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Original Research

Mitigating household air pollution exposure through kitchen renovation

Yatai Men [a], Ke Jiang [a], Yaoji Li [a], Ran Xing [a], Zhihan Luo [a], Tianyao Huang [a], Shuyu Ou'yang [a], Wei Du [b, c], Yuanchen Chen [d], Guofeng Shen [a, c, e, *]

[a] MOE Key Lab for Earth Surface Process, College of Urban and Environmental Sciences, Peking University, Beijing, 100871, China
[b] Yunnan Provincial Key Laboratory of Soil Carbon Sequestration and Pollution Control, Faculty of Environmental Science & Engineering, Kunming University of Science & Technology, Kunming, 650500, China
[c] Southwest United Graduate School, Kunming, 650092, China
[d] Key Laboratory of Microbial Technology for Industrial Pollution Control of Zhejiang Province, College of Environment Research Center of Environmental Science, Zhejiang University of Technology, Hangzhou, 310032, China
[e] Institute of Carbon Neutrality, Peking University, Beijing, 100871, China

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A B S T R A C T

Globally, over three billion people rely on traditional solid fuels for cooking and heating, leading to significant household air pollution and critical public health concerns. While transitioning to clean energy carriers faces challenges of accessibility and affordability—especially among low-income, rural populations—alternative strategies like kitchen layout modifications and the use of ventilation fans may effectively reduce exposure to pollutants. Here, we analyze factors influencing the adoption of separated kitchens and mechanical ventilation and evaluate changes in human exposure to $PM_{2.5}$ under different kitchen renovation scenarios by conducting a nationwide survey of household kitchen characteristics in rural China. We found that although 82% of rural households have kitchens separated from other rooms, only 34% use mechanical ventilation. The adoption of ventilation fans is significantly influenced by income and education levels. We estimate that widespread implementation of ventilation fans and separated kitchen designs could prevent approximately 67400 premature deaths annually, resulting in a health benefit of about USD 19 billion per year—substantially exceeding the costs involved. These findings suggest that cost-effective kitchen renovations offer enormous potential for substantial health benefits and present a practical solution compared to the challenges of clean energy transitions in rural areas.

1. Introduction

Solid-fuel (e.g. coal, wood, crop straws) burning in the residential sector is a major source of air pollution in many low and middle-income countries, contributing not only to ambient air pollution but, more importantly, to direct indoor (household) air pollution [1,2]. The global number of traditional solid-fuel users was estimated to be over three billion and nearly constant in the coming years [3]. Heavy reliance on unclean solid fuels for daily cooking and/or heating often results in severe indoor $PM_{2.5}$ (fine particulate matter with the aerodynamic diameter $\leq$2.5 μm) concentrations, sometimes exceeding 500 μg m^{-3} [4,5]. Exposure to indoor $PM_{2.5}$ associated with solid-fuel use was estimated to have caused about two million premature deaths worldwide in 2019 [6]. Additionally, due to differing behavioral patterns between men and women, they have unequal exposure levels and risks [7].

To mitigate household air pollution from unclean solid-fuel burning, ensuring universal access to clean household energies, such as gas and electricity, is an important task in many countries and is a key indicator of the United Nations Sustainable Development Goal Target 7 (UN SDG 7), affordable clean energy. A recent sustainable development report indicated that there are still high challenges in achieving SDG 7, especially in regions such as East and Southeast Asia [8]. While switching to modern energy is strongly

* Corresponding author. MOE Key Lab for Earth Surface Process, College of Urban and Environmental Sciences, Peking University, Beijing, 100871, China.
E-mail address: gfshen12@pku.edu.cn (G. Shen).

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desired, the costs of these energies are often prohibitively high for most low-income rural households, leading to serious concerns about affordability.

In practice, besides energy transition, behavioral changes and measures (e.g., optimized ventilation) can also effectively reduce exposure to hazardous pollutants [9]. For instance, adding mechanical ventilation equipment can significantly lower indoor air pollutants, including $PM_{2.5}$, from indoor burning processes [10,11], and relatively low costs make it acceptable for most people. Epidemiology studies have shown direct evidence that the use of ventilation is associated with a lower all-cause mortality risk among solid fuel or clean energy users [9].

Considering the importance of household characteristics—particularly the separation of the kitchen from other indoor spaces and the use of ventilation fans—as a cost-effective strategy to reduce household air pollution exposure and achieve health savings, this study represents the first nationwide examination of household characteristics in rural China. This research encompasses factors such as the presence of ventilation equipment and kitchen isolation from other rooms. We delved deeper into analyzing the factors influencing human behaviors of separating a kitchen or installing fans. A statistical approach was developed to quantitatively connect indoor $PM_{2.5}$ levels with different household settings, from which simulation scenarios evaluated health savings and cost–benefit in separating kitchens and/or installing fans for solid-fuel users.

2. Methods

2.1. Household survey and data collection

Kitchen characteristics and resident behavior patterns were obtained from a national-scale survey in rural China, as described by Shen et al. [12]. This survey employed stratified sampling techniques at provincial and municipal levels, ensuring wide-ranging coverage that included all first- and second-level (provincial and municipal) administrative divisions across the country (excluding Hong Kong, Macao, and Taiwan). Below the municipal level, random sampling was utilized to further enhance the representativeness of the data. The sampling density was set at 0.43 ‰ in the nine densely populated provinces known for high pollutant emission densities and 0.22 ‰ for the remaining areas.

Some county units were selected within each municipal division based on their rural populations. Subsequently, villages and households were randomly chosen for participation within each chosen county. The maximum sample size from each county was capped at 300 households to maintain manageability and ensure quality data collection. A minimum of two villages were surveyed in each county, with no more than 80 households sampled per village; this resulted in a sample size of over 50000 households drawn from 488 counties across 276 municipalities.

The survey data were grouped by municipality-level administrative region to infer the overall characteristics of each city via questionnaire samples and integration with city-level data from other large-scale surveys. Population data were sourced from China's seventh national population census [13]. Education level was represented by the average years of schooling received. Per capita income, encompassing both final consumption expenditures and savings accessible to households within the survey timeframe, was derived from the China Statistical Yearbook [14]. Meteorological information was obtained from the National Climate Data Center (ftp://ftp.ncdc.noaa.gov/pub/data/noaa/isd-lite/).

2.2. Geographically weighted regression

Geographic weighted regression (GWR) was utilized to investigate the local spatial variability in the causal relationships between kitchen characteristics and geographic factors. The second-order Akaike information criterion was adopted to identify the optimal bandwidth size. This approach is particularly effective in analyzing geographical non-stationarity, allowing for examining how relationships between a dependent variable and a set of independent variables fluctuate across different regions.

Before the development of a GWR model, variables were analyzed using Moran's I index to determine their spatial autocorrelation. An absolute value of Moran's I index closer to 1 suggests a stronger spatial autocorrelation, implying that the variables' values are more similar in nearby locations than expected under a random spatial distribution [15]. In the GWR model, the regression coefficients indicate local spatial variations, highlighting how the relationship between the dependent and independent variables changes across different geographical locations. The standard errors associated with the GWR model serve as a measure of reliability [16].

2.3. $PM_{2.5}$ concentration and exposure

Ambient $PM_{2.5}$ concentration levels were obtained from the national air quality real-time release platform managed by the China Environmental Monitoring Station [17]. This platform provides data with a time resolution of 1 h, which was then resampled to distinguish between concentrations during the heating and non-heating seasons.

Household air pollution (HAP) is affected by outdoor air pollution and, importantly, internal emission sources. As indoor air pollution is highly variable, strongly challenged in field monitoring on large scales, and cannot be modeled like that for ambient air pollution using atmospheric chemical transport models, the fuel-proxy method, which is a statistical approach, has been adopted in studies on HAP and its health impact assessment [18–23]. Following Yun et al. [24] with small modifications, for households using relatively clean residential energy (e.g., gas and electricity), indoor pollution is primarily influenced by ambient air pollution and a building's permeability [22]; thus, HAP is calculated from ambient pollution levels and indoor–outdoor exchange factors.

For people mainly using solid fuels and whose HAP is largely determined by the incomplete burning of those fuels, statistical results (i.e., means, derivations, and distributions) from the available literature were summarized for different indoor microenvironments (e.g., kitchen, living room, and bedroom) in homes using different fuel and stove types. The database established by Yun et al. [24] was updated in this study with a further classification of kitchen mechanical conditions and is summarized in Table S1 (Supplementary Material). The nationwide questionnaire in rural China collects information such as household energy type, stove type, and location. With this information and the updated HAP database, the HAP for each group (energy type, microenvironment, heating/non-heating days) was directly obtained at the household level and then calculated at the county, regional, and national scales.

$PM_{2.5}$ exposures were calculated for each city based on residents' behavioral patterns and ambient and indoor $PM_{2.5}$ concentrations (Supplementary Material Fig. S1). Exposure was calculated separately for groups of different genders, energy types, and ages. Ultimately, the weighted exposure average was computed based on the population. Integrated population-weighted exposure (IPWE) was employed to characterize the $PM_{2.5}$ exposure [25], being calculated as:

$$IPWE = PWE_{AAP} + PWE_{HAP}$$

where PWE_{AAP} and PWE_{HAP} is the population-weighted $PM_{2.5}$ exposure due to ambient air pollution and HAP, respectively. The detailed calculation process is summarized in Text S1 (Supplementary Material).

2.4. Health impact assessment and cost–benefit analysis

Cause-specific integrated exposure–response functions from Global Burden of Disease (GBD) studies were used to calculate the estimated number of premature deaths linked to IPWE [26–28]. The estimated premature deaths linked to $PM_{2.5}$ exposure were calculated for five diseases: acute lower respiratory infections in children, lung cancer, ischemic heart disease, cerebrovascular disease, and chronic obstructive pulmonary disease. The national background premature deaths data for different ages (<5, 5–14, 15–65, >65) and genders came from the global disease burden (GBD) [29]. As the GBD provides only national premature deaths, the background data were adjusted and divided into urban and rural populations of different regions, based on Yun et al. [24]. Premature deaths associated with $PM_{2.5}$ exposure were calculated using background data and corresponding population-attributable fractions. The detailed calculations are summarized in Text S2 (Supplementary Material).

This study further employed the value per statistical life (VSL) parameter to estimate the monetary value of a health impact. The VSL parameter converts individuals' willingness to pay for a small reduction in mortality to the value of saving a statistical life. The VSL parameter has become a widely accepted metric for assessing the health-related costs of deaths attributable to $PM_{2.5}$ pollution [30]. Various studies have explored the VSL parameter in China, consistently identifying a positive correlation between VSL and income levels [31–34]. The base value of the VSL parameter was derived from several previous studies [31–34], and the VSL parameter for each region was subsequently calculated using the income function outlined in Text S3 (Supplementary Material).

The monetized health benefits derived from kitchen renovations were estimated from avoiding premature deaths across different regions and their respective VSL parameters. The costs associated with kitchen renovations were calculated through market analysis and questionnaire surveys.

2.5. Data and Uncertainty analyses

Data processing and calculation, model development, graphic visualization, and other processes in this study were conducted in Python (Version 3.10.7), with virtual environments managed through Anaconda. The primary Python libraries utilized for data processing and analysis included Pandas (Version 1.16.0), NumPy (Version 1.21.0), SciPy (Version 1.23.3), and GeoPandas (Version 0.14.0).

A significance level of 0.05 was adopted, and household-level results were weighted by the household numbers to obtain city and national averages. Uncertainties in health risks and monetization were addressed by performing 1000 iterations of Monte Carlo simulations.

3. Results and discussion

3.1. Kitchens are mostly separated from other indoor spaces

While burning fuels indoors for cooking or heating, pollutants from incomplete burning would seriously leak into indoor space, causing severe HAP and, consequently, high exposure and health risks. Separating the kitchen from other spaces, such as living rooms and bedrooms, may reduce pollution levels in adjacent environments. Such an architectural layout is not uncommon in China (e.g., Supplementary Material Fig. S2), although the initial objective may not be to prevent air pollutants from a kitchen to other indoor spaces.

Our survey observed that in rural China, over 80% of homes had a separate-kitchen layout, including 46% featuring an internal door connecting a kitchen to other rooms and 37% having completely detached kitchens (Supplementary Material Fig. S3). Spatially, such a layout has a very high spatial similarity across the country (Fig. 1a), with a slightly lower fraction of homes with a separate kitchen in northwest China. Qinghai Province has the lowest proportion of kitchens separated from other rooms, at about 43%.

Unlike the typical design of a separated kitchen, mechanical ventilation using fans or hoods in rural homes is uncommon. Overall, only 31% of rural homes had mechanical ventilation to improve indoor air quality, and there was a large spatial variation in this behavior (Fig. 1b). In some provinces in southeast China, such as Zhejiang and Guangdong, the proportion can reach 60%–75%. In the northwest and northeast regions, the proportion was only 19%, which lagged behind the other areas. Such discrepancies, along with distinct energy mixes and home layout designs, underscore the complex situation and variations in indoor air quality and human health risks among the Chinese. The county-level proportion of homes with separated kitchens was not statistically correlated with the proportion of homes having mechanical ventilation ($p >$ 0.05, Fig. 1c).

Fig. 2 further illustrates the proportion of homes with or without a separated kitchen and a mechanical ventilation. Approximately 26% of the kitchen was separated from other rooms and was equipped with mechanical ventilation. These homes are mostly located in the southeast region. Over half of the households had independent kitchens but lacked mechanical ventilation equipment. Meanwhile, only 4% of homes did not have a separated kitchen but had installed mechanical ventilation fans in the kitchen. It is worth highlighting that there were about 69.6 million people, predominantly situated in the southwest region of China (e.g., the Qingzang Plateau) who neither possessed ventilation equipment nor maintained independent kitchens. In the Qingzang Plateau, because many people still rely heavily on traditional solid fuels, such as firewood and dung cakes, to meet their cooking/heating needs, a shared indoor space without mechanical ventilation makes indoor air quality much worse, posing severe health risks to inhabitants [35,36].

3.2. Mechanical ventilation is popular among those with higher education and income levels

Kitchen characteristics can be influenced by various factors, which could be broadly categorized into socioeconomic and natural geographical factors. Socioeconomic factors (e.g., per capita income, household size, education level, population density) and natural geographical factors (e.g., temperature, humidity, altitude, and rainfall) may affect a household's layout. The interplay of these factors, to some extent, elucidates kitchen settings.

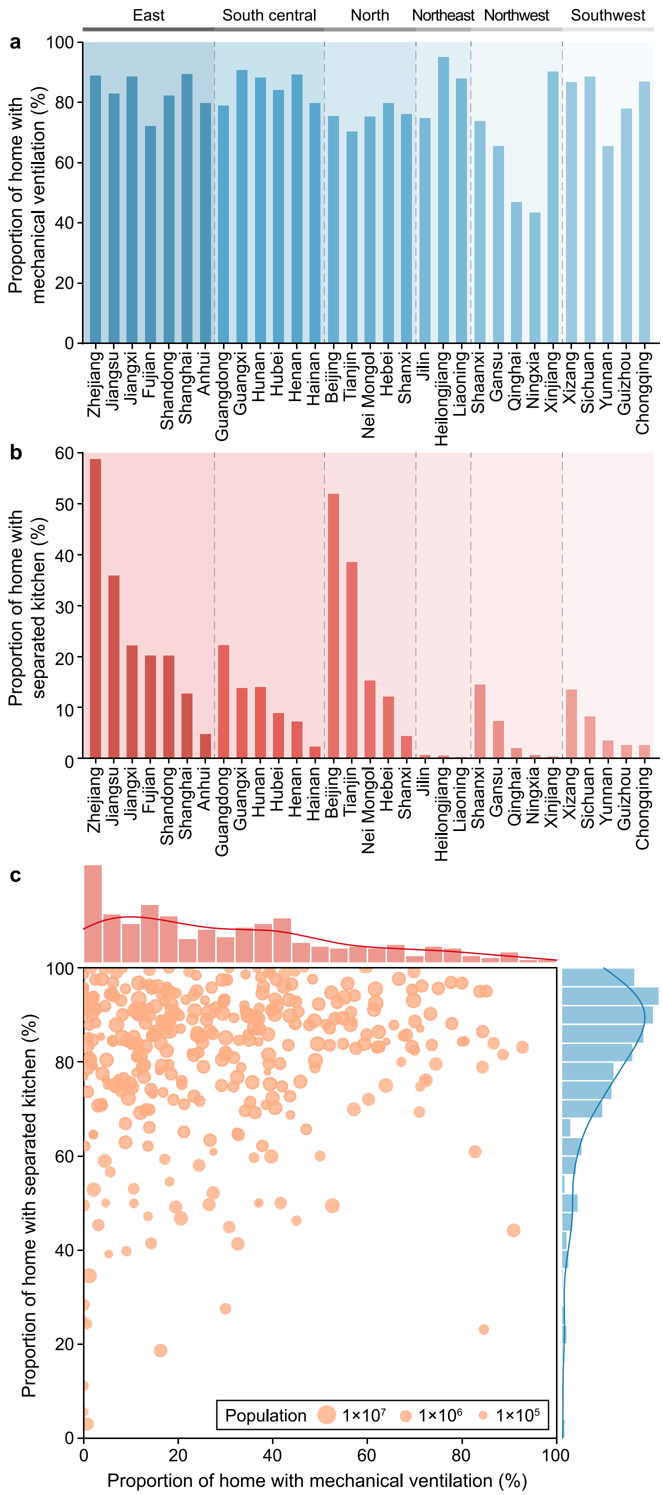

Fig. 1. Proportion of homes with different household characteristics. **a**, Kitchens separated from other indoor spaces. **b**, Kitchens equipped with ventilation fans. **c**, A correlation between the proportion of homes with a separated kitchen and the presence of a ventilation fan in the kitchen at the county level. The frequency distribution charts and curves are also shown in panel **c** for the proportion of separated kitchen (right) and mechanical ventilation (top).

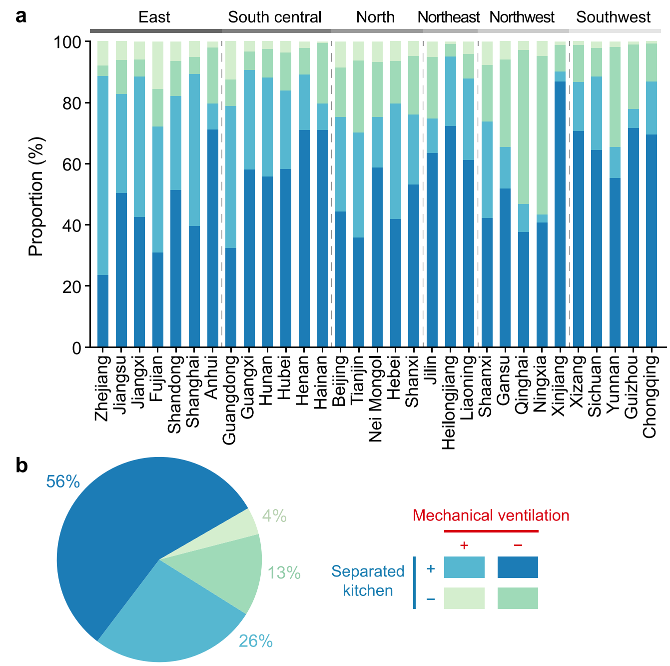

Fig. 2. Proportion of homes by province and region (**a**) and nationwide (**b**) based on the presence of separate kitchens and the use of mechanical ventilation. The symbols "+" and "−" indicate the presence or absence of mechanical ventilation/separated kitchens, respectively.

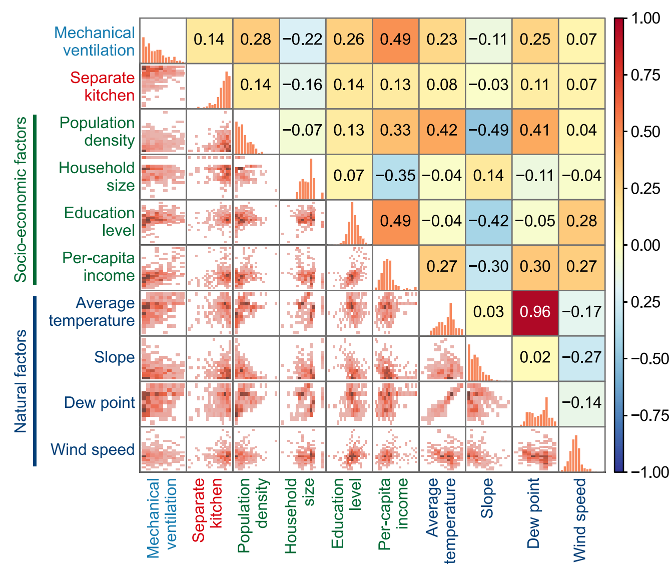

Fig. 3. Correlation analysis between kitchen characteristics (mechanical ventilation and separated kitchens in the present study) and some influencing factors, including socioeconomic and natural geographical factors. The heatmap on the left illustrates the correlation between the respective factors, while the diagonal bar graphs display the distribution of each factor. The numerical values on the right are the corresponding correlation coefficients between those factors.

Some socioeconomic factors, such as per capita income and education level, were significantly correlated with the proportion of homes with a ventilation fan (Fig. 3). Generally, in areas with high incomes and high education levels, it was likelier that people would install a ventilation fan in a kitchen ($p < 0.05$). This trend may have emerged from the clearer awareness of air pollution being severity-associated with higher education levels. Additionally, with higher family incomes, people can easily afford the costs of the installation and the operation of fans, although their operation consumes a small amount of electricity. The correlation analysis also revealed that there was a likely increasing willingness to install a ventilation fan in a kitchen in the areas with higher population densities, displaying a correlation coefficient of 0.28.

Beyond all expectations, when the family size was small, people were likelier to install a ventilation fan ($r = -0.22$). This negative correlation may be attributed to the prevalence of smaller families, particularly those consisting of young couples [37]. Compared to older individuals, younger households tend to be more concerned about indoor air quality and personal protection, which likely increases their propensity to install ventilation fans or range hoods. Additionally, their higher per capita incomes (Supplementary Material Fig. S4) further support their ability to make such investments. In contrast, natural geographical factors influenced the use of ventilation fans less than socioeconomic factors. Factors such as rainfall, slope, and wind speed did not correlate with the proportion of homes with ventilation fans at the county level ($p > 0.05$). There was a strong positive correlation between the temperature, especially the summertime temperature, and the use of a ventilation fan in the kitchen, with a coefficient of 0.43, indicating a lower frequency in installing ventilation fans in those cold areas.

The Moran's I index (refer to the Methods section) highlights a substantial spatial autocorrelation in analyzing these factors (Supplementary Material Fig. S5). Spatial autocorrelation might have caused bias in estimating the global linear regression model; thus, GWR was employed to account for this effect. The detailed model results are summarized in Table S2 (Supplementary Material). The GWR model had an R-squared (R^2) value of 0.59, while the ordinary least squares method resulted in an R^2 value of 0.31, indicating that the GWR model demonstrated superior explanatory capability compared to the global linear regression model based on the least squares method.

The standard deviation of the GWR model's fitting results falling from −2 to 2 across more than 94% suggested a stable relationship between mechanical ventilation and independent variables (Supplementary Material Fig. S6). Thus, higher levels of education, greater household income, increased population density, and higher average temperatures would promote the installation of ventilators in the kitchen (Supplementary Material Table S2). There were substantial regional variations in the degree of these factors (Supplementary Material Fig. S7). In general, the installation of kitchen ventilation equipment in the northeast region was most notably influenced by the level of education, while in the western and southern areas, factors including per capita income and population density emerged as key influencers.

Unlike the impacts of using a ventilation fan, the characteristics of a kitchen being separated from other indoor spaces were not found to be correlated with factors such as education level or natural geographical factors such as temperature and humidity (Fig. 3). A weak but statistically significant positive correlation was found between the per capita income and the fraction of separated kitchen design ($r = 0.13$, $p < 0.05$). This study concluded that household design, with or without a kitchen being separated from other rooms, is more likely to be determined by cultural customs and regional construction practices prevalent in different areas [38,39].

3.3. Distinct exposure to $PM_{2.5}$ with different household settings

Exposure to $PM_{2.5}$, including both indoor and outdoor exposure, was calculated for those with different household settings (refer to the Methods section). Given that HAP significantly exceeds environmental levels and that rural residents spend more time indoors than outdoors, the primary source of exposure is HAP rather than ambient air pollution. The population-weighted $PM_{2.5}$ exposure

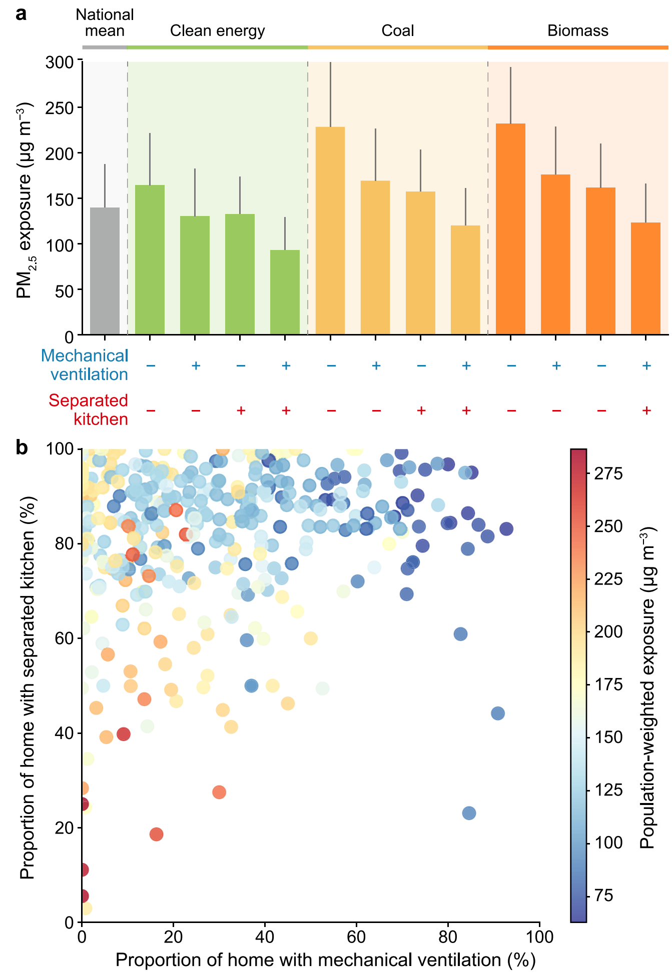

Fig. 4. Population-weighted $PM_{2.5}$ exposure levels for the rural population. **a**, Exposure levels for households using different energies for cooking. The symbols "+" and "−" indicate the presence or absence of mechanical ventilation/separated kitchens, respectively. **b**, Scatter plot of the proportion of homes with mechanical ventilation and separated kitchens in each city, along with the corresponding exposure levels denoted by point colors.

level in rural areas of China was about 136 ± 48 μg m^{-3}, while the $PM_{2.5}$ exposure level in households equipped with both mechanical ventilation and independent kitchens exhibited a markedly lower $PM_{2.5}$ exposure level of 97 ± 38 μg m^{-3}, significantly lower than the average level ($p < 0.05$, Fig. 4a). In contrast, households with kitchens interconnected to other rooms and lacking mechanical ventilation exhibited a notably high $PM_{2.5}$ exposure level of 202 ± 62 μg m^{-3}.

The choice of cooking energy significantly influenced the impact of cooking activities on indoor air quality. The $PM_{2.5}$ exposure levels across households using various cooking energies are compared in Fig. 4a. Households employing clean cooking demonstrated markedly lower exposure levels compared to those using coal or biomass, and in homes employing clean energy for cooking, those equipped with both ventilation systems and independent kitchens exhibited an exposure level of 92 ± 36 μg m^{-3}, lower than households lacking ventilation and featuring kitchens interconnected with other rooms. The disparity in exposure levels became even more pronounced, reaching up to 110 μg m^{-3}, in households relying on solid fuels like coal and biomass for cooking. Evidently, given the substantial emissions of $PM_{2.5}$ resulting from the combustion of solid fuels in indoor environments [40,41], it was more important to promote the use of ventilation equipment and/or isolate a kitchen from other household spaces using solid fuels.

The prevailing circumstance was that women bore the primary responsibility for cooking activities, resulting in higher $PM_{2.5}$ exposure levels than men [42], especially for adult women. The population-weighted exposure of different ages and genders is summarized in Table S3 (Supplementary Material). To a certain extent, ventilation equipment could mitigate gender inequality in cooking activities. In households without ventilation equipment, the exposure level of adult women was 148 ± 49 μg m^{-3}, while the average level of the adult population and adult men was 139 ± 49 and 130 ± 45 μg m^{-3}. In the home equipped with ventilation systems, the exposure level of women decreased to 103 ± 32 μg m^{-3}, and the difference between the male and the female reduced to 10 μg m^{-3}.

Regarding spatial disparity in $PM_{2.5}$ exposure, areas with higher proportions of independent kitchens and mechanical ventilation consistently exhibited lower exposure levels (Fig. 4b). The exposure levels in western China are notably high, particularly on the Qingzang Plateau, surpassing 220 μg m^{-3} (Supplementary Material Fig. S8). Moreover, the exposure level in the northern region was notably greater than in the southern region. There were two primary reasons: (1) the scarcity of ventilation facilities in rural regions of the western and northern areas, and (2) the prevalent use of traditional solid fuels, such as bituminous coal and firewood, for heating and cooking, especially during the long winters in western and northern regions, consequently leading to severe HAP [1].

3.4. The health benefits of separating a Kitchen and installing ventilation fans

To delve into potential reductions of $PM_{2.5}$ exposure among rural residents in diverse regions, this study devised three scenarios: (1) Scenario 1: all rural households install kitchen ventilation equipment; (2) Scenario 2: all rural households construct a separate kitchen; and (3) Scenario 3: both the installation of ventilation equipment and the construction of separate kitchens are implemented simultaneously. In rural households lacking installed mechanical ventilation equipment and featuring kitchens connected to other rooms, the disparity in exposure level reduction between installing ventilation equipment and separating kitchens alone was not notably significant (Fig. 5a). However, given the prevalent absence of ventilation equipment in most rural households, the reduction in exposure levels resulting from the widespread adoption of ventilation equipment was more pronounced (Fig. 5a).

In Scenario 2, the exposure levels in most areas did not exhibit a significant decrease, showing an average reduction of approximately 7% (Supplementary Material Fig. S9). Conversely, in Scenario 1, the exposure levels in rural areas of China witnessed a notable decrease, particularly in the Qingzang Plateau region where exposure decreased from 194 ± 65 to 150 ± 48 μg m^{-3}. Simultaneously, promoting ventilation equipment and a separate-kitchen design (Scenario 3) will further reduce $PM_{2.5}$ exposure levels. The widespread adoption of ventilation equipment and separate-kitchen designs (Scenario 3) would further narrow the regional disparity. Exposure levels in the relatively low-income northwest region would experience a more substantial decrease, thereby reducing potential environmental inequality.

Fig. 5b illustrates the number of premature deaths in rural areas attributed to $PM_{2.5}$ exposure under different scenarios. Despite relatively high uncertainties in estimated premature death numbers due to factors such as exposure classification and the exposure-dose relationship, kitchen design enhancements still had the potential to significantly reduce the health risks associated with $PM_{2.5}$ exposure ($p < 0.05$). At the 2019 exposure level, it was estimated that approximately 860 (580–1200) thousand premature deaths were attributed to $PM_{2.5}$ exposure in rural areas of China.

Via the promotion of ventilation equipment and separate kitchens, premature deaths attributed to $PM_{2.5}$ exposure could be decreased to 790 (510–1100) thousand. The decrease in premature deaths under Scenario 3 was less pronounced than the reduction in $PM_{2.5}$ exposure. This disparity was primarily attributed to the fact that despite improved indoor air quality, the $PM_{2.5}$ exposure levels of rural residents remained relatively high, and there was a nonlinear relationship between $PM_{2.5}$ exposure levels and health risks [43].

Based on Scenario 3, additional measures, such as further transitioning to clean energy sources for rural residents and implementing controls on outdoor air pollution, would contribute to a more substantial reduction in $PM_{2.5}$ exposure levels. This approach has the potential to significantly enhance the protection of residents' health by addressing both indoor and outdoor contributors to air pollution.

Fig. 5c illustrates the monetization of health benefits from implementing Scenario 3 transformations. Under Scenario 3, the monetized health losses of rural households could decrease from USD 249 (167–345) billion to USD 230 (151–323) billion. The detailed changes in premature mortality and economic losses under different scenarios are summarized in Table S4 and Fig. S10 (Supplementary Materials).

Even conservative estimates of lower health benefits substantially surpassed the associated transformation costs. The benefits derived from the widespread adoption of ventilation equipment and the implementation of separate-kitchen designs were particularly pronounced in rural areas characterized by larger populations and severe indoor pollution. Notably, the cost of installing ventilation fans and constructing independent kitchens in rural settings was relatively modest. The expenses associated with installing ventilation fans and separating a kitchen were typically minimal, often less than USD 400 per family.

Compared to monetized benefits, these renovations can yield

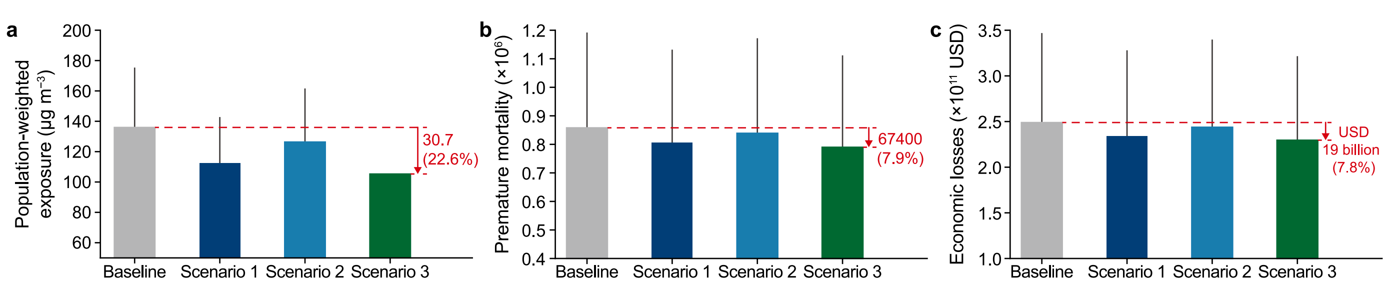

Fig. 5. Health benefits of installing ventilation fans and constructing a separate kitchen: population-weighted exposure levels (**a**), premature mortality (**b**), and economic losses (**c**) in different scenarios.

significant positive outcomes. Nationally, the estimated total cost of kitchen renovations for all rural households amounts to approximately USD 12 billion. Following these renovations, an annual reduction in premature deaths, estimated at 67400, could be achieved, leading to health-related benefits valued at nearly USD 19 billion per year. Kitchen renovation has significant potential for substantial health improvements, thus emphasizing the pivotal importance of government-led promotion efforts in rural kitchens.

3.5. Policy implications and limitations

The present study found that 82% of rural households had kitchens isolated from other rooms, but only 34% had mechanical ventilation in the kitchen. There was still significant potential for kitchen renovation in rural areas of China, particularly in the western and northern regions, where the prevalence of mechanical ventilation in kitchens was relatively low. The ratio of kitchens with mechanical ventilation was related to factors such as income and education levels. Compared to a spontaneous kitchen renovation driven by factors such as increased income and awareness of environment and health protection, the government can take proactive measures to accelerate this process.

It was estimated that rural households with separate kitchens and mechanical ventilation had $PM_{2.5}$ exposure levels approximately 50% lower than households without these features. Also, kitchen renovation has potentials to reduce the difference in exposure levels between men and women and reduce gender inequality. The total cost of kitchen renovation was estimated at USD 12 billion in rural areas nationwide. By contrast, following a kitchen renovation, an annual reduction in premature deaths, estimated at 67400 could be achieved, leading to health-related benefits valued at nearly USD 19 billion per year. Thus, a kitchen renovation may have significant potentials for improvements in health, with benefits significantly exceeding expenses. Effective measures should be taken to support and promote such renovation.

Our study has some uncertainties and limitations. First, some of the interviewed residents concealed information, such as income and education levels, to protect their privacy [44], leading to unreliable socioeconomic data at the individual level. To address this, other large-scale national survey data were adopted for city-level analyses. Second, the overall kitchen characteristics and influencing factors obtained for each city might not fully reflect the specific situation of each household. Future studies are expected to identify and evalaute human behavior characteristics and the influence. Third, due to the scarcity of detailed information from the urban population (e.g., situations of separate kitchens, power sources, and frequencies of using an exhaust fan), this present study concentrated on rural China. It would be valuable to similarly study urban populations to determine the impacts of such behaviors on the health of entire Chinese population.

4. Conclusions

The present study conducted the first nationwide survey on the characteristics of rural household kitchens in China, focusing on separated kitchens, mechanical ventilation, and key factors influencing these setting designs. While most rural households had kitchens separated from other rooms, only about one-third were equipped with mechanical ventilation like a fan. The adoption of mechanical ventilation was significantly influenced by income and education levels. Generally, the prevalence of mechanical ventilation in rural Chinese kitchens is low, indicating significant potentials for a kitchen renovation to improve indoor air quality by optimized ventilation conditions, besides the energy transition. The health benefits would far exceed the associated costs, evident from the cost-benefit analysis on kitchen renovation scenarios. Government interventions aimed at promoting such renovations would be effective and necessary.

CRediT authorship contribution statement

Yatai Men: Writing - Original Draft, Visualization, Methodology, Investigation, Formal Analysis, Data Curation. **Ke Jiang:** Software, Resources, Investigation, Formal Analysis. **Yaoji Li:** Investigation, Formal Analysis, Data Curation. **Ran Xing:** Validation, Methodology, Investigation, Data Curation. **Zhihan Luo:** Validation, Investigation, Formal Analysis. **Tianyao Huang:** Visualization, Validation, Investigation. **Shuyu Ou'yang:** Visualization, Validation, Investigation. **Wei Du:** Writing - Review & Editing, Visualization, Validation, Resources. **Yuanchen Chen:** Writing - Review & Editing, Writing - Original Draft, Visualization, Resources. **Guofeng Shen:** Writing - Review & Editing, Writing - Original Draft, Visualization, Supervision, Project Administration, Funding Acquisition, Formal Analysis, Conceptualization.

Data availability

Data associated with the study are available upon request.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ese.2024.100501.

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