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Field Evaluation of ERV-Related Ventilation Improvements for Indoor Air Quality in School Food Service Facilities

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Abstract

Purpose: This study examined the field performance of energy recovery ventilation (ERV)-related ventilation improvements for indoor air quality (IAQ) in public school food service facilities through a secondary exploratory analysis of previously reported field data and certified ERV performance information. **Research Design and Data:** Pre- and post-improvement reduction rates for seven pollutants (PM_{10}, $PM_{2.5}$, CO_2, NO_2, CO, TVOC, and HCHO) were compiled for cooking rooms and cafeterias in three schools, of which two provided matched before-and-after data. Pollutant reduction patterns were assessed descriptively, and certified ERV indicators, including airflow capacity, power consumption, heat-recovery efficiency, and noise level, were summarized as technical performance information. Because raw repeated-measurement data were unavailable, inferential testing, formal correlation analysis, and causal modeling were not performed. **Results:** Particulate pollutants showed the most consistent reductions, with PM_{10} and $PM_{2.5}$ exceeding 55% across the four matched space-level observations. NO_2 and CO showed moderate reductions, whereas CO_2 showed smaller and more variable changes. TVOC showed inconsistent or negative responses, suggesting the influence of non-ventilation sources such as cooking materials, cleaning agents, and indoor chemical emissions. The available data were insufficient to formally evaluate the relationship between certified ERV airflow capacity and pollutant reduction. **Conclusions:** ERV-related ventilation improvement appears effective for reducing cooking-generated particulates in public school food service facilities. However, VOC control requires source-management strategies in addition to ventilation. These findings provide preliminary field-based evidence for larger multi-site validation studies and future operation-level performance assessments.

Keywords: Energy recovery ventilation; Indoor air quality; School food service facility; Particulate matter; Pollutant reduction; Secondary analysis

JEL Classification Code: Q53, Q55, I18, H54, O32

1. Introduction

Indoor air quality (IAQ) has emerged as a critical public health issue because people spend a large proportion of their daily time indoors, and indoor environments can substantially influence exposure to air pollutants (Klepeis et al., 2001). Public facilities such as school cafeterias, childcare centers, welfare facilities, healthcare institutions, and administrative buildings accommodate large numbers of occupants and are therefore particularly vulnerable to indoor air pollution. Various contaminants, including particulate matter (PM_{10} and $PM_{2.5}$), carbon dioxide (CO_2), nitrogen dioxide (NO_2), carbon monoxide (CO), total volatile organic compounds (TVOCs), and formaldehyde (HCHO), can accumulate indoors and adversely affect occupant health, comfort, and performance (Mendell & Heath, 2005; Seppänen et al., 1999). In particular, elevated CO_2 and VOC exposure have been associated with poorer perceived indoor environmental quality and reduced cognitive performance in controlled exposure studies (Allen et al., 2016; Satish et al., 2012).

Among public facilities, school food service facilities have attracted particular attention because cooking activities generate substantial quantities of particulate matter, combustion by-products, and volatile organic compounds. Cooking emissions vary depending on cooking method, food type, oil use, temperature, ventilation condition, and fuel source, and they can include respirable particles, ultrafine particles, nitrogen oxides, carbon monoxide, aldehydes, and other organic compounds (Abdullahi et al., 2013; Buonanno et al., 2009). Previous studies have also reported that exposure to cooking-generated aerosols may pose health risks to workers in food service environments, especially where ventilation performance is insufficient (See & Balasubramanian, 2006). In Korea, recent studies on school cafeterias and cooking rooms have emphasized the need for ventilation improvement, customized renovation, and field-based evaluation of indoor pollutant reduction in school food service facilities (Gwak et al., 2024; Son et al., 2024).

Energy Recovery Ventilation (ERV) systems have been widely recognized as a ventilation approach that can improve indoor air quality while reducing heating and cooling energy losses. By exchanging indoor and outdoor air while recovering sensible and latent heat, ERV systems can provide outdoor air ventilation more efficiently than simple exhaust-only strategies (Mardiana-Idayu & Riffat, 2012). Recent field and simulation studies have also examined the applicability of ERV systems for improving IAQ in sensitive public facilities, including daycare centers, where CO_2 and $PM_{2.5}$ managemenst are important due to prolonged indoor exposure and occupant vulnerability (Kim & Kang, 2025). However, ERV performance in actual facilities can be affected by airflow capacity, filtration efficiency, installation configuration, outdoor air quality, operating time, maintenance condition, and user behavior.

Despite the growing adoption of ERV systems, field-based evidence regarding their real-world effectiveness under actual operating conditions remains limited. Many previous ventilation studies have focused primarily on engineering performance indicators such as airflow rate, heat recovery efficiency, energy consumption, pressure loss, noise level, or simulation-based airflow distribution. Although these indicators are essential for equipment evaluation, they do not directly demonstrate the magnitude or consistency of indoor pollutant reduction experienced in actual school food service spaces. Therefore, field performance evaluation using observed pollutant reduction data is necessary to understand how ERV-related ventilation improvement may contribute to practical IAQ management.

In Korea, recent school kitchen and cafeteria studies have provided important empirical evidence on the effects of ventilation improvement and customized renovation. For example, Son et al. (2024) evaluated ventilation effectiveness before and after school kitchen renovation and reported improvements in hood face velocity, fan flow rate, particulate reduction, and worker breathing-zone protection. Gwak et al. (2024) also evaluated IAQ improvement in school cafeterias and cooking rooms after customized renovation and provided pollutant reduction data that can be further interpreted through secondary exploratory analysis. These studies suggest that school food service facilities require not only equipment-based performance assessment but also field-based evaluation of pollutant reduction patterns across spaces and pollutant types.

Therefore, the purpose of this study is to conduct a field-based performance evaluation and secondary exploratory analysis of ERV-related ventilation improvement in public school food service facilities. Specifically, this study aims to: (1) evaluate changes in indoor pollutant reduction rates before and after ERV-related ventilation improvement; (2) summarize pollutant-specific reduction patterns using descriptive statistics and reduction-rate variability analysis; and (3) review certified ERV performance characteristics together with observed field-based pollutant reduction outcomes in a contextual and hypothesis-generating manner. The findings are expected to provide preliminary field-based evidence to support future multi-site validation studies, technology optimization, and commercialization-oriented deployment of ERV systems for indoor air quality management in public facilities.

2. Literature Review

2.1. Indoor Air Quality in Public Facilities

Indoor air quality (IAQ) has become an increasingly important environmental and public health issue worldwide. People spend a large proportion of their daily time indoors, making indoor environments a major determinant of pollutant exposure and health risk (Klepeis et al., 2001). Public facilities, including schools, childcare centers, welfare facilities, hospitals, and government buildings, accommodate large numbers of occupants and therefore require systematic IAQ management.
Inadequate ventilation can result in the accumulation of particulate matter, carbon dioxide, volatile organic compounds, biological contaminants, and other indoor pollutants. Previous studies have reported that ventilation rate and indoor CO_2 concentration are associated with health symptoms, perceived air quality, and other occupant

responses in commercial and institutional buildings (Seppänen et al., 1999; Sundell et al., 2011). In school environments, poor indoor environmental quality has also been linked to student health, attendance, and learning-related outcomes (Mendell & Heath, 2005).
CO_2 is often used as an indirect indicator of ventilation adequacy and occupant-generated pollutant accumulation. Controlled exposure studies have suggested that elevated CO_2 concentration and VOC exposure may be associated with reduced cognitive performance and decision-making outcomes (Allen et al., 2016; Satish et al., 2012). Therefore, effective ventilation and source-control strategies are essential for maintaining healthy indoor environments in public facilities. In particular, facilities that generate pollutants through routine indoor activities require not only compliance with ventilation standards but also field-based evaluation of actual pollutant reduction performance.

2.2. Cooking-Related Air Pollutants in School Food Service Facilities

School food service facilities and commercial kitchens represent unique indoor environments where substantial quantities of pollutants can be generated during food preparation, cooking, dishwashing, and cleaning activities. Cooking processes such as frying, grilling, stir-frying, boiling, and heating can emit particulate matter, ultrafine particles, nitrogen oxides, carbon monoxide, volatile organic compounds, aldehydes, and other organic compounds (Abdullahi et al., 2013; Buonanno et al., 2009).

Cooking-generated particles are important because their emission characteristics vary depending on cooking method, cooking temperature, food type, oil use, fuel source, and ventilation condition (Abdullahi et al., 2013; Buonanno et al., 2009). Exposure to cooking-related aerosols has been associated with respiratory concerns and potential health risks, particularly in environments where pollutant generation is frequent and ventilation is insufficient (See & Balasubramanian, 2006). $PM_{2.5}$ and ultrafine particles are especially important because they can penetrate deeply into the respiratory system and remain suspended in indoor air during and after cooking activities.

In school food service facilities, pollutant levels can vary substantially depending on menu type, cooking duration, exhaust efficiency, air supply configuration, occupancy, dishwashing, cleaning activities, and door opening frequency. Recent Korean field studies have emphasized the importance of evaluating school cafeterias and cooking rooms under actual operating conditions. Gwak et al. (2024) evaluated IAQ in school cafeterias and cooking rooms after customized renovation, while Son et al. (2024) examined ventilation effectiveness before and after school kitchen renovation in Gyeongsangnam-do. These studies indicate that school food service facilities require field-based assessment of pollutant reduction, not only equipment-level performance evaluation.

2.3. Energy Recovery Ventilation Systems and IAQ Improvement

Energy Recovery Ventilation (ERV) systems have been increasingly adopted as ventilation solutions that can improve indoor air quality while reducing heating and cooling energy loss. ERV systems exchange indoor and outdoor air while recovering thermal energy from exhaust air streams, thereby reducing ventilation-related energy penalties. Heat and energy recovery technologies for building applications have been widely reviewed as important components of energy-efficient ventilation systems (Mardiana-Idayu & Riffat, 2012).

Previous studies have examined ERV applicability, control strategy, and energy performance under different climatic conditions. Rasouli et al. (2010) reported that the applicability and optimum control of ERV systems depend on climatic conditions and operational strategies. More recent studies have also examined ERV performance in public or semi-public facilities. For example, Kim and Kang (2025) evaluated ERV application in daycare centers in South Korea and showed that ERV operation, particularly when combined with appropriate filtration, can influence CO_2 and $PM_{2.5}$ control.

ERV systems can be combined with air supply and exhaust improvements, filtration, duct configuration, and control strategies to enhance pollutant removal in public facilities. However, certified product performance indicators such as airflow capacity, heat recovery efficiency, power consumption, and noise level do not automatically represent pollutant reduction under actual field conditions. Installation configuration, actual operating airflow, filter condition, maintenance status, outdoor air quality, and user behavior can all influence real-world IAQ outcomes. Accordingly, field measurement data are necessary to evaluate whether ERV-related ventilation improvement produces meaningful pollutant reduction in actual public food service facilities.

2.4. Field Performance Evaluation and Exploratory Statistical Interpretation

Ventilation studies have traditionally focused on engineering indicators such as airflow rate, pressure drop, heat recovery efficiency, energy consumption, and noise level. These indicators are essential for evaluating equipment performance, but they do not directly indicate the magnitude or consistency of indoor air quality improvement experienced in actual facilities. Therefore, field performance evaluation provides practical evidence by comparing pollutant levels before and after ventilation improvement.

Reduction-rate analysis is commonly used to summarize the direction and magnitude of improvement in field studies. However, reduction rates alone may not fully reflect variability across facilities, spaces, pollutants, and operating conditions. For this reason, descriptive statistical interpretation can strengthen field performance evaluation by organizing pollutant-specific trends, comparing variability, and summarizing mean reduction rates, standard deviations, and ranges across available observations.

At the same time, exploratory analyses must be interpreted cautiously when raw repeated-measurement datasets, matched ERV operation records, or large facility samples are not available. In such cases, results should be framed as preliminary evidence for hypothesis generation rather than confirmatory proof of causal relationships. This caution is particularly important when certified product performance data and field pollutant reduction outcomes are reviewed together but are not fully matched at the site-operation level.

2.5. Research Gap

Despite increasing interest in ERV systems and IAQ management, several limitations remain in the existing literature.

First, many studies have emphasized equipment performance, energy efficiency, ventilation control strategy, or airflow simulation rather than field-based pollutant reduction outcomes under actual operating conditions (Mardiana-Idayu & Riffat, 2012; Rasouli et al., 2010). Second, cooking-related pollutant studies have clearly shown that cooking can generate substantial particulate and gaseous pollutants, but these studies have often focused on emission characterization rather than evaluating ERV-related field reduction in public school food service facilities (Abdullahi et al., 2013; Buonanno et al., 2009; See & Balasubramanian, 2006). Third, recent Korean studies have provided valuable field evidence on school kitchen and cafeteria ventilation improvement, but further secondary analysis is needed to synthesize pollutant-specific reduction patterns and variability across spaces (Gwak et al., 2024; Son et al., 2024).

Finally, relatively few studies have integrated previously reported field measurement data, certified ERV performance information, and reduction-rate variability analysis while clearly acknowledging the limitations of secondary data. To address these limitations, the present study conducts a field-based performance evaluation and secondary exploratory analysis of ERV-related ventilation improvement in public school food service facilities. The study summarizes pollutant reduction rates, examines reduction-rate variability, and reviews certified ERV performance characteristics as technical background information. Rather than presenting confirmatory inferential evidence, this study provides preliminary field-based evidence to support future multi-site validation, technology optimization, and commercialization-oriented deployment of ERV systems.

3. Research Methods

3.1. Research Design

This study employed a field-based performance evaluation and secondary exploratory analysis design to assess the indoor air quality improvement effects of Energy Recovery Ventilation (ERV)-related ventilation improvement in public school food service facilities. This is not a confirmatory effectiveness trial. The design was not a randomized controlled experiment but a secondary analysis of previously reported field measurement data. Such nonrandomized pre–post field evaluation designs are commonly used when interventions are implemented in real-world facilities and random assignment is not feasible (Harris et al., 2006).

Previously reported field measurement data from public school cafeterias and cooking rooms were used as the primary dataset. Certified technical performance data of ERV products were additionally reviewed to summarize ventilation performance characteristics. This study did not conduct a new field experiment. Instead, it reanalyzed previously reported field performance results to describe pollutant reduction patterns and evaluate the practical magnitude and consistency of indoor air quality improvement.

The methodological structure of this study was guided by principles of transparent reporting for observational studies, including clear description of data source, study setting, variables, analytical approach, and limitations (Vandenbroucke et al., 2007). Because the available data were derived from field observations rather than controlled laboratory experiments, the analysis was framed as descriptive and exploratory rather than confirmatory.

The research procedure consisted of the following stages:
1) Extraction of previously reported field measurement data before and after ERV-related ventilation improvement.
2) Calculation of pollutant reduction rates.
3) Summary of certified ERV performance characteristics.
4) Descriptive and exploratory comparison of pollutant reduction patterns.
5) Variability analysis of pollutant reduction rates across available space-level observations.
6) Contextual review of ERV performance characteristics and indoor air quality improvement outcomes.

3.2. Study Sites

Three public school food service facilities were included in the analysis. The investigated spaces consisted mainly of cooking rooms, cafeterias, and washing rooms where cooking-related pollutants, water vapor, and cleaning-related emissions may be generated during daily operation. These spaces were selected because school facilities are high-occupancy public environments where indoor air quality can vary depending on activity type, ventilation condition, occupancy, and building operation.

Field-based IAQ studies in school environments have commonly measured pollutants such as CO_2, PM_{10}, $PM_{2.5}$, temperature, humidity, and ventilation-related indicators under actual operating conditions to characterize exposure and ventilation adequacy (Dorizas et al., 2015; Fromme et al., 2007). Previous classroom-based studies have also shown that CO_2 concentration and ventilation-related parameters can be used as practical indicators for evaluating indoor environmental conditions in schools (Bakó-Biró et al., 2012; Wargocki et al., 2020). Although the present study focused on food service spaces rather than general classrooms, these prior field studies support the methodological relevance of evaluating IAQ under real school operating conditions.

Among the three facilities, Schools B and C had available before-and-after pollutant reduction data after ventilation improvement. School A was used primarily to describe site characteristics and ventilation improvement measures because post-renovation measurement data were limited. These facilities were considered suitable for secondary exploratory analysis because they represent typical public food service environments in which indoor pollutants may be generated through cooking, meal distribution, dishwashing, cleaning, and occupant activities.

3.3. Indoor Air Quality Indicators

The following indoor air pollutants were analyzed in this study: PM_{10}, $PM_{2.5}$, CO_2, NO_2, CO, TVOCs, and HCHO. These pollutants were selected because they are commonly used indicators for evaluating indoor air quality in public facilities and school environments. Particulate matter, especially PM_{10} and $PM_{2.5}$, is widely used to assess airborne particle exposure in indoor environments, while CO_2 is commonly used as an indirect indicator of ventilation adequacy and occupant-related indoor air accumulation (Clements-Croome et al., 2008; Dorizas et al., 2015; Fromme et al., 2007).

Gaseous pollutants, including NO_2 and CO, were included because they may be generated during combustion-related cooking processes and can reflect the effectiveness of ventilation and exhaust control in food service environments. TVOCs and HCHO were also included because volatile organic compounds and formaldehyde are important indoor chemical pollutants that may originate from cooking materials, cleaning agents, indoor finishing materials, storage conditions, and other indoor sources (Jones, 1999; Salthammer et al., 2010).

Pollutant reduction rates were calculated using the following equation:
Reduction Rate (%) = [(C_before − C_after) / C_before] × 100 where C_before represents the pollutant concentration before ventilation improvement and C_after represents the pollutant concentration after ventilation improvement. Positive values indicate pollutant reduction after ventilation improvement, whereas negative values indicate increased pollutant concentrations or inconsistent responses after improvement. Because the present study used previously reported field measurement data rather than newly collected time-series data, the reduction-rate approach was used as a descriptive indicator of the direction and magnitude of IAQ change.

3.4. ERV Performance Indicators

Certified ERV performance data were reviewed to characterize the ventilation systems considered in this study. The following indicators were summarized: airflow capacity, power consumption, sensible heat recovery efficiency, total heat recovery efficiency, and noise level. These indicators are commonly used to evaluate the technical performance of heat recovery and energy recovery ventilation systems because they reflect ventilation delivery capacity, energy demand, thermal recovery performance, and operational acceptability (Kim & Kang, 2025; Rasouli et al., 2010).

Airflow capacity was reviewed as a basic ventilation performance indicator, while heat recovery efficiency was reviewed to characterize the energy-saving function of ERV systems. Power consumption and noise level were also summarized because energy use and acoustic performance can affect the practical feasibility of ERV operation in public facilities. Previous ERV studies have shown that system performance can vary depending on climatic conditions, filtration configuration, control strategy, and operating conditions; therefore, certified product specifications should not be interpreted as direct evidence of pollutant reduction under actual field operation (Kim & Kang, 2025; Rasouli et al., 2010).

These indicators were used only to describe the technical performance characteristics of ERV products. Because matched field operation data, actual operating airflow, installation configuration, filter condition, operating time, and sufficient site-level ERV performance observations were not available, these indicators were not used for formal regression-based causal inference.

3.5. Statistical Analysis

Descriptive and exploratory statistical analyses were conducted. The main analyses included:
1) Descriptive comparison of pollutant reduction rates.
2) Summary of pollutant-specific reduction patterns across facilities and spaces.
3) Calculation of mean reduction rates, standard deviations, and ranges across investigated spaces.
4) Visualization of pollutant reduction patterns using grouped bar charts and mean reduction plots.
5) Variability analysis of pollutant reduction rates across available space-level observations.

Because this study was based on previously reported field measurement data, the analysis was framed as a secondary exploratory analysis rather than a confirmatory intervention trial. This approach is consistent with the use of observational or quasi-experimental field data when random assignment, repeated raw measurements, or fully controlled experimental conditions are not available (Harris et al., 2006; Vandenbroucke et al., 2007).

Because raw repeated-measurement datasets and sufficient matched before-and-after summary statistics were not available, standardized effect sizes such as Cohen's d or Hedges' g were not calculated in the final analysis. Instead, this study summarized pollutant reduction patterns using descriptive statistics, including mean reduction rates, standard deviations, and ranges across the available space-level observations. The emphasis on descriptive statistics and transparent reporting is appropriate for exploratory field-based analysis when the available dataset does not support inferential testing or causal modeling (Vandenbroucke et al., 2007; Wargocki et al., 2020).

This study did not perform formal paired t-tests, repeated-measures ANOVA, ANCOVA, mixed-effects modeling, confirmatory regression analysis, or formal correlation analysis. Therefore, the results should be interpreted as descriptive and exploratory secondary analyses rather than confirmatory inferential statistical evidence. Any observed relationship between ERV performance characteristics and pollutant reduction outcomes was interpreted only as a preliminary observation for hypothesis generation, not as evidence of a causal relationship.

4. Research Results

4.1. Characteristics of Study Sites and ERV Systems

Table 1 summarizes the characteristics of the investigated public school food service facilities and the ventilation improvement measures applied to each site.

Table 1: Characteristics of Study Sites and ERV-Related Ventilation Improvement Measures

Facility / Space	Main Issue	Improvement / Pollutants
School A / Cafeteria	Insufficient outdoor air intake and exhaust duct connection	Outdoor air inflow and exhaust duct construction for ERV Pollutants: PM_{10}, $PM_{2.5}$, NO_2, CO_2, CO
School A / Cooking room	Air-conditioner suction problem	Installation of inlet and filter box Pollutants: PM_{10}, $PM_{2.5}$, NO_2, CO_2, CO
School B / Cafeteria	Absence of ERV in cafeteria	Installation of ERV units Pollutants: PM_{10}, $PM_{2.5}$, NO_2, CO_2, CO, TVOC, HCHO
School B / Cooking room	Need for air supply and exhaust inspection	Inspection and adjustment of air supply and exhaust system Pollutants: PM_{10}, $PM_{2.5}$, NO_2, CO_2, CO, TVOC, HCHO
School C / Washing room	Mismatch between steam source and exhaust outlet	Replacement and enlargement of exhaust hood Pollutants: PM_{10}, $PM_{2.5}$, NO_2, CO_2, CO, TVOC, HCHO
School C / Cooking room	Risk of re-entry of exhaust air	Replacement of air supply filter, exhaust system maintenance, and up-firing installation Pollutants: PM_{10}, $PM_{2.5}$, NO_2, CO_2, CO, TVOC, HCHO

Note. Reanalyzed from previously reported field measurement data in Gwak et al. (2024). The present study used the data for secondary exploratory analysis.

The study sites consisted of school cafeterias, cooking rooms, and washing rooms where cooking-related airborne pollutants may be generated during daily food preparation, meal distribution, dishwashing, and cleaning activities. Previous studies have shown that cooking and kitchen operations can generate particulate matter, ultrafine particles, combustion-related gases, and volatile organic compounds, depending on cooking method, temperature, food type, oil use, and ventilation conditions (Abdullahi et al., 2013; Buonanno et al., 2009; See & Balasubramanian, 2006).

Recent Korean field studies have also emphasized the importance of ventilation improvement in school food service facilities. Gwak et al. (2024) evaluated indoor air quality in school cafeterias and cooking rooms after customized renovation, while Son et al. (2024) assessed ventilation effectiveness before and after school kitchen renovation in Gyeongsangnam-do. These studies support the relevance of evaluating school food service facilities as high-emission indoor environments requiring field-based ventilation assessment.

In School A, the ventilation improvement focused on the cafeteria ERV system and cooking room air-conditioning system. In School B, ERV units were newly installed in the cafeteria, and the air supply and exhaust systems in the cooking room were inspected. In School C, the ventilation improvement focused on the washing room exhaust hood, cooking room air supply filter, exhaust system, and up-firing exhaust configuration. These site-specific improvement measures are consistent with prior findings that kitchen ventilation performance can be affected by exhaust configuration, air supply balance, hood performance, and pollutant source characteristics (Son et al., 2024).

4.2. Changes in Indoor Air Pollutant Concentrations

Table 2 presents the pollutant reduction rates after ERV-related ventilation improvement in Schools B and C. Because School A did not have available post-renovation measurement data for reduction-rate calculation, the quantitative reduction-rate analysis was conducted mainly for Schools B and C. The analyzed pollutants included PM_{10}, $PM_{2.5}$, NO_2, CO_2, CO, TVOC, and HCHO, which are commonly used indicators for evaluating indoor air quality in cooking-related environments.

Table 2: Pollutant Reduction Rates after ERV-Related Ventilation Improvement

Facility / Space	Particulate Reductions	Gaseous and Chemical Reductions
School B / Cooking room	PM_{10} (%) 60.60; $PM_{2.5}$ (%) 61.90	NO_2 (%) 36.45; CO_2 (%) 7.77; CO (%) 14.29; TVOC (%) -22.01; HCHO (%) 14.04
School B / Cafeteria	PM_{10} (%) 55.21; $PM_{2.5}$ (%) 55.45	NO_2 (%) 44.34; CO_2 (%) -2.08; CO (%) 33.33; TVOC (%) 37.21; HCHO (%) 34.92
School C / Cooking room	PM_{10} (%) 59.15; $PM_{2.5}$ (%) 57.66	NO_2 (%) 60.47; CO_2 (%) 21.15; CO (%) 33.33; TVOC (%) -202.02; HCHO (%) 0.00
School C / Cafeteria	PM_{10} (%) 59.13; $PM_{2.5}$ (%) 55.74	NO_2 (%) 65.83; CO_2 (%) 11.13; CO (%) 50.00; TVOC (%) -72.43; HCHO (%) 0.00

Note. Positive values indicate concentration reduction after ventilation improvement, whereas negative values indicate increased concentrations after improvement. Values were reanalyzed from previously reported field measurement data in Gwak et al. (2024).

Overall, particulate pollutants showed substantial decreases after ventilation improvement. In School B, PM_{10} and $PM_{2.5}$ reduction rates were 60.60% and 61.90% in the cooking room, respectively. In School C, PM_{10} and $PM_{2.5}$ reduction rates were 59.15% and 57.66% in the cooking room, respectively. These results are consistent with previous cooking-emission studies showing that cooking activities can generate substantial particulate matter and that ventilation conditions strongly influence indoor particle concentrations (Abdullahi et al., 2013; Buonanno et al., 2009). Buonanno et al. (2009), for example, reported that particle emission factors vary by cooking temperature, food type, and oil use, supporting the interpretation that cooking spaces require effective ventilation control.

Gaseous pollutants such as NO_2, CO_2, and CO also decreased in most spaces, although the magnitude of reduction varied by facility and space. NO_2 and CO may be associated with combustion-related or cooking-related processes, whereas CO_2 can be influenced by occupancy, air exchange, and door-opening conditions. In contrast, TVOC showed inconsistent patterns, including negative reduction rates in several cases. This finding suggests that TVOC concentrations may have been influenced by cooking ingredients, cleaning agents, detergents, indoor materials, storage conditions, or temporal environmental variation rather than ventilation performance alone. Prior studies have similarly indicated that cooking aerosols and related indoor pollutants can vary substantially depending on source conditions and cooking practices (See & Balasubramanian, 2006; Zhao & Zhao, 2018).

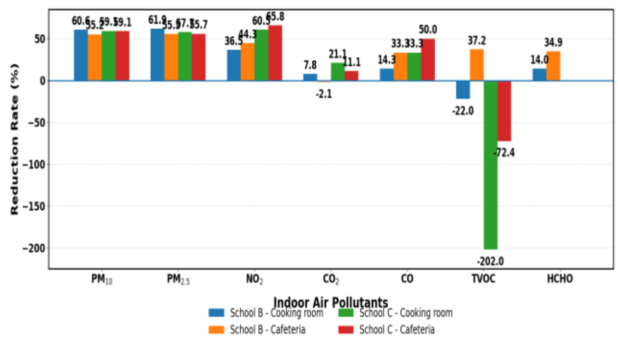

Figure 1: Space-Level Pollutant Reduction Rates after ERV-Related Ventilation Improvement in School Food Service Facilities

Note. Positive values indicate pollutant reduction after ventilation improvement, whereas negative values indicate increased concentrations or inconsistent responses. PM_{10}, $PM_{2.5}$, NO_2, and CO generally showed reduction, whereas TVOC exhibited inconsistent responses across spaces.

4.3. Pollutant Reduction Effectiveness

PM_{10} and $PM_{2.5}$ showed the most consistent reduction patterns across the available facility spaces. PM_{10} reduction rates exceeded 50% in all analyzed spaces, while $PM_{2.5}$ showed similar reduction patterns. These findings suggest that ERV-related ventilation improvement may be particularly effective in reducing cooking-generated airborne particulate matter. Previous studies have shown that cooking-related particles can be effectively reduced when exhaust airflow, capture efficiency, and source-control conditions are properly maintained (Delp & Singer, 2012; Lunden et al., 2015; Rim et al., 2012). However, the observed particulate reduction should not be interpreted as the effect of ERV equipment alone. Particle removal in cooking environments can be influenced by exhaust flow rate, hood geometry, burner or cooking-source position, particle size, filter performance, and air supply–exhaust balance. Prior studies on kitchen exhaust systems have reported that capture efficiency varies substantially depending on airflow rate and source location, which supports the need to interpret the present field results as combined outcomes of ventilation improvement, exhaust configuration, and operational conditions rather than as an isolated equipment effect (Lunden et al., 2015; Rim et al., 2012).

NO_2 and CO also showed positive reduction trends in most spaces, although their reduction levels varied by facility and space. These pollutants may be affected by combustion-related processes, cooking activities, air exchange, and local exhaust performance. Previous field studies on gas cooking have shown that kitchen exhaust ventilation can substantially influence indoor combustion pollutant concentrations, including NO_2 and CO, but the degree of reduction depends on exhaust use, airflow, and cooking conditions (Singer et al., 2017).

CO_2 showed smaller and more variable changes than particulate pollutants. Therefore, CO_2 reduction should be interpreted cautiously because CO_2 concentration is affected not only by ventilation rate but also by occupancy density, meal distribution time, door opening, and outdoor air exchange conditions. In contrast, TVOC showed inconsistent responses, including negative reduction rates in several cases. This suggests that TVOC concentrations may have been influenced by source-related factors such as cooking materials, cleaning agents, detergents, storage conditions, and indoor finishing materials, in addition to ventilation performance.

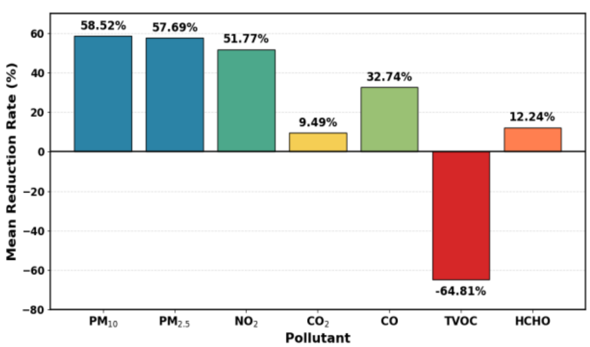

Figure 2: Mean Pollutant Reduction Rates after ERV-Related Ventilation Improvement

Note. Bars represent mean reduction rates calculated from the four available space-level observations, and error bars indicate standard deviations. Positive values indicate pollutant reduction, whereas negative values indicate increased or unstable responses.

4.4. Contextual Review of ERV Performance Characteristics and Field Reduction Outcomes

Table 3 presents a contextual summary of certified ERV product performance characteristics and field-based pollutant reduction outcomes. The certified ERV data include technical specifications such as airflow capacity, power consumption, heat recovery efficiency, and noise level. In contrast, the field data summarize pollutant reduction rates observed in school food service facilities after ERV-related ventilation improvement. Because these two datasets were not fully matched at the site-operation level, they were reviewed together only to provide technical background for interpreting the observed IAQ improvement.

Table 3: Certified ERV Performance Characteristics and Field-Based Pollutant Reduction Outcomes

ERV / Facility	Performance Context	Field Outcome / Interpretation
School B	Airflow: — Power: — Heat recovery: — Noise: —	PM_{10} 60.60%, $PM_{2.5}$ 61.90% in cooking room
School C	Airflow: — Power: — Heat recovery: — Noise: —	PM_{10} 59.15%, $PM_{2.5}$ 57.66% in cooking room
ES-100	Airflow: 100 Power: 38.3 Heat recovery: 72.9 heating / 64.5 cooling Noise: 30.1	Certified ERV performance data
ES-200	Airflow: 200 Power: 71.8 Heat recovery: 72.3 heating / 65.6 cooling Noise: 34.8	Certified ERV performance data

Note. The school-level rows summarize field-based pollutant reduction outcomes, whereas the ES-series rows summarize certified ERV product performance data. Because the certified product data and field reduction outcomes were not fully matched at the site-operation level, this table is intended for contextual interpretation only.

The certified product data and the field reduction outcomes were reviewed together to provide technical context for interpreting the observed IAQ improvement. However, the two types of data were not fully matched at the site-operation level. Specifically, matched facility-level ERV operation records, actual operating airflow, installation configuration, filter condition, operating time, and raw repeated-measurement datasets were not available.
Previous studies have shown that ventilation and filtration performance cannot be evaluated only by nominal airflow or product specifications. For example, particle removal performance can vary depending on filter efficiency, particle size, system configuration, and actual operating conditions (Fazli et al., 2019; Stephens & Siegel, 2012). Similarly, ERV control strategies may influence both indoor $PM_{2.5}$ exposure and energy performance, indicating that field operation data are essential for interpreting actual IAQ outcomes (Zhong et al., 2020).

Therefore, this study did not conduct formal correlation analysis, regression analysis, or causal modeling between ERV performance indicators and pollutant reduction rates. Table 3 should be interpreted as a contextual comparison between certified product performance characteristics and observed field-based reduction outcomes, rather than statistical evidence that specific ERV performance indicators directly determined pollutant reduction.

The comparison suggests that certified ERV performance indicators may provide useful background information for interpreting field-based IAQ improvement. However, the present data do not allow direct evaluation of how airflow capacity, heat recovery efficiency, power consumption, or noise level affected pollutant reduction in each facility. Future studies should collect matched facility-level ERV operation records, actual airflow measurements, installation conditions, filter status, operating time, and repeated IAQ monitoring data. Such data would allow formal correlation analysis, regression modeling, or mixed-effects modeling to evaluate how ventilation performance characteristics are associated with pollutant reduction under real operating conditions.

4.5. Variability Analysis of Pollutant Reduction Patterns

To further evaluate the consistency of pollutant reduction after ERV-related ventilation improvement, reduction-rate variability was examined across the investigated spaces. Because raw repeated-measurement datasets were not available and the number of before-and-after observations was limited, standardized effect sizes such as Cohen's d or Hedges' g were not calculated in the final analysis. Instead, this study summarized mean reduction rates, standard deviations, and ranges of reduction rates for each pollutant.

This descriptive approach was adopted because the available dataset was not sufficient for formal inferential testing or causal modeling. In exploratory field studies with limited observations, descriptive variability indicators can help characterize the magnitude and consistency of observed changes without overstating statistical certainty. The absence of inferential statistical testing should not be interpreted as evidence that no effect exists; rather, it reflects the limitations of the available dataset and the need for cautious interpretation (Altman & Bland, 1995; Greenland et al., 2016; Wasserstein & Lazar, 2016).
Table 4 presents the variability of pollutant reduction patterns across the investigated spaces. PM_{10} and $PM_{2.5}$ showed consistently high mean reduction rates with relatively small variability. This indicates that ERV-related ventilation improvement was most consistently associated with reductions in particulate pollutants generated during cooking activities. Previous studies have shown that cooking activities can produce substantial fine and ultrafine particles, and that indoor particle concentrations can vary depending on source strength, activity type, ventilation, and particle dynamics (He et al., 2004; Wallace et al., 2004).

Table 4: Variability Analysis of Pollutant Reduction Rates after ERV-Related Ventilation Improvement

Pollutant	Reduction Statistics	Interpretation
PM_{10}	Mean: 58.52 SD: 2.27 Range: 55.21 to 60.60	Consistent high reduction
$PM_{2.5}$	Mean: 57.69 SD: 2.91 Range: 55.45 to 61.90	Consistent high reduction
NO_2	Mean: 51.77 SD: 13.87 Range: 36.45 to 65.83	Moderate to high reduction
CO_2	Mean: 9.49 SD: 9.61 Range: -2.08 to 21.15	Small to moderate and variable reduction
CO	Mean: 32.74 SD: 14.58 Range: 14.29 to 50.00	Moderate but variable reduction
TVOC	Mean: -64.81 SD: 99.25 Range: -202.02 to 37.21	Unstable or increased response
HCHO	Mean: 12.24 SD: 16.20 Range: 0.00 to 34.92	Limited and variable reduction

Note. Values were calculated from the four available space-level reduction rates shown in Table 2. Positive values indicate pollutant reduction after ventilation improvement, whereas negative values indicate increased concentrations or inconsistent responses. Standardized effect sizes were not calculated because raw repeated-measurement datasets were unavailable.

NO_2 and CO also showed positive mean reduction rates, although their variability was greater than that of particulate matter. CO_2 showed a smaller mean reduction rate and wider variability, suggesting that CO_2 levels may be more strongly affected by occupancy density, door opening, meal distribution, and outdoor air exchange conditions. These results indicate that gaseous pollutants and occupancy-related indicators may be more sensitive to short-term operational conditions than particulate reduction rates alone.

In contrast, TVOC showed a negative mean reduction rate and large variability. This finding indicates that TVOC responses were unstable and may have been influenced by site-specific emission sources, including cooking ingredients, cleaning agents, detergents, storage materials, indoor finishing materials, and secondary chemical reactions. Previous studies have shown that cleaning products and air fresheners can emit glycol ethers, terpenes, and other reactive compounds, and that indoor ozone reactions with these compounds may generate secondary pollutants, including fine particles and oxygenated VOCs (Nazaroff & Weschler, 2004; Singer et al., 2006a; Singer et al., 2006b). Therefore, TVOC reduction should not be interpreted as a direct outcome of ventilation improvement alone.

4.6. Summary and Discussion

The findings of this study indicate that ERV-related ventilation improvement was associated with improved indoor air quality outcomes in public school food service facilities. The most consistent improvements were observed for particulate pollutants. PM_{10} and $PM_{2.5}$ showed reductions exceeding 55% across the four matched space-level observations from Schools B and C, suggesting that ERV-related ventilation improvement may be particularly effective in reducing cooking-generated airborne particles.

This result is important because particulate matter generated during cooking activities is one of the most direct and persistent indoor air quality concerns in school food service facilities. Previous field studies have shown that cooking can be a strong indoor particle source, with source strength and particle number concentration varying by cooking method, fuel type, ventilation condition, and occupant activity (He et al., 2004; Wallace et al., 2004). The relatively consistent reduction patterns of PM_{10} and $PM_{2.5}$ observed in the present study imply that improved air supply, exhaust configuration, and ERV-related airflow management can contribute to the removal and dilution of particle-phase contaminants under actual operating conditions.

Gaseous pollutants also showed generally positive reduction trends, but their responses were less uniform than those of particulate pollutants. NO_2 and CO showed moderate to high reductions in several spaces, suggesting that ventilation improvement may also contribute to the reduction of combustion-related pollutants. CO_2 showed smaller and more variable changes, which may reflect the influence of occupancy density, meal distribution time, door opening frequency, and outdoor air exchange conditions.

In contrast, TVOC showed inconsistent and, in some cases, negative reduction rates. This finding should not be interpreted simply as failure of ventilation improvement. Indoor VOC concentrations may be affected by multiple non-ventilation factors, including cleaning agents, air fresheners, indoor materials, storage conditions, ozone reactions, and human activities. Prior studies have shown that cleaning products and air fresheners can act as important indoor VOC sources and may also contribute to secondary pollutant formation under certain indoor chemical conditions (Nazaroff & Weschler, 2004; Singer et al., 2006a; Singer et al., 2006b; Weschler, 2009). Therefore, TVOC should be treated as a complex indicator requiring additional source control strategies in addition to ventilation improvement.

The contextual review of certified ERV performance characteristics provided technical background for interpreting the field-based reduction outcomes. However, because the certified product data and field reduction outcomes were not fully matched at the site-operation level, the present study could not determine how specific ERV performance indicators, such as airflow capacity, heat recovery efficiency, or power consumption, affected pollutant reduction in each facility.

Overall, the results support the practical applicability of ERV-related ventilation improvement for indoor air quality management in public food service facilities. The findings suggest that ERV-related ventilation improvement may be especially useful for reducing particulate pollutants generated during cooking activities. However, for volatile organic compounds and other source-dependent pollutants, ventilation should be combined with source control, cleaning-material management, storage management, and operational protocols.

From a technology commercialization perspective, this study provides preliminary field-based evidence that can support the deployment of ERV-related ventilation systems in public facilities. Nevertheless, future studies should include larger numbers of facilities, raw time-series measurement data, matched ERV operation records, actual airflow measurements, installation conditions, filter status, and standardized measurement protocols. Such data would enable more rigorous correlation analysis, regression modeling, and performance evaluation of ERV systems under real operating conditions. The present findings should therefore be interpreted as exploratory and hypothesis-generating rather than as confirmatory statistical evidence.

5. Conclusion

This study evaluated the field performance of ERV-related ventilation improvement for indoor air quality management in public school food service facilities. Using previously reported field measurement data and certified ERV performance information, this study conducted a secondary exploratory analysis focusing on pollutant reduction rates, reduction-rate variability, and practical performance implications.

The results showed that particulate pollutants were reduced most consistently after ventilation improvement. PM_{10} and $PM_{2.5}$ showed reductions exceeding 55% across the four matched space-level observations from Schools B and C, indicating that ERV-related ventilation improvement may be effective for reducing cooking-generated airborne particles in school food service environments.

Gaseous pollutants, including NO_2, CO_2, and CO, also showed overall reduction trends, although the magnitude of improvement varied by facility and space. In contrast, TVOC showed inconsistent responses, suggesting that volatile organic compounds may be influenced by source-related and site-specific factors beyond ventilation performance alone. Certified ERV performance characteristics were reviewed as technical background information for interpreting the field-based reduction outcomes. However, due to the limited number of field observations and the absence of matched site-level operation data, this study could not formally evaluate the relationship between ERV performance indicators and pollutant reduction outcomes.

Overall, this study provides preliminary field-based evidence supporting the practical application of ERV-related ventilation improvement in public food service facilities. The findings suggest that ERV-related ventilation improvement may be particularly useful for reducing particulate pollutants generated during cooking activities. However, for volatile organic compounds and other source-dependent pollutants, ventilation improvement should be combined with source control, cleaning-material management, and operational protocols.

Future research should include larger facility samples, raw time-series monitoring data, matched ERV operation records, actual airflow measurements, installation conditions, filter status, and standardized measurement protocols. Such data would allow more rigorous inferential statistical testing, correlation analysis, regression modeling, and performance evaluation of ERV systems under real operating conditions.

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