





Impact of residential solid fuel usage and fuel conversion on children's lung function

Received: 12 April 2022

Accepted: 10 October 2024

Published online: 19 October 2024

 Check for updates

Yanwen Wang^{1,2,11}, Can Zhang^{1,2,11}, Wenjing Zhang^{1,3}, Dandan Xu⁴, Zhen Ding⁵, Hong Jin⁶, Xiaofeng Wang⁴, Jie Zhang⁷, Liangliang Cui^{8,9}, Yangyang Wu¹⁰, Lei Huang¹⁰   & Tiantian Li^{1,2}  

Solid fuel combustion exposure is a leading global health risk factor, yet evidence on its effects, especially on vulnerable children, is sparse. This large-scale, multi-center prospective study aimed to address this gap by involving 9997 schoolchildren across China between 2013 and 2015. Here we show that lung function levels exhibited a marginally significant decline among children exposed to solid fuel usage. Specifically, FVC and FEV1 decreased by 21.2 mL (95% CI: -15.7, 58.1) and 24.1 mL (-8.4, 56.6), respectively. Additionally, PEF, FEF₂₅ and FEF₇₅ decreased by 25.7 mL/s (-46.5, 98.0), 32.7 mL/s (-42.7, 108.2), and 35.4 mL/s (-5.9, 76.7), respectively. Persistent exposure to solid fuel usage in children led to greater lung damage. Children with allergy history were more susceptible to solid fuel exposure. Our study highlights the adverse impact of solid fuel usage on children and the need to promote clean fuel usage for this vulnerable population.

Exposure to pollutant emissions of residual combustion pollutants from consuming dirty energy is a key risk factor of the global burden of disease (GBD). As a form of the traditional dirty energy, solid fuel using is the major affecting factor^{1,2}. According to the statistics of GBD, household solid air pollutants are related to 197.05 disability-adjusted life years (DALYs; 95%CI: 121.14, 321.17) per 100000 people for chronic respiratory diseases³. Solid fuel combustion can produce fine particulate matter, as well as carbon monoxide, nitric oxide and other pollutants 100 times as much indoors as outdoors⁴. The pollutants could spread to the ambient environment and cause harm to the larger population. In China, the mortality risk caused by solid fuel combustion is generally high⁵. Residential air pollution due to solid fuel usage has become a major public health and social problem endangering human health. Given the rapid socioeconomic development, China has implemented several household energy intervention programs over

the past few decades^{6,7}. With the adjustment of energy sources policy, general public could convert energy type under health or economic concerns. However, further analysis is essential to understand the relative health effects.

As the susceptible population of air pollution, children's lung function is more likely to be adversely affected by the use of residential solid fuel^{8,9}. Previous study suggested that use of solid fuels can increase the risk of airway obstruction in children^{10,11}. Pulmonary function can deteriorate for children who live in a house heated by a wood-burning stove¹². In general, schoolchildren population is in a critical period of growth and development of respiratory system, and their lung function is relatively vulnerable to air pollution. Nevertheless, existing studies are mostly cross-sectional, and there are limited multi-center and large sample size prospective cohort studies to support causal analysis. Moreover, studies have mainly been

¹China CDC Key Laboratory of Environment and Population Health, National Institute of Environmental Health, Chinese Center for Disease Control and Prevention, Beijing, China. ²National Key Laboratory of Intelligent Tracking and Forecasting for Infectious Diseases, National Institute of Environmental Health, Chinese Center for Disease Control and Prevention, Beijing, China. ³Jiangsu Provincial Institute of Sports and Health, Jiangsu, China. ⁴Zhejiang Provincial Center for Disease Control and Prevention, Zhejiang, China. ⁵Jiangsu Provincial Center for Disease Control and Prevention, Jiangsu, China. ⁶Hebei Provincial Center for Disease Control and Prevention, Hebei, China. ⁷Henan Provincial Center for Disease Control and Prevention, Henan, China. ⁸Jinan Municipal Center for Disease Control and Prevention, Shandong, China. ⁹Jinan Mental Health Center, Shandong, China. ¹⁰State Key Laboratory of Pollution Control and Resource Reuse, School of the Environment, Nanjing University, Jiangsu, China. ¹¹These authors contributed equally: Yanwen Wang, Can Zhang.

 e-mail: huanglei@nju.edu.cn; litiantian@nieh.chinacdc.cn

conducted in adults, there are still insufficient research on susceptible populations such as children, and the health indicators used in previous studies were insufficient to evaluate the level of lung function. Since solid fuel usage remains a health issue for some developing countries, nationwide longitudinal studies of lung function in children are important.

In this work, we conduct a multi-center longitudinal cohort in China among schoolchildren aged 6–14 years old to investigate the effects of residential solid fuel usage on lung function. We find that lung function levels exhibit a marginally significant decline among children exposed to solid fuel usage. Children with persistent exposure to solid fuel usage or a history of allergy appear more susceptible to solid fuel exposure. These findings emphasize the importance of adopting and maintaining the use of clean energy for indoor cooking and heating, which can positively contribute to public health.

Results

Characteristics of study participants

Characteristic description of the study participants are presented in Table 1. Of the 9997 participants, the mean (SD) age was 9.0 (0.9) with 52.3% males, and the mean (SD) BMI was 17.8 (3.8) kg/m². Overall, 23.2% and 85.4% of participants reported to have passive smoking and pet keeping in the residence. 22.6% and 17.3% of participants reported to

Table 1 | Characteristic description of the study participants

	N / mean	% / std
Number	9997	100%
Age	9.0	0.9
Sex		
Male	5233	52.3%
Female	4764	47.7%
BMI	17.8	3.8
Mother Education		
Junior High School and below	3194	31.9%
High School and above	6783	67.9%
Passive Smoking	2316	23.2%
Pet Keeping	8540	85.4%
Respiratory Diseases	2264	22.6%
Allergies	1728	17.3%

std: Standard deviation.

have respiratory disease and allergies history. The average number of visits per student was 2.4 and the SD was 0.8.

Characteristic description of changing either or both the fuel types of cooking and heating are presented in Table 2. Out of the 9997 participants in our study, 9365 (93.7%) were persistent users of clean fuel; 109 (1.1%) were previous users of solid fuel; 367 (3.7%) were persistent users of solid fuel; and 81 (0.8%) were previous users of clean fuel.

Effects of residential solid fuel on lung function

Figure 1 shows the change of lung function of residential solid fuel usage compared to clean fuel usage, controlling for sex, age, BMI, mother education level, indoor passive smoking, pet keeping, history of respiratory disease, allergy history, ozone exposure level, temperature, relative humidity; as well as the districts and counties where participants' schools located, and the month of performing lung function test. Among the participants who used solid fuel in the residence, FVC marginal decreased by 21.2 mL (95%CI: -15.7, 58.1). The usage of residential solid fuel was also associated with drop of 24.1 mL (95%CI: -8.4, 56.6) in FEV₁, and 35.4 mL/s (95%CI: -5.9, 76.7) in FEF₇₅. PEF (-25.7 mL/s, 95%CI: -98.0, 46.5) and FEF₂₅ (-32.7 mL/s, 95%CI: -108.2, 42.7) also decreased with residential solid fuel usage.

Effect of residential fuel type changing on lung function

The responses of lung function by changing of residential fuel type, which adjusted for sex, age, BMI, mother education level, indoor passive smoking, pet keeping, history of respiratory disease, allergy history, ozone exposure level, temperature, relative humidity, the districts and counties where participants' schools located, first time pulmonary function measurement value, and the month of performing lung function test in model, are shown in Fig. 2. Compared to the participants who are persistent users of clean fuel in the residence, the participants who are persistent solid fuel users demonstrated decline in PEF by 92.0 mL/s (95%CI: -12.8, 196.8), and they also experienced decrease of 46.6 mL/s (95%CI: -10.2, 103.5) in FEF₇₅. Participants who switched their fuel type from solid fuel to clean fuel showed no significant association compared to those who are persistent clean fuel users.

Stratified analysis

Stratified analysis results in different group of participants are presented in Table 3. Among the users of residential solid fuel, male participants experienced significant drop of 52.2 mL (95%CI: 1.2, 103.3) and 59.1 mL/s (95%CI: 4.5, 113.8) in FVC and FEF₇₅, respectively; while

Table 2 | Characteristic description of changing either or both the fuel types of cooking and heating

Characteristic	Always Clean	Solid to Clean	Always Solid	Clean to Solid
	N(%) / mean(std)			
Number	9365(100%)	109(100%)	367(100%)	81(100%)
Age	9.4(0.9)	9.9(0.7)	9.6(0.9)	9.7(0.8)
Sex				
Male	4899(52.3%)	62(56.9%)	198(54.0%)	43(53.1%)
Female	4466(47.7%)	47(43.1%)	169(46.0%)	38(46.9%)
BMI	17.8(3.8)	17.8(3.5)	18.1(3.6)	17.6(3.5)
Mother Education				
Junior High School and below	2818(30.1%)	73(67.0%)*	243(66.2%)*	37(45.7%)*
High School and above	6536(69.8%)	36(33.0%)	122(33.2%)	43(53.1%)
Passive Smoking	2162(23.1%)	24(22.0%)	92(25.1%)	29(35.8%)*
Pet Keeping	1283(13.7%)	28(25.7%)*	90(24.5%)*	24(29.6%)*
Respiratory Diseases	2165(23.1%)	18(16.5%)	55(15.0%)*	10(12.3%)*
Allergies	1646(17.6%)	12(11.0%)	50(13.6%)	8(9.9%)

*Significant difference compared to group with always clean fuel usage, $p < 0.05$.

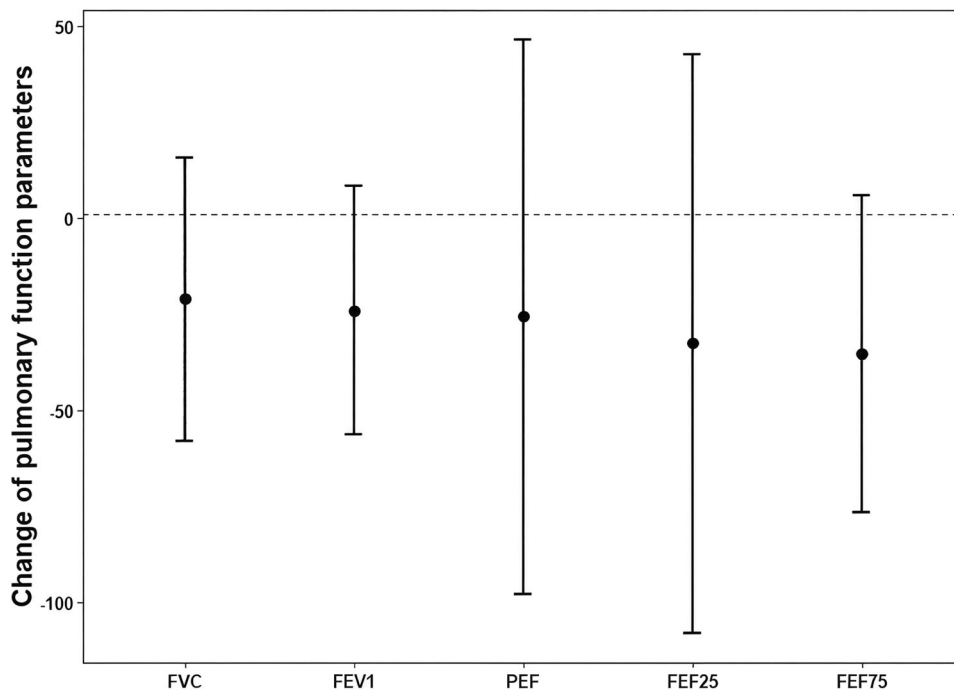


Fig. 1 | Effect of residential solid fuel usage on lung function. FVC (mL) forced vital capacity, FEV1 (mL) forced expiratory volume in 1 s, PEF (mL/s) peak expiratory flow, FEF25 (mL/s) forced expiratory flow at 25%, FEF75 (mL/s) forced expiratory flow at 75%. Points represent the estimated change of pulmonary function

parameters. Vertical lines represent the 95% confidence interval (CI). The sample size used to estimate these changes consisted of 9997 schoolchildren across 24371 visits in China. Source data are provided as a Source Data file.

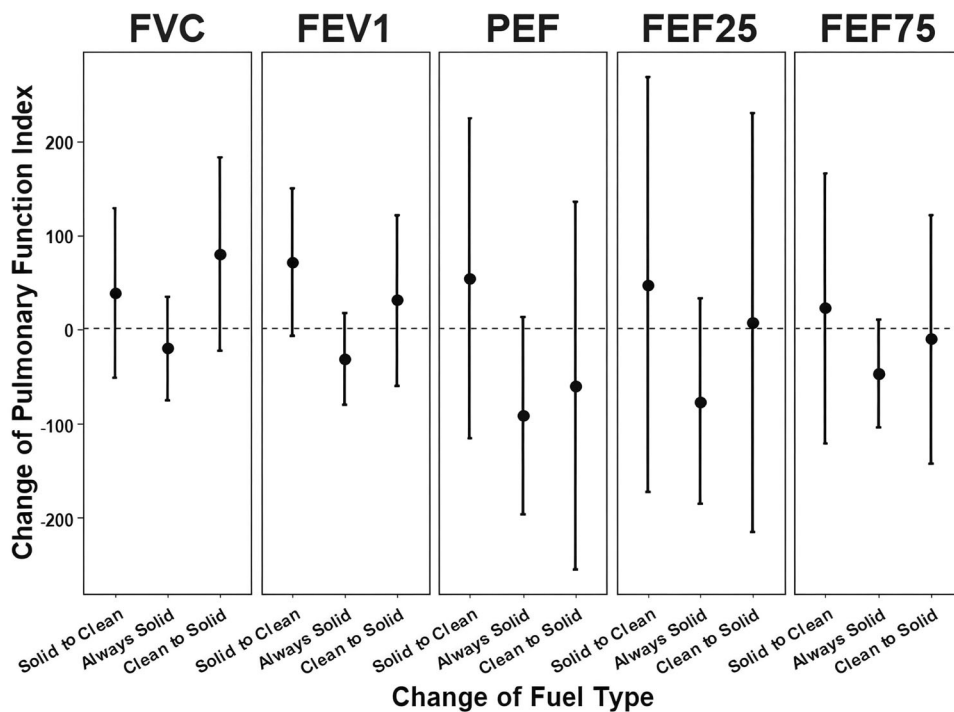


Fig. 2 | Effect of changing residential fuel type on lung function. FVC (mL) : forced vital capacity; FEV1 (mL) : forced expiratory volume in 1s; PEF (mL/s) peak expiratory flow, FEF25 (mL/s) forced expiratory flow at 25%, FEF75 (mL/s) forced expiratory flow at 75%. Points represent the estimated change of pulmonary

function parameters. Vertical lines represent the 95% confidence interval (CI). The sample size used to estimate these changes consisted of 9997 schoolchildren across 24371 visits in China. Source data are provided as a Source Data file.

female participants exhibited little change of lung function. Participants with allergy history showed significant decrease of 241.6 mL/s (95%CI: 44.3, 438.9) in PEF and 117.4 mL/s (95%CI: 7.1, 227.7) in FEF₇₅, indicating greater effects felt by those without reported allergy

history. Participants with respiratory symptoms showed significant drop of 102.4 mL/s (95%CI: 1.0, 203.9) in FEF₇₅, while those without respiratory symptoms had no obvious change of lung function. There was little difference between participants with different BMI, mother

Table 3 | Stratified analysis results for the association between solid fuel exposure and lung function indicators

Variable	β (95% CI)				
	FVC (ml)	FEV ₁ (ml)	PEF (ml/s)	FEF ₂₅ (ml/s)	FEF ₇₅ (ml/s)
Sex					
Male ^a	-52.2(-103.3,-1.2)	-43.3(-87.9,1.3)	71.4(-171.2,28.3)	-53.2(-156.4,49.9)	-59.1(-113.8,-4.5)
Female	19.5(-33.7,72.8)	0.97(-33.7,72.8)	21.7(-82.8,126.3)	-15.0(-125.3,95.3)	-4.4(-66.8,57.9)
BMI					
Normal weight ^a	-21.7(-66.3,23.0)	-28.1(-66.3,23.0)	-51.2(-140.7,38.4)	76.1(-169.7,17.4)	-34.7(-86.5,17.1)
Emaciation	-143.7(-299.9,12.5)	-150.9(-288.4,-13.3)	-188.2(-497.2,120.8)	-66.6(-402.4,269.1)	-57.8(-233.1,117.5)
Overweight	-54.8(-152.8,43.2)	-44.9(-130.2,40.4)	15.6(-176.8,208)	15.6(-176.8,208.1)	-41.7(-141.6,58.2)
Obesity	38.4(-67.4,142.3)	52.4(-39.7,144.4)	96.8(-97.5,291.1)	140.7(-69.6,351.1)	10.9(-107.8,129.6)
Mother education					
Junior high school and below ^a	-19.6(-67.6,28.4)	-13.9(-56.2,28.4)	-0.5(-94.6,93.6)	7.6(-91.9,107.1)	-10.0(-64.0,44.0)
High school and above	-22.1(-80.4,36.3)	-34.4(-85.8,17.0)	-68.4(-182.5,45.6)	-82.6(-199.2,34.1)	-68.4(-132.3,-4.5)
Passive smoking					
No ^a	-8.7(-53.1,35.6)	-13.9(-52.8,25.0)	-0.6(-87.5,86.3)	-21.5(-112.3,69.3)	-19.2(-68.7,30.3)
Yes	-66.5(-133.2,0.3)	-59.7(-119.4,-0.01)	-87.2(-218.5,44.2)	-67.6(-204.2,69.0)	-81.2(-156.8,-5.6)
Pet					
No ^a	-21.8(-64.5,21.0)	-29.7(-64.5,21.0)	-29.1(-67.3,7.9)	-29.7(-116.6,57.1)	-37.5(-84.7,9.7)
Yes	-16.3(-90.3,57.8)	4.2(-61.9,70.3)	12.9(-139.5,165.4)	-9.2(-167.6,149.2)	-13.2(-100.8,74.3)
Allergies					
No ^a	-17.7(-57.5,22.0)	-19.7(-54.8,15.5)	1.9(-76.1,79.9)	-15.3(-96.6,65.9)	-21.7(-66.5,23)
Yes	-43.1(-143.9,57.7)*	-57.8(-144.8,29.2)	-241.6(-438.9,-44.3)	-153.6(-362.9,55.7)	-117.4(-227.7,-7.1)
Respiratory symptoms					
No ^a	-28.7(-69.4,11.9)	-24.8(-60.7,11.1)	-17.3(-96.3,61.6)	-13.5(-95.7,68.8)	-23.0(-68.4,22.5)
Yes	21.4(-68.7,111.4)	-16.4(-94.7,6.0)	-69.3(-250.4,111.8)	-114.4(-305.2,76.4)	-102.4(-203.9,-1.0)

^aReference group.

*Significant difference compared with the reference group.

education, with or without residential passive smoking or pet keeping. Stratified analysis results of different regions for the association between solid fuel exposure and lung function indicators were shown in Fig. S1, and no significant difference between north and south region of China was found in the study. Detailed results of sensitivity analysis and interaction results for stratified analysis were shown in Tables S1–S2, with no significant difference were found in the sensitivity analysis and interaction analysis models.

Discussion

We conducted large sample nationwide perspective study among 9997 schoolchildren undergoing 24371 visits in China to investigate the impact of residential solid fuel on children's lung function. We found that pulmonary lung function decreased among children exposed to household solid fuel, and children who persistently used solid fuel would suffer more significant lung injuries. Participants with allergies history are more susceptible to residential solid fuel exposure. This study revealed the health effects of solid fuel using among children. Our finding supports the urgent need of promoting residential clean energy usage among children population.

Our study indicated that exposed under residential solid fuel would affect lung function of schoolchildren aged 6–14 years old. Previous study reported the positive association of solid fuel usage with weaker lung function. For instance, a meta-analysis reported that exposure to household air pollution was associated with a lower growth rate of several lung function indices (FVC, FEV₁, FEF_{25–75}) in children (under 18 years of age), consistent with our findings¹³. A study in Ecuador showed that children aged 7–15 years old living in homes that use biomass fuel had lower FVC and lower FEV₁ ($P < 0.05$). They reported significantly lower FVC among children living in homes that cooked with solid fuel only, when compared with children living in

homes that cooked with clean fuel¹⁴. Another study in rural India also showed the significant association of exposure to cooking smoke from biomass combustion with poorer lung function, where children aged 5–10 years old using biomass showed 2.1 ± 0.3 (L/s) and children using liquefied petroleum gas showed 3.8 ± 0.9 (L/s) of FVC (mean \pm SD)¹⁵. A recent study in China followed children aged 6–13 years old for up to 4 years and found relation of coal usage as a household fuel to 16.5 ml/year lower and 20.5 ml/year lower growths in children's FEV₁ and FVC, respectively¹⁶. However, these studies only examined the lung function index of FEV₁ and FVC, and lacked the index to estimate small airway function. In a sense, our work here addressed the inadequate understanding about the effect of indoor solid fuel combustion on small airway function of children in previous studies.

In addition to the effect of solid fuel, we also studied the effect of fuel type conversion on lung function. Compared with persistent clean fuel users, fuel conversion has adverse effect on lung function. Children who persistently used solid fuel suffered more lung injuries compared to persistent clean fuel users. Research evidence of effect of fuel type conversion on lung function among children is scarce. In an intervention research in India, decreases in FEV₁ of 44 mL/year (95%CI: -91, 4) and PEF growths of 173 mL/min/year (95%CI: -341, -7) were observed with stove installation at 18 months compared with stove installation at birth, indicating that switching to clean fuel could significantly affect the lung function among children¹⁷. Besides the study of lung function affected by solid fuel usage among children, the study on the state of respiratory diseases provided aside confirmation of the effect of fuel type conversion on respiratory system. The China Kadoorie Biobank (CKB) cohort found that compared with persistent solid fuel users, participants who reported having previously switched from solid to clean fuels for cooking had a lower risk of all-cause mortality (Absolute Rate Difference (ARD) per 100,000 person-years,

407 (95% CI: 317, 497); Hazard Ratio (HR), 0.87 (95% CI: 0.79–0.95)¹⁸. However, the lung function indicators used in previous studies were less comprehensive due to the lack of representativeness of health evaluation of small airways. FVC and FEV1 measurements provided estimation of vital capacity which dropped among the population using solid fuel, yet responded null to the changing of domestic fuel type. Our study indicated the adverse association of PEF with changing of fuel type, yet reacted null to the usage of solid fuel. This confirms that PEF measurement can provide acute estimates of airflow through the bronchi and possible obstruction, and it is more sensitive to the change of exposure from external environment. Since PEF is a sensitive indicator of lung function, a drop in PEF (as shown in Fig. 2) reflects small airway obstruction due to fuel type conversion. Therefore, it is essential to change the fuel type, and we should adhere to the use of clean fuel.

Our study also found that the lung function of children with allergic history is more likely to be affected by the usage of solid fuel. Allergic sensitive children have been reported to have fragile respiratory system and are more sensitive to traffic-related air pollution¹⁹. Some studies also demonstrated an association between air pollution and sensitization to outdoor allergens^{20,21}. According to the proportion of allergic reactions in children in recent years, 40.9% (95% CI: 40.1, 41.6) of parents of infants aged 0–24 months reported that their children had or were suffering from allergic diseases in China²². Our study provided some evidence which supports the need of protecting allergic children from health impact of residential solid fuel usage.

Our study has several advantages. First, this work is a multi-center prospective study in China. This study covered research sites with various geographical environment and climate characteristics, which should enhance the representativeness and reliability of the research results. Second, we conducted a long-term longitudinal study on schoolchildren, capturing important period of children's growth and development, and credibly provided evidence on the health effects of fuel type change on population. Third, we applied stratified analysis among populations of different sex, BMI and disease history. We explored the lung function injury intensity of different populations exposed to solid fuel usage, and identified the susceptible population of residential solid fuel exposure. Fourth, we used multiple health indicators to estimate lung function, and the evaluation of health level is more comprehensive.

There were also several limitations in our study. First, the exposure data of this study were obtained by self-reported questionnaire, hence recall bias might exist. And we matched meteorological variables with schools as a unit, ignoring the differences among children, which may cause deviation. However, in a county, the outdoor temperature and humidity do not change much, and the children's range of activities is also small. Therefore, it is valuable to use the temperature and humidity around the school to represent children's meteorological exposure. Second, domestic fuel type is closely related to socioeconomic status, which is also associated with respiratory health status and lung function. We adjusted the related variables such as parental education level, however, there could be some residual confounding. Third, this study only lasted for 3 years, which might weaken the effects caused by switching of domestic fuel type. Long-term cohort studies could be added to analyze the long-term health effects and changes in energy types in the future. Fourth, specific types of pets were not recorded in the questionnaire. The type of pet might affect the indoor condition, and future studies could include detailed inquiries to improve the covariant. Fifth, we haven't recorded the secondary fuel types and other potential exposures, which may affect the estimate effects of domestic solid fuel usage on lung function. Last, since we did not use random sampling, so the results cannot be extrapolated nationally. Nevertheless, this is, to our knowledge, the largest epidemiological study focusing on the effect of residential solid fuel usage

on children's lung function^{14–17}. Future studies can improve in the above aspects for further amelioration.

This study quantitatively evaluates the health effects of solid fuels on children, provides a reference for further precise prevention and control of solid fuel pollution, and provides guidance for public protection measures. Governments should develop clean fuels and encourage households to reduce their use of solid fuels and transition to clean fuels. Hospitals should pay attention to children's health and give parents protection guidance. Schools should strengthen children's health education, give protective guidance, and always pay attention to children's health. Parents should use clean fuels as much as possible in their homes and reduce the use of solid fuels. Children should improve their awareness of the health effects of solid fuels, strengthen personal protection, use clean fuels, and seek medical attention in time if they have adverse symptoms.

This national wide multi-center perspective study revealed the health impact of domestic solid fuel usage on lung function among school children population, and revealed the population susceptible to solid fuel exposure. The study findings emphasized the importance of using and maintaining using clean energy for indoor cooking and heating, which can positively contribute to public health.

Methods

Study design and population

We conducted a perspective cohort study among 46 cities, from 28 provinces, municipalities, or municipal districts across all 7 geographical divisions in China. The selected cities have set up national level (or provincial or city level) ambient air quality monitoring stations. The selected counties are located within the monitoring range of national level (or provincial or city level) ambient air quality monitoring stations. A total of 78 counties were recruited in our study. Study locations were shown in Fig. S2. The specific selecting criteria were shown in Text S1.

Study general design was shown in Fig. S3. Specifically, the selection of participating children was done by random sampling. First, select 1–2 primary schools within 5 km of the monitoring site. Then, using random sampling method, 150 primary school students in grades 3–5 were selected to carry out questionnaire survey and pulmonary function test. If a participating child has obvious physical discomfort during the pulmonary function test, the relevant test will be stopped, the child will be excluded, and the children not selected in the first sampling will be randomly replaced. During the period 2013–2015, there were 31,078 participants. Participants who completed at least two visits were included in the study, and a total of 9997 participants from grade 3 to grade 6 and 24371 visits were included in the analysis. During each visit, all the participants completed questionnaire survey with help of their parents. Questionnaire included basic information, indoor condition, as well as the disease and symptoms of students; basic information included sex, age, BMI, mother education level; indoor condition included indoor passive smoking, pet keeping; disease and symptoms included history of respiratory disease, allergy history; and the allergy history information was captured according to the records of doctors when participants went to the hospital in recent years. The participants also completed the pulmonary lung function test during each visit. For detailed information please see Supplementary Information Text S1–S3.

Our study obtained approvals (Chinese Environmental Public Health Tracking and Risk Assessment, 202102) from the ethics committee of the National Institute of Environmental Health, Chinese Center for Disease Control and Prevention (NIEH, China CDC). Written informed consent was obtained from guardians of all participants.

Assessment of solid fuel exposure

All the participants were asked to provide detailed information about the conditions of household fuel usage. Participants who reported

household cooking and use heating in winter were asked to provide the primary fuel type used in their house, e.g., coal, natural gas, liquid gas, pipeline gas, electricity, straw, central heating and other unspecified fuels. If more than one fuel type was used in their house, the most frequently used fuel type was recorded. The use of natural gas, liquid gas, pipeline gas, electricity and central heating were considered as clean fuel; while the use of coal and straw were considered as solid fuel. Clean fuel usage for both cooking and heating would consider to be clean fuel using participants, otherwise the participants would be assigned as solid fuel exposure.

We also assessed the change of residential solid fuel type. The changing of fuel types was defined by the fuel type using during the last visit compared to the first visit, and was divided into the following types, always clean, solid to clean, always solid and clean to solid. During the study period 2013–2015, the participants who always used clean fuel were classified as “always clean”. Participants who used solid fuel in 2013 and used clean fuel later, or recruited and used solid fuel in 2014 and used clean fuel later, were classified as “solid to clean”. Similar classifications were defined in “always solid” and “clean to solid”.

Lung function measurement

Pulmonary function tests included forced vital capacity (FVC), forced expiratory volume in 1 s (FEV₁), peak expiratory flow (PEF), and forced expiratory flow (FEF) at 25% and 75% (FEF₂₅, FEF₇₅). The pulmonary function test was conducted by the medical staff in charge of pulmonary function test in the hospital or physical examination center. Before each lung function test, the height and weight of the participants were measured. During the test, participants took standing position, clamped the nose clip and took a calm breath with their mouth. When air leakage occurred during the detection process, or the expiratory mode of the detected object was incorrect, the detection would be repeated, and the results from the most standard performance would be recorded.

Statistical analysis

Baseline characteristics of the study population were described as means with standard deviations (SDs) or numbers with percentages. Body mass index (BMI) was calculated by the height and weight. Education levels of the participants' mothers were classified as junior high school and below, and high school and above. To further evaluate the exposure level, we obtained meteorological parameters (e.g., temperature and relative humidity (RH)) and ozone concentration. The temperature and RH values were obtained from the nearest environmental monitoring station. The ozone concentrations were simulated by high-precision random forest model, which used the meteorological variables, chemical model output value, geographical parameters and socio-economic variables to obtain 1 km × 1 km resolution data set covering all study regions. More detailed description about the simulated ozone concentrations can be found in recent published study²³. All the pollution concentration and meteorological data were matched according to the longitude and latitude of the school.

We used a linear mixed-effects model to estimate the relation between residential solid fuel usage and lung function level.

$$Y_{ij} = \beta_0 + \beta_1 f_{uel} + \beta_2 X_{1,ij} + \dots + \beta_n X_{n-1,ij} + \xi_j + e_{ij} \quad (1)$$

which, Y_{ij} represents the pulmonary function measurement index (FVC, FEV₁, PEF, FEF₂₅, FEF₇₅), β_0 is the total intercept, β_1 is the regression coefficient for solid fuel, $\beta_2 \dots \beta_n$ are the regression coefficients for the covariates in the model, $X_1 \dots X_{n-1}$ are the covariates in the model, ξ_j is the random effect of study participants, j represents study participants, i represents the study time, e_{ij} is the residual term.

We adjusted the basic information, including sex, age, BMI, mother education level; indoor condition, including indoor passive smoking, pet keeping; disease and symptoms, including history of respiratory disease, allergy history; ambient condition, including ozone exposure level, temperature, relative humidity; as well as the districts and counties where participants' schools located, and the month of performing lung function test. The covariates controlled in different models were shown in Table S3. Clean fuel usage was regarded as reference when estimating the effect of residential solid fuel usage on lung function, and always use clean fuel was regarded as reference when estimating the effect of residential fuel type change on lung function.

We also conducted a stratified analysis of sex, BMI, maternal education level, passive smoking, pet keeping, history of respiratory diseases, history of allergies, and geographical region. BMI was classified as normal weight, emaciation, overweight, and obesity according to the classification standard of Chinese childhood obesity. We further analyzed the differences in the correlation between residential solid fuel exposure and lung function between each covariate group. To test the robustness of the results, we conducted multiple sensitivity analysis in the study. For model 2–4, the degree of freedom of meteorological variables was altered to 2,4,5, respectively. For model 5–9, variables such as pet keeping, month, allergies, mother education level, and passive smoking was eliminated from the main model to test the sensitivity of the model. For model 10, we also control the annual average PM_{2.5} concentration for sensitivity analysis. The covariates controlled in different models were shown in Table S3. Data analysis was performed using R version 4.0.3 software with the lmerTest package.

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

All data supporting the findings of this study are available within this manuscript and its Supplementary Information files. The data generated in this study are available under restricted access for the identifiable nature of the data and data management requirements. Access can be obtained by contacting the corresponding author (litiantian@nieh.chinacdc.cn) and will be answered within 12 weeks. The data can be used through collaborative research with authors. Source data are provided with this paper.

Code availability

The code used in this study is available online at (https://github.com/sunshineann/Fuel_usage_children_NatureComm).

References

1. Norman, R., Barnes, B., Mathee, A., Bradshaw, D. & South African Comparative Risk Assessment Collaborating G. Estimating the burden of disease attributable to indoor air pollution from household use of solid fuels in South Africa in 2000. *S Afr. Med J.* **97**, 764–771 (2007).
2. Yin, P. et al. The effect of air pollution on deaths, disease burden, and life expectancy across china and its provinces, 1990–2017: an analysis for the global burden of disease study 2017. *Lancet Planet Health* **4**, e386–e398 (2020).
3. Global Burden of Disease Collaborative Network. *Global Burden of Disease Study 2021 (GBD 2021) Results*. Seattle, United States: Institute for Health Metrics and Evaluation (IHME) <https://vizhub.healthdata.org/gbd-results/> (2022).
4. Vardell, E. Global health observatory data repository. *Med. Ref. Serv. Q* **39**, 67–74 (2020).

5. Lin, H. H., Murray, M., Cohen, T., Colijn, C. & Ezzati, M. Effects of smoking and solid-fuel use on copd, lung cancer, and tuberculosis in China: a time-based, multiple risk factor, modelling study. *Lancet* **372**, 1473–1483 (2008).
6. Jiang, X., Sommer, S. G. & Christensen, K. V. A review of the biogas industry in china. *Energy Policy* **39**, 6073–6081 (2011).
7. Tao, S. et al. Quantifying the rural residential energy transition in china from 1992 – 2012 through a representative national survey. *Nat. Energy* **3**, 567–573 (2018).
8. Dherani, M. et al. Indoor air pollution from unprocessed solid fuel use and pneumonia risk in children aged under five years: A systematic review and meta-analysis. *Bull. World Health Organ* **86**, 390–398C (2008).
9. Po, J. Y., FitzGerald, J. M. & Carlsten, C. Respiratory disease associated with solid biomass fuel exposure in rural women and children: Systematic review and meta-analysis. *Thorax* **66**, 232–239 (2011).
10. Berkey. Indoor air pollution and pulmonary function growth in preadolescent children. *Am. J. Epidemiol.* **148**, 1–14 (1986).
11. Grigg, J. Particulate matter exposure in children: relevance to chronic obstructive pulmonary disease. *Proc. Am. Thorac. Soc.* **6**, 564–569 (2009).
12. Guneser. Effects of indoor environmental factors on respiratory systems of children. *J. Trop. Pediatr.* **40**, 114–6 (1994).
13. Aithal, S. S. et al. The effects of household air pollution (Hap) on lung function in children: a systematic review. *Int. J. Environ. Res. public health* **18**, 11973 (2021).
14. Rinne, S. T. et al. Relationship of pulmonary function among women and children to indoor air pollution from biomass use in rural ecuador. *Respir. Med.* **100**, 1208–1215 (2006).
15. Padhi, B. K. & Padhy, P. K. Domestic fuels, indoor air pollution, and children’s health. *Ann. N. Y Acad. Sci.* **1140**, 209–217 (2008).
16. Roy, A. et al. Indoor air pollution and lung function growth among children in four chinese cities. *Indoor Air* **22**, 3–11 (2012).
17. Heinzerling, A. P. et al. Lung function in woodsmoke-exposed guatemalan children following a chimney stove intervention. *Thorax* **71**, 421–428 (2016).
18. Yu, K. et al. Association of solid fuel use with risk of cardiovascular and all-cause mortality in rural China. *JAMA* **319**, 1351–1361 (2018).
19. Rosenlund, M. et al. Traffic-related air pollution in relation to respiratory symptoms, allergic sensitisation and lung function in schoolchildren. *Thorax* **64**, 573–580 (2009).
20. Gauderman, W. J. et al. The effect of air pollution on lung development from 10–18 years of age. *N. Engl. J. Med.* **351**, 1057–1067 (2004).
21. Penard-Morand, C. et al. Long-term exposure to background air pollution related to respiratory and allergic health in school-children. *Clin. Exp. Allergy* **35**, 1279–1287 (2005).
22. Wang, S. et al. Epidemiological investigation on symptoms of allergic diseases in urban infants aged 0 ~ 24 months. *Chin. J. Child Health Care* **24**, 119–122 (2016).
23. Ma, R. et al. Full-coverage 1 km daily ambient PM2.5 and O3 concentrations of China in 2005–2017 based on multi-variable random forest model. *Earth Syst. Sci. Data* **14**, 943 (2022).

Acknowledgements

This study was supported by the National Natural Science Foundation of China (82425051, T.L.; 71921003, L.H.; 82241051, T.L.).

Author contributions

T.L. conceived the study. T.L. and L.H. organized and supervised the study. Y.W., C.Z., W.Z., D.X., Z.D., H.J., X.W., J.Z., and L.C. performed the data cleaning and data analysis. Y.W. and C.Z. prepared tables, figures and drafted paper. T.L., L.H., Y.W., C.Z. and Y.W. reviewed and edited the paper. All authors contributed to the manuscript. All authors have given approval to the final version of the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information The online version contains supplementary material available at <https://doi.org/10.1038/s41467-024-53386-z>.

Correspondence and requests for materials should be addressed to Lei Huang or Tiantian Li.

Peer review information *Nature Communications* thanks Horacio Riojas-Rodríguez and the other anonymous reviewer(s) for their contribution to the peer review of this work. A peer review file is available.

Reprints and permissions information is available at <http://www.nature.com/reprints>

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

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

© The Author(s) 2024