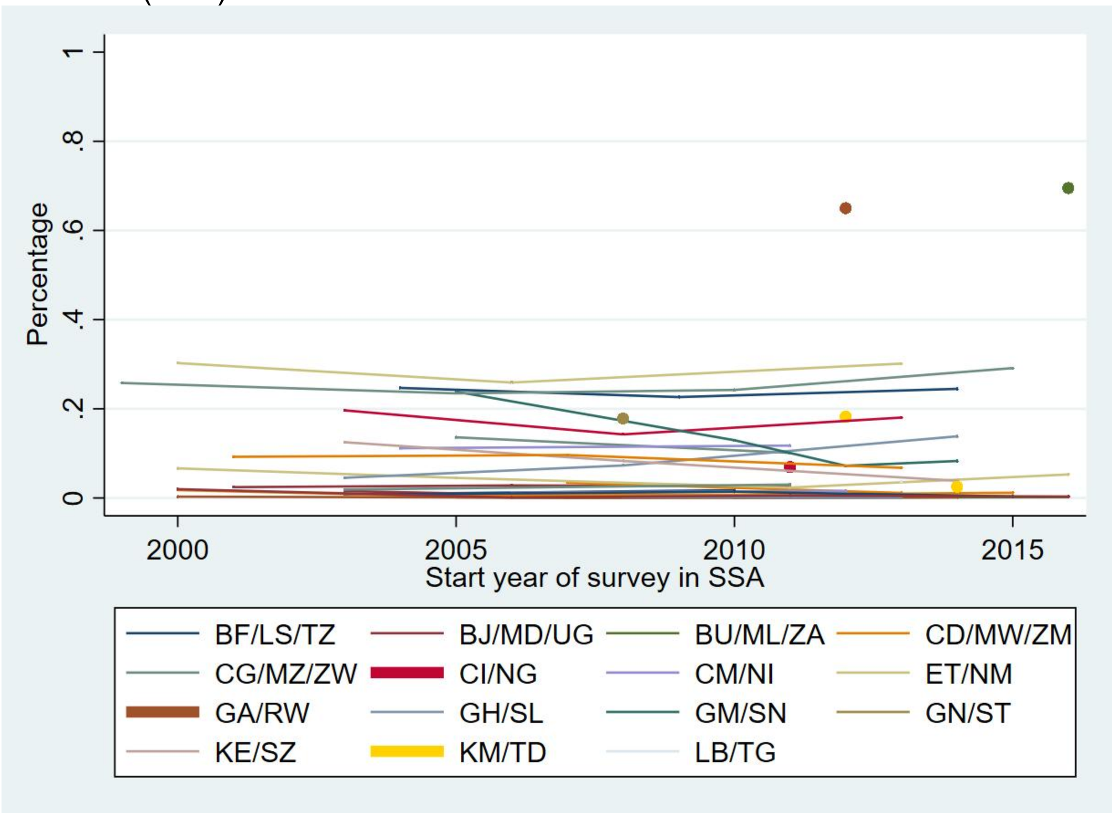


Figure 3 Prevelance of stunting, wasting, underweight and anemia of the sample children, by regions

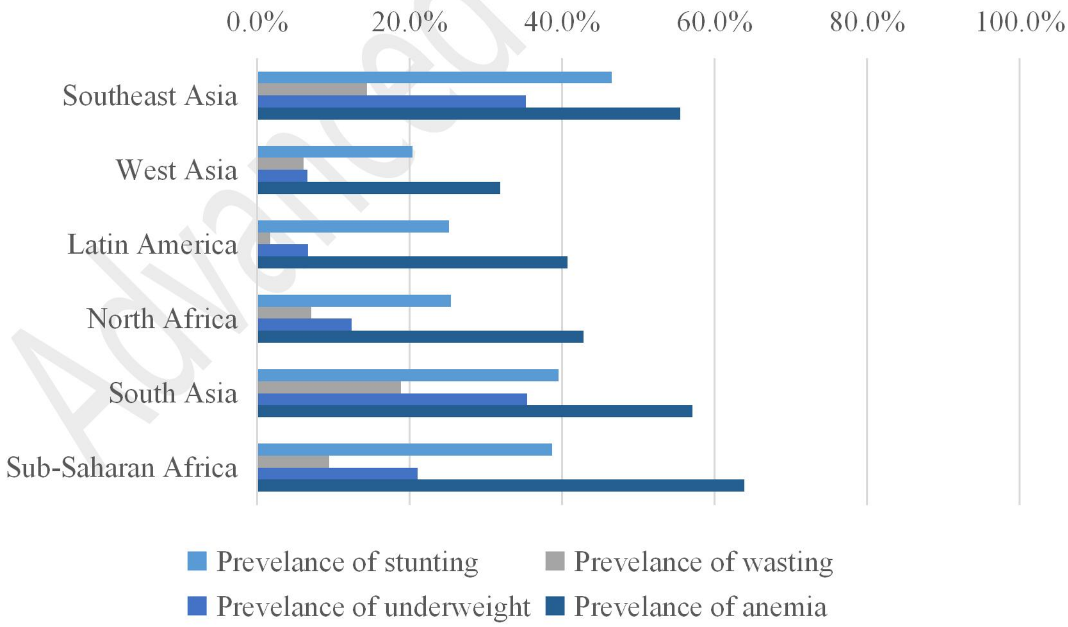


Figure 4 Prevelance of underweight, overweight and anemia of the sample mothers, by regions

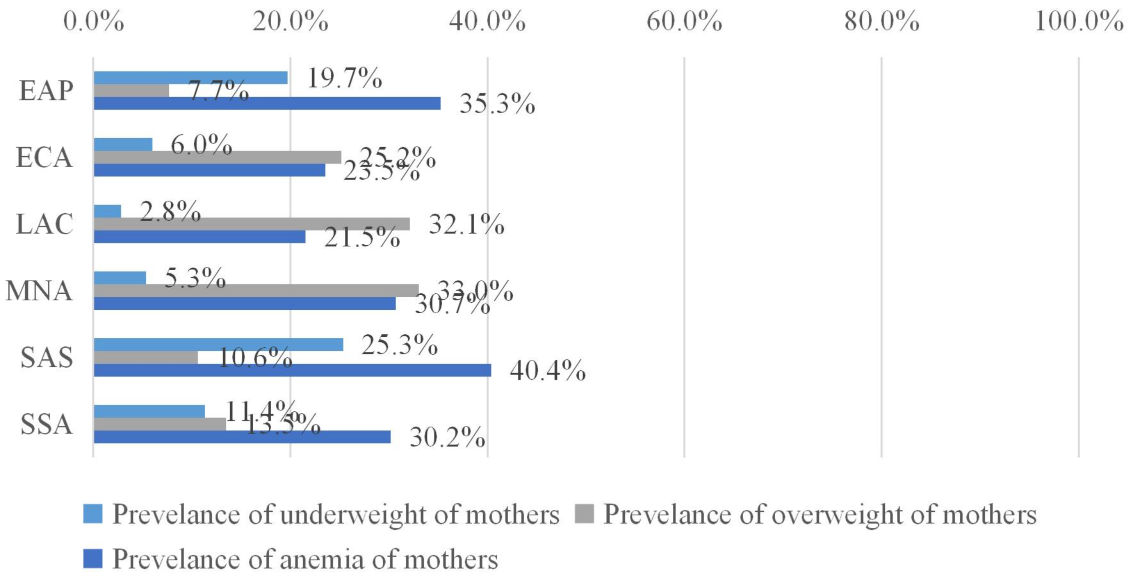
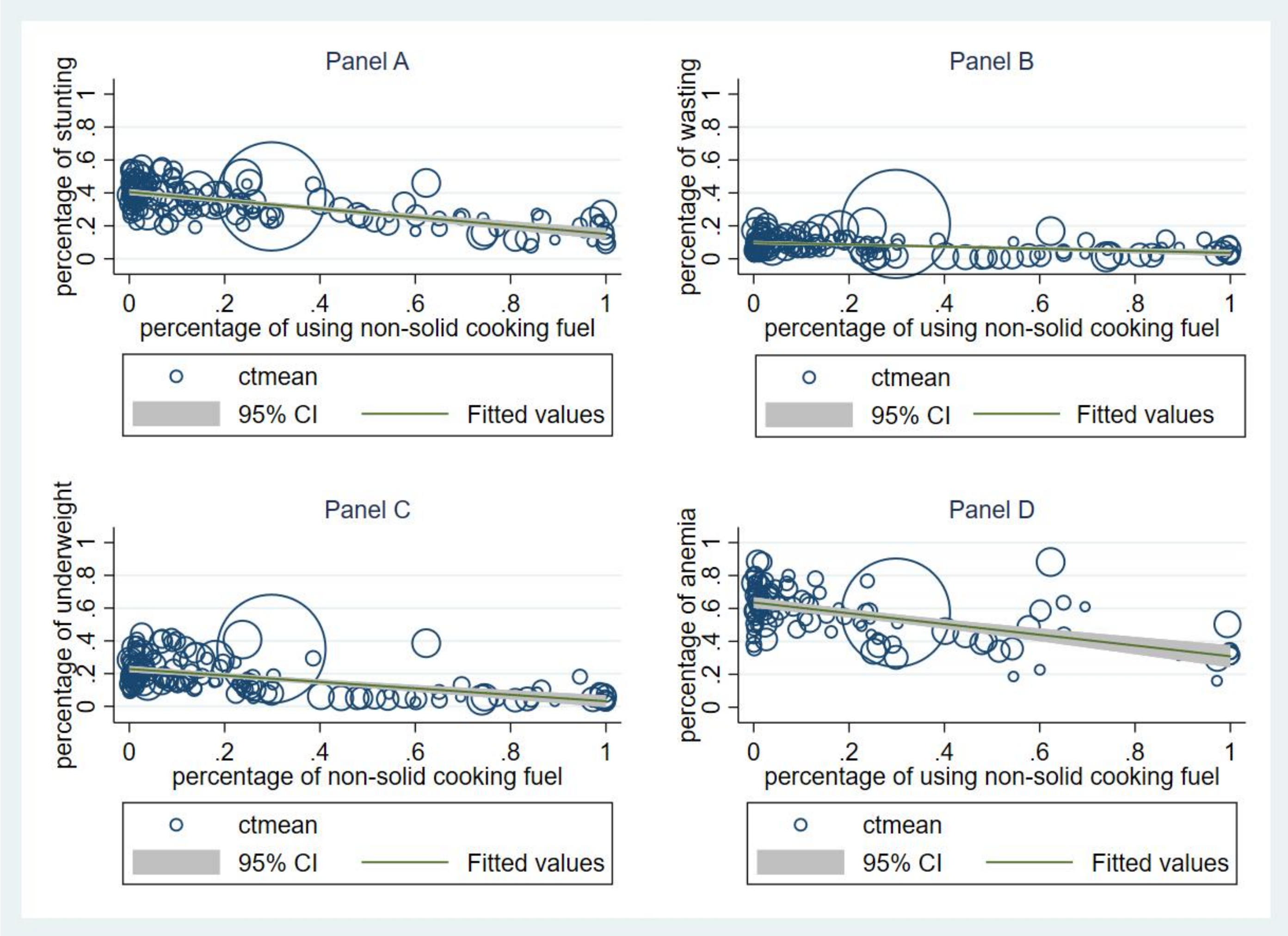
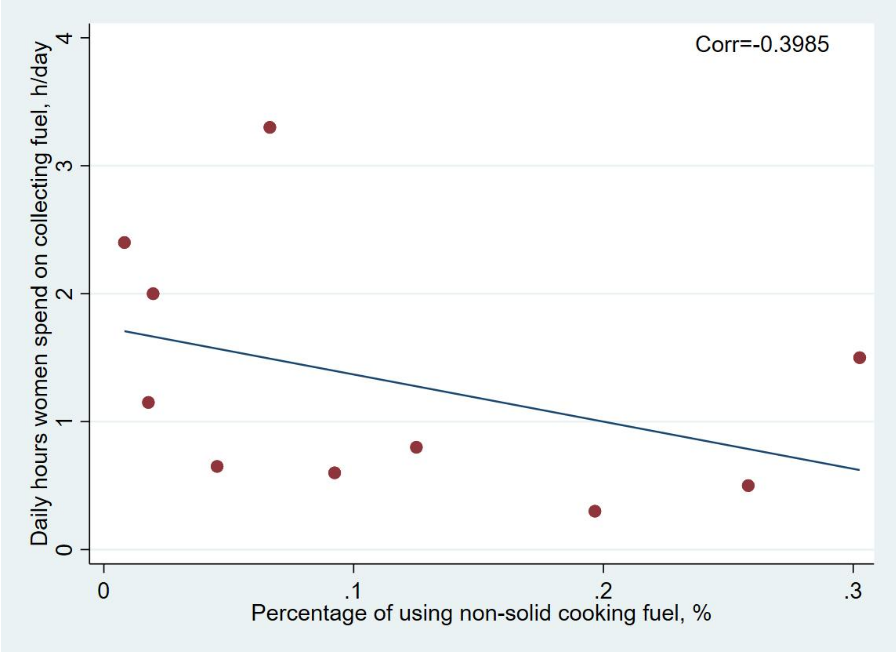


Figure 5 Correlation between proportion of households using non-solid cooking fuel and nutrition outcomes, by countries and years of survey



Notes: The green line is the fit curve, and the gray section shows the range of the 95% confidence interval. The size of the blue bubbles represents the sample size of a country in a given survey year.

Figure 6 Correlation between proportion of households using non-solid cooking fuel and daily hours women spend on collecting cooking fuel



Notes: We draw on the DHS dataset to calculate the proportion of households using non-solid cooking fuel of the above ten countries, where samples surveyed after 2003 are not included in the calculation. Information on daily hours women spend on collecting fuel (1990-2003) of the ten Sub-Saharan African countries comes from http://www.energia.org/.

Appendix I:

In this Appendix, we will describe first the source of the datasets used in this study, and then the procedures we took to clean and merge them to construct the dataset used in this paper.

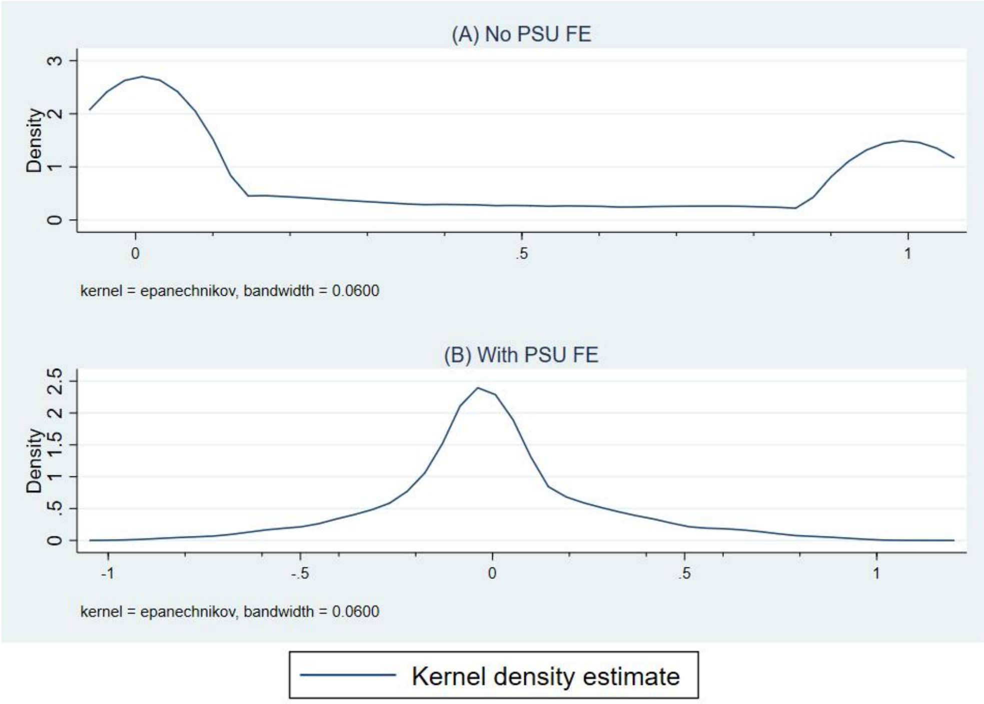
The datasets used for this study are assembled from 343 DHS surveys, which are available on the DHS website: https://dhsprogram.com/data/. DHS surveys collect primary data by administering five questionnaires: household questionnaire, woman's questionnaire, man's questionnaire, the biomarker questionnaire (for children, women, and men), and other country-specific questionnaires. For the purpose of this study, we draw on information of the first four questionnaires by taking a three-step approach to construct the dataset to be used in the rest of this study.

In the first step, of more than 400 DHS surveys covering seven waves in 92 countries, we kept those with the biomarker questionnaire for children (shown in Table A1) so that we could get information on child nutrition.

Secondly, we merge information from the questionnaires of households, women, men and children. To do so, we need to make sure that the matching variables are named the same across different questionnaires. For example, to match information from the household questionnaire with that in the under-five child questionnaire, we have to rename HV001 to V001 and HV002 to V002 in the household questionnaire, just as the way they were named in the child questionnaire. In the meantime, we also need to make sure that variables with the same meaning but different names in different survey years are named the same.

After the above two steps, the final step is to combine and merge those data from different questionnaires and different survey years together. The variables used for merging across questionnaires are shown in Table A2. Immediately afterwards, as described in the second paragraph on page 7 of the revised manuscript, we further restrict the sample to those children that meet our including critaria to construct the study sample and dataset to be used in the rest of the paper.

Figure A1 Distribution of the share of non-solid fuel in PSU



Notes: The analyses reported in this figure are done at the PSU level. (A) The original distribution of the share of non-solid fuel in PSU. (B) The conditional distribution of the share of non-solid fuel in PSU, which is the distribution of residuals obtained from regressing the share of non-solid fuel in PSU on fixed effects at the PSU level.

Table A1 DHS surveys used in our dataset

Country	Country code	Survey indicated by their start and end years
Albania	AL	2008-2009
Armenia	AM	2000-2000, 2005-2005, 2010-2010, 2015-2016
Azerbaijan	AZ	2006-2006
Bangladesh	BD	1996-1997, 1999-2000, 2004-2004, 2007-2007, 2011-2011, 2014-2014
Benin	BJ	1996-1996, 2001-2001, 2006-2006, 2011-2012
Bolivia	BO	1994-1994, 1998-1998, 2003-2003, 2008-2008
Brazil	BR	1996-1996
Burkina Faso	BF	1993-1993, 1998-1999, 2003-2003, 2010-2010
Burundi	BU	2010-2010, 2016-2017
Cambodia	KH	2000-2000, 2005-2005, 2010-2010, 2014-2014
Cameroon	CM	2004-2004
Cameroon	CM	2011-2011
Central African Republic	CF	1994-1995
Chad	TD	2004-2004, 2014-2015
Colombia	CO	1995-1995, 2000-2000, 2005-2005, 2010-2010
Comoros	KM	1996-1996, 2012-2012
Congo	CG	2005-2005, 2011-2012
Congo Democratic Republic	CD	2007-2007, 2013-2014
Cote d'Ivoire	CI	1994-1994, 1998-1999, 2011-2012
Dominican Republic	DR	1996-1996, 2002-2002, 2007-2007, 2013-2013
Egypt	EG	1992-1992, 1995-1995, 2000-2000, 2003-2003, 2005-2005, 2008-2008, 2014-2014
Ethiopia	ET	2000-2000, 2005-2005, 2011-2011, 2016-2016
Gabon	GA	2000-2000, 2012-2012
Gambia	GM	2013-2013
Ghana	GH	1993-1993, 1998-1998, 2003-2003, 2008-2008, 2014-2014
Guatemala	GU	1995-1995, 1998-1999, 2014-2015
Guinea	GN	1999-1999, 2005-2005, 2012-2012
Guyana	GY	2009-2009
Haiti	HT	2000-2000, 2005-2006, 2012-2012
Honduras	HN	2005-2006, 2011-2012
India	IA	1992-1993, 1998-1999, 2005-2006, 2015-2016
Jordan	JO	1990-1990, 1997-1997, 2002-2002, 2007-2007, 2009-2009, 2012-2012
Kazakhstan	KK	1995-1995, 1999-1999
Kenya	KE	1993-1993, 1998-1998, 2003-2003, 2008-2009, 2014-2014

Kyrgyz Republic	KY	1997-1997, 2012-2012
Lesotho	LS	2004-2004, 2009-2010, 2014-2014
Liberia	LB	2007-2007, 2013-2013
Madagascar	MD	1992-1992, 1997-1997, 2003-2004, 2008-2009
Malawi	MW	1992-1992, 2000-2000, 2004-2004, 2010-2010, 2015-2016
Maldives	MV	2009-2009
Mali	ML	1995-1996, 2006-2006, 2012-2013
Moldova	MB	2005-2005
Morocco	MA	1992-1992, 2003-2004
Mozambique	MZ	1997-1997, 2003-2003, 2011-2011
Myanmar	MM	2015-2016
Namibia	NM	1992-1992, 2000-2000, 2006-2007, 2013-2013
Nepal	NP	1996-1996, 2001-2001, 2006-2006, 2011-2011, 2016-2016
Nicaragua	NC	1998-1998, 2001-2001
Niger	NI	1998-1998, 2006-2006, 2012-2012
Nigeria	NG	1990-1990, 1999-1999, 2003-2003, 2008-2008, 2013-2013
Pakistan	PK	1990-1991, 2012-2013
Paraguay	PY	1990-1990
Peru	PE	1991-1992, 1996-1996, 2000-2000, 2003-2008, 2009-2009, 2010-2010, 2011-2011, 2012-2012
Rwanda	RW	1992-1992, 2000-2000, 2005-2005, 2007-2008, 2010-2010, 2014-2015
Sao Tome and Principe	ST	2008-2009
Senegal	SN	1992-1993, 2005-2005, 2010-2011, 2012-2013, 2014-2014
Sierra Leone	SL	2008-2008, 2013-2013
South Africa	ZA	2016-2016
Swaziland	SZ	2006-2007
Tajikistan	TJ	2012-2012
Tanzania	TZ	1991-1992, 1996-1996, 1999-1999, 2004-2005, 2010-2010, 2015-2016
Timor-Leste	TL	2009-2010
Togo	TG	1998-1998, 2013-2014
Turkey	TR	1993-1993, 1998-1998, 2003-2003
Uganda	UG	1995-1995, 2000-2001, 2006-2006, 2011-2011, 2016-2016
Uzbekistan	UZ	1996-1996
Yemen	YE	1991-1992, 2013-2013
Zambia	ZM	1992-1992, 1996-1996, 2001-2002, 2007-2007, 2013-2014
Zimbabwe	ZW	1994-1994, 1999-1999, 2005-2006, 2010-2011, 2015-2015

Table A2 Variables used in merging across questionnaires

Questionnaires	Matching variables: For households	Matching variables: For women
Household	HV001+HV002	V001+V002+V003
Women	V001+V002	
Children	V001+V002	V001+V002+V003
Men	MV001+MV002	Couples MV001+MV002+MV034i

Table A3 Effects of non-solid cooking fuel on nutrition outcomes of under-five children, for subsamples whose IV is greater than zero

	Stunting		Wasting		Underweight		Anemia	
	FE	IV	FE	IV	FE	IV	FE	IV
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Panel A: FE or IV Estimates								
Non-solid cooking fuel	-0.041***	-0.065***	-0.005***	0.003	-0.029***	-0.024***	-0.004	-0.001
	(0.003)	(0.007)	(0.002)	(0.005)	(0.003)	(0.007)	(0.003)	(0.009)
Sub-national region FEs	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FEs	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
*Region*Year FEs*	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Constant	0.787***		0.254***		0.562***		0.994***	
	(0.010)		(0.011)		(0.020)		(0.015)	
Observations	458,331	458,331	480,098	480,098	494,622	494,622	255,269	255,269
R-squared	0.118	0.049	0.082	0.011	0.170	0.035	0.159	0.068
Panel B: First-stage estimation (Outcome: Non-solid cooking fuel)								
Share of non-solid fuel in PSU		0.834***		0.837***		0.837***		0.859***
		(0.011)		(0.010)		(0.010)		(0.011)
Cragg-Donald Wald F statistic		6.1e+05		6.1e+05		6.5e+05		6.5e+05

Notes: (1) The odd columns report estimates from the FE model, the even columns report estimates from the IV model. (2) All the columns include sub-national region fixed effects, survey year fixed effects, the interactions of region fixed effects and survey year fixed effects. (3) Standard errors clustered at the sub-national region level are reported in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Table A4 Effects of Share of non-solid fuel in PSU on nutrition outcomes of under-five children, for subsamples from households using solid fuel

	Stunting	Wasting	Underweight	Anemia
	(1)	(2)	(3)	(4)
Share of non-solid fuel in PSU	-0.030***	-0.003	0.005	0.007
	(0.008)	(0.005)	(0.007)	(0.011)
Sub-national region FEs	Yes	Yes	Yes	Yes
Year FEs	Yes	Yes	Yes	Yes
*Region*Year FEs*	Yes	Yes	Yes	Yes
Constant	0.744***	0.282***	0.611***	0.972***
	(0.013)	(0.008)	(0.012)	(0.011)
Observations	721,448	753,359	778,856	428,026
R-squared	0.088	0.071	0.121	0.146

Notes: (1) All the columns include sub-national region fixed effects, survey year fixed effects, the interactions of region fixed effects and survey year fixed effects. (2) Standard errors clustered at the sub-national region level are reported in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.