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The Relationship Between Indoor Air Quality and Natural Ventilation in Residential Buildings: *A Critical Review and Future Research Agenda*

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ABSTRACT: Natural ventilation is an important strategy for improving indoor air quality (IAQ) in residential buildings because it can provide outdoor-air exchange with minimal mechanical energy. However, its effectiveness is highly variable and depends on climate, building design, outdoor air quality, pollutant generation, and occupant behavior. This review critically examines these interacting factors and compares natural ventilation with mechanical and hybrid approaches. Evidence indicates a substantial gap between designed and actual ventilation performance, primarily because window opening is intermittent and strongly influenced by thermal comfort, privacy, security, noise, weather, and outdoor pollution. Natural ventilation can effectively dilute indoor-generated pollutants, including CO_2 and volatile organic compounds (VOCs), when adequate airflow is achieved. However, opening windows can increase indoor particulate matter when outdoor air is polluted. Mechanical ventilation generally provides more consistent airflow and pollutant control, but requires energy, installation, and maintenance. Recent advances in smart sensing, probabilistic occupant-behavior modeling, and data-driven ventilation-rate estimation provide opportunities to improve adaptive ventilation. The evidence supports

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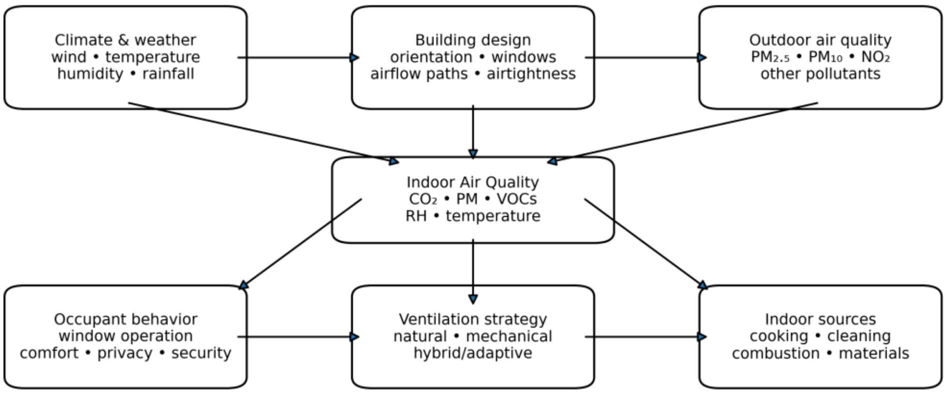
hybrid systems that combine natural ventilation with low-energy mechanical backup and real-time IAQ monitoring. Future research should focus on multi-family and existing housing, health outcomes, outdoor–indoor pollution interactions, behavioral interventions, and real-world validation of smart ventilation systems.

Keywords: *Indoor air quality; natural ventilation; residential buildings; occupant behavior; ventilation rate; hybrid ventilation; smart ventilation*

Graphical Abstract

Figure 1. Conceptual framework linking determinants of natural ventilation and residential IAQ.



Graphical abstract. Integrated determinants of residential IAQ and natural ventilation.

1. Introduction

Indoor air quality (IAQ) is an important determinant of healthy residential environments. Inadequate ventilation allows pollutants generated by occupants, cooking, cleaning, building materials, and combustion to accumulate indoors [1–3]. The importance of ventilation became particularly evident during the COVID-19 pandemic because increasing outdoor-air exchange can reduce the concentration of airborne infectious aerosols in occupied spaces [4].

Natural ventilation occurs through windows, doors, vents, and other openings as a result of wind and buoyancy forces [5]. It is attractive because it can provide ventilation without continuous fan energy and may also contribute to passive cooling. Nevertheless, natural ventilation is fundamentally different from mechanical ventilation because its performance depends on changing environmental conditions and occupant decisions.

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Window-opening behavior is influenced by temperature, humidity, outdoor pollution, noise, privacy, security, and personal preference [6–8]. Consequently, a dwelling designed for effective natural ventilation may not achieve adequate air exchange during actual occupancy. Conversely, appropriately timed window opening can substantially improve IAQ under favorable conditions.

Another important limitation is outdoor pollution. Natural ventilation can remove indoor-generated contaminants but can simultaneously introduce outdoor $PM_{2.5}$, PM_{10}, NO_2, and other pollutants when outdoor concentrations are high [7,9]. Therefore, the effectiveness of natural ventilation should be considered in relation to both indoor pollutant sources and outdoor air quality.

This review critically evaluates the relationship between natural ventilation and residential IAQ, emphasizing the roles of climate, building design, occupant behavior, outdoor pollution, emerging monitoring technologies, and hybrid ventilation strategies.

2. Natural Ventilation and Indoor Air Quality

Natural ventilation primarily improves IAQ through dilution and removal of indoor-generated contaminants. In a simplified well-mixed space, increasing the ventilation rate generally reduces the steady-state concentration of a continuously generated pollutant [2,3]. However, residential pollutant generation is often intermittent. Cooking, cleaning, showering, and other household activities can produce short-term concentration peaks, meaning that average air-change rate alone may not adequately describe exposure.

Natural ventilation performance depends on wind pressure, temperature differences, window size and position, building orientation, and airflow pathways [5]. Cross-ventilation can provide effective air exchange when openings are appropriately located, whereas single-sided ventilation may be more limited.

A critical issue is that increased ventilation is not necessarily equivalent to improved IAQ. If outdoor $PM_{2.5}$ or other pollutants exceed indoor concentrations, opening windows may increase indoor exposure [7,9]. Natural ventilation should therefore be regarded as conditionally beneficial rather than universally beneficial.

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CO_2 is widely used as an indicator of ventilation adequacy because occupants are an important source and measurements are inexpensive. However, CO_2 should not be considered a complete measure of IAQ because it does not represent all indoor pollutants. A room may have an acceptable CO_2 concentration while still containing elevated VOCs or particulate matter.

Figure 2. Conceptual response of indoor pollutants to window operation.

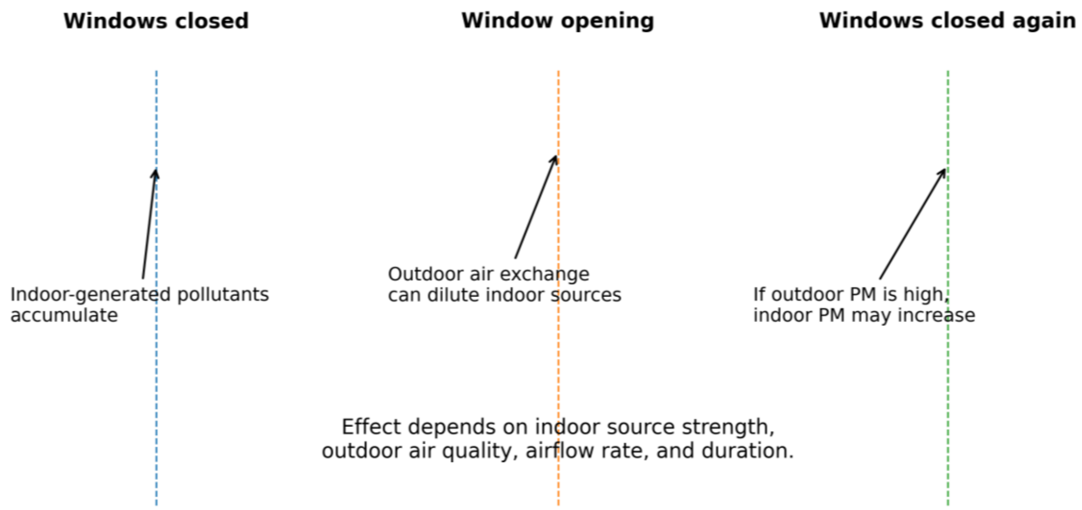

Figure 2. Conceptual response of indoor pollutant concentrations to window operation. The schematic is qualitative and should not be interpreted as empirical concentration data.

3. Factors Determining Natural Ventilation Effectiveness

3.1 Climate and Season

Climate strongly influences both the physical potential for natural ventilation and occupant willingness to open windows. During cold weather, windows are often kept closed to reduce heat loss, while during hot and humid conditions occupants may also restrict opening because of thermal discomfort [6,8].

Field studies demonstrate strong seasonal variation in residential window operation. Research in Chinese residential buildings showed that window-opening probability was associated with outdoor temperature, relative humidity, and outdoor $PM_{2.5}$ [7]. Studies in Norwegian bedrooms have similarly demonstrated that window operation varies considerably among occupants and that window opening does not always guarantee adequate ventilation [8].

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Natural ventilation therefore performs differently across climatic regions. Tropical climates may provide greater opportunities for year-round ventilation, whereas temperate and cold climates present stronger conflicts between ventilation, thermal comfort, and energy consumption.

Climate change may intensify these conflicts through increased heatwaves, changing humidity, and more frequent episodes of outdoor air pollution. Annual and future-climate assessments are therefore needed rather than relying only on short-term measurements.

Figure 3. Main environmental and contextual drivers of residential window-opening behavior.

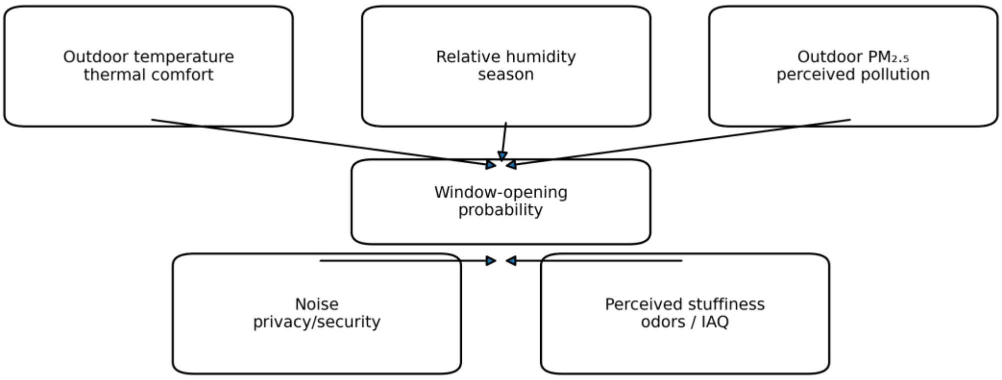

Figure 3. Main environmental and contextual drivers of residential window-opening behavior, adapted conceptually from the factors discussed in [6–8,15,17–19].

3.2 Building Design and Airtightness

Window geometry, size, position, and orientation determine the potential for wind-driven and buoyancy-driven airflow [5]. Cross-ventilation is generally enhanced when openings are positioned to create a clear airflow path through the dwelling.

However, maximizing window area is not necessarily optimal because large openings may increase heat gain or loss, noise, security concerns, and privacy problems. Natural ventilation should therefore be designed as part of a multi-objective building-performance strategy.

Building airtightness presents another important consideration. High airtightness improves energy efficiency by reducing uncontrolled infiltration, but it also increases the importance

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of intentional ventilation [16]. Retrofitting older homes can therefore create IAQ problems if air leakage is reduced without providing an adequate ventilation strategy.

The appropriate design principle is consequently not to choose between airtightness and ventilation, but to combine a well-sealed envelope with reliable intentional ventilation.

Figure 4. Conceptual relationship between envelope airtightness and ventilation requirements.

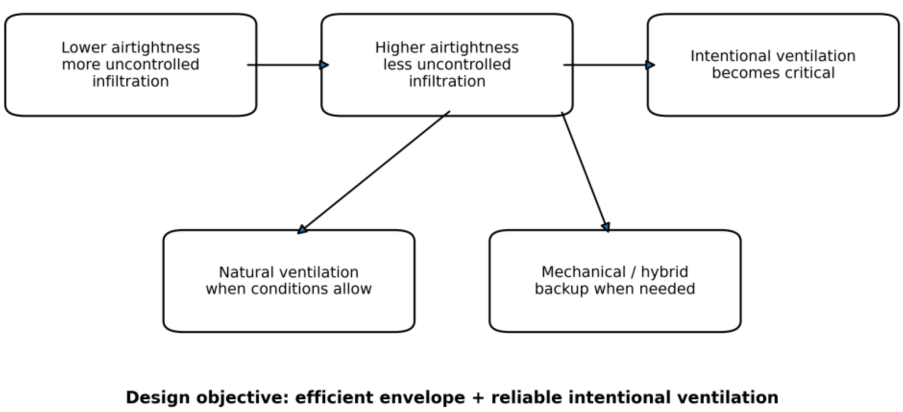

Figure 4. Conceptual relationship between building airtightness and the need for reliable intentional ventilation [16].

3.3 Occupant Behavior

Occupant behavior is arguably the most uncertain determinant of natural ventilation performance. Window operation is influenced by thermal comfort, odors, perceived stuffiness, outdoor air quality, noise, privacy, and security [6,18].

Occupants may open windows because a room feels stuffy without knowing the actual CO_2 concentration, while keeping windows closed despite elevated CO_2 because of outdoor noise or security concerns. These competing priorities explain why similar buildings can have very different ventilation outcomes.

Traditional building simulations commonly use deterministic window-opening schedules, which cannot adequately represent this variability. Probabilistic models that respond to environmental and contextual variables provide a more realistic approach [10,22].

Recent research has emphasized the importance of room-specific and seasonal behavioral patterns, indicating that a single universal window-opening model is unlikely to be appropriate for all residential environments [15].

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4. Natural, Mechanical, and Hybrid Ventilation

Natural ventilation offers several advantages, including low auxiliary energy use, simple operation, and potential for passive cooling. It can be particularly valuable in climates and socioeconomic settings where mechanical systems are unavailable or difficult to maintain [1].

However, its principal weakness is lack of consistency. Airflow changes with wind and temperature, while window operation depends on occupants. Consequently, natural ventilation may provide excellent air exchange at one time and inadequate ventilation shortly afterward.

Mechanical ventilation provides greater control because airflow can be regulated independently of outdoor wind conditions and occupant window operation. Mechanical systems can also incorporate filtration, heat recovery, and demand-controlled operation [10,11].

Evidence from residential studies indicates that mechanical ventilation can reduce indoor VOC and particulate concentrations more consistently than reliance on natural ventilation alone. Smart ventilation research further suggests that sensor-based mechanical systems can maintain IAQ while reducing unnecessary energy consumption [10,11].

Nevertheless, mechanical ventilation has disadvantages, including installation cost, electricity consumption, maintenance requirements, and dependence on correct operation. For many existing homes, complete mechanical retrofitting may also be impractical.

For these reasons, hybrid ventilation may provide a more practical solution. Natural ventilation can be used when outdoor temperature and air quality are favorable, while mechanical ventilation can provide backup when windows remain closed or outdoor conditions are unsuitable.

A smart hybrid system could use indoor CO_2 and $PM_{2.5}$ sensors together with outdoor air-quality and weather information to determine whether windows should be opened or mechanical ventilation activated.

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Table 1. Comparison of natural, mechanical, and hybrid ventilation strategies.

Aspect	Natural ventilation	Mechanical ventilation	Hybrid ventilation
Energy use	Very low	Moderate to high	Low to moderate
Consistency	Low	High	Medium to high
IAQ control	Conditional	High (with filtration)	High (adaptive)
Installation cost	Very low	High	Moderate
Maintenance	Very low	Moderate to high	Moderate
Dependence on occupant	High	Low	Medium
Existing homes	Easy	Often difficult	Feasible
Outdoor AQ adaptability	Low	High	High

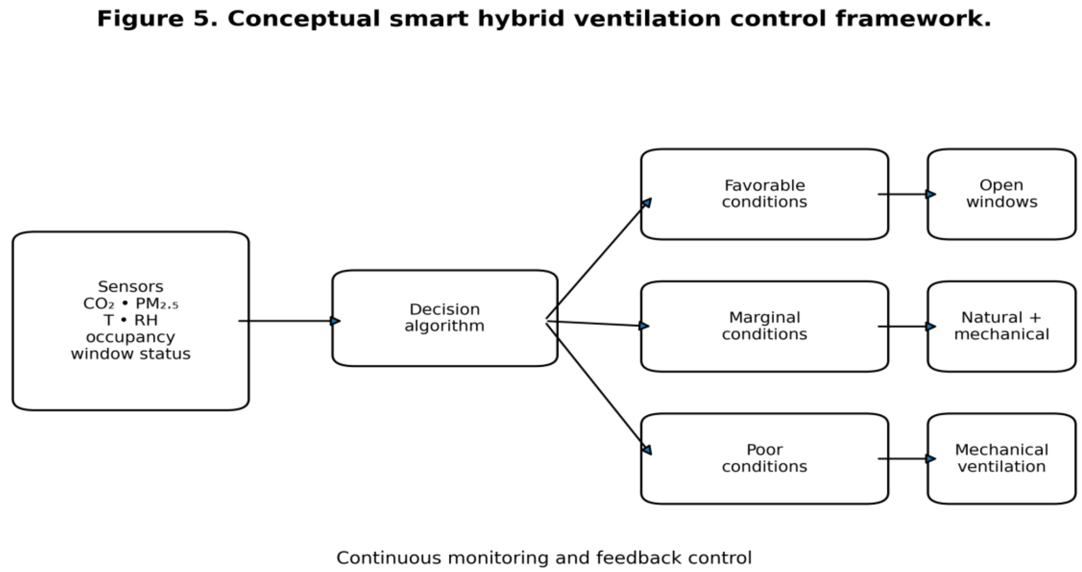

Figure 5. Conceptual smart hybrid ventilation control framework integrating indoor sensing, outdoor conditions, and adaptive decision-making [10,11].

5. Emerging Methods and Technologies

5.1 CO_2-Based Ventilation Estimation

CO_2-based mass-balance methods are widely used to estimate ventilation rates. Their main limitations are uncertainty in occupant CO_2 generation, sensor error, imperfect mixing, and rapidly changing airflow [12,13].

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Recent physics-informed machine-learning approaches seek to overcome these limitations. LSTM-based physics-informed neural networks have been proposed for real-time natural ventilation-rate estimation, combining time-series learning with physical constraints [12]. Adaptive particle-filter methods have similarly been developed to improve the stability of ventilation estimates during rapid changes in occupancy and window operation [13].

These methods are promising but require validation under real residential conditions before routine application.

Figure 6. Evolution toward data-driven estimation of natural ventilation rates

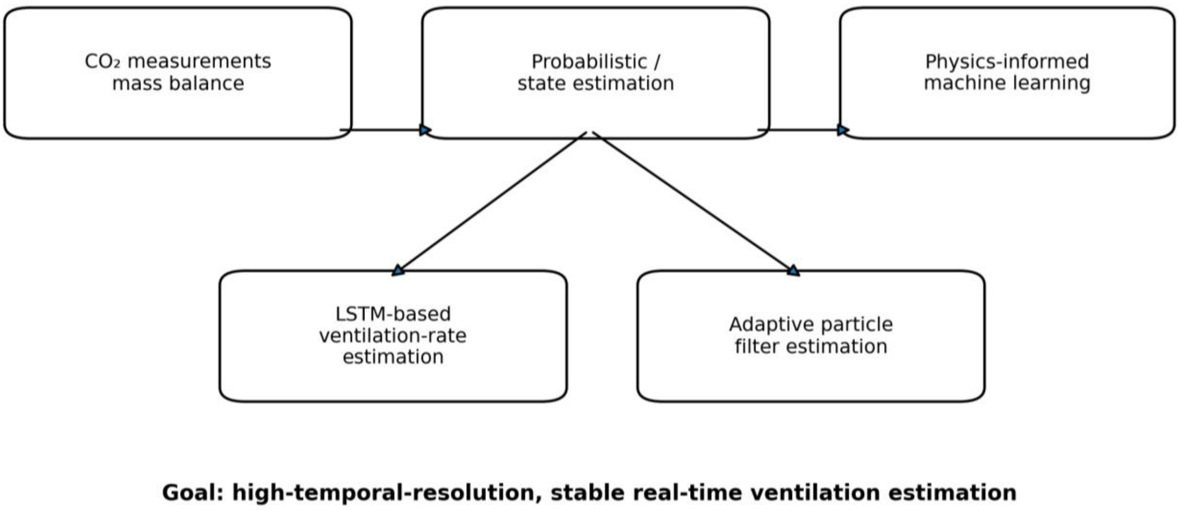

Figure 6. Evolution from conventional CO_2 mass-balance estimation toward probabilistic and physics-informed data-driven ventilation-rate estimation [12,13].

5.2 Smart Ventilation

Smart ventilation combines environmental sensing, computational models, and automated control. Such systems can respond dynamically to IAQ and outdoor conditions rather than relying on fixed schedules [10,11].

Current evidence suggests that smart ventilation can improve IAQ while reducing unnecessary energy consumption. However, many published studies remain simulation-based, and relatively few have been validated over long periods in occupied homes [11].

The next research step should therefore focus on field-tested systems that integrate indoor CO_2, particulate matter, temperature, humidity, outdoor air quality, occupancy, and window position.

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6. Research Gaps and Future Directions

6.1 Multi-family and Existing Housing

Research has concentrated disproportionately on single-family and newer buildings. Multi-family housing requires greater attention because shared spaces, different household schedules, and complex airflow pathways may alter ventilation behavior and performance.

Existing buildings also require greater representation because airtightness, window characteristics, heating systems, and pollutant sources can differ substantially from those of new construction.

6.2 Health Outcomes

Most studies evaluate IAQ through environmental indicators such as CO_2, PM, and VOC concentrations. Direct evidence linking specific ventilation interventions to health outcomes remains limited. Longitudinal studies are needed to determine whether improvements in ventilation translate into measurable health benefits.

6.3 Outdoor Pollution

Future ventilation systems should consider outdoor air quality explicitly. Window opening should be encouraged when outdoor air is favorable but restricted when pollution levels are high.

6.4 Occupant Behavior

More research is required to determine how occupants can be encouraged to use natural ventilation effectively without compromising comfort, privacy, or security. Behavioral interventions should be evaluated experimentally rather than assumed to be effective.

6.5 Model Validation

Probabilistic occupant models and machine-learning ventilation models require validation across different climates, building types, and populations. Models developed in one location should not automatically be assumed to be transferable to another.

6.6 Integrated Performance Assessment

Future studies should evaluate ventilation using a combined set of indicators, including:

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- ventilation rate
- CO_2
- $PM_{2.5}$
- VOCs
- temperature and relative humidity
- outdoor air quality
- thermal comfort
- energy consumption
- occupant satisfaction

This integrated approach would provide a more meaningful assessment than considering IAQ or energy performance independently.

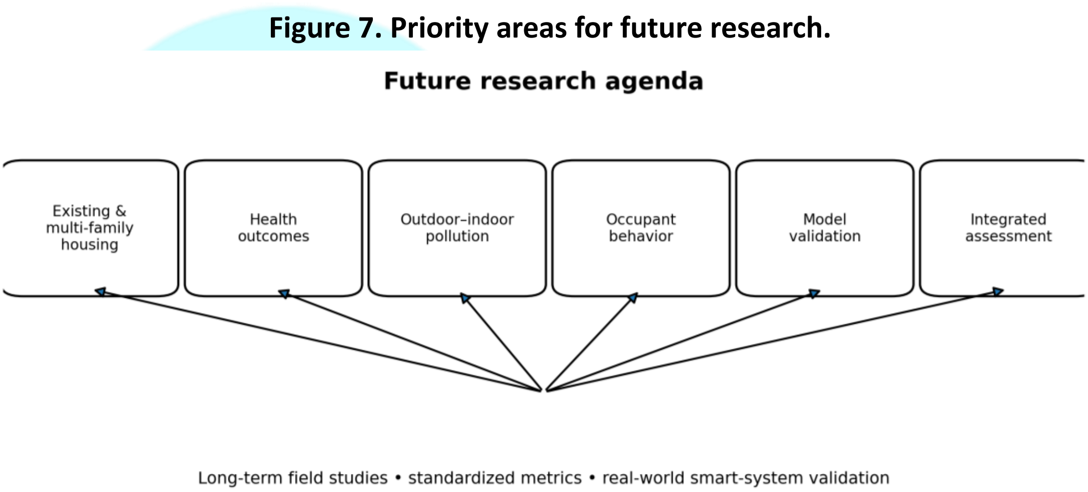

Figure 7. Priority research directions for advancing evidence-based residential ventilation strategies.

7. Conclusions

Natural ventilation remains a valuable strategy for residential IAQ management, but its effectiveness is highly context-dependent. It can substantially reduce indoor-generated pollutants when adequate airflow is achieved, yet its performance is limited by climatic variability, building characteristics, outdoor pollution, and occupant behavior.

The major challenge is the gap between theoretical ventilation potential and actual occupied performance. Occupants frequently control windows according to thermal comfort, privacy, security, noise, and outdoor conditions rather than IAQ alone.

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Consequently, natural ventilation cannot always provide the consistency required for reliable IAQ control.

Mechanical ventilation provides greater controllability and more predictable airflow but involves energy, cost, installation, and maintenance requirements. The evidence therefore supports a transition toward hybrid and adaptive ventilation, in which natural ventilation is used whenever environmental conditions are favorable and mechanical ventilation provides supplementary control when necessary.

Emerging technologies, including low-cost sensors, probabilistic behavioral models, physics-informed machine learning, and adaptive control algorithms, provide an opportunity to make residential ventilation more responsive to real-time conditions.

Future research should prioritize multi-family and existing housing, long-term field studies, health outcomes, outdoor–indoor pollution interactions, behavioral interventions, and standardized evaluation methods. Ultimately, residential ventilation should be designed as an adaptive system integrating building physics, occupant behavior, indoor pollutants, outdoor air quality, thermal comfort, and energy performance.

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