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RECEIVED 14 October 2024

ACCEPTED 23 January 2025

PUBLISHED 13 February 2025

CITATION

Wang Z, Hou J, Fu J, Tian Z, Feng S,
Kosonen R and Sun Y (2025) Health-demand
ventilation control strategy in northern
Chinese homes: how much ventilation do we
need to protect occupants' health.
Front. Built Environ. 11:1510965.
doi: 10.3389/fbuil.2025.1510965

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Health-demand ventilation control strategy in northern Chinese homes: how much ventilation do we need to protect occupants' health

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Introduction: Indoor air quality in dwellings has particular importance regarding occupants' health. Ventilation is an important means to improve indoor air quality and guarantee occupants' health.

Methods: We utilized CO₂ produced by occupants to measure air exchange rate (i.e., the volumetric out-to-indoor airflow rate divided by building volume, h⁻¹) in Chinese homes, which were then linked to health outcomes like asthma and sick building syndrome symptom. Finally, we proposed a "health-demand" ventilation control strategy according to the relationship between air exchange rate and health outcomes.

Results and Discussion: Each 0.1 h⁻¹ increase in air exchange rate at night was associated with adjusted odds ratios of 0.97 (Confidence Interval (CI): 0.94–1.00) for rhinitis among children and 0.95 (95% CI: 0.91–0.98) for mucosal sick building symptom among adults. Finally, we proposed a "health-demand" ventilation control strategy according to the relationship between air exchange rate and health outcomes. Air exchange rate of 2.5 h⁻¹ and 6.5 h⁻¹ was suggested to deal with sick building syndrome symptoms among adults and rhinitis symptoms among children, respectively.

KEYWORDS

air exchange rate, carbon dioxide, sick building syndrome, asthma and allergy, dose-response relationship

Introduction

People spend most of their time indoors, and especially in homes (Tudor-Locke et al., 2009). Indoor environment plays an important role on occupants' comfort and health. With China's rapid modernization and urbanization in just a few decades, hundreds of millions of Chinese have experienced rapid and dramatic changes in indoor air environment. Dwellings in Chinese cities have changed from Pingfang (i.e., one-story single family house) to

high-rise buildings (China Statistical Yearbook, 2018). A variety of new synthetic building materials, furniture, personal care and indoor cleaning products have been widely used in homes. Pollutants, including formaldehyde, volatile organic compounds (VOCs), semi-VOCs, and bioeffluent have been found indoors, indicating a common indoor air quality (IAQ) issue in Chinese residences (Huang et al., 2017; Zhang et al., 2020). Some indoor pollutants produce odors or are related to irritation, while some pose chronic and/or acute health effects on occupants via inhalation, dermal or other pathways (Ostro et al., 2015; Sundell, 2017; Zhu et al., 2022; Wan et al., 2024; Zhao et al., 2024).

Ventilation is one of the most important means to remove or dilute indoor pollutants and maintain a habitable space for human beings (Sundell et al., 2011; Wargocki et al., 2002; Chenari et al., 2016). Bornehag (Bornehag et al., 2005) studied the association of ventilation with asthma and allergy among Swedish children. They found that children with no signs of any allergies were living in homes with higher ventilation rates, compared to those in homes of allergic children (0.37 h^{-1} v. s. 0.32 h^{-1}). Smedje (Smedje et al., 2017) investigated indoor environments in 1,160 adults' homes in Sweden and found that both mucous and dermal symptoms were less prevalent among occupants living in bedrooms with higher ventilation rates. Few study on health effects of ventilation has been performed in Chinese homes. Sun et al. reported significant higher prevalence of wheezing and sick building syndrome (SBS) symptoms among college students in dorm rooms with air exchange rate less than 0.7 h^{-1} (Sun et al., 2011; Sun et al., 2013).

The establishment of ventilation requirements for occupied spaces has a long history. The minimum ventilation rate nowadays is recommended mainly on perception of air quality, rather than directly addressing occupants' health (Janssen, 1999; Sundell et al., 2011; Klauss et al., 2011). For example, the ASHRAE Standard 62 (ASHRAE, 2016) sets outdoor airflow rate of 21–35 L/s as the required ventilation in homes for a 47–93 m² floor area, which is equivalent to air exchange rate of 0.5–0.6 h⁻¹. This was basically the lowest permissible ventilation rate to dilute occupant odors to a concentration acceptable to 80% of occupants. Carbon dioxide was used as a surrogate for occupant odor, but not a health risk, with ceiling concentration of 1,000 ppm (0.1%). A ventilation standard based on health effects rather than air quality perception is more important.

Previous studies have not fully established a quantitative relationship between ventilation rate and health outcomes of occupants. Therefore, the aims of this paper are: 1) to provide knowledge on the relationship between ventilation in residences and occupants' health; 2) to propose a health-demand ventilation control strategy in residential buildings.

Materials and methods

Measurement of ventilation in northern Chinese homes

We measured ventilation rate (expressed as air exchange rate, h⁻¹) in northern Chinese homes by using occupants-generated CO₂ as tracer gas (Hou et al., 2018). This method ("CO₂ method") is based

on the mass balance of CO₂ in investigated space (Equation 1).

$$F + NV \cdot c_o = V \frac{dc}{dt} + NV \cdot c \quad (1)$$

where F is the emission rate of CO₂ (m³/h), N is the air exchange rate (h⁻¹), V is the volume of the space (m³), c_o is the outdoor CO₂ concentration (m³/m³), c is the indoor CO₂ concentration (m³/m³), t is the time (h).

The emission rate of CO₂ can be calculated as in Equation 2 (Persily, 1996):

$$F = RQ \cdot 0.00201 \cdot H^{0.725} \cdot W^{0.425} \cdot M / (0.23 \cdot RQ + 0.77) \quad (2)$$

where RQ is the respiratory quotient assumed to be 0.83, H is the height of the occupant (m), W is the weight of the occupant (kg), M is the metabolic level (met).

By solving Equation 1, indoor CO₂ concentration can be expressed as in Equation 3:

$$c = c_1 \exp(-N \cdot t) + \left(F \cdot \frac{10^6}{NV} + c_o \right) (1 - \exp(-N \cdot t)) \quad (3)$$

where c_1 is CO₂ concentration in the initial measurement (ppm).

We measure CO₂ concentrations in the investigated space continuously by CO₂ monitors (AZ 7798, China, see Figure 1) at an interval of 1 min for at least 24 h and ask the height and weight of each occupant. Outdoor CO₂ concentrations are assumed as 400 ppm. CO₂ concentration measured during sleeping time is used to estimate air exchange rate. A presumed air exchange rate, as well as initial value of measured CO₂ concentration, outdoor CO₂ concentration, emission rate of CO₂, volume of space are inputted into Equation 3 to estimate value of CO₂ concentrations at each t . The least square method is applied to find the minimum of errors [sum of all individual differences between measured and estimated values (Equation 4)] by changing the value of estimated air exchange rate. Therefore, the air exchange rate is the only one unknown parameter of Equation 3. Figure 2 shows the fitting of non-linear curve of measured and estimated CO₂ concentration.

$$\text{Error} = \sum_{i=0}^{i=m} (c_{i,meas} - c_{i,est})^2 \quad (4)$$

where $c_{i,meas}$ is measured CO₂ concentration at time i , ppm; $c_{i,est}$ is estimated CO₂ concentration at time i , ppm.

This "CO₂" method does not require apparatus to inject tracer gas, with no intervention on occupants' behavior, therefore can measure long-term ventilation rate in real living conditions.

Investigation on associations of ventilation with children's asthma and allergy

From 2013 to 2016, we performed a study on children's asthma and allergy and home environment in Tianjin, China as part of the CCHH (China, Children, Homes, Health) study. In the Tianjin CCHH study, we surveyed the prevalence rate of asthma and allergy among 7366 children who were 0–8 years old (Sun et al., 2019b). Questionnaires were sent to daycare centers and elementary schools. Parents responded to the questionnaire, giving us information on

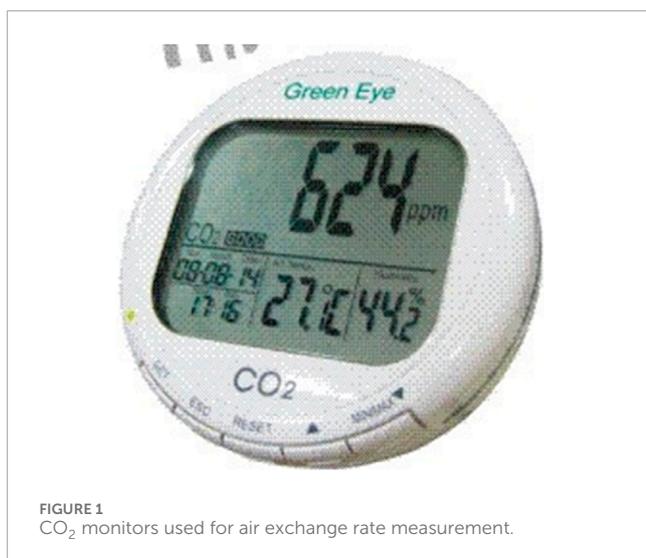


FIGURE 1
CO₂ monitors used for air exchange rate measurement.

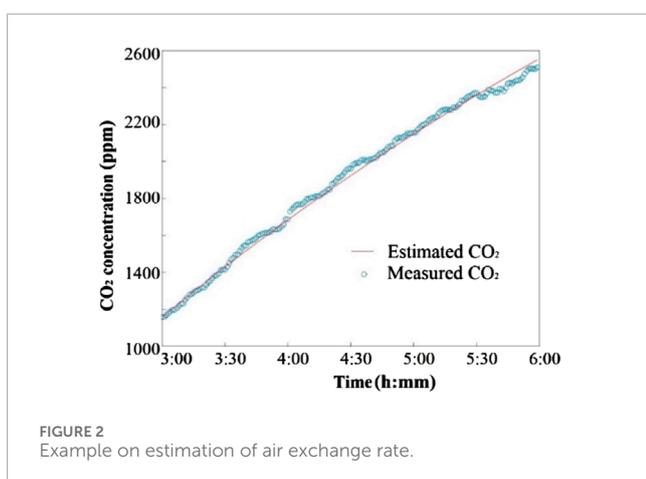


FIGURE 2
Example on estimation of air exchange rate.

their children. Based on this cross-sectional data, 200 case children (with at least two symptoms of asthma, rhinitis and eczema) and 200 controls (without any asthma and allergy symptoms) were invited into home inspections, during which we measured ventilation rate (expressed as air exchange rate) in their home based on “CO₂ method,” as well as a serial of physical (air temperature, relative humidity and CO₂ concentrations), chemical (such as phthalates) and biological (house dust mite allergen and endotoxin) parameters (Sun et al., 2024).

Investigation on associations of ventilation with sick building syndrome symptoms

From Mar. 2018 to Feb. 2019, we conducted a “Indoor Air Quality (IAQ) and Ventilation in Homes” study in Tianjin, China, during which we repeatedly inspected 32 Chinese homes, once during each season. During each home inspection, occupants responded to questionnaires that surveyed their SBS symptoms. The home inspection process included measurements of environmental parameters such as indoor air temperature (T), relative humidity

(RH), CO₂, air exchange rate, volatile organic compounds (VOCs), formaldehyde, particulate matters and ozone (Sun et al., 2019a).

Statistical analysis

Logistic regression analyses were used to evaluate the association of occupants’ health with air exchange rate. Potential confounders were determined *a priori* from literature review (Weinmayr et al., 2013). The confounders were gender, age, family allergic history, dampness, environmental tobacco smoke exposure, outdoor PM₁₀ and measurement seasons for the asthma and allergy analysis. Gender, age and household income were adjusted for SBS symptoms analysis. These variables have been found to be related to either ventilation or health outcomes. Therefore, they were adjusted for the association of ventilation with asthma and allergy, and SBS symptoms.

Results and discussion

Northern China is cold and dry in winter, and warm and moist in summer. Almost all homes in China have natural ventilation system, which rely on opening windows and infiltration for outdoor air supply. In northern China, people prefer to close windows on most days, especially in cold winter to keep indoor thermal comfort. Previous study has reported that more than 70% of the time during winter months had window closed at home (Hou et al., 2018).

Dose-response relationship between air exchange rate and asthma and allergy among children

In the “China, Children, Homes, Health” study, we surveyed the prevalence of wheeze, rhinitis and eczema symptoms in the last 12 months among 7,366 children (aged 0–8 years old) in Tianjin region (see Table 1). We obtained the air exchange rates in 374 children’s bedroom (see Table 2) and investigated its association with children’s asthma and allergy (see Table 3). It shows that the median value of air exchange rate was 0.4 h⁻¹. Air exchange rate in child’s bedroom revealed a clear dose-response relationship with child’s rhinitis symptom in the last 12 months. Previous study discovered that with the increment of air exchange rate ($\Delta = 1 \text{ h}^{-1}$), house dust mite allergen concentration decreased by 32%–57% (Sun et al., 2022). Epidemiologic studies have shown that exposure to house dust mite increased the prevalence rate of asthma and allergy (Celedón et al., 2007; Wan et al., 2024). Therefore, the impact of insufficient ventilation on child’s asthma and allergy might be explained through the “chain” of house dust mite exposure in tightly constructed buildings.

In this study the adjusted odds ratio (AOR) of stepwise increment of air exchange rate ($\Delta = 0.1 \text{ h}^{-1}$) was 0.97 (95% Confidence Interval (CI): 0.94–1.00) for rhinitis symptom. Based on the background level of 29.8% for rhinitis (see Table 1) and the median value of 0.4 h⁻¹ for air exchange rate in children’s bedrooms (see Table 2), the prevalence of rhinitis could be regressed as a function of air exchange rate, as shown in Equation 5. Assuming this

TABLE 1 Prevalence of wheeze, rhinitis and eczema in the last 12 months among children 0–8 years old in Tianjin, China, 2013.

	Total, N ^a = 7,366	0–2 years, N = 225	3–5 years, N = 3,238	6–8 years, N = 3,903
Wheeze, n (%) ^b	333 (4.9)	18 (8.5)	172 (5.8)	143 (4.0)
Rhinitis, n (%)	2002 (29.8)	63 (30.9)	960 (32.3)	979 (27.6)
Eczema, n (%)	998 (14.9)	63 (30.3)	494 (16.7)	441 (12.5)

^aSample size.

^bNumber and valid percentage for the related symptom.

TABLE 2 Distribution of air exchange rates in children's bedrooms, Tianjin, China, 2013^a.

	Air exchange rate, h ⁻¹		
	1st quartile	Median	3rd quartile
Total, N ^b = 374	0.21	0.37	0.70
Spring, N = 62	0.18	0.29	0.50
Summer, N = 65	0.30	1.06	2.09
Autumn, N = 97	0.19	0.32	0.50
Winter, N = 150	0.23	0.37	0.56

^aBedroom had the same air exchange rate as the whole residence if the differences of CO₂ concentrations in different zones were <10%.

^bSample size.

relationship to be causal, we may predict the rhinitis prevalence with various ventilation rates.

$$y_1 = 0.341e^{(-0.336N)} \quad (5)$$

Where y_1 is the prevalence of rhinitis symptoms among children; N is air exchange rate, h⁻¹.

Dose-response relationship between air exchange rate and SBS symptoms among adults

In the “IAQ and Ventilation in Homes” study, we surveyed and measured 32 homes repeatedly in each season. Among the 120 valid samples for self-reported SBS symptoms, the complaining frequency for general symptoms was 73%, followed by 67% for mucous and 40% for dermal symptoms (see Table 4). The distribution of 123 measurements of air exchange rate in adults' bedrooms at night and its association with SBS symptoms are shown in Tables 5, 6 respectively. Dose-response relationship was observed between air exchange rate and SBS symptoms, especially for mucosal symptoms which indicated that a low air exchange rate at night increased the risk of mucosal complaints. Our result is consistent with previous studies. The Swedish Office Illness study indicated that increased air exchange rate decreased the risk of SBS (Sundell et al., 1994).

Sun et al. (2013) found that prevalence of general and skin symptoms among students living in dorms increased with air exchange rate below 0.7 h⁻¹. In another paper, we observed that low air exchange rate in rooms led to higher concentrations of formaldehyde and volatile organic compounds (Sun et al., 2019a). Studies in Australia, Japan and Sweden have shown that high formaldehyde concentration was associated with increased risk of SBS symptoms as well as of asthma, allergies, and airway diseases (Zuraimi et al., 2007; Norback et al., 1995; Garrett et al., 1999; Wieslander et al., 1997). Exposure to higher concentration of VOCs due to low ventilation might be the mechanism “chain” for the association between air exchange rate and SBS symptom complaints.

We found the adjusted odds ratio (AOR) of stepwise increment of air exchange rate ($\Delta = 0.1 \text{ h}^{-1}$) was 0.95 (95% CI: 0.91–0.98) for mucous symptom. Based on the background level of 66% for mucous symptoms among adults (see Table 4) and the median value of 0.4 h⁻¹ for air exchange rate in Tianjin homes (see Table 5), the prevalence of mucous SBS symptom complaint can be expressed as a function of air exchange rate, see Equation 6.

$$y_2 = 0.832e^{(-0.555N)} \quad (6)$$

Where y_2 is the prevalence of mucosal SBS symptoms among adults; N is air exchange rate, h⁻¹.

Practical application of a health-demand ventilation control strategy

The dose-response relationship between air exchange rate and health outcomes (i.e., Equations 5, 6) provides basic data and guidance on ventilation to guarantee occupants' health in dwellings, based on which we propose a health-demand ventilation control strategy to meet the health needs of occupants and to minimize energy consumption as well. For occupancy scenario, ventilation shall be maintained to protect child from rhinitis and adult from mucosal SBS symptom. Otherwise minimum ventilation rate recommended in the existing domestic/international standards for indoor air quality shall be met.

The health-demand ventilation control strategy is described as follows in details:

- When the space is not occupied, ventilation is maintained at base rate as recommended in the existing ventilation standards (e.g., 0.5 h⁻¹ as in ASHRAE Standard 62, 2016);
- When the space is occupied, required ventilation is determined directly to deal with health effects.

TABLE 3 Dose-response relationship between air exchange rate in child’s bedroom and allergic symptoms among children, Tianjin, China.

		Adjusted odds ratio (95% confidence interval) ^a		
		Wheeze ^b	Rhinitis	Eczema
Air exchange rate, h ⁻¹	4th Quartile (>0.71)	1.00	1.00	1.00
	3rd Quartile (0.37–0.71)	0.88 (0.31, 2.47)	1.79 (0.93, 3.44)	1.64 (0.81, 3.29)
	2nd Quartile (0.22–0.37)	1.30 (0.50, 3.35)	1.76 (0.91, 3.38)	1.00 (0.49, 2.05)
	1st Quartile (<0.22)	0.52 (0.18, 1.48)	2.23 (1.18, 4.19)^c	0.78 (0.39, 1.56)

^aOdds ratios are adjusted for gender, age, family allergic history, dampness, environmental tobacco smoke exposure, outdoor PM₁₀ and measurement seasons.

^bCurrent wheeze, rhinitis, eczema symptoms in the last 12 months.

^cBold indicates *P*-value < 0.05.

TABLE 4 Prevalence of sick building syndrome symptoms among adults in the investigate homes in Tianjin, China, 2018.

	Yes, n (%)	No, n (%)
≥One general symptom ^a	88 (73.4)	32 (26.6)
Fatigue	79 (66.3)	40 (33.7)
Heavy head	28 (23.3)	92 (76.7)
Headache	26 (21.8)	93 (78.2)
Dizziness	14 (11.7)	106 (88.3)
Difficulty concentrating	26 (21.6)	94 (78.4)
≥One mucous symptom ^b	80 (66.7)	40 (33.3)
Eye irritation	29 (24.2)	91 (75.8)
Nose irritation	33 (27.7)	86 (72.3)
Throat hoarse	65 (54.1)	55 (45.9)
Cough	47 (39.2)	73 (60.8)
≥One dermal symptom ^c	48 (40.0)	72 (60.0)
Dry facial skin	27 (22.5)	93 (77.5)
Itchy ears	31 (25.8)	89 (74.2)
Dry hands	25 (21.0)	94 (79.0)

^aAt least one of the following general SBS, symptoms: fatigue, heavy head, headache, dizziness, difficulty concentrating.

^bAt least one of the following mucosal SBS, symptoms: eye irritation, nose irritation, throat hoarse, cough.

^cAt least one of the following skin SBS, symptoms: dry facial skin, itchy ears, dry hands.

- ◆ The cause of SBS symptoms might be within host factors as well, besides by environmental factors. We are dealing with a window of complaint rate above 20% (Wolkoff, 2018). When the SBS symptoms among adults are supposed to be at 20%, the demand ventilation is 2.5 h⁻¹ (see Equation 6);

TABLE 5 Distribution of air exchange rates in adults’ bedrooms, Tianjin, China, 2018.

	Air exchange rate, h ⁻¹		
	1st quartile	Median	3rd quartile
Total, N ^a = 123	0.24	0.45	0.78
Spring, N = 32	0.22	0.36	0.66
Summer, N = 32	0.37	0.78	1.85
Autumn, N = 29	0.24	0.37	0.62
Winter, N = 30	0.21	0.41	0.73

^aSample size.

- ◆ The population attributable fraction of genetic factor to rhinitis among child was 12% (Sun et al., 2019b). Therefore, we are dealing with a lower limit of 4% [i.e., prevalence of rhinitis 29.8% (see Table 1)*12% = 4%] regarding the rhinitis symptom among child. The corresponding demand ventilation is 6.5 h⁻¹ (see Equation 5).

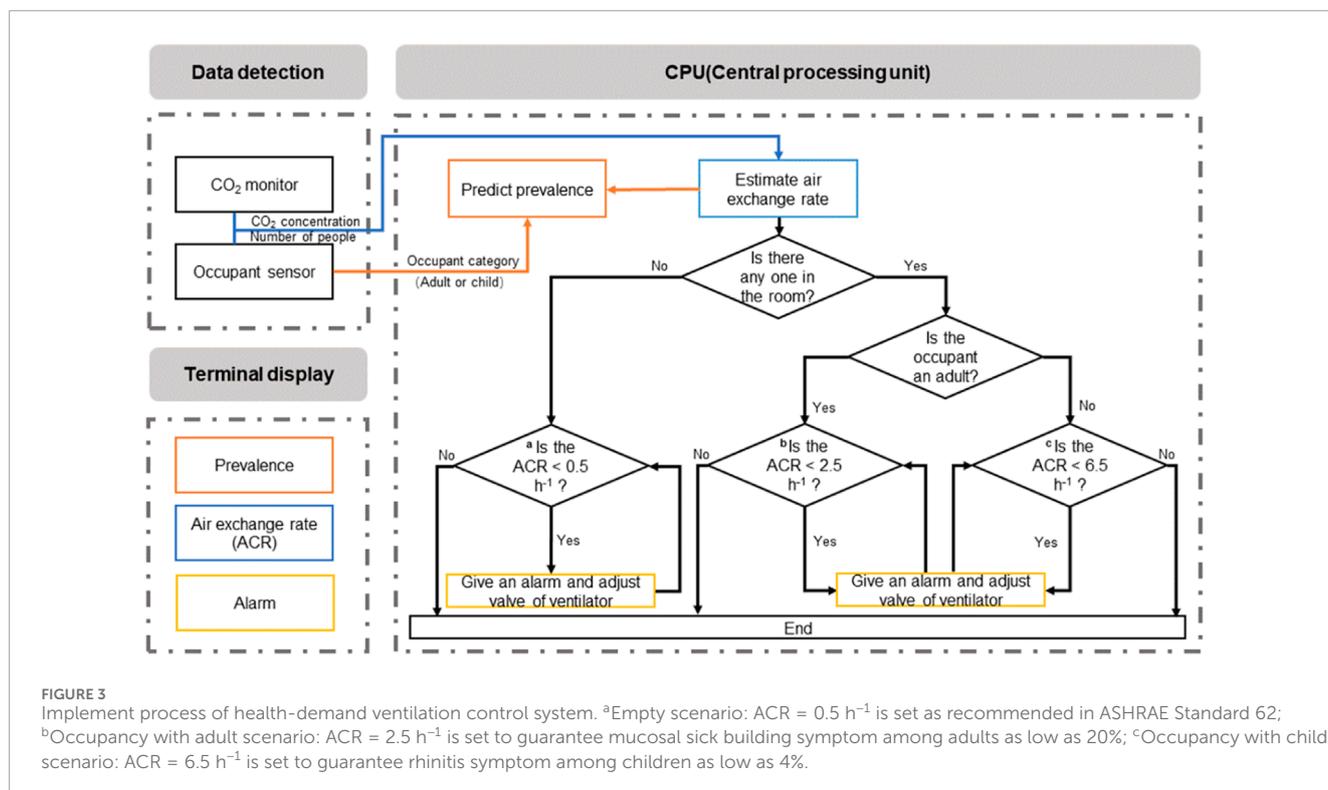
We additionally calculated required ventilation rate for controlling formaldehyde and house dust mite concentrations in typical northern Chinese homes, as shown in Supplementary Material. The minimum ventilation rate for indoor air quality demand regarding formaldehyde or house dust mite concentration was supposed to be 0.57 h⁻¹ and 0.46 h⁻¹, respectively. This is lower than the required ventilation rate for health demand, which indicates the complex health effects of indoor pollutants’ mixture. Source control strategy can be effective in reducing concentration of indoor pollutants, such as using indoor decoration materials with low emission rate of volatile organic compounds and/or decreasing occupancy level to reduce indoor moisture contents. When it is not possible to remove or control the source of indoor air pollution, and air filtration is ineffective, the pollution concentration can only be lowered by ventilation with fresh air, i.e., by diluting the

TABLE 6 Dose-response relationship between air exchange rate in adults' bedroom and sick building syndrome symptoms, Tianjin, China.

		Adjusted odds ratio (95% confidence interval) ^a		
		One general symptom ^b	One mucosal symptom ^b	One dermal symptom ^b
Air exchange rate, h ⁻¹	4th Quartile (>0.78)	1.00	1.00	1.00
	3rd Quartile (0.45–0.78)	1.04 (0.31,3.56)	0.75 (0.26,2.19)	0.73 (0.24,2.22)
	2nd Quartile (0.24–0.45)	1.54 (0.43,5.49)	2.30 (0.73,7.26)	0.72 (0.24,2.18)
	1st Quartile (<0.24)	1.25 (0.34,4.67)	2.25 (0.66,7.70)	1.23 (0.39,3.92)

^aAdjusted for gender, age, household income.

^bAt least one general/mucosal/dermal symptoms: yes vs. never.



indoor pollutants with outdoor fresh air. Sufficient ventilation rate to guarantee occupants' health should be regulated.

The health-demand ventilation control strategy can be implemented through a smart ventilation control system, which consists of data detection unit, central processing unit (CPU) and terminal display unit (as shown in Figure 3). The data detection unit includes CO₂ sensor and occupancy sensor. The CPU processes CO₂ concentration and occupancy level to estimate real-time air exchange rate by using CO₂ method, meanwhile the corresponding prevalence rate of rhinitis and mucosal SBS symptom can be predicted using Equations 5, 6 respectively. Terminal display unit demonstrates the real-time air exchange rate and the predicted prevalence of health outcomes. In addition, the CPU compare the real-time air exchange rate and the desired values in different scenarios, based on which to control and adjust ventilator.

This smart control system can work for hybrid ventilation, which is a combination of mechanical and natural ventilation. When wind pressure or temperature gradients are not sufficient to drive the flow by natural means, the desired ventilation rates can still be maintained by the mechanical systems. We believe the control system simultaneously guarantees occupants' health and lowers energy consumption.

Strengths and limitations

The clear dose-response relationship between ventilation and health outcomes were obtained through systematic measurements and multivariable analysis in large scale Chinese home studies.

There are several limitations. Firstly, we only considered the health effects of ventilation on asthma, allergy, and SBS symptoms. Other health outcomes should be considered in further studies. Secondly, the health effects investigated in this study were specific to residential building, and the applicability may vary in other types of building. Thirdly, air exchange rate was estimated during night with ignoring diurnal dynamic variations. However, the significant associations between air exchange rate and health outcomes cannot be explained by this limitation.

Conclusion

Dose-response relationships between ventilation and asthma and allergy among children {prevalence of current rhinitis = $0.341 * e^{-0.336 * (\text{air exchange rate})}$ } and SBS symptoms among adults {prevalence of mucous symptoms = $0.832 * e^{-0.555 * (\text{air exchange rate})}$ } are established. Further studies on dose-response relationship between ventilation and other health outcomes are needed in the future. Based on the health effects of ventilation, a health-demand ventilation control strategy is proposed, with required air exchange rate of 0.5 h^{-1} and $2.5\sim 6.5 \text{ h}^{-1}$ for empty and occupancy scenario, respectively. This indicates that in order to guarantee occupants' health in urban area as Tianjin, ventilation rate in dwellings needs to be improved greatly.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving humans were approved by the Tianjin University Research Office. The studies were conducted in accordance with the local legislation and institutional requirements. Written informed consent for participation in this study was provided by the participants' legal guardians/next of kin.

Author contributions

ZW: Conceptualization, Investigation, Writing–original draft, Writing–review and editing. JH: Data curation, Methodology, Writing–original draft, Writing–review and editing. JF: Formal Analysis, Visualization, Writing–original draft, Writing–review and editing. ZT: Conceptualization, Supervision, Writing–original draft, Writing–review and editing. SF: Data curation, Writing–original

draft, Writing–review and editing. RK: Conceptualization, Writing–original draft, Writing–review and editing. YS: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Supervision, Methodology, Writing–original draft, Writing–review and editing.

Funding

The author(s) declare that financial support was received for the research, authorship, and/or publication of this article. This work was supported by the (China-Finland Intergovernmental Joint Project) under Grant (2024YFE0106800) (National Key Research and Development Program of China) under Grant (2023YFC3708400); and (National Natural Science Foundation of China) under Grant (21207097).

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Supplementary material

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fbuil.2025.1510965/full#supplementary-material>

References

ASHRAE (2016). "Ventilation for acceptable indoor air quality in residential buildings," in *ASHRAE. ANSI/ASHRAE standard 62.2-2016* (Atlanta, GA, USA: ASHRAE).

Bornehag, C. G., Sundell, J., Hägerhed-Engman, L., and Sigsgaard, T. (2005). Association between ventilation rates in 390 Swedish homes and allergic symptoms in children. *Indoor Air* 15 (4), 275–280. doi:10.1111/j.1600-0668.2005.00372.x

- Celedón, J. C., Milton, D. K., Ramsey, C. D., Litonjua, A. A., Ryan, L., Plattsmills, T. A. E., et al. (2007). Exposure to dust mite allergen and endotoxin in early life and asthma and atopy in childhood. *J. Allergy Clin. Immunol.* 120 (1), 144–149. doi:10.1016/j.jaci.2007.03.037
- Chenari, B., Carrilho, J. D., and da Silva, M. G. (2016). Towards sustainable, energy-efficient and healthy ventilation strategies in buildings: a review. *Renew. Sustain. Energy Rev.* 59, 1426–1447. doi:10.1016/j.rser.2016.01.074
- China Statistical Yearbook (2018). *China statistical yearbook*, 4–5. Beijing: National Bureau of Statistics of China.
- Garrett, M. H., Hooper, M. A., Hooper, B. M., Rayment, P. R., and Abramson, M. J. (1999). Increased risk of allergy in children due to formaldehyde exposure in homes. *Allergy* 54 (4), 330–337. doi:10.1034/j.1398-9995.1999.00763.x
- Hou, J., Zhang, Y. F., Sun, Y. X., Wang, P., Zhang, Q. N., Kong, X. R., et al. (2018). Air change rates at night in northeast Chinese homes. *Build. Environ.* 132, 273–281. doi:10.1016/j.buildenv.2018.02.187
- Huang, S. D., Wei, W. J., Weschler, L. B., Salthammer, T., Kan, H. D., Bu, Z. M., et al. (2017). Indoor formaldehyde concentrations in urban China: preliminary study of some important influencing factors. *Sci. Total Environ.* 590, 394–405. doi:10.1016/j.scitotenv.2017.02.187
- Janssen, J. E. (1999). The history of ventilation and temperature control. *ASHRAE J.* 41 (10), 62–71.
- Klauss, A. K., Tull, R. H., Roots, L. M., and Pfafflin, J. R. (2011). History of the changing concepts in ventilation requirements. *ASHRAE J.* 53 (2), 34–43.
- Norback, D., Bjornsson, E., Janson, C., Widstrom, J., and Boman, G. (1995). Asthmatic symptoms and volatile organic compounds, formaldehyde, and carbon dioxide in dwellings. *Occup. Environ. Med.* 52 (6), 388–395. doi:10.1136/oem.52.6.388
- Ostro, B., Hu, J. L., Goldberg, D., Reynolds, P., Hertz, A., Bernstein, L., et al. (2015). Associations of mortality with long-term exposures to fine and ultrafine particles, species and sources: results from the California teachers study cohort. *Environ. Health Perspect.* 123 (6), 549–556. doi:10.1289/ehp.1408565
- Persily, A. (1996). Evaluating building IAQ and ventilation with indoor carbon dioxide. *ASHRAE Trans.* 103.
- Smedje, G., Wang, J., Norbäck, D., Nilsson, H., and Engvall, K. (2017). SBS symptoms in relation to dampness and ventilation in inspected single-family houses in Sweden. *Int. Archives Occup. Environ. Health* 90 (7), 703–711. doi:10.1007/s00420-017-1233-z
- Sun, Y. X., Cui, L. W., Hou, J., Luo, S. G., Norbäck, D., and Sundell, J. (2022). Role of ventilation and cleaning for controlling house dust mite allergen infestation: a study on associations of house dust mite allergen concentrations with home environment and life styles in Tianjin area, China. *Indoor Air* 32 (8), e13084. doi:10.1111/ina.13084
- Sun, Y. X., Hou, J., Cheng, R. S., Sheng, Y., Zhang, X. Y., and Sundell, J. (2019a). Indoor air quality, ventilation and their associations with sick building syndrome in Chinese homes. *Energy Build.* 197, 112–119. doi:10.1016/j.enbuild.2019.05.046
- Sun, Y. X., Hou, J., Sheng, Y., Kong, X. R., Weschler, L. B., and Sundell, J. (2019b). Modern life makes children allergic. A cross-sectional study: associations of home environment and lifestyles with asthma and allergy among children in Tianjin region, China. *Int. Archives Occup. Environ. Health* 92 (4), 587–598. doi:10.1007/s00420-018-1395-3
- Sun, Y. X., Marasinghe, S. A., Hou, J., Wang, P., Zhang, Q. N., and Sundell, J. (2024). Household indoor air quality in northeast China: on-site inspection and measurement in 399 Tianjin area residences. *Environ. Int.* 190, 108825. doi:10.1016/j.envint.2024.108825
- Sun, Y. X., Zhang, Y. F., Bao, L. J., Fan, Z. G., and Sundell, J. (2011). Ventilation and dampness in dorms and their associations with allergy among college students in China: a case-control study. *Indoor Air* 21 (4), 277–283. doi:10.1111/j.1600-0668.2010.00699.x
- Sun, Y. X., Zhang, Y. F., Bao, L. J., Fan, Z. G., Wang, D. S., and Sundell, J. (2013). Effects of gender and dormitory environment on sick building syndrome symptoms among college students in Tianjin, China. *Build. Environ.* 68, 134–139. doi:10.1016/j.buildenv.2013.06.010
- Sundell, J. (2017). Reflections on the history of indoor air science, focusing on the last 50 years. *Indoor Air* 27 (4), 708–724. doi:10.1111/ina.12368
- Sundell, J., Levin, H., Nazaroff, W. W., Cain, W. S., Fisk, W. J., Grimsrud, D. T., et al. (2011). Ventilation rates and health: multidisciplinary review of the scientific literature. *Indoor Air* 21 (3), 191–204. doi:10.1111/j.1600-0668.2010.00703.x
- Sundell, J., Lindvall, T., and Stenberg, B. (1994). Associations between type of ventilation and air flow rates in office buildings and the risk of SBS-symptoms among occupants. *Environ. Int.* 20 (2), 239–251. doi:10.1016/0160-4120(94)90141-4
- Tudor-Locke, C., Washington, T. L., Ainsworth, B. E., and Troiano, R. P. (2009). Linking the American time use survey (ATUS) and the compendium of physical activities: methods and rationale. *J. Phys. Activity & Health* 6 (3), 347–353. doi:10.1123/jpah.6.3.347
- Wan, M. F., Sun, Y. X., Luo, S. G., Hou, J., and Norback, D. (2024). Associations between house dust mite concentrations in bedroom dust in Northern China and childhood asthma, rhinitis and eczema. *Build. Environ.* 247, 110952. doi:10.1016/j.buildenv.2023.110952
- Wargocki, P., Sundell, J., Bischof, W., Brundrett, G., Fanger, P. O., Gyntelberg, F., et al. (2002). Ventilation and health in non-industrial indoor environments: report from a European multidisciplinary scientific consensus meeting (EUROVEN). *Indoor Air* 12 (2), 113–128. doi:10.1034/j.1600-0668.2002.01145.x
- Weinmayr, G., Gehring, U., Genuneit, J., Büchele, G., Kleiner, A., Siebers, R., et al. (2013). Dampness and moulds in relation to respiratory and allergic symptoms in children: results from phase two of the international study of asthma and allergies in childhood (ISAAC phase two). *Clin. Exp. Allergy* 43 (7), 762–774. doi:10.1111/cea.12107
- Wieslander, G., Norback, D., Bjornsson, E., Janson, C., and Boman, G. (1997). Asthma and the indoor environment: the significance of emission of formaldehyde and volatile organic compounds from newly painted indoor surfaces. *Int. Archives Occup. Environ. Health* 69 (2), 115–124. doi:10.1007/s004200050125
- Wolkoff, P. (2018). The mystery of dry indoor air-An overview. *Environ. Int.* 121, 1058–1065. doi:10.1016/j.envint.2018.10.053
- Zhang, Q. H., Sun, Y. X., Zhang, Q. N., Hou, J., Wang, P., Kong, X. R., et al. (2020). Phthalate exposure in Chinese homes and its association with household consumer products. *Sci. Total Environ.* 719, 136965. doi:10.1016/j.scitotenv.2020.136965
- Zhao, Y. X., Liu, Y. X., Cui, L. W., Hou, J., Gao, F., Norback, D., et al. (2024). Endotoxins in household dust in Northern China: associations with home environment factors and childhood asthma and allergies. *Atmosphere* 15, 759. doi:10.3390/atmos15070759
- Zhu, C. Q., Sun, Y. X., Zhao, Y. X., Hou, J., Zhang, Q. N., and Wang, P. (2022). Associations between children's asthma and allergic symptoms and phthalates in dust in metropolitan Tianjin, China. *Chemosphere* 302, 134786. doi:10.1016/j.chemosphere.2022.134786
- Zuraimi, M. S., Tham, K. W., Chew, F. T., and Ooi, P. L. (2007). The effect of ventilation strategies of child care centers on indoor air quality and respiratory health of children in Singapore. *Indoor Air* 17 (4), 317–327. doi:10.1111/j.1600-0668.2007.00480.x