International Journal of Environmental Epidemiology

OPEN ACCESS
Article

Multi-pollutant indoor air quality, ventilation, and cognitive status among nursing home residents with dementia: a pilot cross-sectional environmental assessment in Oklahoma, USA

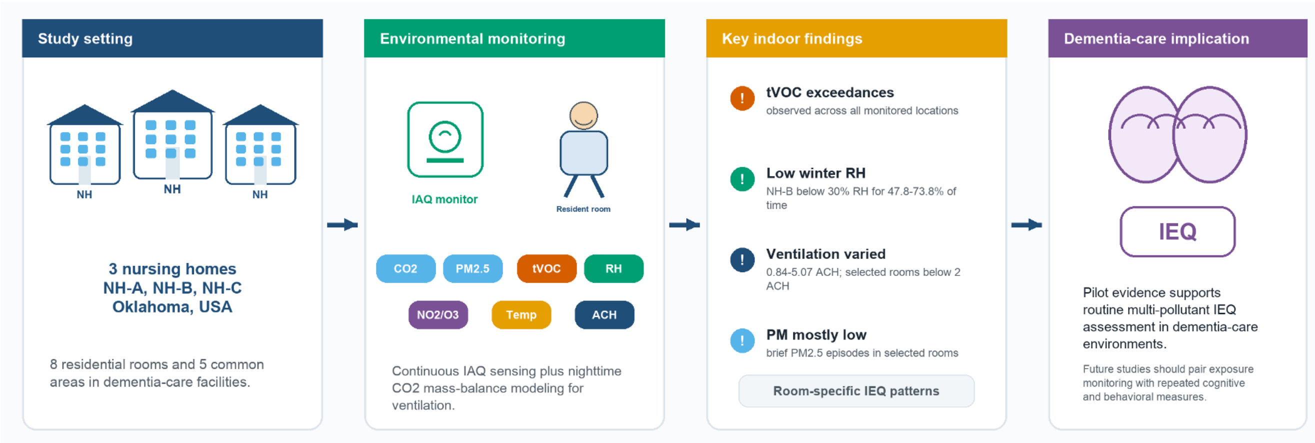
Hongwan Li*, Xiaosu Ding, Mika Cheng, Julie Gordon, Shakil Shimul, Xiaobo Quan, Diana Sturdevant, Yao Yang and Javeed Kittur

***E-mail:** hongwan-li@ou.edu

Received 15 April 2026; Revised 4 August 2026; Accepted 24 August 2026; Published 28 August 2026

https://doi.org/10.55092/ijee20260012

Graphical Abstract



Highlights:

- Multi-pollutant IAQ monitoring was conducted in three dementia-care nursing homes.
- tVOC exceedances were common across residential rooms and shared areas.
- Winter monitoring identified persistent low relative humidity in one facility.
- Estimated ventilation varied by room, with selected rooms below 2 ACH.

Multi-pollutant indoor air quality, ventilation, and cognitive status among nursing home residents with dementia: a pilot cross-sectional environmental assessment in Oklahoma, USA

Hongwan Li[1,*], Xiaosu Ding[1], Mika Cheng[1], Julie Gordon[2], Shakil Shimul[3], Xiaobo Quan[4], Diana Sturdevant[2], Yao Yang[1] and Javeed Kittur[5]

[1] Department of Occupational and Environmental Health, Hudson College of Public Health, University of Oklahoma Health Campus, Oklahoma City, USA

[2] Fran and Earl Ziegler College of Nursing, University of Oklahoma Health Campus, Oklahoma City, USA

[3] Christopher C. Gibbs College of Architecture, University of Norman, Norman, USA

[4] School of Architecture & Design, The University of Kansas, Lawrence, USA

[5] Engineering Pathways program, the Gallogly College of Engineering, University of Norman, Norman, USA

***E-mail:** hongwan-li@ou.edu.

Abstract: Background: Older adults in nursing homes (NHs), particularly those with Alzheimer's disease and related dementias (ADRD), spend most of their time indoors and may be vulnerable to poor indoor environmental quality (IEQ). Multi-pollutant IEQ in U.S. dementia care facilities remain limited. **Objectives:** To characterize indoor air quality (IAQ), thermal comfort, and ventilation across residential and common rooms in three NHs serving residents with dementia, and to descriptively explore room-level environmental conditions with cognitive status. **Methods:** TSI AirAssure monitors were deployed in eight residential rooms and five common areas across three Oklahoma NHs (NH-A, NH-B, NH-C) in October 2023 and February 2024. Temperature, relative humidity (RH), CO_2, $PM_{2.5}$, PM_{10}, total volatile organic compounds (tVOC), CO, NO_2, and O_3 were recorded at 1- or 15-minute intervals. Ventilation rates (air changes per hour, ACH) were estimated from CO_2 decay curves. Residents' cognitive status, depression scores, and clinical diagnoses were abstracted from the Minimum Data Set (MDS). **Results:** Temperature and RH generally met ASHRAE 55 guidelines, though the winter-monitored facility showed low-humidity exceedances. CO_2 concentrations were predominantly below the 1000 ppm ASHRAE 62.1 threshold, although one residential room in NH-C exceeded this guideline 29.9% of the time. tVOC exceeded the Comité Européen action level (0.4 mg m^{-3}) across 19.2%–100% of observations in every monitored location. $PM_{2.5}$ and PM_{10} were generally low, with short duration spikes in several rooms in NH-B. Estimated ventilation rates ranged from 0.84 to 5.07 ACH. **Conclusions:** This pilot multi-facility assessment identifies IEQ concerns in Oklahoma NHs serving residents with dementia, particularly elevated tVOC levels, winter-season low humidity, and low estimated ventilation in selected rooms. The findings support targeted source control, humidity, ventilation, and motivate larger longitudinal studies to evaluate whether chronic indoor environmental exposures are related to cognitive or behavioral outcomes in this vulnerable population.

Keywords: indoor air quality; nursing homes; dementia; Alzheimer's disease; ventilation; volatile organic compounds; environmental epidemiology

1. Introduction

The global prevalence of Alzheimer's disease and related dementias (ADRD) is projected to exceed 150 million by 2050, with approximately 50% of affected older adults residing in institutional long-term care settings such as nursing homes (NHs) [1,2]. In the United States alone, more than 1.2 million individuals live in approximately 15,000 Medicare- and Medicaid-certified NH facilities, and residents with ADRD constitute the majority of this population [2]. These individuals spend an estimated 90% or more of their time indoors, making the quality of the indoor environment a critical, yet often overlooked, determinant of their health and well-being [3,4].

Indoor environmental quality (IEQ) includes thermal comfort, indoor air quality (IAQ), lighting, and acoustics, all of which have been linked to the behavioral and psychological symptoms of dementia (BPSD), including agitation, aggression, sleep disturbances, and depressive affect [5–7]. Tartarini *et al.* demonstrated that cumulative exposure to temperatures above or below an empirically derived reference temperature of 22.6 °C was linearly correlated with agitation frequency in NH residents with dementia [8]. Ma *et al.* reported that low indoor humidity during heating seasons and elevated nighttime CO_2 concentrations were the primary environment related complaints in a Dutch NH [9]. The landmark Geriatric study in Europe on health effects of air quality in nursing homes (GERIE) study, a multi-country European investigation, found that even at low concentrations, PM_{10}, NO_2, and formaldehyde were associated with excess risks of breathlessness, cough, and wheeze among NH residents, with effects more pronounced in poorly ventilated facilities [4]. More recently, a scoping review highlighted that total volatile organic compound (tVOC) levels were significantly correlated with behavioral changes in people with moderate to severe dementia [7].

Despite the growing evidence, comprehensive multi-pollutant IEQ assessments in U.S. NHs remain limited. Prior studies have largely focused on single parameters (e.g., temperature or CO_2 alone) or have been conducted in European or Asian settings where building codes, climate, heating, ventilation, and air conditioning (HVAC) systems, and care delivery models differ substantially from those in the U.S. [10,11]. Furthermore, the intersection of IAQ with residents' cognitive status, as measured by validated clinical instruments such as the Brief Interview for Mental Status (BIMS), has rarely been explored in field studies [12–14]. This gap is particularly consequential in Oklahoma and the broader south-central U.S. [15,16], where extreme seasonal temperature variations, reliance on forced air HVAC, aging building stock, and healthcare infrastructure disparities may create exposure conditions that are not be adequately represented by studies conducted elsewhere.

To address these knowledge gaps, we conducted a pilot cross-sectional environmental assessment across three NH locations in Oklahoma serving residents with ADRD. Our objectives were to: (1) characterize the spatial and temporal distribution of nine IAQ parameters (temperature, RH, CO_2, $PM_{2.5}$, PM_{10}, tVOC, CO, NO_2, O_3) in residential and common rooms; (2) evaluate these parameters against established regulatory or guideline values and compare them with findings from the international literature; and (3) descriptively explore room-level IEQ in relation to residents' cognitive function. The findings are intended to inform IEQ management practices in dementia care facilities and to guide the design of future epidemiological studies examining chronic indoor environmental exposures in this vulnerable population.

2. Methods

2.1. Study setting and design

This pilot cross-sectional environmental assessment was conducted in three NH facilities (NH-A, NH-B, and NH-C) in Oklahoma, USA. Facility labels are anonymized study identifiers and do not indicate monitoring order. This study was reviewed and approved by the University of Oklahoma Institutional Review Board (IRB-15818). NH-A and NH-C were monitored in October 2023 (fall), and NH-B was monitored in February 2024 (winter). In total, 87 occupants resided in these three facilities at the time of monitoring. The linked resident-level analyses were limited to the eight residents occupying the monitored residential rooms. Eight residential rooms and five common rooms were selected for monitoring across the three facilities (Table 1). Each residential room in NH-A and NH-C accommodated one resident, while each room in NH-B accommodated two residents. Common rooms included dining areas, an activity room, a front lobby, and a television room, which were shared by occupants within the respective facilities for meals, recreation, and socialization.

Table 1. Monitoring configuration and resident characteristics among the eight monitored residential rooms.

Characteristic	NH-A	NH-B	NH-C	Overall
Monitored resident rooms, n	2	4	2	8
Monitored common areas, n	2	1	2	5
Monitoring window	2023-10-10 to 2023-10-12	2024-02-06 to 2024-02-11	2023-10-17 to 2023-10-21	2023-10-10 to 2024-02-11
Residents with linked MDS, n	2	4	2	8
Age, years, mean (SD)	81.8 (11.6)	81.0 (21.1)	71.5 (13.2)	78.8 (16.0)
Female, n/N (%)	1/2 (50.0%)	3/4 (75.0%)	2/2 (100.0%)	6/8 (75.0%)
White, n/N (%)	1/2 (50.0%)	4/4 (100.0%)	2/2 (100.0%)	7/8 (87.5%)
BIMS score, median (IQR)	8.5 (5.8–11.2)	2.5 (1.8–6.0)	0.5 (0.2–0.8)	2.5 (1.0–5.8)
Depression score, median (IQR)	1.5 (0.8–2.2)	0.0 (0.0–0.2)	0.0 (0.0–0.0)	0.0 (0.0–0.2)
Any dementia, n/N (%)	2/2 (100.0%)	4/4 (100.0%)	2/2 (100.0%)	8/8 (100.0%)
Chronic lung disease, n/N (%)	1/2 (50.0%)	1/4 (25.0%)	1/2 (50.0%)	3/8 (37.5%)
Respiratory failure, n/N (%)	1/2 (50.0%)	1/4 (25.0%)	0/2 (0.0%)	2/8 (25.0%)
Dyspnea, n/N (%)	0/2 (0.0%)	1/4 (25.0%)	0/2 (0.0%)	1/8 (12.5%)
Oxygen therapy, n/N (%)	0/2 (0.0%)	1/4 (25.0%)	1/2 (50.0%)	2/8 (25.0%)
Current tobacco use, n/N (%)	0/2 (0.0%)	Not available	0/2 (0.0%)	0/4 (0.0%)

2.2. Indoor environmental monitoring

Indoor environmental parameters were continuously monitored using TSI AirAssure IAQ Monitors (Model 8144-6, TSI Inc., Minnesota, USA) [17,18]. These multi-sensor instruments simultaneously measure temperature, RH, barometric pressure, PM_1, $PM_{2.5}$, PM_4, and PM_{10}, CO_2, CO, NO_2, O_3, and tVOC. Full sensor specifications, ranges, and accuracies are detailed in Table S1 of the Supplementary Information. Data were logged at 15-minute intervals in NH-A and NH-C and at 1-minute intervals in NH-B because the NH-B deployment used an updated logging configuration implemented after the fall monitoring visits.

Monitors were placed at a height of approximately 2.0 to 2.2 m above the floor (Figure S1) to minimize disturbance or accidental contact, since residents with dementia may move unpredictably within the room and could tamper with or displace equipment if it were installed at a lower height. Monitors were located away from direct HVAC supply diffusers, windows, and doors to minimize localized airflow artifacts. The PM response was further verified in the laboratory by co-locating each study monitor with a reference instrument and reviewing inter-instrument agreement before deployment.

2.3. Ventilation assessment

For each residential room, the ventilation rate (air changes per hour, ACH) was estimated by fitting nighttime indoor CO_2 measurements to a single-zone mass-balance model [19,20]. The model considers CO_2 generation from occupant exhalation and removal through ventilation exchange with outdoor air:

$$\frac{dC_{in}(t)}{dt} = \frac{n \cdot S}{V} + ACH \times C_{out} - ACH \times C_{in}(t) \quad (1)$$

where $C_{in}(t)$ is the indoor CO_2 concentration at time t, S is the CO_2 generation rate per occupant, n is the number of occupants, V is the room volume, and C_{out} is the outdoor CO_2 concentration. The CO_2 generation rate was assumed to be 9 $L\ h^{-1}$ per person for older adult occupants based on measurements reported by Yan *et al*. and outdoor CO_2 C_{out} was assumed to be 450 ppm, consistent with typical outdoor background levels reported by American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) [21,22].

Under the assumptions of constant source strength, constant outdoor concentration, and well-mixed room air, the analytical solution to Equation (1) is:

$$C_{in}(t) = C_{out} + \frac{n \cdot S}{V \cdot ACH} + \left(C_{in}(0) - C_{out} - \frac{n \cdot S}{V \cdot ACH}\right)e^{-ACH \cdot t} \quad (2)$$

where $C_{in}(0)$ is the indoor CO_2 concentration at the start of the analysis period. The room-specific ACH was estimated by fitting Equation (2) to observed nighttime CO_2 data for each room. Candidate fitting windows were selected from periods with relatively stable inferred occupancy, operationally defined as nighttime intervals with no abrupt CO_2 step changes, no obvious door/window disturbance signatures, and a coherent decay pattern after peak CO_2. Room-specific ACH values were then obtained by nonlinear least-squares fitting, with ACH constrained to positive values. ACH was not estimated for common rooms because continuous and variable occupancy precluded identification of clean decay periods. Because NH-B used 1-minute data while NH-A and NH-C used 15-minute data, the fitted decay curves differ in temporal resolution and should be interpreted as approximate screening estimates rather than directly comparable precision measurements.

2.4. Resident health data

Resident demographic and clinical data were shared by the participating nursing homes and abstracted from the Minimum Data Set (MDS) [13]. Abstracted items (Table 1) included the BIMS score, an integer score ranging from 0 to 15 and commonly classified as cognitively intact (13–15), moderately impaired (8–12), or severely impaired (0–7) [17]; mood/depression score; diagnoses of Alzheimer's disease and non-Alzheimer's dementia; chronic lung disease; respiratory failure; dyspnea; oxygen therapy; and current tobacco use. Demographic variables included age, sex, and race/ethnicity. For all monitored residents, the MDS Assessment Reference Date fell within three days before the start of environmental monitoring. All eight residents in the monitored rooms had a documented diagnosis of either Alzheimer's disease or non-Alzheimer's dementia.

2.5. Regulatory guidelines

Measured IAQ parameters were evaluated against the following guidelines: temperature and RH against ASHRAE Standard 55 (thermal comfort for sedentary occupants, 20–26 °C and RH 30%–60%) [23]; CO_2 against ASHRAE Standard 62.1 (1000 ppm above outdoor levels, approximated as 1000 ppm total) [24]; $PM_{2.5}$ and PM_{10} against the U.S. Environmental Protection Agency (EPA) 24-hour National Ambient Air Quality Standards (NAAQS; 35 and 150 μg m^{-3}, respectively) [25] and the World Health Organization (WHO) 2021 Air Quality Guidelines (15 μg m^{-3} for $PM_{2.5}$) [26]; tVOC against the Comité Européen (CE) action level (~0.4 mg m^{-3}) [27]; CO against the EPA 8-hour NAAQS (9 ppm) [25]; NO_2 against the EPA 1-hour NAAQS (100 ppb) and WHO 24-hour guideline (25 ppb) [25,26]; and O_3 against the WHO 8-hour guideline (60 ppb) [26]. The CE tVOC action level was used because no directly comparable U.S. ASHRAE pollutant-specific tVOC guideline was available for this study context, and the CE value provides a commonly cited screening benchmark for indoor volatile organic compound (VOC) burden.

2.6. Data analysis

Descriptive statistics were calculated for each parameter by facility and room type (residential *vs.* common). The percentage of monitoring time during which each parameter exceeded the applicable guideline was computed. Box plots and time-series visualizations were generated to illustrate spatial and temporal variability across facilities and room types. To facilitate inter-room comparison, IAQ parameters were min-max normalized and presented as radar plots overlaid on BIMS scores. Because the sample included only eight residents and rooms were clustered within facilities, all room-level health-environment comparisons are presented as descriptive and exploratory only; no multiplicity adjustment or clustering model was applied. Spearman rank correlation analysis was conducted only for NH-B because it had the largest and highest resolution monitoring dataset, and the analysis was used to describe correlations among IAQ parameters rather than to test hypotheses. ACH was plotted against BIMS scores and summarized by broad BIMS category for visualization only All analyses were conducted in R using packages including tidyverse, ggplot2, dplyr, and stats for data processing and visualization [28].

3. Results

3.1. Facility and resident characteristics

Table 1 summarizes the monitoring configuration and linked resident characteristics for the eight monitored residential rooms and these values should not be interpreted as facility-level demographic summaries of all 87 occupants. The three NHs were monitored for 2 to 5 days each. The eight monitored residents (six female, 75.0%) had a mean age of 78.8 years (SD = 16.0). All eight had documented dementia diagnoses, including non-Alzheimer's dementia (n = 6), and Alzheimer's disease (n = 2). Median BIMS scores ranged from 0.5 (IQR: 0.2–0.8) in NH-C to 8.5 (IQR: 5.8–11.2) in NH-A. Three residents (37.5%) had chronic lung disease, two (25.0%) had respiratory failure, and two (25.0%) were receiving oxygen therapy, indicating a clinically vulnerable monitored sample rather than a purposively selected respiratory disease cohort.

3.2. Thermal comfort

Figure 1 shows box plots of IAQ parameters stratified by nursing home and room type, while Figure S2 presents the time series of multiple IAQ parameters across the three nursing homes. Mean indoor temperatures ranged from 22.3 °C (NH-C residential rooms) to 24.5 °C (NH-B residential rooms), with all facility-level means within the ASHRAE 55 comfort range of 20–26 °C (Table 2) [23]. At the room level, B_NH_2 exceeded 26 °C for 28.5% of the monitoring period, and B_NH_3 exceeded this threshold 9.2% of the time (Table S2). These exceedances were intermittent, with maximum temperatures of 28.6–28.7 °C.

Relative humidity differed markedly by season. In the fall-monitored facilities (NH-A and NH-C), mean RH ranged from 42.5% to 47.8%, comfortably within the ASHRAE 55 recommended range of 30%–60% [23]. In contrast, the winter-monitored NH-B exhibited substantially lower RH, with facility-level means of 28.7%–28.8%. At the room level, RH fell below 30% for 47.8%–73.8% of monitoring time across all five NH-B locations (Table S3), with the lowest values reaching 20% RH. This pattern is consistent with winter forced-air heating without supplemental humidification.

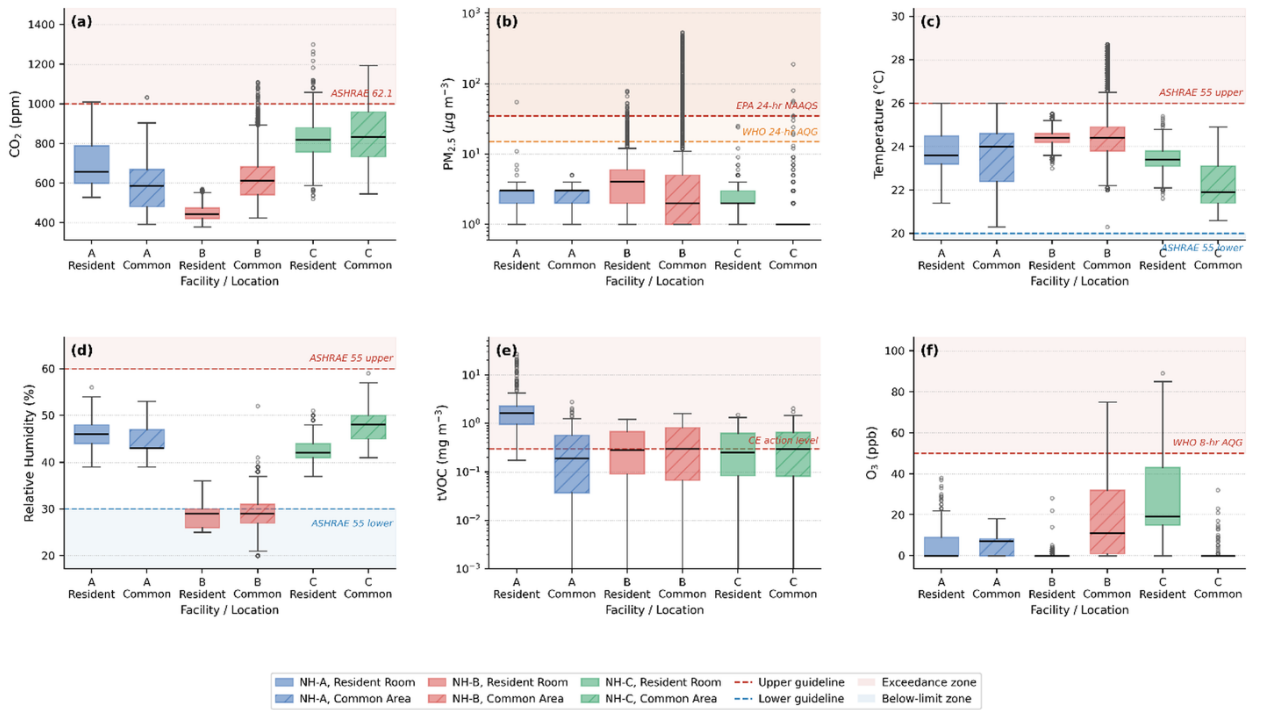


Figure 1. Box plots of air quality parameters by nursing home and room type. **(a)** CO_2; **(b)** $PM_{2.5}$; **(c)** Temperature; **(d)** Relative humidity; **(e)** tVOC; **(f)** O_3. Boxes represent the interquartile range with median line; whiskers and points show the plotted distribution according to the figure settings. Guideline lines, where shown, are screening thresholds rather than inferential cutoffs.

Table 2. Summary statistics of indoor air quality parameters by nursing home and room type (mean ± SD [median; IQR]). Values in parentheses indicate percent of observations exceeding the listed screening guideline. Bold indicates mean values outside the listed screening guideline.

Parameter	Guideline (Reference)	NH-A Common Area	NH-A Resident Rooms	NH-B Common Area	NH-B Resident Rooms	NH-C Common Area	NH-C Resident Rooms
Temperature (°C)	20–26 (ASHRAE 55)	23.8 ± 0.9 [23.6; 23.2–24.5]	23.4 ± 1.5 [24.0; 22.4–24.6]	24.4 ± 0.4 [24.4; 24.2–24.6]	24.5 ± 1.3 [24.4; 23.8–24.9] (10% > guideline)	23.4 ± 0.6 [23.4; 23.1–23.8]	22.3 ± 1.1 [21.9; 21.4–23.1]
Relative Humidity (%)	30–60 (ASHRAE 55)	46.1 ± 3.3 [46.0; 44.0–48.0]	44.8 ± 3.5 [43.0; 43.0–47.0]	28.7 ± 2.5 [29.0; 26.0–30.0]	28.8 ± 3.3 [29.0; 27.0–31.0]	42.5 ± 2.5 [42.0; 41.0–44.0]	47.8 ± 3.3 [48.0; 45.0–50.0]
CO_2 (ppm)	1000 (ASHRAE 62.1)	688.1 ± 110.3 [657.5; 599.2–788.0] (0% > guideline)	595.7 ± 128.0 [586.0; 481.0–669.5] (1% > guideline)	449.5 ± 36.4 [442.0; 422.0–474.0]	616.8 ± 93.2 [613.0; 541.0–682.0] (0% > guideline)	822.9 ± 104.5 [818.0; 757.0–879.0] (5% > guideline)	848.9 ± 134.5 [833.0; 734.0–959.0] (18% > guideline)
$PM_{2.5}$ (µg m^{-3})	35 (EPA 24-hr NAAQS)	2.9 ± 3.4 [3.0; 2.0–3.0] (0% > guideline)	2.7 ± 0.6 [3.0; 2.0–3.0]	4.7 ± 4.6 [4.0; 2.0–6.0] (0% > guideline)	4.5 ± 22.9 [2.0; 1.0–4.0] (1% > guideline)	2.6 ± 1.5 [2.0; 2.0–3.0]	2.6 ± 10.3 [1.0; 1.0–1.0] (1% > guideline)
PM_{10} (µg m^{-3})	150 (EPA 24-hr NAAQS)	2.9 ± 3.4 [3.0; 2.0–3.0]	2.7 ± 0.6 [3.0; 2.0–3.0]	5.1 ± 5.6 [4.0; 2.0–6.0]	5.2 ± 29.3 [2.0; 1.0–4.0] (1% > guideline)	2.6 ± 1.9 [2.0; 2.0–3.0]	2.7 ± 11.6 [1.0; 1.0–2.0] (0% > guideline)
tVOC (mg m^{-3})	0.4 (CE action level)	**2.9 ± 4.3 [1.6; 1.0–2.3] (100% > guideline)**	0.3 ± 0.4 [0.1; 0.0–0.4] (24% > guideline)	0.4 ± 0.3 [0.3; 0.1–0.7] (41% > guideline)	**0.4 ± 0.4 [0.2; 0.0–0.8] (42% > guideline)**	0.3 ± 0.3 [0.2; 0.1–0.6] (38% > guideline)	0.4 ± 0.3 [0.2; 0.1–0.6] (41% > guideline)
CO (ppm)	9 (EPA 8-hr NAAQS)	0.8 ± 0.4 [0.9; 0.4–1.2]	0.3 ± 0.2 [0.4; 0.1–0.5]	0.0 ± 0.0 [0.0; 0.0–0.0]	2.6 ± 0.8 [2.6; 2.0–3.1]	1.4 ± 0.4 [1.4; 1.1–1.6]	0.7 ± 0.3 [0.7; 0.5–0.9]
NO_2 (ppb)	100 (EPA 1-hr NAAQS)	11.9 ± 10.6 [10.0; 0.2–21.0]	6.8 ± 11.5 [0.0; 0.0–14.2]	3.3 ± 5.2 [0.0; 0.0–6.0]	9.3 ± 13.9 [0.0; 0.0–16.0] (0% > guideline)	2.9 ± 6.3 [0.0; 0.0–4.0]	51.6 ± 22.2 [55.0; 36.0–67.0] (1% > guideline)
O_3 (ppb)	60 (WHO 8-hr)	5.6 ± 8.7 [0.0; 0.0–9.0]	5.5 ± 4.1 [7.0; 0.0–8.2]	0.1 ± 0.6 [0.0; 0.0–0.0]	21.4 ± 23.0 [11.0; 1.0–32.0] (7% > guideline)	28.0 ± 20.3 [19.0; 15.0–43.0] (11% > guideline)	0.5 ± 2.7 [0.0; 0.0–0.0]

3.3. Carbon dioxide and ventilation

Room-level mean CO_2 concentrations ranged from 449.5 ppm (NH-B common area, Table 2) to 898.0 ppm (C_NH_1), Table S2. Most locations remained below the 1000 ppm ASHRAE 62.1 screening threshold; however, C_NH_1 exceeded this threshold 29.9% of the time, and C_NH_2 exceeded it 15.1% of the time (Table S3). These rooms also had low estimated ACH values (1.16 and 1.09 h^{-1}, respectively; Table S4). Common room C_CR_2 exceeded 1000 ppm of CO_2 for 8.5% of observations, consistent with periods of higher occupancy.

Table S4 summarizes the estimated ACH values for the eight residential rooms. Estimated ventilation ranged from 0.84 ACH (A_NH_2) to 5.07 ACH (B_NH_4) (Figure 2a). Using the ASHRAE 170 minimum threshold of 2 ACH as a reference [29], five rooms met or exceeded this benchmark (A_NH_1, B_NH_1, B_NH_2, B_NH_3, and B_NH_4), while A_NH_2, C_NH_1, and C_NH_2 were below 2 ACH. Because logging intervals differed by facility, these ACH values should be compared descriptively.

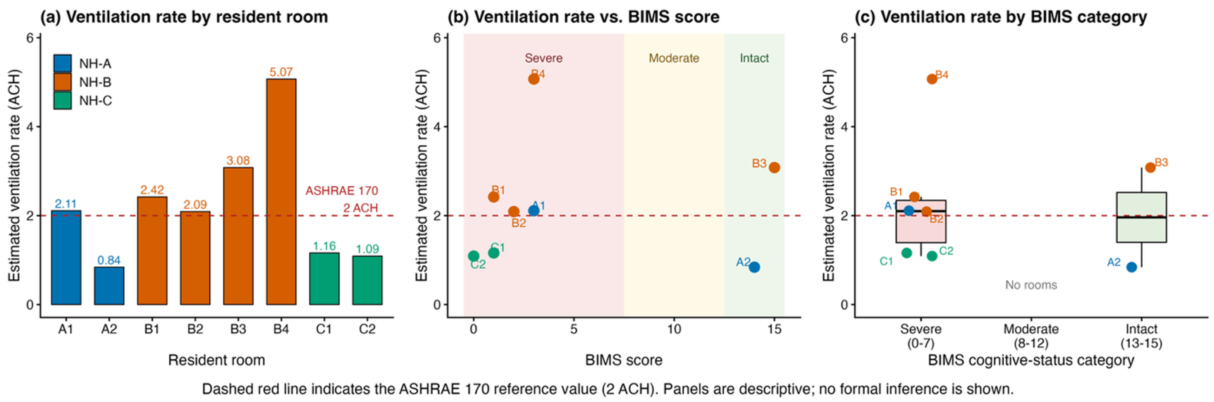


Figure 2. Descriptive ventilation rate results across eight resident rooms. **(a)** Estimated ACH by room with corresponding BIMS score; **(b)** Scatterplot of ACH and BIMS score; **(c)** ACH summarized by broad BIMS category. Room labels are abbreviated for readability: A1 = A_NH_1, A2 = A_NH_2, B1 = B_NH_1, B2 = B_NH_2, B3 = B_NH_3, B4 = B_NH_4, C1 = C_NH_1, and C2 = C_NH_2.

3.4. Particulate matter

Figure 1 shows that $PM_{2.5}$ concentrations were generally low across all facilities, with most room-level means in the range of 1.1–4.7 μg m^{-3}, well below the EPA 24-hour NAAQS of 35 μg m^{-3} [25]. Room B_NH_4 had short duration $PM_{2.5}$ episodes reaching a maximum of 532 μg m^{-3}, but only 4.3% of observations exceeded the EPA threshold and 5.5% exceeded the WHO guideline of 15 μg m^{-3} (Table S2). Similarly, C_NH_1 exceeded the EPA $PM_{2.5}$ guideline 4.1% and the WHO guideline 10.3% of the time (Table S2) [26]. These transient episodes may reflect localized indoor activities, with coarse particles plausibly related to housekeeping or bedmaking and fine particles potentially reflecting combustion, resuspension, or other short lived indoor sources [30]. Without activity logs or outdoor monitoring, source attribution remains uncertain. PM_{10} concentrations followed a similar low-baseline pattern, with exceedances occurring only sporadically in rooms with high PM events.

3.5. Total volatile organic compounds

tVOC was the most consistently elevated pollutant across all three facilities (Table 2). Every monitored location exceeded the CE action level of 0.4 mg m^{-3} for at least a portion of the monitoring period [31], ranging from 19.2% (A_NH_1) to 100% (A_CR_1) of observations (Table S2). Common areas in NH-A showed strikingly elevated tVOC (mean 2.9 mg m^{-3} in A_CR_1, with a maximum of 27.15 mg m^{-3}), with room-level means 7-fold above the action level and 99.2%–100% guideline exceedance. In NH-B, tVOC exceedance ranged from 26.3% to 49.0% across residential rooms (Table S2). NH-C showed a similar pattern (21.6%–50.8% exceedance) (Table S2). Potential sources include cleaning products, disinfectants, personal care products, building materials, furnishings, and incontinence care supplies, all of which are commonly used in NH environments [32,33].

3.6. Gaseous pollutants: CO, NO_2, and O_3

Table 2 indicates that CO concentrations remained well below the EPA 8-hour NAAQS of 9 ppm across all locations [25]. NH-B residential rooms showed the highest CO levels (mean 2.0–2.8 ppm), which were below the regulatory threshold, but higher than those in NH-A (mean 0.1–0.5 ppm) and NH-C (mean 0.6–0.8 ppm) (Table 2). These descriptive differences may reflect differences in cooking equipment proximity, HVAC configuration or outdoor infiltration.

NO_2 concentrations showed substantial spatial heterogeneity. While most locations remained below the EPA 1-hour NAAQS of 100 ppb [25], several rooms exceeded the more health-protective WHO 24-hour guideline of 25 ppb for substantial proportions of monitoring time (Table S2) [26]. Notably, C_NH_1 exceeded the WHO NO_2 guideline 69.1% and C_NH_2 exceeded it 91.7% of the time, with mean concentrations of 30.3 and 57.0 ppb, respectively. In NH-B, B_NH_1 (23.4%) and B_NH_3 (22.4%) also showed frequent WHO guideline exceedances (Table S2) [26]. The GERIE study identified NO_2 as a risk factor for breathlessness and cough in older adult NH residents [4], suggesting these exposures merit further investigation. Because outdoor NO_2 was not monitored concurrently, indoor sources and outdoor infiltration cannot be distinguished.

O_3 concentrations were generally low in most rooms, but B_NH_2 exhibited mean concentrations of 58.5 ppb with 29.1% of observations exceeding the WHO 8-hour guideline of 60 ppb (Table S2) [26]. Common room C_CR_2 similarly exceeded the O_3 guideline 21.4% of the time. These elevated O_3 levels may reflect outdoor infiltration or indoor photochemical reactions involving precursor pollutants. Without concurrent outdoor measurements, the relative contribution of each pathway cannot be determined.

3.7. Inter-parameter correlations

Descriptive Spearman correlation analysis of the NH-B dataset (Figure S3) showed moderate positive correlations between CO_2 and temperature (ρ = 0.40–0.55), consistent with possible occupancy related co-elevation. tVOC was positively correlated with $PM_{2.5}$ (ρ = 0.25–0.45), suggesting possible shared timing of indoor activities. NO_2 and O_3 showed moderate negative correlations (ρ = −0.30 to −0.50), consistent with ozone titration by nitric oxide (NO). Temperature and RH were inversely correlated (ρ = −0.55 to −0.70), as expected given the thermodynamic relationship. These correlations were not adjusted for multiple comparisons or facility-level clustering and are presented only to describe patterns within NH-B.

3.8. Diurnal patterns

Diurnal analysis of NH-B (Figure S4) showed temporal variations in several IAQ parameters. CO_2 was higher during the predefined daytime window (08:00–18:00) and lower during the nighttime window (22:00–07:00). Hours outside these windows were treated as transition periods and not classified as daytime or nighttime. tVOC followed a similar pattern, and temperature increased modestly during. daytime hours by approximately 1–2 °C. These patterns are consistent with, but do not prove, activity-related variation in indoor air.

3.9. IEQ and cognitive status: exploratory observations

Figure 3 presents normalized IAQ profiles for each resident room, color-coded by facility and annotated with the occupant's BIMS score. In most rooms, CO_2 and temperature were the dominant features, while $PM_{2.5}$ and O_3 remained comparatively low, and RH showed moderate variability.

Overall, visual inspection did not indicate a consistent gradient between BIMS score and the composite environmental profile. Differences appeared more strongly related to room-specific or facility-specific conditions than to cognitive status alone.

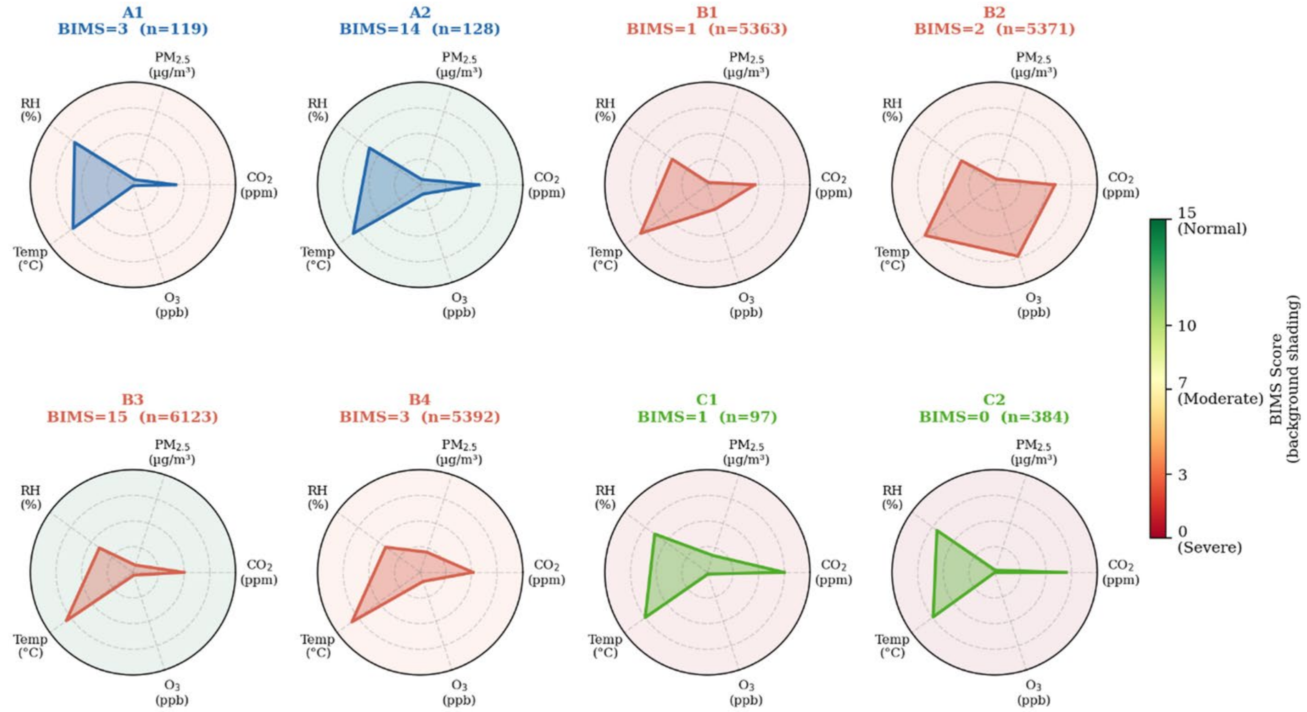


Figure 3. Normalized indoor air quality parameters for each resident room. Values are min-max normalized across monitored resident rooms for visualization. Colors indicate nursing home facility, and labels report the linked resident BIMS score. The figure is descriptive and not a statistical comparison.

Figure 2b illustrates the descriptive relationship between ACH and BIMS scores. BIMS scores were distributed across a broad range of ventilation rates, with no significant linear pattern in this pilot sample. Figure 2c summarizes ACH by broad BIMS category: residents with higher BIMS scores (8–15) and lower BIMS scores (0–7) both occupied rooms spanning low to high estimated ventilation rates.

We emphasize that these observations are descriptive only and do not establish causal relationships. The directionality of any possible relationship is ambiguous: room conditions may be influenced by care routines, door position, room location, HVAC operation, resident mobility, or other facility-level factors. Conversely, prior literature raises the hypothesis that chronic air pollution exposure could influence cognitive trajectories [34]. With only eight residents, confounding by facility, room location, disease severity, or other unmeasured factors cannot be excluded. These patterns are presented only to generate hypotheses for future studies.

3.10. Cross-study comparison of nursing home IAQ studies

To contextualize the descriptive results, we conducted an informal narrative comparison with recent nursing home IAQ studies reporting $PM_{2.5}$, CO_2, tVOC, or NO_2 (Figure 4). Studies were selected from the literature cited in the Introduction and Discussion and from targeted searches of peer-reviewed nursing-home or elderly-care IAQ studies. This comparison was not a systematic review or meta-analysis.

Mean $PM_{2.5}$ concentrations in the present facilities were generally at the low end of the reported nursing home range, and mean CO_2 concentrations were broadly consistent with mechanically ventilated facilities in prior European and U.S. studies [35–38]. However, the room-level spread in CO_2 within NH-C illustrates the heterogeneity that can be missed by facility-level or common-area-only monitoring. The $PM_{2.5}$ maxima observed in B_NH_4 and C_NH_1 are best interpreted as short-duration episodes rather than sustained high exposures; therefore, mean values and percent-time-above-threshold metrics are emphasized for cross-study interpretation.

Mean tVOC values in the present study, especially in NH-A common areas, were relatively higher than values reported in several European and Korean nursing-home studies [4,37–39]. Because the present measurements used a photoionization detector and prior studies used heterogeneous sampling and analytical methods, these comparisons should be interpreted cautiously [3]. NO_2 concentrations in NH-C residential rooms were also higher than those reported in many prior nursing-home studies [4,6,35]. Because outdoor concentrations were not measured concurrently, these room-level exceedances cannot be attributed definitively to indoor combustion, outdoor infiltration, or both.

Overall, the comparison supports the value of simultaneous multi-pollutant monitoring in both resident rooms and common areas, while underscoring that the present pilot data should be used to generate hypotheses for larger studies rather than to establish generalizable facility-level rankings.

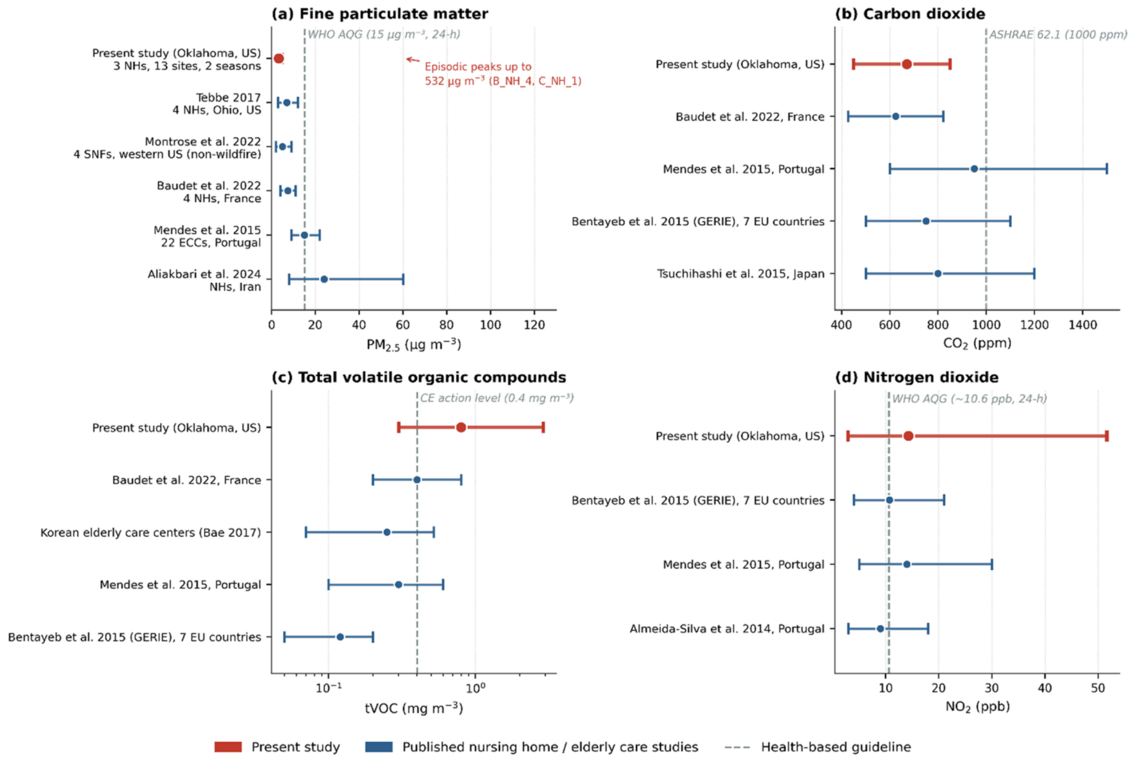


Figure 4. Cross-study comparison of indoor air quality in nursing homes. Comparisons are narrative and based on reported mean/range values from selected peer-reviewed studies; monitoring methods, instruments, seasons, and room types differed across studies.

4. Discussion

This pilot study provides a comprehensive multi-pollutant indoor environmental assessment of three Oklahoma nursing homes serving residents with dementia. By simultaneously monitoring nine air quality parameters across eight residential rooms and five common areas, we identified several IEQ concerns that merit further study and practical attention.

4.1. tVOC: a pervasive and underrecognized concern

The most consistent finding was the elevation of tVOC concentrations. Every monitored location exceeded the CE action level of 0.4 mg m^{-3} for at least one-fifth of the monitoring period [31], and common areas in NH-A exceeded the guideline continuously. These concentrations were considerably higher than those reported in the GERIE study [4], which found mean tVOC levels below 0.2 mg m^{-3} in European NHs [31], and higher than values reported in Korean NHs (0.07–0.52 mg m^{-3}) [32], although cross-study comparisons should be interpreted cautiously because monitoring instruments, sampling durations, seasons, room types, and VOC metrics differed. The elevated tVOC in our study may reflect cleaning and disinfection products, incontinence care products, air fresheners, personal care items, building materials, or furnishings commonly present in dementia care environments [40].

Chronic tVOC exposure may be relevant for older adults with dementia, but the present study cannot determine health effects due to pilot scope and feasibility. Prior epidemiological and toxicological studies have linked some VOC exposures with neuroinflammation, oxidative stress, impaired cognitive function, and respiratory irritation [41]. In this pilot sample, three of eight monitored residents had documented chronic lung disease, supporting the need for cautious source identification and exposure reduction rather than causal interpretation.

4.2. Thermal comfort and humidity

Temperature was generally well controlled across all three facilities, with most rooms maintaining conditions within the ASHRAE 55 comfort range [23]. Localized temperature exceedances above 26 °C in two NH-B rooms were intermittent. These findings are relevant because Tartarini *et al.* reported increased agitation when temperatures deviated from 22.6 °C in NH residents with dementia [8], and a UK dementia hospital study identified increased odds of aggression on warmer days [42].

The most notable thermal comfort issue was low RH in NH-B during winter monitoring. With 47.8%–73.8% of monitoring time below 30% RH, conditions in this facility may contribute to discomfort or respiratory irritation [43]. Ma *et al.* similarly identified low humidity as a problematic IEQ indicator in a Dutch NH during the heating season [9]. These findings support further evaluation of supplemental humidification in mechanically heated NHs during winter.

4.3. Carbon dioxide and ventilation adequacy

While most locations in our study maintained CO_2 below the 1000 ppm ASHRAE threshold [24], exceedances in NH-C residential rooms suggest possible periods of inadequate ventilation. The estimated ACH values of 0.84–1.16 h^{-1} in the low-ventilation rooms of NH-A and NH-C fall below the 2 ACH minimum recommended by ASHRAE 170 for patient rooms in healthcare facilities [24]. In the Japanese geriatric facility studied by Tsuchihashi *et al.*, baseline ACH of 2.0–6.2 h^{-1} was measured [44], comparable to the range in our study These comparisons should be interpreted cautiously because our estimates rely on CO_2 model assumptions and different logging intervals across facilities.

4.4. Particulate matter and NO2

$PM_{2.5}$ and PM_{10} concentrations were low in most rooms, while selected rooms showed transient spikes (e.g., rooms B_NH_4 and C_NH_1). These episodes may be important for susceptible residents, but they should not be interpreted as sustained facility-wide exposure. Future studies should combine time-weighted averages, percent-time-above-threshold, event duration, activity logs, and outdoor monitoring to distinguish local indoor events from outdoor infiltration.

The elevated NO_2 concentrations in NH-C (mean up to 57.0 ppb, with 91.7% exceedance of the WHO 24-hour guideline) were the most notable nitrogen dioxide finding [26]. Potential contributors include roadway infiltration, gas cooking equipment, or combustion appliances. Because outdoor NO_2 was not measured, source attribution is not possible. Chronic NO_2 exposure has been associated with respiratory morbidity in older adult populations and warrants source identification and mitigation [45].

4.5. Implications for dementia care

The room-level IEQ and BIMS patterns in this pilot study should be interpreted cautiously. We did not observe a consistent descriptive gradient between BIMS score and the composite environmental profile, and reverse causation or confounding is plausible: residents with more severe dementia may be less mobile, may have doors kept closed for safety, or may require care routines that alter indoor pollutant levels. Separately, broader epidemiological literature links long-term air pollution exposure, particularly fine particulate matter and NO_2, to accelerated cognitive decline and increased dementia incidence [34,46]. The present data therefore support further investigation of indoor environmental exposures in dementia care, but they do not show that IEQ contributed to cognitive decline in these residents.

The recent scoping review noted that indoor environmental factors, including tVOC, were correlated with BPSD occurrence in specific NH areas [7]. Our data are consistent with the need to consider multiple indoor pollutants in U.S. dementia care facilities. Future longitudinal studies should incorporate repeated IEQ monitoring alongside serial cognitive and behavioral assessments (e.g., BIMS, Cohen-Mansfield Agitation Inventory) to clarify temporal sequence and potential mechanisms.

4.6. Limitations

Several limitations should be acknowledged. The small sample size (n = 8 residents in 8 rooms) limits statistical power and generalizability; findings are hypothesis-generating, not confirmatory. The monitoring duration (2–5 days per facility) captures a snapshot rather than long-term exposure patterns. NH-B was monitored at 1-minute resolution while NH-A and NH-C used 15-minute intervals, creating differences in temporal granularity and in the precision of CO_2 decay fitting. Monitors were installed at approximately 2.0 to 2.2 m above the floor to reduce the likelihood of disturbance or tampering by residents with dementia. As a result, measurements may not fully represent the resident breathing zone. Outdoor air quality was not concurrently measured, precluding calculation of indoor-to-outdoor ratios and limiting source attribution for NO_2, O_3, and particulate episodes. The cross-sectional design and use of MDS assessments preceding monitoring cannot establish temporal or causal relationships between IEQ and cognitive function. Finally, specific VOC speciation (e.g., formaldehyde, benzene) was not possible with the PID-based tVOC sensor; future studies should incorporate compound-specific measurements to identify actionable sources.

5. Conclusions

This pilot multi-facility environmental assessment of three nursing homes in Oklahoma identifies IEQ concerns relevant to residents with dementia. Elevated tVOC across all facilities, winter-season low humidity in mechanically heated environments, and low estimated ventilation in selected residential rooms represent modifiable conditions that may be addressed through VOC source reduction, supplemental humidification during heating seasons, and targeted ventilation review in rooms with ACH below 2.0 h^{-1}.

The room-level cognitive analyses remain exploratory and do not support causal inference. Large scale longitudinal studies incorporating continuous IEQ monitoring, speciated VOC measurements, personal exposure assessment, outdoor monitoring, activity logs, and repeated neurocognitive and behavioral evaluations are needed to determine whether indoor environmental exposures contribute to cognitive or behavioral outcomes in ADRD care settings. In the interim, proactive IEQ management is a reasonable precautionary strategy in dementia care facilities.

Supplementary data

Supplementary material associated with this article includes additional monitoring details, summary tables, and supporting figures, including Tables S1–S4 and Figures S1–S4. The supplementary material is provided as a separate file.

Data availability statement

The de-identified indoor environmental monitoring data supporting the findings of this study are available from the corresponding author upon reasonable request. Resident-level clinical data are not publicly available because they contain potentially identifiable health information and are subject to institutional review and data-sharing restrictions.

Declaration of generative AI and AI-assisted technologies

During the preparation of this manuscript, the authors used generative AI tools only to improve language and readability. Specifically, the authors used ChatGPT for language polishing only in substantial portions. The authors take full responsibility for the content of the manuscript.

Acknowledgments

This work was supported by the Health, Well-Being, and the Built Environment Seed Grant, jointly funded by the University of Oklahoma and the University of Oklahoma Health Campus. This study was also supported by Presbyterian Health Foundation Equipment Grants, which provided essential support for the environmental monitoring component of the project. The authors gratefully acknowledge the administrators, staff, residents, and family members at the participating nursing homes for their cooperation, time, and support throughout the study.

Authors' contribution

H.L.: conceptualization, methodology, investigation, formal analysis, visualization, writing—original draft, project administration, funding acquisition; X.D.: data analysis, writing—review and editing; M.C.: investigation, data curation, formal analysis, writing—review and editing; J.G.: resources, investigation, supervision, writing—review and editing, funding acquisition; S.S.: methodology, visualization, writing—review and editing; X.Q.: methodology, supervision, writing—review and editing; D.S.: resources, investigation, writing—review and editing; Y.Y.: methodology, writing—review and editing; J.K.: methodology, supervision, writing—review and editing. All authors have read and agreed to the published version of the manuscript.

Conflicts of interest

The authors declare no conflicts of interest.

References

[1] Alzheimer's Disease International (ADI). World Alzheimer Report 2023: reducing dementia risk: never too early, never too late. 2023. Available: https://www.alzint.org/resource/world-alzheimer-report-2023/ (accessed on 5 January 2026).

[2] GBD 2019 Dementia Forecasting Collaborators. Estimation of the global prevalence of dementia in 2019 and forecasted prevalence in 2050: an analysis for the Global Burden of Disease Study 2019. *Lancet Public Health* 2022, 7(2):E105–E125. DOI: 10.1016/S2468-2667(21)00249-8

[3] Klepeis NE, Nelson WC, Ott WR, Robinson JP, Tsang AM, *et al*. The National Human Activity Pattern Survey (NHAPS): a resource for assessing exposure to environmental pollutants. *J. Exposure Sci. Environ. Epidemiol.* 2001, 11:231–252. DOI: 10.1038/sj.jea.7500165

[4] Bentayeb M, Norback D, Bednarek M, Bernard A, Cai G, *et al*. Indoor air quality, ventilation and respiratory health in elderly residents living in nursing homes in Europe. *Eur. Respir. J.* 2015, 45(2):1228–1238. DOI: 10.1183/09031936.00082414

[5] Livingston G, Huntley J, Sommerlad A, Ames D, Ballard C, *et al*. Dementia prevention, intervention, and care: 2020 report of the Lancet Commission. *Lancet* 2020, 396(10248):413–446. DOI: 10.1016/S0140-6736(20)30367-6

[6] Garre-Olmo J, López-Pousa S, Turon-Estrada A, Juvinyà D, Ballester D, *et al*. Environmental determinants of quality of life in nursing home residents with severe dementia. *J. Am. Geriatr. Soc.* 2012, 60(7):1230–1236. DOI: 10.1111/j.1532-5415.2012.04040.x

[7] Au-Yeung WTM, Miller L, Wu C, Beattie Z, Nunnerley M, *et al*. Examining the relationships between indoor environmental quality parameters pertaining to light, noise, temperature, and humidity and the behavioral and psychological symptoms of people living with dementia: scoping review. *Interact. J. Med. Res.* 2024, 13:e56452. DOI: 10.2196/56452

[8] Tartarini F, Cooper P, Fleming R, Batterham M. Indoor air temperature and agitation of nursing home residents with dementia. *Am. J. Alzheimers Dis. Other Demen.* 2017, 32(5):272–281. DOI: 10.1177/1533317517704898

[9] Ma C, Guerra-Santin O, Grave A, Mohammadi M. Supporting dementia care by monitoring indoor environmental quality in a nursing home. *Indoor Built Environ.* 2023, 32(9):1843–1861. DOI: 10.1177/1420326X231175340

[10] Rodríguez M, Seseña S, Valiente N, Palop ML, Rodríguez A. Indoor air quality in elderly care centers: a multidisciplinary approach. *Build. Environ.* 2024, 262:111832. DOI: 10.1016/j.buildenv.2024.111832

[11] Wu H, Kumar P, Xi C, Ding J, Cao S. Ventilation and air quality of a densely occupied multipurpose room in an elderly care center. *Indoor Air* 2025. DOI: 10.1155/ina/1125427

[12] Saliba D, Buchanan J, Edelen MO, Streim J, Ouslander J, *et al*. MDS 3.0: brief interview for mental status. *J. Am. Med. Dir. Assoc.* 2012, 13(7):611–617. DOI: 10.1016/j.jamda.2012.06.004

[13] CMS. Minimum Data Set (MDS) 3.0 Resident Assessment Instrument (RAI) Manual. Available: https://www.cms.gov/medicare/quality/nursing-home-improvement/resident-assessment-instrument-manual (accessed on 4 April 2026).

[14] Chodosh J, Edelen MO, Buchanan JL, Yosef JA, Ouslander JG, *et al*. Nursing home assessment of cognitive impairment: development and testing of a brief instrument of mental status. *J. Am. Geriatr. Soc.* 2008, 56(11):2069–2075. DOI: 10.1111/j.1532-5415.2008.01944.x

[15] Cianfarani F, Schaefer S, Mutukundu K. Identifying the affordable housing shortage: a study for Oklahoma. *Urban Plann.* 2024, 9. DOI: 10.17645/up.8636

[16] Rhubart DC, Monnat SM, Jensen L, Pendergrast C. The unique impacts of U.S. social and health policies on rural population health and aging. *Public Policy Aging Rep.* 2020, 31(1):24–29. DOI: 10.1093/ppar/praa034

[17] Almendares OM, Ruffin JD, Gard LC, Selvarangan R, Sasidharan A, *et al*. Indoor air quality conditions and respiratory virus detections in elementary schools—Kansas City, Missouri, February–March 2023. *Indoor Air* 2025, 2025:9935344. DOI: 10.1155/ina/9935344

[18] Chen R, Lin Y, Liao J, Qiu C, Chen W, *et al*. Fine particulate matter levels and HEPA filtration in Los Angeles homes during a wildland-urban-interface fire. *Npj Clean Air* 2026, 2:3. DOI: 10.1038/s44407-025-00042-5

[19] Persily A, de Jonge L. Carbon dioxide generation rates for building occupants. *Indoor Air* 2017, 27:868–879. DOI: 10.1111/ina.12383

[20] Batterman S. Review and extension of CO_2-based methods to determine ventilation rates with application to school classrooms. *Int. J. Environ. Res. Public Health* 2017, 14(2):145. DOI: 10.3390/ijerph14020145

[21] Yan Y, Lan L, Kang M, Zhang H, Fan X, *et al*. Emission rate of carbon dioxide by older adults while sleeping. *Build. Environ.* 2023, 236:110299. DOI: 10.1016/j.buildenv.2023.110299

[22] ASHRAE. Standards addenda 2020. 2020. Available: https://www.ashrae.org/technical-resources/standards-and-guidelines/standards-addenda (accessed on 4 April 2026).

[23] ASHRAE. Standard 55—thermal environmental conditions for human occupancy 2020. 2020. Available: https://www.ashrae.org/technical-resources/bookstore/standard-55-thermal-environmental-conditions-for-human-occupancy (accessed on 4 April 2026).

[24] ASHRAE. Standards 62.1 & 62.2. 2022. Available: https://www.ashrae.org/technical-resources/bookstore/standards-62-1-62-2 (accessed on 4 April 2026).

[25] US EPA. NAAQS Table. 2014. Available: https://www.epa.gov/criteria-air-pollutants/naaqs-table (accessed on 4 April 2026).

[26] WHO. WHO global air quality guidelines: particulate matter ($PM_{2.5}$ and PM_{10}), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide. 2021. Available: https://www.who.int/publications/i/item/9789240034228 (accessed on 4 April 2026).

[27] iTeh Standards. EN 16798-1:2019—indoor environmental parameters for building energy performance. 2019. Available: https://standards.iteh.ai/catalog/standards/cen/b4f68755-2204-4796-854a-56643dfcfe89/en-16798-1-2019 (accessed on 4 April 2026).

[28] RStudio. RStudio: Integrated Development for R. 2022. Available: https://posit.co/ (accessed on 10 February 2026).

[29] ASHRAE. Interpretations for Standard 170-2017. 2017. Available: https://www.ashrae.org/technical-resources/standards-and-guidelines/standards-interpretations/interpretations-for-standard-170-2017 (accessed on 4 April 2026).

[30] Morawska L, Allen J, Bahnfleth W, Bluyssen PM, Boerstra A, *et al*. A paradigm shift to combat indoor respiratory infection. *Science* 2021, 372(6543):689–91. DOI: 10.1126/science.abg2025

[31] Bienfait D, Fanger PO, Fitzner K, Jantunen M, Lindvall T, *et al*. Guidelines for ventilation requirements in buildings. 1992. Available: https://iifiir.org/en/fridoc/guidelines-for-ventilation-requirements-in-buildings-96628 (accessed on 4 April 2026).

[32] Lee K, Choi JH, Lee S, Park HJ, Oh YJ, *et al*. Indoor levels of volatile organic compounds and formaldehyde from emission sources at elderly care centers in Korea. *PLoS One* 2018, 13:e0197495. DOI: 10.1371/journal.pone.0197495

[33] Schieweck A, Uhde E, Salthammer T, Salthammer LC, Morawska L, *et al*. Smart homes and the control of indoor air quality. *Renewable Sustainable Energy Rev.* 2018, 94:705–718. DOI: 10.1016/j.rser.2018.05.057

[34] Peters R, Ee N, Peters J, Booth A, Mudway I, *et al*. Air pollution and dementia: a systematic review. *J. Alzheimers Dis.* 2019, 70(s1):S145–S163. DOI: 10.3233/JAD-180631

[35] Tebbe HM. Evaluation of indoor air quality in four nursing home facilities in northwest Ohio. Master's Thesis, University of Toledo, 2017.

[36] Montrose L, Walker ES, Toevs S, Noonan CW. Outdoor and indoor fine particulate matter at skilled nursing facilities in the western United States during wildfire and non-wildfire seasons. *Indoor Air* 2022, 32(6):e13060. DOI: 10.1111/ina.13060

[37] Mendes A, Bonassi S, Aguiar L, Pereira C, Neves P, *et al*. Indoor air quality and thermal comfort in elderly care centers. *Urban Clim.* 2015, 14:486–501. DOI: 10.1016/j.uclim.2014.07.005

[38] Baudet A, Baurès E, Guegan H, Blanchard O, Guillaso M, *et al*. Indoor air quality in healthcare and care facilities: chemical pollutants and microbiological contaminants. *Atmosphere* 2021, 12(10):1337. DOI: 10.3390/atmos12101337

[39] Lee J, Lee J, Huh D, Moon KW. Association between environmental exposure to phthalates and allergic disorders in Korean children: Korean National Environmental Health Survey (KoNEHS) 2015–2017. *Int. J. Hyg. Environ. Health* 2021, 238:113857. DOI: 10.1016/j.ijheh.2021.113857

[40] Dancer SJ, Li Y, Hart A, Tang JW, Jones DL. What is the risk of acquiring SARS-CoV-2 from the use of public toilets? *Sci. Total Environ.* 2021, 792:148341. DOI: 10.1016/j.scitotenv.2021.148341

[41] Kicinski M, Vrijens J, Vermier G, Den Hond E, Schoeters G, *et al*. Neurobehavioral function and low-level metal exposure in adolescents. *Int. J. Hyg. Environ. Health* 2015, 218(1):139–146. DOI: 10.1016/j.ijheh.2014.09.002

[42] Hamza N, Reid K, Anderson D, Townsend L. Indoor environmental conditions and likelihood of reported violence and aggression in a purpose-built residential dementia hospital. *J. Environ. Psychol.* 2024, 100:102477. DOI: 10.1016/j.jenvp.2024.102477

[43] Sundell J, Levin H, Nazaroff WW, Cain WS, Fisk WJ, *et al*. Ventilation rates and health: multidisciplinary review of the scientific literature. *Indoor Air* 2011, 21(3):191–204. DOI: 10.1111/j.1600-0668.2010.00703.x

[44] Ishigaki Y, Yokogawa S, Minamoto Y, Saito A, Kitamura H, *et al*. Pilot evaluation of possible airborne transmission in a geriatric care facility using carbon dioxide tracer gas: case study. *JMIR Form. Res.* 2022, 6(12):e37587. DOI: 10.2196/37587

[45] Eum KD, Kazemiparkouhi F, Wang B, Manjourides J, Pun V, *et al*. Long-term NO_2 exposures and cause-specific mortality in American older adults. *Environ. Int.* 2019, 124:10–15. DOI: 10.1016/j.envint.2018.12.060

[46] Cacciottolo M, Wang X, Driscoll I, Woodward N, Saffari A, *et al*. Particulate air pollutants, APOE alleles and their contributions to cognitive impairment in older women and to amyloidogenesis in experimental models. *Transl. Psychiatry* 2017, 7:e1022. DOI: 10.1038/tp.2016.280