

Article

Experimental Study of Energy Recovery Ventilator for Enhancing Indoor Air Quality in Daycare Centers: A Case Study in South Korea

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Abstract: Improving indoor air quality (IAQ) in daycare centers is essential due to children's vulnerability to pollutants and prolonged indoor exposure. To address these challenges, energy recovery ventilators (ERVs) with varying filtration efficiencies were evaluated through field measurements and CONTAM simulations. Baseline assessments of CO₂ and PM_{2.5} levels revealed significant impacts from outdoor pollutant infiltration. ERVs successfully reduced CO₂ concentrations, maintaining levels below 1000 ppm during most occupancy periods. However, low-efficiency filters (MERV 8 or lower) permitted outdoor particulate matter infiltration, increasing indoor PM_{2.5} levels. High-performance filters (MERV 13 or higher) reduced indoor PM_{2.5} concentrations by up to 50%, significantly improving air quality. Findings emphasize the necessity of combining high-efficiency filtration with ERVs to mitigate pollutant infiltration and ensure healthy indoor environments. Policymakers and practitioners are urged to implement ventilation systems equipped with MERV 13 or higher filters, particularly in regions with high outdoor pollution. These strategies are critical for safeguarding children's health and meeting IAQ standards in daycare facilities.



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Keywords: energy recovery ventilator; daycare center; PM_{2.5}; indoor air quality; children

1. Introduction

Recently, the global deterioration in air quality, represented by fine particulate matter, has become a significant social issue. The World Health Organization (WHO) revised its “WHO Air Quality Guidelines” in 2021, tightening the annual average concentration standards for PM₁₀ (particulate matter with a diameter of 10 µm or less) and PM_{2.5} (particulate matter with a diameter of 2.5 µm or less) to 5 µg/m³ for both [1].

Children are particularly vulnerable to pollutant exposure compared to adults, necessitating special attention. During childhood, when pulmonary functions are still developing, exposure to pollutants can negatively impact lung function even into adulthood [2]. Furthermore, prolonged exposure to airborne pollutants increases the risk of respiratory diseases such as pediatric asthma [3].

Daycare centers are essential spaces where children from infancy to school age spend much of their time indoors, participating in various activities that play a vital role in their development but may also expose them to indoor pollutants [4–6]. Therefore, special attention is required to address these exposures [7–9]. Winifred et al. recognized the issue of indoor air quality (IAQ), and reviewed measurement data and studies on daycare

centers. The findings revealed that the concentrations of pollutants were the highest in the following order: particulate matter, carbon dioxide, formaldehyde, carbon monoxide, and total volatile organic compounds [10]. As a result, IAQ in daycare centers requires significantly more attention compared to those in other building types.

In South Korea, to improve IAQ, the installation of ventilation facilities became mandatory for newly constructed buildings starting in 2009. After this regulation came into effect, indoor particle pollution emerged as a major social issue, leading to the widespread adoption of air purifiers and stricter standards for ventilation facility filters. Daycare centers are subject to the following two regulations related to ventilation facilities: (1) Ventilation system and airflow standards: Daycare centers with a gross floor area of 430 m² or more are required to install ventilation systems with a minimum airflow of 36 m³/h per person; (2) Indoor air quality standards: PM₁₀ must not exceed 100 µg/m³, PM_{2.5} must not exceed 50 µg/m³, and CO₂ concentrations must remain below 1000 ppm [11]. Most daycare centers built before the implementation of these regulations use medium-level filters with a Minimum Efficiency Reporting Value (MERV) rating of 14 or lower. Under such conditions, insufficient filter performance allows outdoor particles to enter easily, potentially worsening IAQ [12–14].

The majority of existing daycare centers predominantly depends on natural ventilation due to the lack of dedicated ventilation systems [15,16]. With the escalation of fine particulate matter pollution, the widespread adoption of air purifiers has provided partial relief for IAQ issues in daycare centers. However, significant challenges persist. Daycare centers are critical environments where children spend extensive periods indoors, engaging in various activities such as cooking, sleeping, playing, and cleaning, which collectively contribute to the generation of diverse pollutants. Consequently, the IAQ at daycare centers is intricately linked to children's health [17–20].

Kim et al. conducted extensive long-term measurements in daycare centers, revealing that PM_{2.5} and CO₂ concentrations frequently exceeded acceptable thresholds, presenting potential risks for infectious diseases among children [7]. Zheng et al. demonstrated the viability of using low-cost sensors for monitoring IAQ in daycare centers, particularly in tracking the deterioration caused by various events [21]. Furthermore, Kim et al. investigated artificial neural network (ANN) models to measure and predict CO₂ and PM_{2.5} concentrations, highlighting that pollutant concentrations not only surpassed permissible limits but also surged significantly during peak activity periods, necessitating careful management and intervention [22].

While numerous studies have examined children and daycare centers, there remains a critical gap in research addressing practical solutions and actionable strategies to improve IAQ. In many countries, including South Korea, aging infrastructure and inadequate facilities in existing daycare centers pose significant challenges, underscoring the urgent need for targeted interventions. Enhancing IAQ is paramount to safeguarding children's health.

The primary objective of this study is to substantially improve the IAQ of daycare centers by implementing energy recovery ventilators (ERVs). This research systematically analyzed the indoor environment of existing daycare centers and employed CONTAM simulations to evaluate annual variations in indoor conditions under changing external environmental factors. By focusing on critical indicators such as indoor PM_{2.5} and CO₂ levels, this study aims to propose robust, evidence-based solutions for effectively addressing IAQ challenges in daycare centers, contributing to healthier environments for children.

2. Materials and Methods

2.1. Description of Daycare Center

The daycare center selected for the field experiment is located in Goyang, Gyeonggi Province, South Korea. Constructed in 2008, it is a single-story facility situated within an apartment complex (Figure 1). The total area of the building is 155 m², with a ceiling height of 2.3 m.



Figure 1. Experimental daycare center: (a) is a front view figure of the experimental daycare center building; (b) is an indoor photo of the classroom.

In this study, non-conditioned spaces such as the main entrance, storage rooms, and kitchen were excluded. The analysis focused solely on areas actively used by children and staff. The daycare center accommodates up to 28 children and 8 staff members. Unlike typical buildings, daycare centers involve a wide range of occupancy activities, including cooking, dining, educational activities, and sleeping. However, this study did not account for particulate matter generated during cooking activities. Cooking-related emissions vary significantly depending on the activity and require specific ventilation strategies or systems in the kitchen to mitigate their impact [23–25].

The occupancy factor of children was analyzed in advance through on-site measurements and surveys (Table 1). Variations in occupancy schedules were observed based on daily routines and activities. These schedules were averaged arithmetically and used as input data, as shown in Figure 2. The calculated occupancy factor was utilized to estimate indoor PM_{2.5} and CO₂ emissions.

Table 1. Schedule of targeting daycare center. This table outlines the daily schedule of the activities and the number of occupants.

Time	Occupant Behavior	Number of Occupants
07:30–09:00	Getting in daycare center	1–3
09:00–09:30	Eating snack	4–5
09:30–12:00	Activity	6–8
12:00–13:00	Eating lunch	9–12
13:00–15:00	Napping	9–12
15:00–15:30	Eating snack	9–12
15:30–16:30	Activity and vacuuming	6–12
16:30–20:00	Getting out of daycare center	0–5

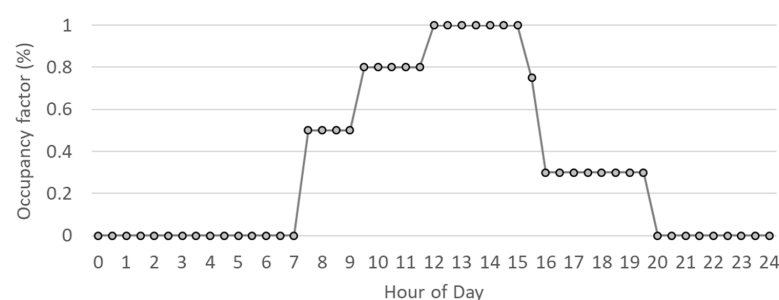


Figure 2. Occupancy factor of target building.

2.2. Field Measurement in Daycare Center

To evaluate changes in the indoor environment, this study employed CONTAM simulations, as illustrated in Figure 3. The simulations incorporated the following two primary components: (1) network simulation and (2) particle simulation. Key influencing factors for the simulations were derived from on-site measurements, referred to as experimental factors. These factors were obtained through rigorous field-based data collection.

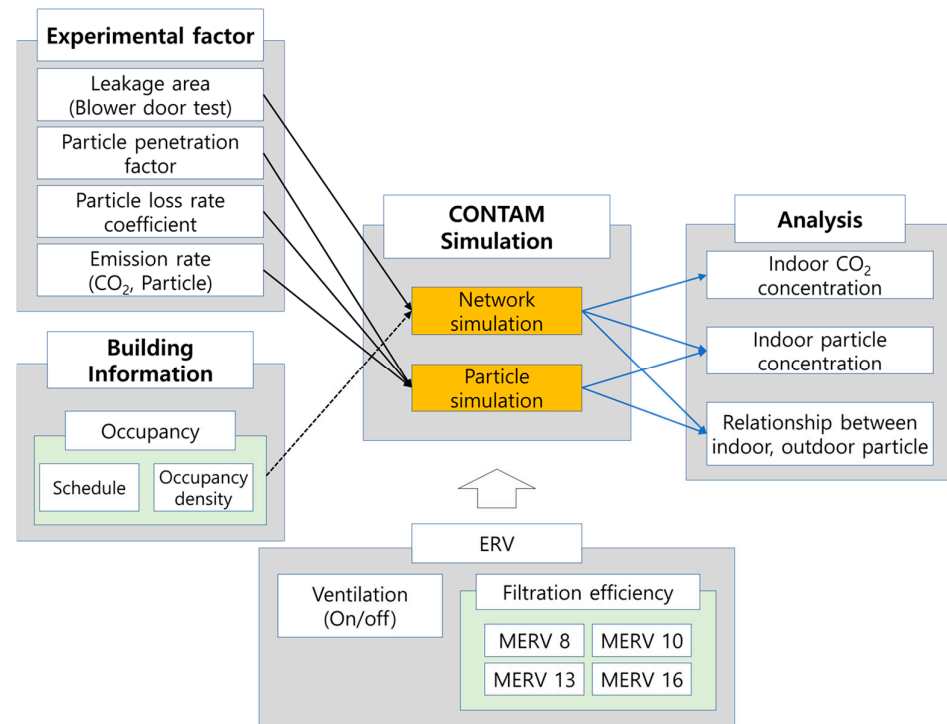


Figure 3. Schematic diagram of CONTAM simulation.

A blower door test was conducted during non-occupancy periods (weekends) using a Retrotec 6100 device (Retrotec, Everson, WA, USA). The test adhered to the standards outlined in ASTM E779 and ISO9972: Europe [26,27]. The results indicated an equivalent leakage area (eqLA) of 1.29 cm²/m² and an air change rate at 50 Pa (ACH₅₀) of 5.36 h^{−1}, reflecting suboptimal airtightness. The daycare center, originally remodeled from the first floor of an apartment building, demonstrated inadequate air-sealing performance. This lack of airtightness likely facilitates infiltration and increases the risk of outdoor particulate matter penetrating the indoor environment.

To calculate the particulate matter-related coefficients of the target building (deposition rate and penetration factor), indoor and outdoor concentrations of particulate matter and CO₂ were simultaneously measured at 1-min intervals. Particulate matter was measured using optical particle counters (OPS, model 3330, TSI Inc., Shoreview, MN, USA), and CO₂ levels were monitored with a CO₂ logger (TR-76Ui, T&D Inc., Matsumoto, Japan).

The penetration factor (*P*) represents the ratio of particles in infiltrating air that penetrate the building envelope. Under well-mixed conditions, and assuming no internal particle generation, the penetration factor can be calculated using the following mass balance equation [28–30]:

$$\frac{dC_{in}}{dt} = \lambda PC_{out} - (\lambda + k)C_{in} \quad (1)$$

where *C_{in}*, *C_{out}* is the indoor and outdoor particle concentration (µg/m³), *λ* is the air exchange rate, *P* is the penetration factor, *k* is the deposition rate (1/h), *V* is the volume of indoor space (m³), and *t* is the time (h).

In the Equation (1), λPC_{out} is the rate at which outdoor particles are penetrated into the indoor spaces, and $\lambda + k$ represents the particle loss rate coefficient, with which indoor particles are discharged to the outside through exfiltration (AER), and the deposition rate k . P and k can be calculated according to the indoor particle concentration and decay rate that reached steady states. This can be expressed as shown in Equation (2) [30]:

$$\ln\left(\frac{C_{in}(0) - C_{in}(eq)}{C_{in}(t) - C_{in}(eq)}\right) = (\lambda + k) \times \Delta t \quad (2)$$

where $C_{in}(0)$ is the indoor particle concentration at time 0, $C_{in}(t)$ is the concentration at time t , and $C_{in}(eq)$ is the indoor particle number equilibrium concentration.

When the natural log of the indoor concentration and time in Equation (2) is plotted, the slope is given as $(\lambda + k)$. The slope becomes the particle deposition rate, which is estimated by excluding the influence of the AER.

The penetration factor was estimated using Equation (3), which is given as follows:

$$P = \frac{C_{in}(eq)}{C_{out}} \times \left(\frac{\lambda + k}{\lambda}\right) \quad (3)$$

2.3. CONTAM Simulation

In this study, CONTAM was utilized to model the daycare center and to compare and analyze the changes in the indoor environment based on the application of ventilation systems and variations in the filter performance. CONTAM was developed by the National Institute of Standards and Technology (NIST) and is extensively used as a simulation program to analyze indoor airflow and pollutant distribution [31–33].

The network simulation in CONTAM used for the airflow paths is based on the empirical relationship between the airflow and the pressure difference across a building crack in the building envelope [34], as follows:

$$Q = C_d A \sqrt{\frac{2\Delta P}{\rho}} \quad (4)$$

where Q is the volumetric flow rate (kg/s), C_d is the discharge coefficient, A is the leakage (orifice) area of the airflow paths (m^2), ΔP is the pressure difference between zones (Pa), and ρ is the air density.

In CONTAM, the contaminant concentration is calculated using the following equation [34]:

$$\frac{dm_i^\alpha}{dt} = \sum_j F_{j \rightarrow i} (1 - \eta_j^i) C_j^\alpha + G_i^\alpha + m_i \sum_\beta K^{\alpha,\beta} C_i^\beta - \sum_j F_{i \rightarrow j} C_i^\alpha - R_i^\alpha C_i^\alpha \quad (5)$$

where m_i^α is the mass of contaminant α in control volume i (kg), $F_{j \rightarrow i}$ is the rate of air mass flow from control volume i to j (kg/s), η_j^i is the filtration efficiency in the airflow path, C_j^α is the mass concentration of contaminant α in control volume j (kg/kg), G_i^α is the contaminant α generation rate (emission rate) in control volume i (kg/s), $K^{\alpha,\beta}$ is the kinetic reaction coefficient in control volume i between contaminant α and contaminant β , C_i^β is the mass concentration of contaminant β in control volume i , $F_{i \rightarrow j}$ is the rate of air mass flow from control volume i to j , C_i^α is the mass concentration α in control volume i , and R_i^α is removal rate of contaminant α in control volume i (kg/s).

Before performing CONTAM modeling, experimental factors and building information were collected. The input data for the simulation are summarized in Table 2.

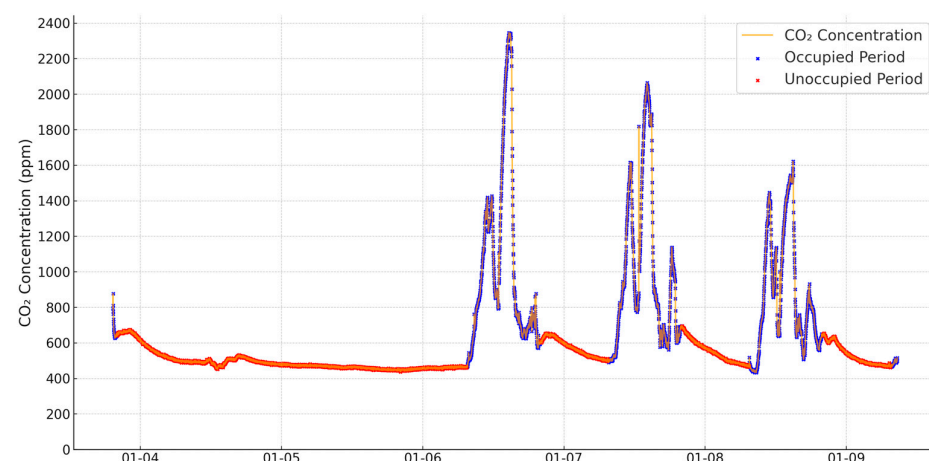
Table 2. Input data for CONTAM simulation.

Building Information	Floor area	66.5 m ²
	Volume	153.0 m ³
	Temperature	20 °C
	Occupancy schedule	09:00–20:00
Air Leakage Parameter	ACH ₅₀	5.36 h ^{−1}
	EqLA at 10 Pa	1.29 cm ² /m ²
Particle Parameter	Emission rate	0.018 mg/min
	Penetration factor	0.62
	Deposition rate	0.09 h ^{−1}
CO₂ Parameter	Emission rate	0.22 L/min

3. Results and Discussion

3.1. Indoor Air Quality in Target Building by Field Measurements

To assess the indoor environment, CO₂ concentrations were continuously measured over approximately 133 h. January 4 and 5 were weekend days (Figure 4). The results showed significant differences in CO₂ levels between occupied and unoccupied periods. During unoccupied periods, the CO₂ concentration averaged 514.6 ± 61.5 ppm, whereas the average concentration during occupied periods was 945.4 ± 439.6 ppm, indicating a strong correlation between the occupancy density and indoor CO₂ levels.

**Figure 4.** Indoor CO₂ concentration in daycare center.

CO₂ concentrations during occupied periods increased up to 2347 ppm. This trend aligned with occupancy patterns, with peaks observed during periods of high occupancy, such as late mornings, lunchtime, naptime, and afternoon activities. Following these peak periods, active natural ventilation during cleaning or before leaving significantly reduced CO₂ concentrations, with a decline rate exceeding 10 h^{−1}.

Carbon dioxide (CO₂) is a critical indicator of indoor air quality (IAQ). As stated in the introduction, South Korea recommends maintaining indoor CO₂ concentrations below 1000 ppm. Additionally, several international standards emphasize specific thresholds for CO₂ levels to ensure acceptable indoor environments [35–37]. Among high-occupancy facilities, daycare centers warrant special attention, as they are spaces where children spend a significant amount of time and are highly susceptible to adverse air quality conditions.

Previous studies assessing IAQ in South Korean daycare centers have reported similar patterns. Kim et al. investigated low-cost sensors to monitor indoor particulate matter and CO₂ concentrations over a year, presenting seasonal variations in their findings [7].

Although the annual average CO₂ concentration remained below 1000 ppm, elevated levels frequently exceeding 2000 ppm were observed during the fall and winter seasons. Similarly, Hwang et al. conducted IAQ measurements in daycare centers and found that, while the average indoor CO₂ concentration was 638.3 ppm, the maximum levels exceeded 1500 ppm [38]. These consistent trends across studies suggest that operational and ventilation conditions in daycare centers are similar, despite differences in building configurations and occupancy densities. Seasonal factors significantly influence IAQ, particularly during the winter season, when outdoor temperatures are low, resulting in limited natural ventilation. This study observed that natural ventilation typically occurred only once in the morning and evening, with sporadic, irregular ventilation during cleaning activities. Consequently, reduced ventilation frequency led to significant increases in indoor CO₂ concentrations.

Indoor particulate matter levels were continuously measured over approximately 72 h from January 6 to January 9. While indoor particulate matter concentrations were partly influenced by occupancy, they were found to be more significantly affected by outdoor particle levels (Figure 5). The indoor/outdoor (I/O) ratio analysis revealed a value of 0.74 during occupied periods and 0.51 during unoccupied periods. These results indicate that, while various indoor factors contribute to increased indoor particulate matter concentrations, the influx of outdoor particulate matter has a more substantial impact compared to indoor particle generation.

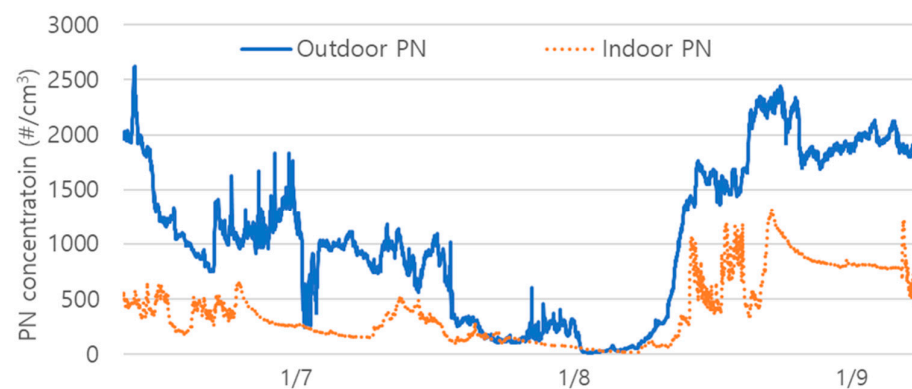


Figure 5. Indoor particle concentration in a daycare center.

3.2. Measurement of Building Characteristics for Particles

The deposition rate and penetration factor are the most influential parameters affecting indoor particulate matter concentrations. These parameters vary depending on building conditions and particulate matter characteristics. Therefore, the values obtained through field measurements were utilized as input data for the CONTAM simulation.

Size-resolved analysis was performed to evaluate the decay rate of elevated particulate matter concentrations under unoccupied conditions, considering natural ventilation or previous occupant activities (Figure 6).

Table 3 summarizes the results obtained from the measurements. The deposition rate increased with the particle size, indicating a higher deposition rate for larger particles. The penetration factor varied depending on the building conditions, but the measured values showed trends consistent with previous studies [28,39]. Using these values, the particle number concentration was converted to the mass concentration to derive the PM_{2.5} deposition rate and penetration factor, which were calculated as 0.40 and 0.63, respectively. While these values showed slight differences compared to prior studies, they exhibited similar trends [13,17,40,41].

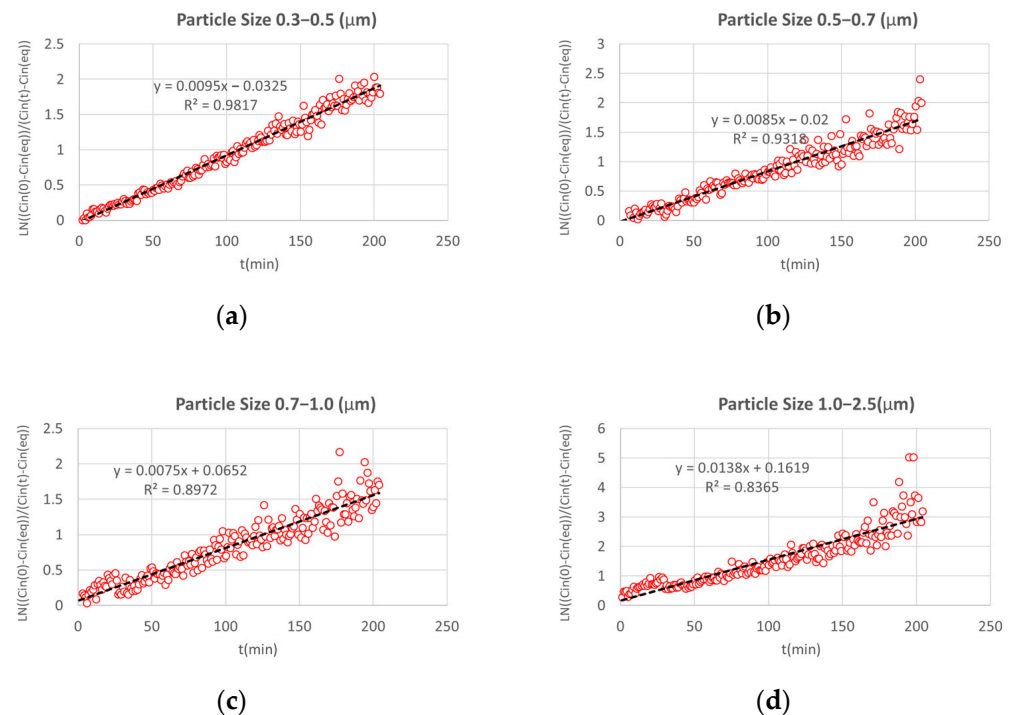


Figure 6. Size-resolved indoor particle loss rate coefficient by manipulation. (a) 0.3–0.5 μm ; (b) 0.5–0.7 μm ; (c) 0.7–1.0 μm ; (d) 1.0–2.5 μm .

Table 3. Summary of size-resolved particle penetration and deposition rate (0.3–2.5 μm).

	0.3–0.5 μm	0.5–0.7 μm	0.7–1.0 μm	1.0–2.5 μm
Deposition rate	0.31	0.25	0.26	0.35
Penetration factor	0.63	0.54	0.52	0.65

3.3. CO₂ Reduction Impact by ERV Operation

Ventilation plays a critical role in reducing CO₂ concentrations, particularly in high-occupancy spaces, including to daycare centers. The operation of ERVs in such environments not only enhances the indoor air quality, such as CO₂, but also significantly contributes to building energy efficiency, underscoring its importance in sustainable building management [42]. The CONTAM simulation was used to compare indoor CO₂ concentrations with and without the application of an ERV. The “No vent” scenario represented conditions where CO₂ reduction occurred solely through natural ventilation and infiltration without the operation of a mechanical ventilation system. Since CO₂ concentrations are not influenced by filter performance, the simulation specifically compared CO₂ levels in scenarios with and without ERV application (Figure 7).

The simulation applied an ERV with a capacity of 300 m³/h, which reflects the typical capacity of energy recovery ventilators commonly manufactured in South Korea. When the ERV was operational, the average indoor CO₂ concentration decreased to 517 ppm. Based on both field measurements and simulation results, the continuous introduction of outdoor air significantly reduced indoor CO₂ concentrations to levels below the standard threshold. However, during certain periods, CO₂ concentrations exceeded 1000 ppm, particularly between 12:00 and 15:00 when the occupancy density reached its maximum. This suggests that additional ventilation might be necessary during peak occupancy periods. However, for most of the occupancy duration, the ERV effectively kept the indoor CO₂ concentrations below the standard threshold.

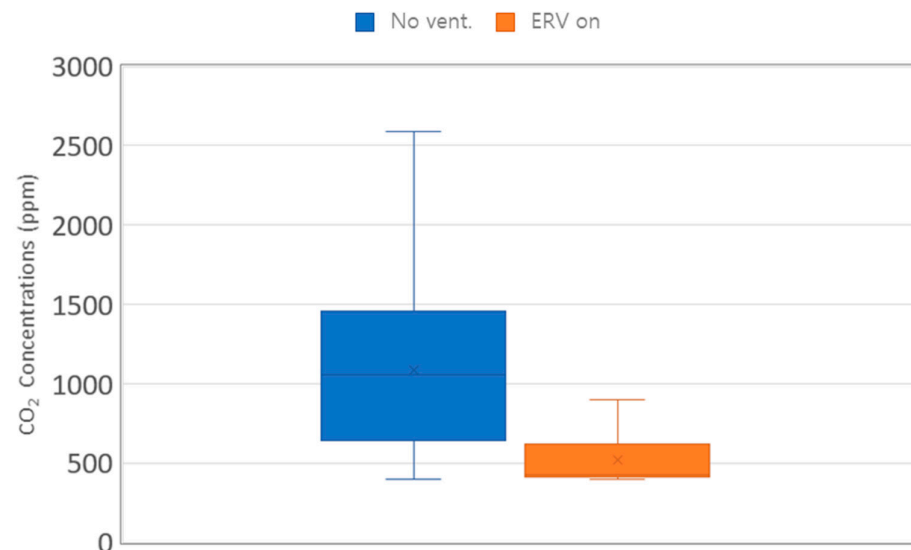


Figure 7. Result of indoor CO₂ concentration.

With a maximum occupancy of 12 people, the legal ventilation rate requirement is 432 m³/h. However, considering the children's activity levels and respiration rates, it appears feasible to maintain indoor CO₂ levels below 1000 ppm with a ventilation rate of 300 m³/h.

Figure 8 denotes the indoor CO₂ concentration and temperature from previous studies on daycare centers, showing that many studies have identified high CO₂ levels as a significant issue (Figure 8). In most of the previous studies, the indoor CO₂ concentrations exceeded the IAQ standard of 1000 ppm, which can be attributed to the following two main factors: (1) a high occupancy density and (2) low ventilation rates.

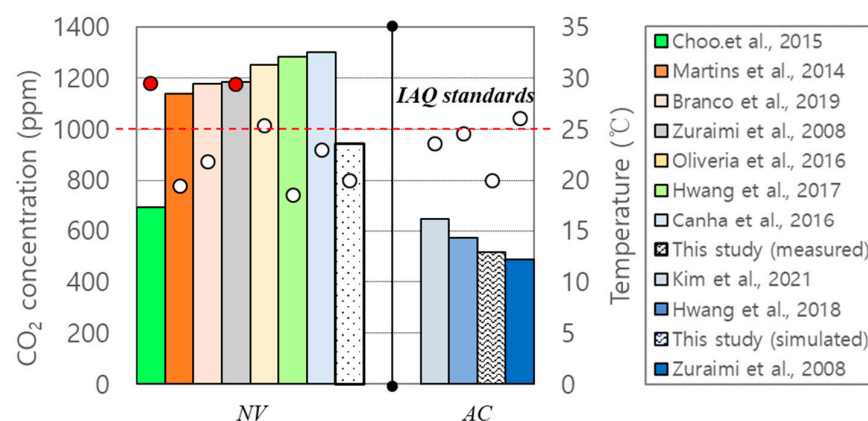


Figure 8. Comparison of indoor CO₂ concentration and temperature [6,7,18,38,43–47]. NV (natural ventilation); AC (air conditioning). Red dot denotes overheating cases.

In particular, many daycare centers utilizing natural ventilation (NV) recorded CO₂ concentrations ranging between 945 and 1300 ppm, with peak indoor levels frequently exceeding 3000 ppm. This indicates that natural ventilation alone is not effective in controlling CO₂ levels in daycare centers. Although natural ventilation can rapidly remove indoor pollutants when applied properly, the infrequent use of ventilation leads to repeated CO₂ buildup during enclosed periods. On the other hand, daycare centers equipped with mechanical ventilation (AC) consistently maintained CO₂ levels below 1000 ppm. This suggests that, if existing daycare centers undergo remodeling, it is essential to integrate mechanical ventilation systems, such as energy recovery ventilators (ERVs). Most of the pre-

vious studies reported minimal indoor temperature fluctuations (20–25 °C) due to HVAC operation. However, some of the studies observed high indoor temperatures (30 °C and 29.4 °C), mainly in tropical climates. Nevertheless, no strong correlation was found between the CO₂ concentration and indoor temperature variations based on climate differences.

3.4. Filtration Efficiency and Indoor Particle Concentration

When applying an ERV to daycare centers, a case study was conducted by categorizing filtration efficiency into MERV 8 to MERV 16 levels (Table 4). Since particulate matter can enter with the outdoor air introduced by the ERV, filters were installed on the outdoor duct side.

Table 4. Case study in the CONTAM simulation.

Case	Boundary Condition of Ventilation Type and Filtration	Ventilation Rate
No vent	No mechanical ventilation	Natural ventilation
MERV 8	ERV + MERV 8	Natural ventilation + 300CMH
MERV 10	ERV + MERV 10	
MERV 13	ERV + MERV 13	
MERV 16	ERV + MERV 16	

The simulation results revealed differences in indoor particulate matter concentrations based on filter levels (Figure 9). In the absence of ventilation (No vent), the annual average indoor PM_{2.5} concentration was 24.4 µg/m³. When MERV 8 filters were applied, the concentration slightly decreased to 23.6 µg/m³, and, with MERV 10 filters, it further reduced to 22.3 µg/m³. These findings suggest that using filters rated at MERV 8–10 or lower in mechanical ventilation systems allows for the infiltration of outdoor particulate matter into the indoor environment. In contrast, applying a MERV 13 filter significantly reduced the annual average indoor PM_{2.5} concentration to 14.6 µg/m³. When a MERV 16 filter was used, the concentration further decreased to 12.4 µg/m³, demonstrating a substantial improvement in air quality.

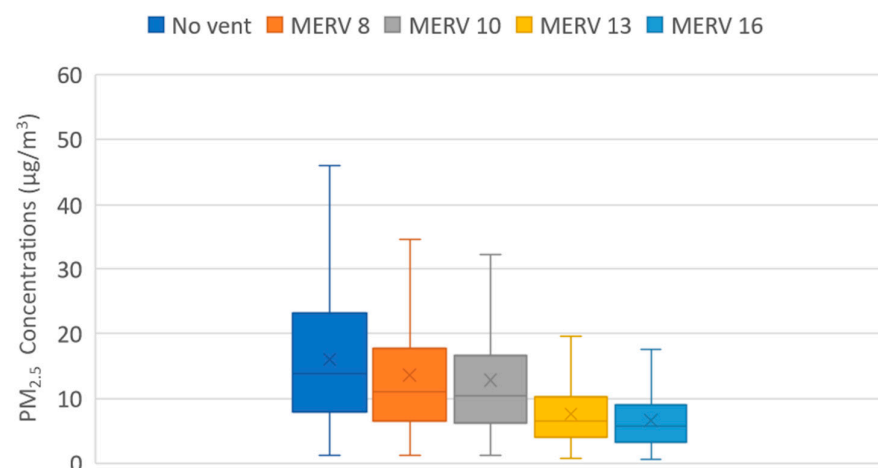


Figure 9. Result of indoor particle concentration.

These changes were also evident through the analysis of the indoor/outdoor (I/O) ratio. Without ventilation systems, the I/O ratio was 1.10, indicating a significant contribution from indoor particle generation. In contrast, the application of an ERV resulted in a substantial reduction in the I/O ratio. With MERV 8 and MERV 10 filters, the I/O ratio

decreased to 0.79 and 0.66, respectively. However, with MERV 13 and MERV 16 filters, the I/O ratio was significantly reduced further to 0.39 and 0.34 (Figure 10).

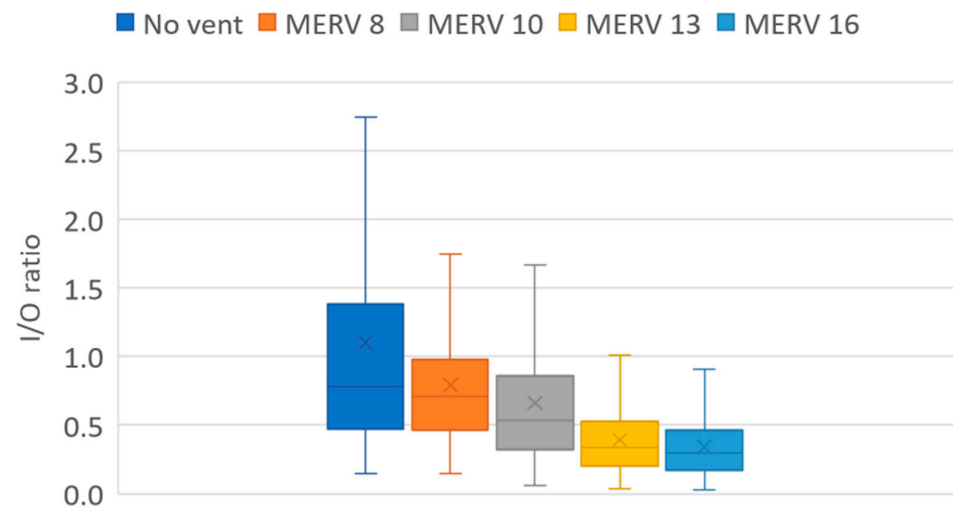


Figure 10. Result of the I/O ratio.

The simulation results demonstrated that applying an ERV appropriate for the occupancy density could simultaneously reduce the indoor particulate matter and CO₂ concentrations. However, achieving the effective removal of indoor particulate matter requires the use of high-performance filters rated MERV 13 or higher to filter outdoor air before it enters the indoor environment. The appropriate filter level may vary depending on factors such as the extent of outdoor air pollution and trends in indoor pollutant generation.

The correlation between indoor and outdoor particulate matter concentrations varied depending on the ventilation system and filter performance (Figure 11). In the absence of a ventilation system, the indoor–outdoor correlation coefficient was $r^2 = 0.39$. In contrast, with ERV operation, the correlation increased to 0.48–0.66.

The indoor PM_{2.5} concentrations are heavily influenced by outdoor levels, as evidenced by the linear relationships in Figure 10. However, the slope of the regression lines and the R^2 values indicate that the degree of this influence varies with the filtration efficiency. Without filtration (Figure 11a), the high slope and low R^2 suggest poor IAQ control and a strong reliance on outdoor conditions. As filtration efficiency increases (from MERV 8 to MERV 16, as shown in Figure 11b–e), the slopes decrease and the indoor PM_{2.5} levels become less sensitive to outdoor fluctuations. This demonstrates the efficiency of high-performance filters in mitigating outdoor pollution’s impact on indoor environments.

This improvement can be attributed to the continuous ventilation provided by the ERV, which removes outdoor particulate matter before introducing air indoors, compared to reliance on natural ventilation. Additionally, scatter plots illustrated the changes in indoor particulate matter concentrations as influenced by varying outdoor particulate matter levels and the filter performance. These plots provide a clear visualization of how filtration efficiency affects the indoor environment.

The indoor particle concentration in daycare centers from previous studies revealed a wide variation ($46.1 \pm 34.7 \mu\text{g}/\text{m}^3$) [6,7,43,45–48]. The following two primary factors were identified as the reasons for this large variation: (1) differences in occupant behavior (e.g., ventilation patterns, cooking activities, and cleaning) and (2) variations in outdoor particulate matter concentrations. Among these, occupant behavior generally has a minor impact during regular activities. However, daycare centers often face high-intensity PM generation due to cooking and cleaning activities, which have been repeatedly reported as significant sources of indoor pollution. In this study, PM resuspended due to general

occupancy was incorporated into the simulation, but indoor peak events such as cooking and intensive cleaning were not considered. This suggests the need for further research on South Korean daycare centers to better understand the impact of these activities on indoor PM levels.

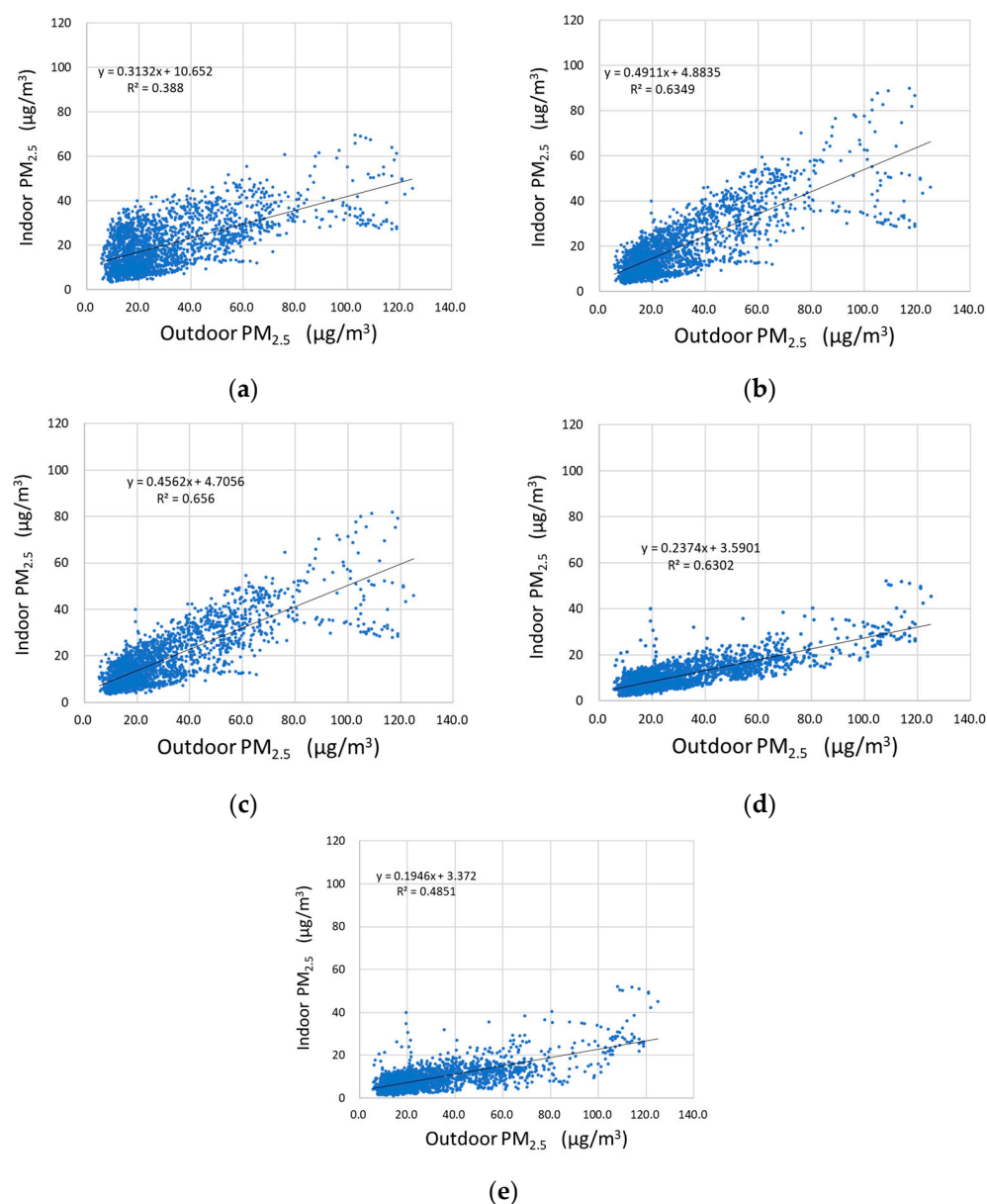


Figure 11. Scatter plots showing the correlation of indoor and outdoor PM_{2.5} concentrations: (a) No vent; (b) ERV + MERV8; (c) ERV + MERV10; (d) ERV + MERV13; (e) ERV + MERV16.

Additionally, differences in outdoor PM concentrations had a significant effect on indoor levels. The indoor/outdoor (I/O) ratio from previous studies was 0.80 ± 0.15 , indicating that outdoor PM significantly contributes to indoor air pollution. As discussed earlier, most daycare centers rely on natural ventilation, making them highly susceptible to outdoor PM infiltration. Therefore, careful consideration is needed to manage outdoor pollutant exposure in these facilities.

Additionally, beyond ERVs, most heating, ventilation, and air conditioning (HVAC) systems use filters when introducing outdoor air. The disparity in average annual PM_{2.5} concentrations between countries further highlights the need for appropriate filtration standards. While the United States reports an annual average PM_{2.5} concentration of

8 $\mu\text{m}/\text{m}^3$ [49], South Korea's average is significantly higher at 27 $\mu\text{m}/\text{m}^3$, making it one of the highest among OECD countries [50]. This discrepancy underscores the necessity for higher filter levels in regions like South Korea.

Stephens et al. investigated MERV levels in HVAC filters across residential buildings in Texas, finding that most filters ranged from MERV 6 to 8 [29]. Similarly, Alavy et al. conducted a study on residential HVAC filters in Toronto, Canada, reporting MERV levels between 8 and 14 [51]. Both studies provide insight into typical North American filtration practices, though ASHRAE has recently recommended MERV 13 or higher due to the COVID-19 pandemic [52]. The WHO has also endorsed MERV 14 filters as part of its 2021 guidelines [53].

In South Korea, daycare centers often employ filters with MERV 14 [15], while residential buildings commonly use MERV 11 [54]. Schools, which share similar requirements, recommend filters between MERV 12 and 15 [55]. Recently, some new daycare centers in South Korea have adopted MERV 16 or HEPA-level filters in response to severe particulate matter issues.

4. Conclusions

This study aimed to improve the IAQ of daycare centers in an energy-efficient manner by combining field measurements and simulations to identify appropriate solutions for applying energy recovery ventilators (ERVs). The conclusions can be summarized as follows:

1. Applying ERVs is an energy-efficient solution for removing indoor CO_2 . It facilitates the introduction of outdoor air, effectively eliminating gaseous pollutants generated indoors and maintaining CO_2 concentrations below 1000 ppm.
2. Daycare centers, where various occupant activities occur, generate indoor pollution sources. However, due to poor airtightness, they are more vulnerable to outdoor pollution sources. Applying ERVs reduces penetration and introduces filtered, clean outdoor air into indoor spaces, emphasizing the importance of this approach.
3. During periods of heightened particulate matter pollution, the use of ERVs requires careful consideration of filter performance. Low-performance filters can worsen indoor particulate matter concentrations compared to sealed conditions without ventilation. Therefore, it is crucial to use filters with a minimum performance of MERV 13 or higher to maintain IAQ during ventilation.

Given the findings of this study, daycare centers should implement filters with a minimum MERV rating of 13 to ensure optimal indoor air quality (IAQ), particularly for CO_2 and $\text{PM}_{2.5}$, and to protect children's health. However, this study was limited to winter conditions and did not account for seasonal variations in filtration efficiency, ERV performance, or indoor environmental factors affecting CO_2 concentrations. Considering South Korea's significant seasonal fluctuations in air pollution and climate, future research should explore these variables to develop a more comprehensive approach to IAQ management in daycare centers.

Additionally, a thorough assessment of indoor PM emissions is essential to better understand their impact on air quality. Future studies should focus on the long-term monitoring of daycare centers in South Korea, combined with experimental analyses under various conditions, to refine and enhance IAQ management strategies.

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Abbreviations

ERV	Energy recovery ventilator
MERV	Minimum Efficiency Reporting Value
ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers
ISO	International Organization for Standardization
PM	Particulate matter
IAQ	Indoor air quality
ACH ₅₀	Air changes per hour at 50 pascals
eqLA	Equivalent leakage area
CMH	Cubic meter per hour
CO ₂	Carbon dioxide
HVAC	Heating, ventilation, and air conditioning

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