Journal of Integrative Agriculture 2024, 23(2): 397–413

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RESEARCH ARTICLE

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

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Abstract

This paper examines the nutrition impacts of using non-solid cooking fuel on under-five children in developing countries. We draw on data from more than 1.12 million children in 62 developing countries from the Demographic and Health Surveys (DHS). Results from both fixed effects (FE) and instrumental variable (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 experiencing stunting (by 5.9 percentage points) and being underweight (by 1.2 percentage points). Our further investigation provides evidence for several underlying mechanisms, such as improved indoor air quality, 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 socioeconomic 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 (2021b) reports the prevalence of anemia in children aged 6–59 months as high as 42%, and 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 long-lasting damage to children's nutrition and health outcomes. On the one hand, recent studies have

Received 20 February, 2023 Accepted 15 May, 2023
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doi: 10.1016/j.jia.2023.11.032

found that 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), NO_2 (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 harms 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 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 NO_x 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). Moreover, some other studies have revealed that reliance on solid fuels forces mothers in developing countries to spend more than one hour per day gathering fuel (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 in developing countries, are exposed to HAP from 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 fuels 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 offer 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 world's 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 the questionnaires of household, women, and men 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 a 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 heterogeneous effects of using non-solid fuels with boys, children above 3 years old, and those from households of lower socioeconomic 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, this paper supplements 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; Alexander and Schwandt 2022; Balietti *et al.* 2022). While previous studies mostly focus on the 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 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 compares 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 data and method. Section 3 presents and discusses our empirical findings. The final section concludes.

2. Data and methods

2.1. Survey and sample

The Demographic and Health Survey (DHS) Our analyses draw on data from the 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 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 as an example, while Zimbabwe conducted the survey in 1999, Niger did so in 2001. Finally, as the frequency and continuation of DHS depend 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 participated in all eight phases, while 19 (21%) participated in only one phase, and 47 (51%) engaged in 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 that had 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 A. 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.

During each phase of the surveys, a set of questionnaires was 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 women's questionnaire, where we draw on information about the nutrition outcomes

Table 1 Population coverage survey frequency for the 62 sample countries

Region	Number of countries surveyed	Survey countries	Survey years	Observations
Southeast Asia	2	Cambodia, Timor-Leste	2000, 2005, 2009, 2010, 2014	25,213
West Asia	6	Albania, Armenia, Azerbaijan, Kyrgyz Republic Moldova, Tajikistan	2000, 2005, 2006, 2008, 2010, 2012, 2015	20,477
Latin America	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	4	Egypt, Jordan, Morocco, Yemen	2000, 2002, 2003, 2005, 2007, 2009, 2012, 2013	73,924
South Asia	6	Bangladesh, India, Maldives, Myanmar, Nepal, Pakistan	1998, 2001, 2004, 2006, 2007, 2009, 2011, 2012, 2014, 2015, 2016	329,533
Sub-Saharan Africa	35	Benin, Burkina Faso, Burundi, Cameroon, Chad, Comoros, Congo, D.R. Congo, 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: Demographic and Health Surveys (DHS).

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 as "Underweight," and with a WHZ less than minus two as "Wasting". Following WHO (2021b), children aged 6 to 59 months are defined as "Anemia" if their altitude-adjusted hemoglobin is less than 110 g L^{-1}.

Health indicators of mothers We focus on four health indicators of children's mothers provided in DHS. The first one is the BMI score. The next two indicators are generated from the 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", which 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^{-1} 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 among the 770,395 sample households with children under five, 30% mainly use 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 region and country. As shown in Figs. 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 noteworthy point is that the share of households using non-

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
Respiratory 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 (HH) 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: Demographic and Health Surveys (DHS).

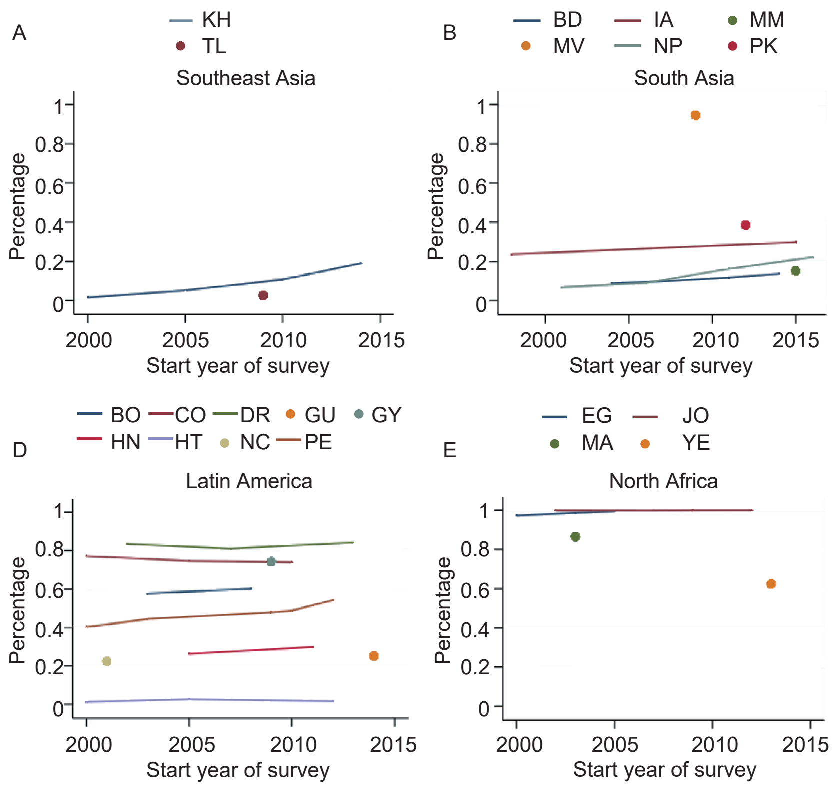

Fig. 1 Proportion of households using non-solid cooking fuel in the sample countries outside sub-Saharan Africa. The subgraphs represent the non-solid cooking fuel use of countries from Southeast Asia, South Asia, West Asia, Latin America, and North Africa, respectively. The combination of the two uppercase letters in the figure represents the country codes, as detailed in Appendix A.

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).

Our sample children seem to lag far behind the global average (Table 2, Panel A) with obvious variations across regions (Fig. 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 2021b). By region, 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

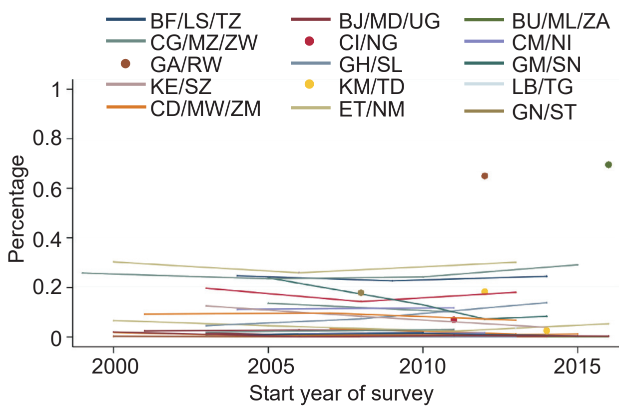

Fig. 2 Proportion of households using non-solid cooking fuel in the sample countries in sub-Saharan Africa. The combination of the two uppercase letters in the figure represents the country codes, as detailed in Appendix A.

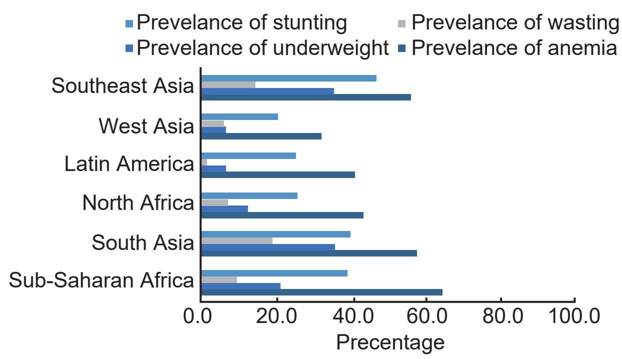

Fig. 3 Prevalence of stunting, wasting, underweight, and anemia of the sample children by region.

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% of sample children had a cough or fever in the two weeks before the interview.

When it comes to the health outcomes of the 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). Fig. 4 further reveals the non-negligible variation by region 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%).

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 weigh 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 (Fig. 5).

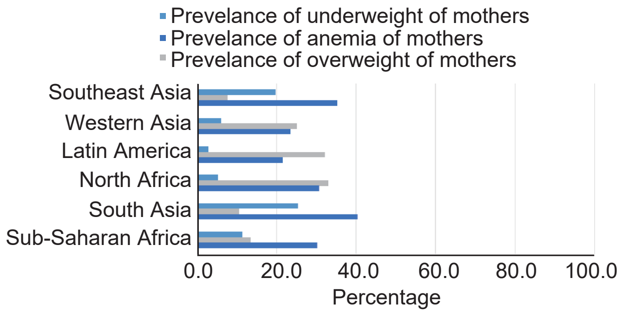

Fig. 4 Prevalence of underweight, overweight, and anemia of the sample mothers by region.

2.4. Empirical specification

To examine the causal effects of using non-solid cooking fuel on children's nutrition outcomes, we have to address

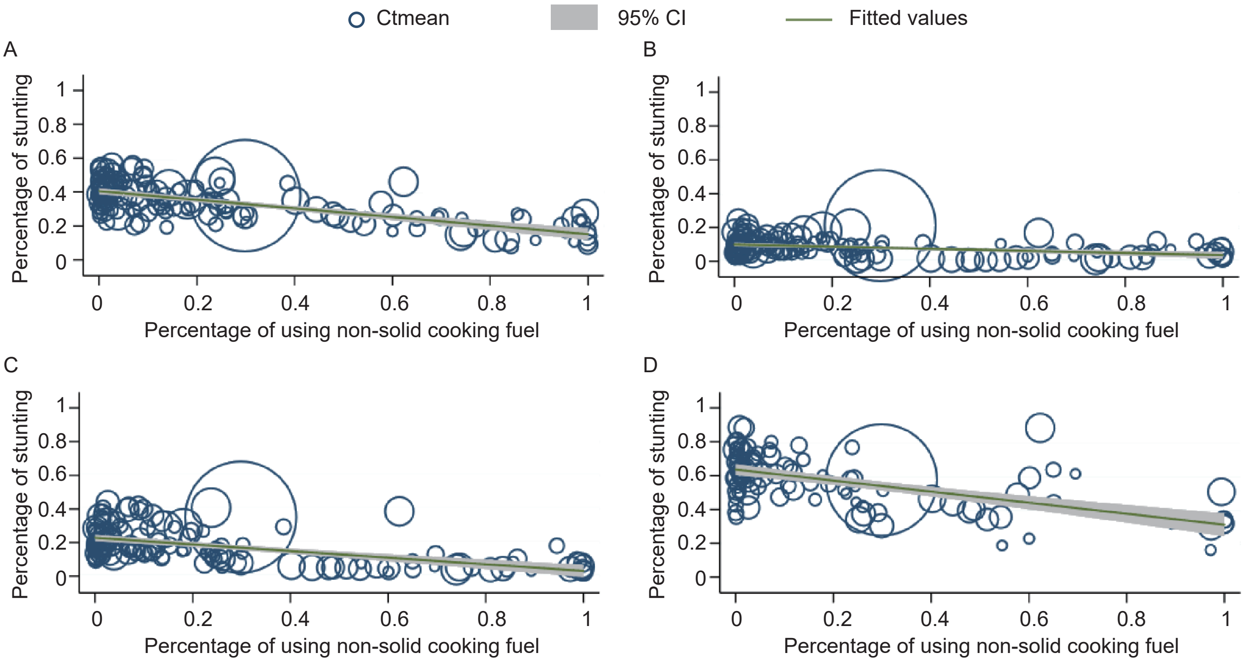

Fig. 5 Correlation between proportion of households using non-solid cooking fuel and nutrition outcomes, by country and survey year. The green line is the fit curve, and the gray section shows the range of the 95% confidence interval. The size of the blue bubbles represents the sample size of a country in a given survey year.

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,

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

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} denote 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 (Balietti and Datta 2017; Kurata *et al.* 2020) and use the availability of non-solid cooking fuel as an 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.

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

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

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

Stage 2: $$Y_{icdt}=\alpha+\beta\widehat{Non\_solid}_{icdt}+\boldsymbol{Z}'_{icdt}\boldsymbol{\gamma}+\eta_d+\alpha_t+\delta_{ct}+\sigma_{icdt} \quad (4)$$

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

The proportion of children living in households from the same PSU that mainly use non-solid 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), 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 focused 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 Appendix C show that in these villages with energy infrastructure, IV remains 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 the socioeconomic 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 Appendix D show that in most cases, the IV estimates using subsamples are

[1] It is shown in Appendix B that more than 50% of the sample villages do not have 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 Appendix B, it shows that the distribution of residuals is approximately normal.

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)
Covariates[1)]	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
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^2	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[2)]		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

[1)] 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, marriage status of parents, labor market participation of mother, mother's smoking status, no. of antenatal visits, female head of household (HH), HHs living in rural areas, HHs with improved toilet, HHs with clean water, HHs with electricity.
[2)] PSU, primary sampling unit.
Standard errors clustered at the sub-national region level are reported in parentheses. ***, $P<0.01$; **, $P<0.05$.

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 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 a potential impact exists, it would be relatively small for the following reasons. On the one hand, indoor pollutant levels are typically twice as high as in the outdoors, and people spend 80–90% of their lives 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 2021a). 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 a 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. Regarding wasting, results from FE suggest a 0.4 pp reduction in the probability, and the estimate from IV is not significant.

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; Amadu *et al.* 2021; Upadhyay *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), who 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 a 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 fuel 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 fuel 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 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 1,000 μg m^{-3} during meal preparations in the household using solid fuel, which is 40 times greater than the safe limit (25 μg m^{-3}) (Somanathan *et al.* 2022). There is also evidence that switching from solid cooking fuel to LPG is associated with a reduction of 295 μg m^{-3} in PM2.5 and 23.8 ppm in CO, and switching to an induction cooker further leads to a reduction of 200–450 μg m^{-3} 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 m^{-3} 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 reductions 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 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.

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 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 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

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)
Covariates[1)]	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
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^2	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[2)]		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

[1)] 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, marriage status of parents, labor market participation of mother, mother's smoking status, no. of antenatal visits, female head of household (HH), HHs living in rural areas, HHs with improved toilet, HHs with clean water, HHs with electricity.
[2)] PSU, primary sampling unit.
Standard errors clustered at the sub-national region level are reported in parentheses. ***, $P<0.01$; **, $P<0.05$.

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)
Covariates[1)]	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	960,847	960,847	960,847	960,847	960,847	960,847	663,063	663,063
R^2	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[2)]		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

[1)] 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, marriage status of parents, labor market participation of mother, mother's smoking status, no. of antenatal visits, female head of household (HH), HHs living in rural areas, HHs with improved toilet, HHs with clean water, HHs with electricity.
[2)] PSU, primary sampling unit.
Standard errors clustered at the sub-national region level are reported in parentheses. ***, $P<0.01$.

pressure (Baumgartner *et al.* 2011) for women.

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 and Noam 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 fuel in 13 African countries between 1990 and 2003 from a WHO report (Hutton *et al.* 2006). Among these countries, ten 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 (Fig. 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 mothers spend 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 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 fuel or cooking to 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 eqs. (1)–(4) separately and interact it with the dummy variable indicating households' adoption of non-solid cooking fuel before we reran the regressions.

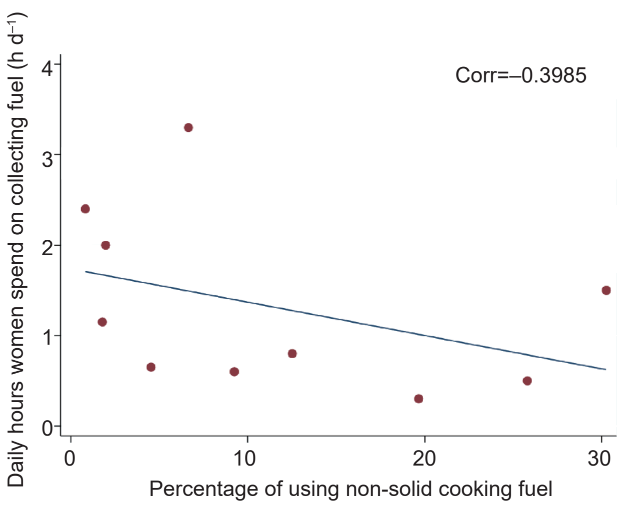

Fig. 6 Correlation between proportion of households using non-solid cooking fuel and daily hours women spend on collecting cooking fuel. We draw on the Demographic and Health Surveys (DHS) dataset to calculate the proportion of households using non-solid cooking fuel in the above ten countries, where samples surveyed after 2003 are not included in the calculation. Information on the daily hours women spend collecting fuel (1990–2003) in the 10 sub-Saharan African countries comes from http://www.energia.org/.

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 the 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), who find that girls benefit 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, Table 6) but less in terms of wasting. One possible explanation is that older children are more likely to participate in cooking in the kitchen and help collect cooking fuel, such as firewood and dung, than their younger peers (Rehfuess and WHO 2006). In this case, transitioning to cleaner cooking fuel can protect 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, Table 6). 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 region Results from heterogeneous analyses also

Table 6 Heterogeneous analyses by gender, age, region, and family socioeconomic status (SES)

	Stunting		Wasting		Underweight		Anemia	
	FE (1)	IV (2)	FE (3)	IV (4)	FE (5)	IV (6)	FE (7)	IV (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[1)]	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[1)]	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[1)]	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[1)]	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

[1)] 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, marriage status of parents, labor market participation of mother, mother's smoking status, no. of antenatal visits, female head of household (HH), HHs living in rural areas, HHs with improved toilet, HHs with clean water, HHs with electricity.

Standard errors clustered at the sub-national region level are reported in parentheses. ***, P<0.01; **, P<0.05; *, P<0.1.

suggest that the nutrition impacts of households' adoption of non-solid cooking fuel vary by region (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, and its inadequate combustion can lead to black

Table 7 Heterogeneous analyses by region

	Stunting		Wasting		Underweight		Anemia	
	FE (1)	IV (2)	FE (3)	IV (4)	FE (5)	IV (6)	FE (7)	IV (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[1)]	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

[1)] 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, marriage status of parents, labor market participation of mother, mother's smoking status, no. of antenatal visits, female head of household (HH), HHs living in rural areas, HHs with improved toilet, HHs with clean water, HHs with electricity.

Standard errors clustered at the sub-national region level are reported in parentheses. ***, P<0.01; **, P<0.05.

carbon emissions, which would also damage health outcomes (Curto *et al.* 2019).

4. Conclusion and policy recommendation

This study examined whether households' adoption of non-solid cooking fuel would benefit children's nutrition outcomes in developing countries. We took fixed effects and instrumental variable approaches based on a cross-country dataset covering 1,128,085 under-five children from 62 countries in six regions. We found that households' adoption of non-solid fuel reduces the prevalence of stunting and underweight among under-five children. We also provided empirical evidence that improvement in mothers' health is one potential mechanism underlying these research findings, along with suggestive evidence of improvement in household air quality, reduction in children's respiratory symptoms, and reduction in mothers' fuel collection or cooking time. 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 least, we found consistent evidence that households' adoption of non-solid cooking fuel exerts nutrition benefits on under-five children in developing countries in four of the six regions, except 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 about the frequency and quantity of households' adoption of cooking fuels. Such being the case, we can 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, 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 is 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 support 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 mothers' 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.

Acknowledgements

This work was supported by the National Natural Science Foundation of China (71861147003 and 71925009).

Declaration of competing interest

The authors declare that they have no conflict of interest.

Appendices associated with this paper are available on https://doi.org/10.1016/j.jia.2023.11.032

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