

# Meeting IAQ requirements in a South Australian canteen environment

Reverse Cycle versus Indirect Evaporative Cooling — A real-world comparative study measuring indoor air quality across two systems in the same space.

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## STUDY SETTING

South Australian Canteen  
552 m<sup>3</sup> · Summer Season

## FUNDING

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# The Case for Indirect Evaporative Cooling

Poor indoor air quality is increasingly recognised as a hidden health risk, driving respiratory problems, exacerbating chronic disease, and accelerating the transmission of airborne infections. This study evaluated whether indirect evaporative cooling (IDEC) systems can improve indoor air quality (IAQ) and infection control risks compared with conventional reverse cycle (RC) systems.

Experiments were conducted in a South Australian canteen during the summer season — selected as a high-occupancy environment with consistent cooking and occupancy conditions across treatments. The Climate Wizard CW-X2 supplied 7,200 m<sup>3</sup>/h of 100% outdoor air, achieving an air change rate of 13.05/h and conditioning the full air volume within 4.6 minutes.

CO<sub>2</sub>, PM, and TVOC levels were all statistically significantly lower with IDEC compared with reverse cycle (p<0.01), while relative humidity remained within the optimal 40–60% range for infection control and thermal comfort. IDEC performance met key targets under ASHRAE Standard 241, the IAQ Blueprint, and the Lancet Commission's ventilation benchmarks.

## KEY FINDINGS AT A GLANCE

|                                                                                                                                              |                                                                                                                                                                  |                                                                                                                            |                                                                                                                                                |
|----------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------|
| <div>CO<sub>2</sub></div> <div>437</div> <div>ppm median (IDEC)<br/>vs 562 ppm (RC)</div> <div>↓ 23% reduction</div> <div>p &lt; 0.001</div> | <div>PM<sub>2.5</sub></div> <div>10.1</div> <div>µg/m<sup>3</sup> (IDEC)<br/>vs 52.1 µg/m<sup>3</sup> (RC)</div> <div>↓ 81% reduction</div> <div>p = 0.005</div> | <div>TVOC</div> <div>1.00</div> <div>ppm (IDEC)<br/>vs 1.83 ppm (RC)</div> <div>↓ 45% reduction</div> <div>p = 0.003</div> | <div>AIR CHANGES</div> <div>13</div> <div>ACH (IDEC)<br/>vs 2.3–2.5 ACH (RC)</div> <div>Full refresh: 4.6 min</div> <div>vs ~25 min (RC)</div> |
|----------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------|



### 1.1 STANDARDS & REGULATIONS

Clean indoor air has now been recognised as a fundamental human right, with the World Health Organization calling for ventilation to be treated as central to protecting public health (Allen, 2024). The COVID-19 pandemic further underscored the urgent need for buildings designed with infection control in mind, where ventilation and air cleaning act as primary barriers to airborne disease transmission (Chen & Li, 2024; Heydari & Abbasianjahromi, 2024). Yet, despite decades of IAQ research, most building codes still prioritise thermal comfort over infection risk reduction (Allen, 2024; ASHRAE, 2020; Zaniboni & Albatici, 2022).

In response, recent international efforts, including The Lancet COVID-19 Commission (The Lancet COVID-19 Commission Task Force on Safe Work, 2022), the Science IAQ blueprint (Morawska, 2024 #17195) and ASHRAE Standard 241 have shifted the focus to health-based and performance-driven ventilation standards (Azimi, 2022; Jones et al., 2025; Morawska et al., 2024). These documents collectively establish higher minimum ventilation requirements and performance standards to safeguard against airborne transmission in all built environments.

### 1.2 HEALTH EFFECTS OF INDOOR AIR CONTAMINANTS

Indoor air contaminants can present a significant human health risk. The partial pressure of carbon dioxide ( $p\text{CO}_2$ ) is the measure of  $\text{CO}_2$  within arterial or venous blood (Messina & Patrick, 2022). It serves as a physiological marker of sufficient alveolar ventilation within the lungs (Messina & Patrick, 2022). Carbon dioxide ( $\text{CO}_2$ ) concentration, typically reported in parts per million (ppm), reflects the amount of  $\text{CO}_2$  present in indoor air. In indoor environments, elevated  $\text{CO}_2$  concentrations can lead to corresponding increases in  $p\text{CO}_2$  in the blood through inhalation, linking environmental exposure to physiological response (Azuma et al., 2018). Exposure to ambient  $\text{CO}_2$  values which result in  $p\text{CO}_2$  levels  $>600\text{ppm}$  has been shown to lead to “sick-building syndrome,” a situation in which the occupants of a building experience acute health- or comfort-related effects that seem to be linked directly to the time spent in the building resulting in irritation, fatigue, anxiety, headaches, poor cognitive performance and sleep apnoea, linked to elevated  $p\text{CO}_2$  in blood (Du et al., 2020; Guyenet & Bayliss, 2015; Iwayama et al., 2025; Joshi, 2008; Seppänen et al., 1999; Tsai et al., 2012). However, the role of  $\text{CO}_2$  at these concentrations remains debated, with many studies indicating that  $\text{CO}_2$  primarily acts as an indicator of ventilation effectiveness and co-accumulated bioeffluents rather than a direct causal agent of adverse health effects (Mendell et al., 2021; Persily, 2015; Wargocki et al., 2020). Improvements in occupant outcomes have been observed with increased ventilation rates (e.g. 10–20L/s per person), often at  $\text{CO}_2$  concentrations below 800ppm, suggesting that ventilation-related factors rather than  $\text{CO}_2$  alone may drive these effects. Existing studies on the effect of elevated  $\text{CO}_2$  on human health focus on the effects of exposure to acute  $\text{CO}_2$  levels and/or cognitive responses to elevated indoor  $\text{CO}_2$  levels (Du et al., 2020; Karnauskas et al., 2020). The effects of human exposure to elevated  $\text{CO}_2$  levels have been mostly assessed in terms of physiological and cognitive levels (Jacobson et al., 2019). Higher  $\text{CO}_2$  concentrations ( $>1,200$ – $1,600\text{ppm}$ ) have been I., 1997; Tunnicliffe et al., 1994).

more consistently associated with direct physiological effects, although thresholds remain uncertain. However, subtle changes may operate through disruptions of human proteome functions under chronic exposure to elevated CO<sub>2</sub> levels (C. M. Duarte et al., 2020). This has been proposed as a hypothesis rather than confirmed evidence, suggesting a potential mechanistic pathway under prolonged exposure to elevated concentrations. The effects of human exposure to elevated CO<sub>2</sub> on the proteome can elicit broad systemic impacts, but is an area that requires further research (Carlos M. Duarte et al., 2020).

New evidence suggests that volatile organic compounds (VOCs) such as aromatic and aliphatic compounds in the indoor home environment are associated with an increased risk of asthma and asthma-like symptoms (including wheeze) in adults (Paterson et al., 2021). Particulate matter (PM), regardless of particle size, can have negative health impacts, including increasing risk of cardiovascular and respiratory morbidity. Indoor PM specifically has been associated with increased respiratory symptoms (Simoni, 2002). A study conducted in 421 houses in northern-central Italy showed a positive correlation between indoor PM<sub>2.5</sub> exposure and the presence of bronchitis and asthmatic symptoms, especially during the winter season (Simoni, 2002). A study conducted in Oslo, Norway, showed that indoor suspended PM contained a large amount of potential allergen carriers (soot particles <1µm) (Ormstad, 2000). The presence of organic pollutants together with these allergens or endotoxin may exert a proinflammatory effect, leading to the exacerbation of allergic diseases such as asthma (Leung et al., 2002; Ormstad, 2000). Mechanisms by which PM exerts its adverse respiratory effects by acting as a possible adjuvant have been reviewed previously (Bernstein et al., 2004; Diaz-Sanchez et al., 1997). Indoor PM may carry toxic pollutants and reaction products into the airway, generating oxidative stress (Ormstad, 2000). Many organic chemicals (e.g. polycyclic aromatic hydrocarbons and quinones) associated with ambient PM are redox active and have been shown to induce proinflammatory responses through the generation of oxidative stress (Leem et al., 2005; Li et al., 2003). Finally, reactive compounds, such as free radicals and organic compounds, generated from the interactions between indoor PM, O<sub>3</sub>, or NO<sub>2</sub> can also have proinflammatory effects (Diaz-Sanchez et al., 1997; Mølhave et al., 2005; Strand et al.

### **1.3 REVERSE CYCLE VS. INDIRECT EVAPORATIVE COOLING**

These systems fundamentally differ in their mode of air delivery. IDEC supplies 100% outdoor air without recirculation — aligning closely with health-focused standards including the Non-Infectious Air Delivery Rate (NADR) and the Equivalent Clean Airflow Rate (ECAi) introduced by ASHRAE 241. By contrast, reverse cycle systems remain heavily dependent on recirculated indoor air. IDEC systems, by design, deliver 100% outdoor air without recirculation, aligning closely with health-focused standards such as the Non-Infectious Air Delivery Rate (NADR) defined by the Lancet Commission and the Equivalent Clean Airflow Rate (ECAi) introduced by ASHRAE 241, where EC contributes through direct provision of outdoor air rather than relying on equivalent clean air from filtration or air cleaning technologies. By contrast, reverse cycle systems remain heavily dependent on recirculated air. This study explores how these two approaches to cooling differ in their capacity to deliver clean, safe, and sustainable indoor air.



Evaporative cooling achieves air cooling through the evaporation of water, typically by passing air through a wetted medium or water spray, where the evaporating water absorbs its latent heat of vaporisation from the air, resulting in a reduction in air temperature. This is an adiabatic saturation mechanism in which evaporating water absorbs its heat of evaporation from the flowing air, thus cooling it (Chijioke, 2017; Khalid, 2008; Watt & Brown, 1997). The effectiveness of this process is strongly dependent on ambient conditions, as dry and warm air, with lower absolute humidity, has a greater capacity to absorb water vapour, making evaporative cooling more effective in drier climatic regions (Chijioke, 2017; Khalid, 2008).

| REVERSE CYCLE (RC)                                                                                                                                                                                                                                                                                                   | CLIMATE WIZARD™ IDEC                                                                                                                                                                                                                                                                                                  |
|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <ul style="list-style-type: none"><li>— Recirculates indoor air — no fresh outdoor air supply</li><li>— 2.3–2.5 ACH (internal air movement only)</li><li>— Full conditioning: ~25 minutes</li><li>— CO<sub>2</sub> and pollutants accumulate over time</li><li>— Meets ASHRAE 62.1 — not IRMM requirements</li></ul> | <ul style="list-style-type: none"><li>— Supplies 100% fresh outdoor air continuously</li><li>— 13 ACH — true ventilation, not recirculation</li><li>— Full air refresh: 4.6 minutes</li><li>— Dilutes CO<sub>2</sub>, PM, and TVOC in real-time</li><li>— Meets ASHRAE 241, IAQ Blueprint &amp; Lancet NADR</li></ul> |

1.3.1 TYPES OF EVAPORATIVE COOLING SYSTEM

Evaporative cooling systems are classified into three types and are shown in Fig.1:

- 1.Direct evaporative cooling system (DEC)
- 2. Indirect evaporative cooling system (IDEC)
- 3. Multistage evaporative cooling system.

Direct evaporative cooling (DEC) systems operate by passing hot ambient air through a wetted medium. Figure1 shows the schematic of the DEC system. Heat from the air is absorbed by the water as it evaporates from the wetting medium, resulting in simultaneous cooling and humidification of the supply air. The minimum achievable temperature is the wet-bulb temperature of the incoming air (Abbouda & Almuhanna, 2012; Camargo et al., 2005; Chijioke, 2017; Watt & Brown, 1997). This heat absorption reduces the temperature and increases the humidity of the air due to evaporation of water (Chijioke, 2017). In DEC, the temperature of the air cannot be cooled below the wet-bulb temperature of the air (Chijioke, 2017; Kapilan et al., 2023). This type of cooling is suitable for dry and hot climates (Kapilan et al., 2023).

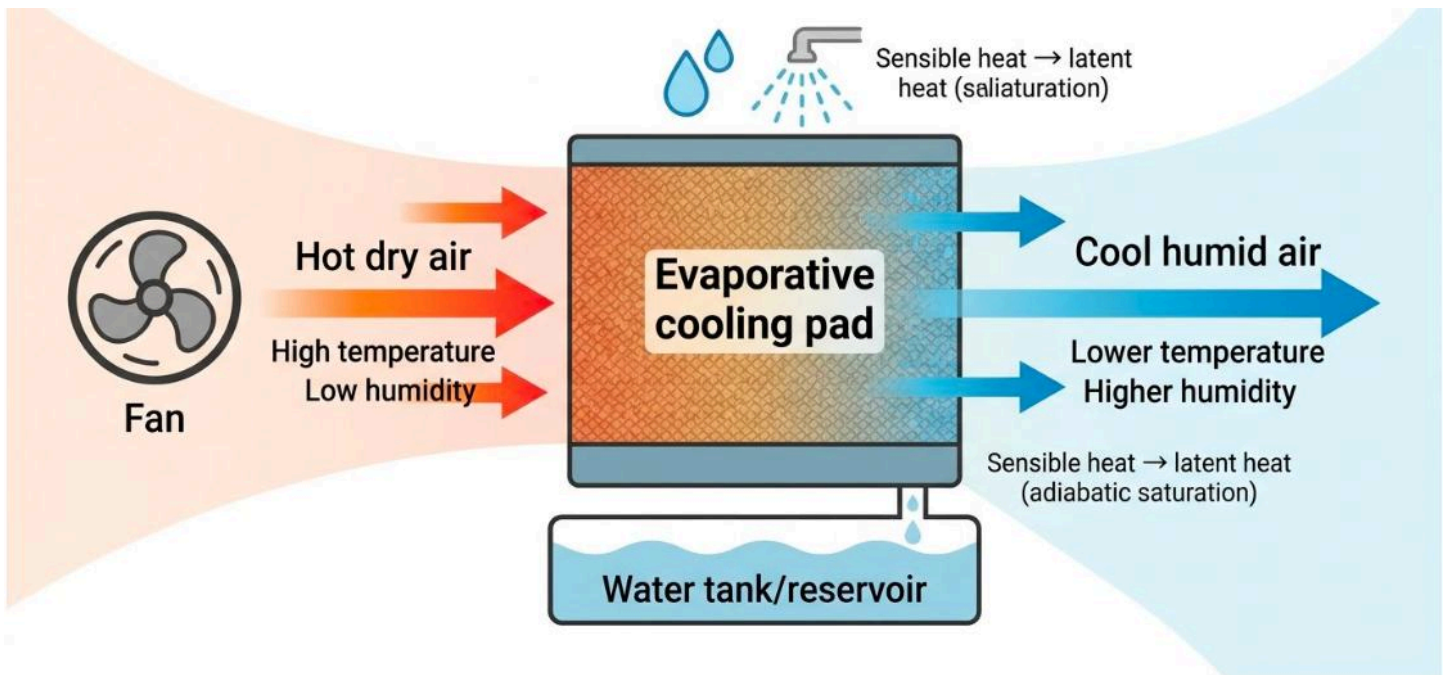


Figure 1. Direct evaporative cooling system

In contrast, an indirect evaporative cooling system (IDEC) differs from the direct type because the temperature of the air is reduced without adding any moisture (Kapilan et al., 2023; Riangvilaikul & Kumar, 2010), an advantage over conventional DEC systems. Indirect evaporative cooling systems utilise a heat exchanger to transfer cooling from a secondary, moisture-laden airstream to a primary supply airstream without direct contact (Duan et al., 2012; Maheshwari et al., 2001). The secondary cooled moist air is released outside, while the conditioned supply air remains dry. The heat exchanger in IDEC system can reduce the temperature below the wet-bulb temperature, making it more suitable for indoor environments where humidity control is required (Gómez et al., 2010; Hsu et al., 1989). Figure 2 shows the schematic of the IDEC system.

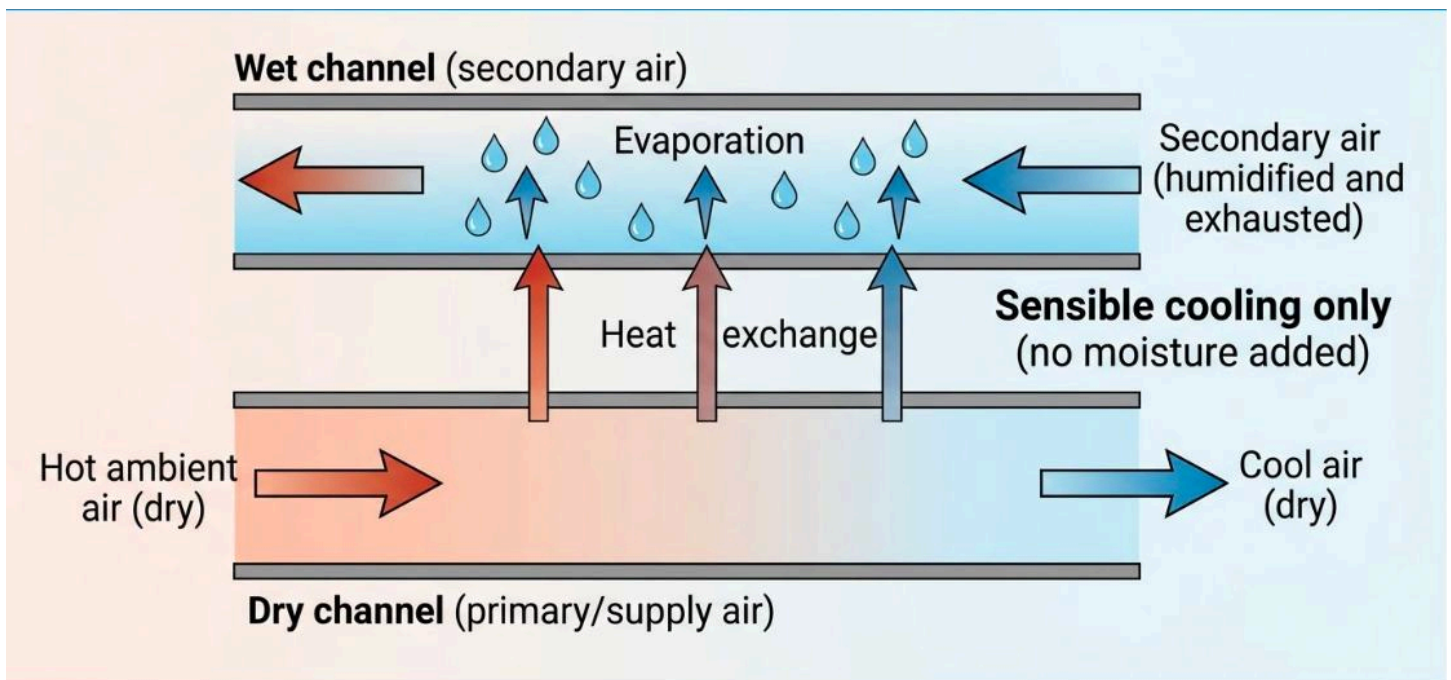


Figure 2. Indirect evaporative cooling system



The system performance remains strongly climate dependent. Since evaporative cooling relies on the air's capacity to absorb moisture, it is most effective in hot, dry, and temperate climates, including arid, semi-arid, and Mediterranean regions (Al-Helal, 2001; Costelloe & Finn, 2003; Guan et al., 2015).

## METHODS

### 2.1 STUDY SETTING

This case study was conducted in a South Australian canteen (volume  $552\text{m}^3$ ) (Figure 3), during the summer season characterised by warm-to-hot ambient temperatures and relatively low humidity. The experiment aimed to compare indoor air quality under two distinct ventilation conditions: a reverse cycle (RC) split system and an indirect evaporative cooling (IDEC) system.

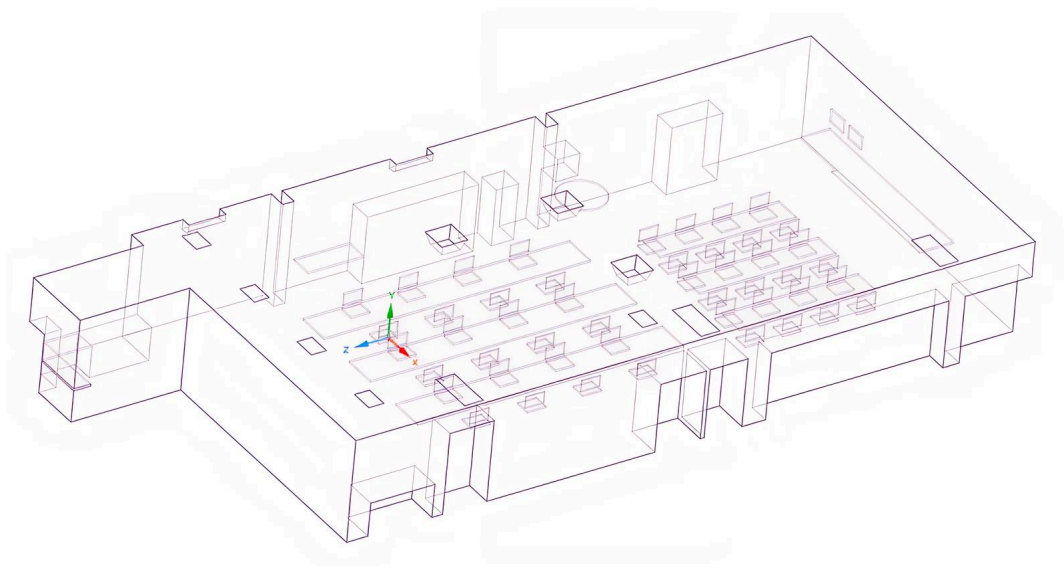


Figure 3. Schematic representation of canteen showing room size, IDEC vents, RC systems, table arrangement, and exhaust vents. This figure illustrates a  $\sim 552\text{m}^3$  room with the IDEC system (CW-X2) delivering  $7,200\text{m}^3/\text{h}$  of 100% outdoor air (13 ACH, 4.6-minute air change), indirect evaporative cooling (IDEC) vents, two RC systems ( $\sim 5.6\text{L/s}$  per person, 2.3–2.5 ACH), and table arrangement for  $\sim 50$  occupants.

The RC condition used two reverse cycle air conditioners. Each unit had a cooling capacity of 8–9kW and a heating capacity of 9–11.5kW under standard conditions (D.B./W.B. 27°C/19°C for cooling; 20°C/15°C for heating). The rated power input was 3.4kW, with a current draw of 14.5A. While the space may warrant additional split systems based on typical sizing, practical constraints such as infrastructure limitations and budget often restrict the number that can be installed in real-world settings. These units recirculated air within the test space and provided an air change rate of approximately 2.3–2.5 ACH per unit. The reverse cycle units were standard wall-mounted split systems that recirculate indoor air and do not introduce outdoor air. Accordingly, the reported air change rates (2.3–2.5 ACH per unit) represent internal air movement rather than true ventilation, and do not contribute to fresh air exchange. This equated to over 23 minutes to condition the facility's air volume, reflecting the limitations of recirculating systems in delivering fresh air exchanges.

In contrast, the indirect evaporative cooling system (CW-X2) supplied 7,200m<sup>3</sup>/h of 100% outdoor air, achieving an air change rate of 13.05/h and conditioning the full air volume within 4.6 minutes. Airflow was measured at 2,400L/s, with a cooling capacity of 25kW. This system was equipped with a MERV 8 filter, providing moderate filtration efficiency by capturing larger airborne particles such as dust, pollen, and mould spores.

The use of MERV 8 filtration is consistent with ASHRAE 62.1 requirements for non-healthcare facilities, including offices, schools, and food preparation areas, where the priority is both equipment protection and removal of coarse particulate matter.

Figures 4 and 5 show the computational fluid dynamics (CFD) modelling of the canteen facility using ANSYS 2024. CO<sub>2</sub> concentration is shown at 1.3m above the floor, representing the breathing zone. Dark blue areas indicate lower concentrations (<500ppm), while yellow to red areas denote elevated levels (>800ppm). Under indirect evaporative cooling, a larger blue zone is visible, reflecting greater dilution of occupant-generated CO<sub>2</sub> compared with reverse cycle operation. Localised yellow-red areas highlight zones of weaker airflow where CO<sub>2</sub> accumulates. Computational fluid dynamics simulations were conducted using ANSYS Fluent (ANSYS 2024 R2).

## REVERSE CYCLE AIR CONDITIONING

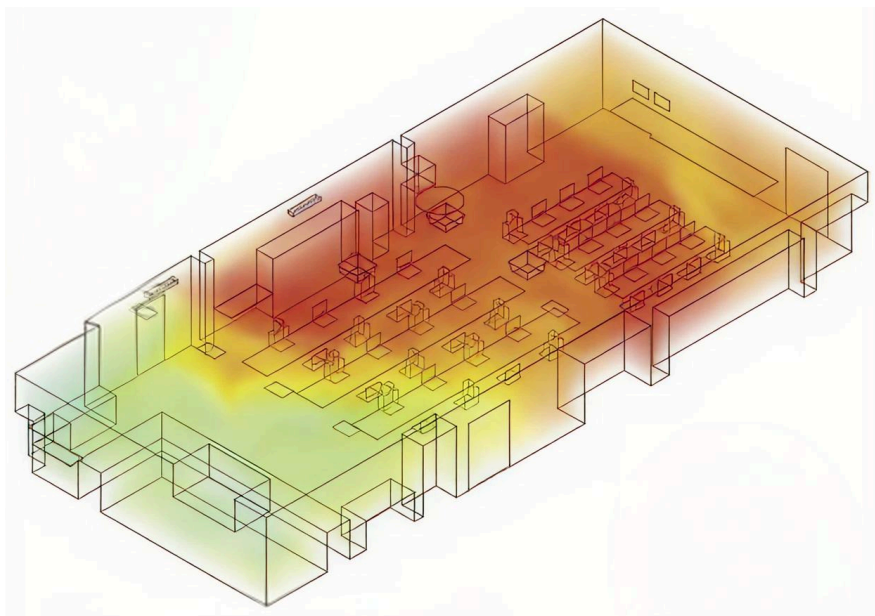


Figure 4. Schematic representation of CO<sub>2</sub> levels in a canteen with reverse cycle split systems. This figure depicts CO<sub>2</sub> concentrations across a roughly 552m<sup>3</sup> room, where two reverse cycle split systems provide estimated 2.3–2.5 air changes per hour, resulting in CO<sub>2</sub> concentrations of 850–1,000ppm.

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## CLIMATE WIZARD™ INDIRECT EVAPORATIVE COOLING

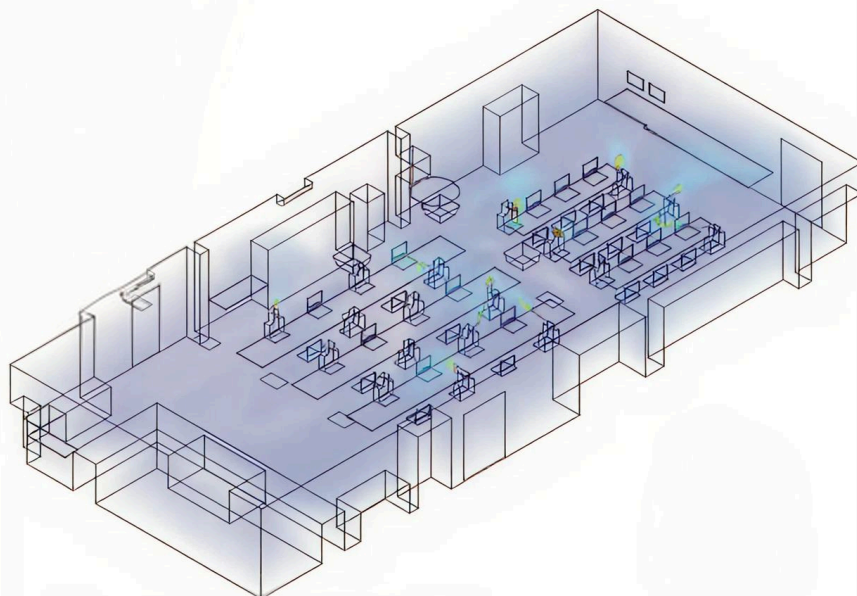


Figure 5. Schematic representation of CO<sub>2</sub> levels in the same canteen with indirect evaporative cooling systems. This figure depicts CO<sub>2</sub> concentrations across the 552m<sup>3</sup> room, where the indirect evaporative cooling system (CW-X2) delivers 7,200m<sup>3</sup>/h of outdoor air (13.05 ACH, 4.6-minute air change), maintaining CO<sub>2</sub> at 450ppm.



## 2.2 MEASUREMENTS

IAQ parameters CO<sub>2</sub>, TVOCs, PM<sub>2.5</sub> and PM<sub>10</sub>, temperature (T) and relative humidity (RH), were continuously monitored using Milesight multisensors integrated with LoRaWAN technology for real-time data transmission. Sensors were positioned at 1.3m above the floor to reflect the breathing zone relevant to seated and standing occupants. To minimise interference from the IDEC supply vents and return ducts, all sensors were placed at least 1.3m away from direct airflow pathways (shown in Figure 3). This ensured accurate measurement of CO<sub>2</sub> concentrations as a proxy for ventilation effectiveness and air quality within the occupied zone. CO<sub>2</sub> levels were measured using a nondispersive infrared (NDIR) sensor with a range of 400–5,000ppm, an accuracy of ±30ppm plus 3% of the reading, and a resolution of 1ppm. TVOC concentrations were detected using a metal oxide (MOX) MEMS sensor with a range of 1.00–5.00 IAQ rating units and a resolution of 0.01. PM<sub>2.5</sub> and PM<sub>10</sub> were monitored via laser scattering with a range of 0–1,000µg/m<sup>3</sup> and a resolution of 1µg/m<sup>3</sup>. Temperature and humidity were recorded using digital MEMS sensors with accuracies of ±0.2°C and ±2% RH, respectively. This setup enabled high-resolution, low-power environmental monitoring under field conditions as described in Table 1.

| PARAMETER                            | SENSOR TYPE      | MEASUREMENT RANGE         | ACCURACY               | RESOLUTION          | DATA PROCESSING (9AM–5PM) |
|--------------------------------------|------------------|---------------------------|------------------------|---------------------|---------------------------|
| CO <sub>2</sub>                      | NDIR             | 400–5,000 ppm             | ±30 ppm                | 1 ppm               | Median per day; IQR       |
| TVOC                                 | MOX MEMS         | 1.00–5.00 (IAQ index)     | ±1 index               | 0.01                | Median per day; IQR       |
| PM <sub>2.5</sub> / PM <sub>10</sub> | Laser scattering | 0–1,000 µg/m <sup>3</sup> | ±10 µg m <sup>-3</sup> | 1 µg/m <sup>3</sup> | Median per day; IQR       |
| Temperature                          | Digital MEMS     | -20 to 60°C               | ±0.2°C                 | 0.1°C               | Median per day; IQR       |
| Relative humidity                    | Digital MEMS     | 0–100% RH                 | ±2% RH                 | 0.5% RH             | Median per day; IQR       |

Table 1 presents sensor specifications used for monitoring indoor environmental parameters. Data were continuously recorded and summarised as median values with interquartile ranges (IQR) for the occupied period (9am–5pm).

Measurements were conducted across three experimental replicate days for each treatment, where each replicate represented a full-day measurement under matched operational conditions, undertaken on alternate days over a two-week period when outdoor temperatures consistently exceeded 30°C. This ensured participants remained comfortable under either RC or IDEC operation. Trials were performed only on fully sunny, hot days to minimise weather variability, with external conditions (temperature, relative humidity, and wind speed/direction) monitored and days selected to ensure comparable ranges across treatments. Five sensors were placed on individual tables and operated from 9am–5pm. Prior to data collection, each system was run until the room was fully conditioned: approximately 25 minutes for RC, consistent with its air change rate, and 4.5 minutes for 8IDEC. Measurements commenced only after complete air conditioning had been achieved, with data during system stabilisation excluded from analysis.

## 2.3 STATISTICAL ANALYSIS

Non-parametric analysis was conducted using Kruskal-Wallis tests to evaluate treatment effects on indoor air quality parameters, and Spearman's rank correlation coefficient ( $\rho$ ) was used to assess correlations between  $\text{CO}_2$  and  $\text{PM}_{2.5}$ ,  $\text{PM}_{10}$ , and TVOC variables using SPSS. A significance level of  $p < 0.05$  was applied.

### Results

A comparative analysis was undertaken to assess the impact of RC and IDEC systems on IAQ parameters. Across all trials, the measured parameters consistently improved under IDEC experimental conditions.

### Carbon dioxide

IDEC systems maintained significantly lower indoor  $\text{CO}_2$  levels than RC systems (Kruskal-Wallis  $H = 22.96$ ,  $p < 0.001$ ), with narrower interquartile ranges indicating stable dilution of occupant-generated  $\text{CO}_2$ . RC treated spaces exhibited higher and more variable concentrations, suggesting reduced ventilation efficacy (Figure 3.1). These findings indicate improved ventilation performance under indirect evaporative cooling conditions.

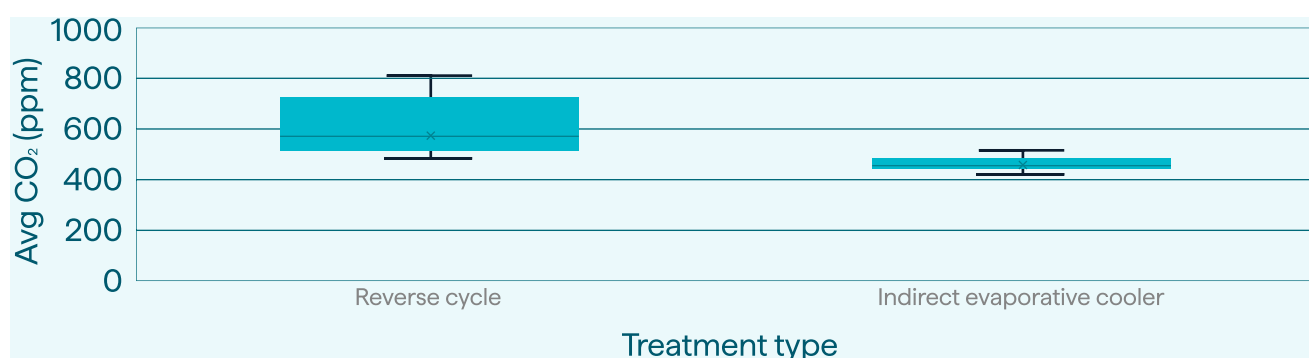


Figure 3.1 Boxplot showing average indoor  $\text{CO}_2$  concentration (ppm) under RC split and indirect IDEC treatments. A statistically significant difference was observed (Kruskal-Wallis  $H = 22.96$ ,  $p < 0.001$ ).

### $\text{PM}_{2.5}$ and $\text{PM}_{10}$

Fine and coarse particle concentrations were higher under RC conditions in this study setting. Indirect evaporative cooling systems significantly reduced indoor  $\text{PM}_{2.5}$  (Kruskal-Wallis  $H = 7.91$ ,  $p = 0.005$ ) and  $\text{PM}_{10}$  (Kruskal-Wallis  $H = 8.15$ ,  $p = 0.004$ ) levels, likely due to higher outdoor air exchange and better dilution of indoor sources (Figures 3.2 and 3.3).

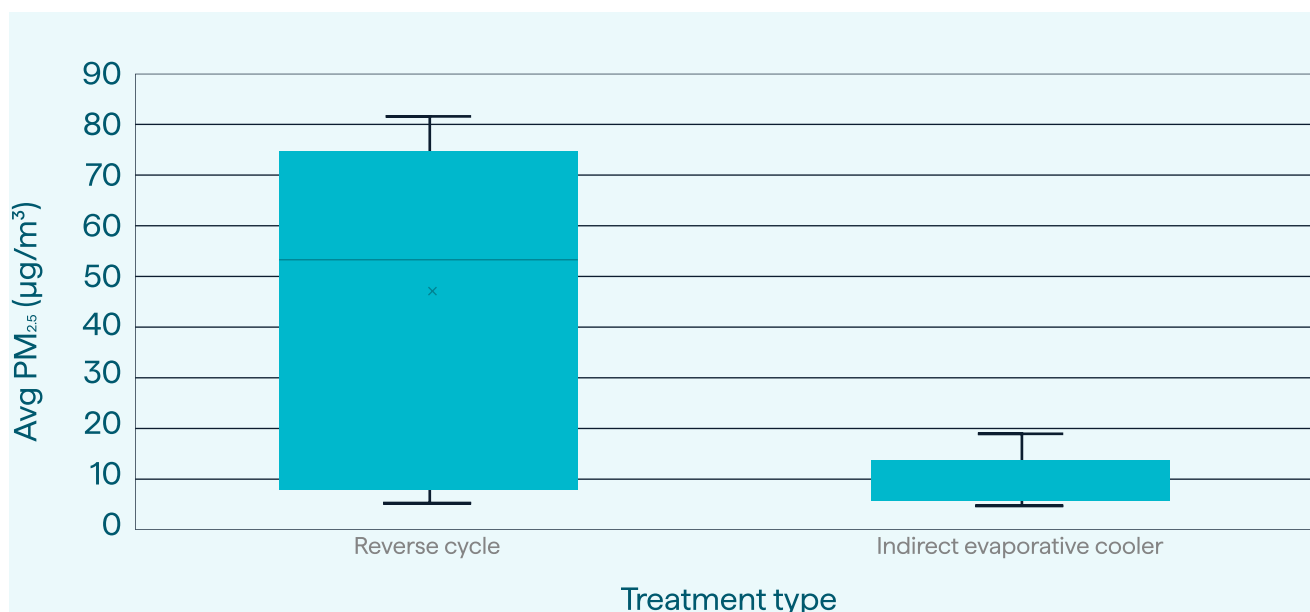


Figure 3.2 Boxplot comparing  $PM_{2.5}$  concentrations ( $\mu\text{g}/\text{m}^3$ ) under RC and indirect IDEC systems. IDEC treatment resulted in significantly lower  $PM_{2.5}$  levels (Kruskal-Wallis  $H = 7.91$ ,  $p = 0.005$ )

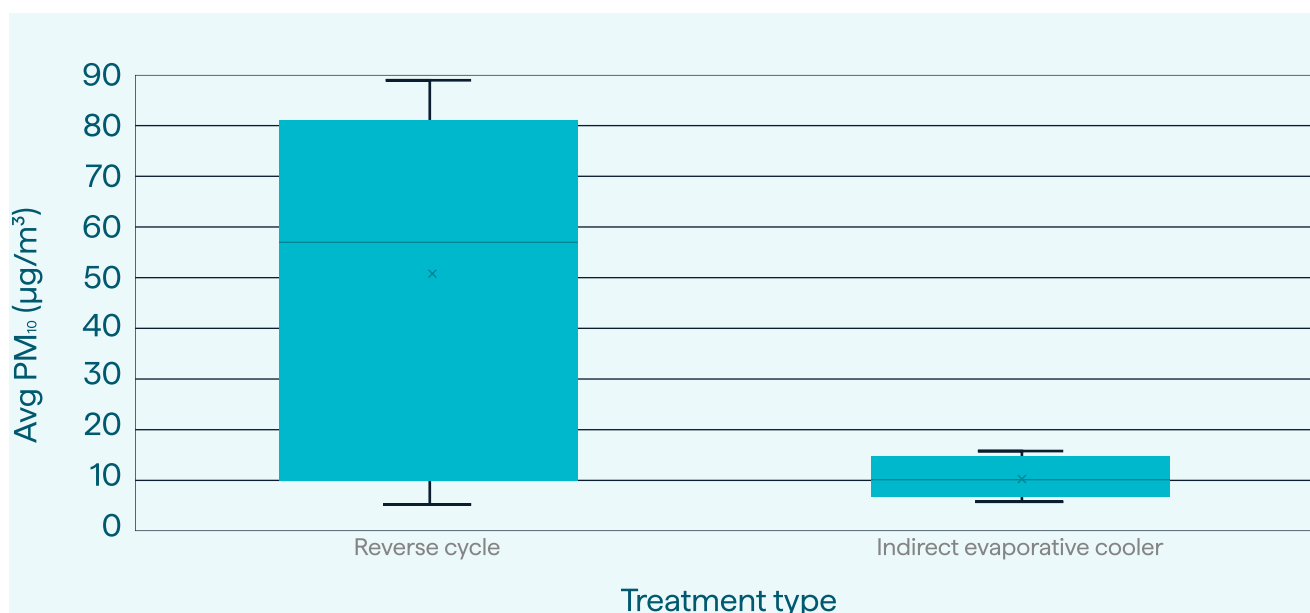


Figure 3.3 Boxplot comparing  $PM_{10}$  concentrations ( $\mu\text{g}/\text{m}^3$ ) under RC and IDEC treatments. IDEC significantly reduced  $PM_{10}$  levels compared to RC (Kruskal-Wallis  $H = 8.15$ ,  $p = 0.004$ ).

The lower concentrations observed under indirect evaporative cooling therefore indicate reduced occupant exposure to particle-related exposure risks.



TVOC

Total volatile organic compounds levels were lower in the IDEC-treated space (Kruskal-Wallis  $H = 9.00$ ,  $p = 0.003$ ) (Figure 3.4). The RC-treated space exhibited higher variability and transient peak concentrations exceeding 3ppm, retained in the analysis and reflected in boxplot distributions (median and interquartile range), rather than excluded as statistical outliers. These peaks likely represent short-duration emission events (e.g. cooking or occupant activities), as data were quality-checked and no evidence of instrument artefacts was identified, potentially due to off-gassing from indoor materials and limited fresh air intake. Elevated VOC exposure is associated with eye and airway irritation, headaches, and reduced wellbeing (Norbäck et al., 2017). Lower and more stable concentrations under IDEC indicate reduced occupant exposure.

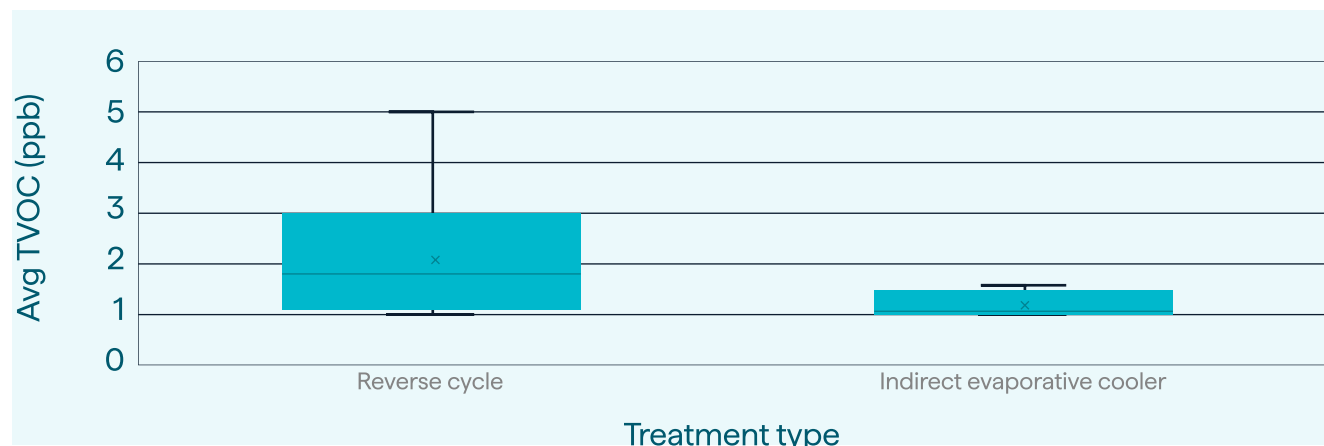


Figure 3.4 Boxplot showing TVOC concentrations (ppm) under RC and IDEC treatments. IDEC significantly reduced TVOC levels (Kruskal-Wallis  $H = 9.00$ ,  $p = 0.003$ ), suggesting better control of indoor gaseous pollutants

Temperature and relative humidity

IDEC systems were associated with slightly lower but more stable indoor temperatures (Kruskal-Wallis  $H = 4.19$ ,  $p = 0.041$ ) (Figure 3.5), although a wider interquartile range indicates greater variability under IDEC conditions.

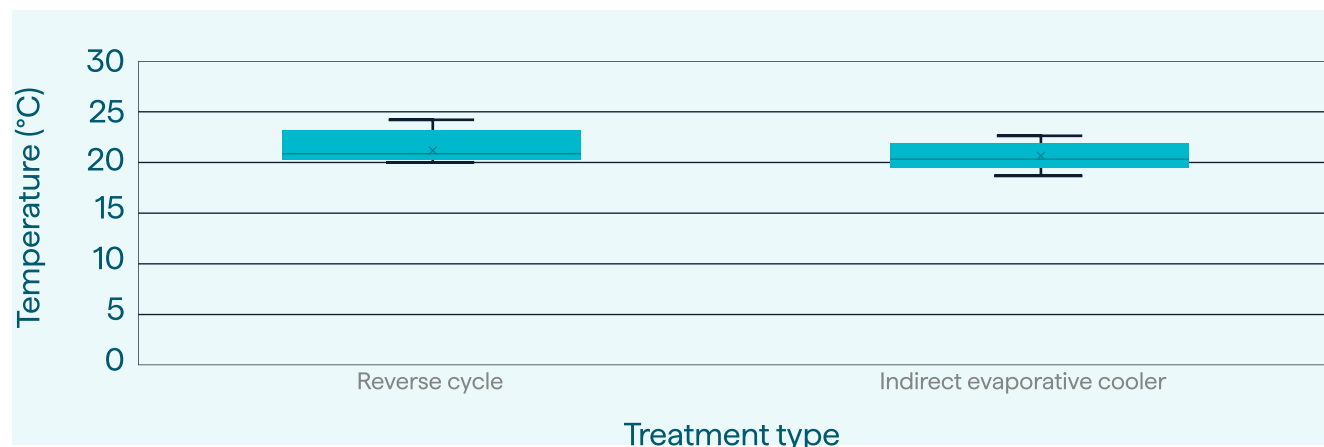


Figure 3.5 Boxplot of indoor temperature under RC and IDEC systems. A small but statistically significant difference was observed (Kruskal-Wallis  $H = 4.19$ ,  $p = 0.041$ ), with RC resulting in slightly higher temperatures.

Relative humidity was significantly higher and more variable in indirect evaporative cooling space, consistent with the humidifying nature of indirect evaporative cooling (Figure 3.6). Relative humidity influences aerosol dynamics, where higher levels can shorten aerosol suspension time and reduce airborne persistence; however, maintaining indoor humidity below approximately 60% is generally recommended, as excessive humidity may promote microbial and mould growth.

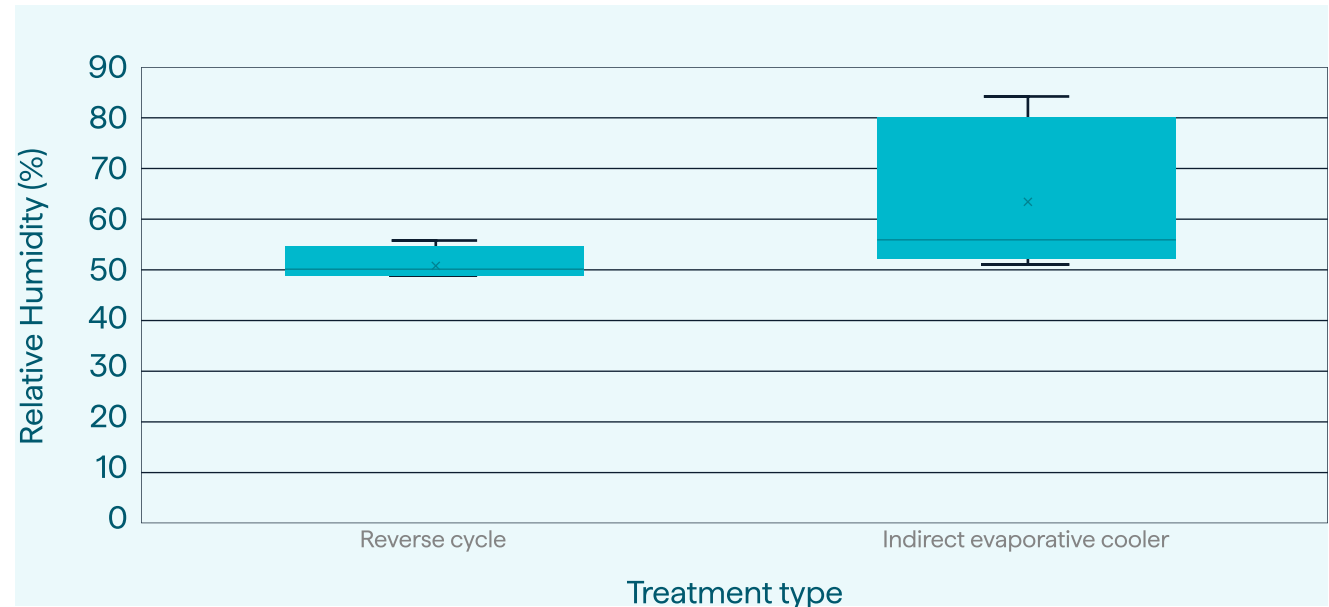


Figure 3.6 Boxplot of indoor relative humidity across treatments. IDEC significantly increased humidity levels compared to RC systems (Kruskal-Wallis  $H = 15.03$ ,  $p < 0.001$ ).

SUMMARY OF FINDINGS

The results showed significantly lower CO<sub>2</sub>, PM<sub>2.5</sub>, PM<sub>10</sub>, and TVOC concentrations under IDEC compared to RC treatment as described in Table 2.

| PARAMETER                 | RC MEDIAN | IDEC MEDIAN | REDUCTION              | P-VALUE     |
|---------------------------|-----------|-------------|------------------------|-------------|
| CO <sub>2</sub> (ppm)     | 562.3     | 436.7       | ↓ 23%                  | $p < 0.001$ |
| PM <sub>2.5</sub> (µg/m³) | 52.1      | 10.1        | ↓ 81%                  | $p = 0.005$ |
| PM <sub>10</sub> (µg/m³)  | 57.0      | 11.1        | ↓ 81%                  | $p = 0.004$ |
| TVOC (ppm)                | 1.83      | 1.00        | ↓ 45%                  | $p = 0.003$ |
| Temperature (°C)          | 20.93     | 20.39       | ↓ 0.5°C                | $p = 0.041$ |
| Relative Humidity (%)     | 50.00     | 55.00       | ↑ within optimal range | $p < 0.001$ |

Table 2 presents the median values for indoor environmental parameters under RC and indirect EC conditions. Values were derived from non-parametric analysis and are reported alongside Kruskal–Wallis test statistics, with indirect EC consistently associated with lower pollutant concentrations and higher relative humidity compared to RC operation.

Median CO<sub>2</sub> concentrations were markedly lower under indirect evaporative cooling (450ppm) than reverse cycle (650ppm), with a Kruskal-Wallis H value of 22.96 ( $p < 0.001$ ). PM concentrations were also significantly reduced under indirect evaporative cooling, PM<sub>2.5</sub> dropped from 55µg/m<sup>3</sup> (reverse cycle) to 10 µg/m<sup>3</sup>, and PM<sub>10</sub> concentrations reduced from 70µg/m<sup>3</sup> to 15µg/m<sup>3</sup> (both  $p < 0.01$ ). Similarly, TVOC values were lower with indirect evaporative cooling (1.1ppm) compared to reverse cycle (2.5 ppm,  $p = 0.003$ ). RH was significantly higher under indirect evaporative cooling (60% vs 50%,  $p < 0.001$ ), supporting occupant comfort and respiratory health. Outdoor data confirmed warm, dry ambient conditions, where increasing RH is beneficial. Evidence indicates infection risk is lowest at 40–60% RH, with low humidity increasing aerosol generation and airway susceptibility, while moderate humidity improves airway function and reduces viral viability (Wolkoff, 2024). Accordingly, the increase in RH observed under indirect evaporative cooling aligns with this optimal range under dry conditions, supporting both thermal comfort and potential reductions in airborne infection risk. Where ambient humidity increases, complementary control strategies, such as hybrid or desiccant-assisted systems, may be applied to maintain RH within this optimal band while preserving ventilation effectiveness. Overall, indirect evaporative cooling systems provided better IAQ (Kapilan et al., 2023).

### Experimental controls

Occupancy was manually counted and verified using IR sensors, with comparable occupancy patterns and activity levels maintained across treatments. Cooking practices and operational schedules were consistent between experimental days. External conditions (temperature, relative humidity, and wind) were monitored, and trials were conducted under similar hot-weather conditions. Measurements were performed over the same time period (9–5pm), with data collected only after system stabilisation.

### Spearman's correlation analysis

Spearman's correlation coefficient is a non-parametric measure of the strength and direction of a monotonic relationship between two variables, calculated using ranked data and appropriate for non-normally distributed datasets. Spearman's correlation coefficient describes how strongly two variables change together, based on their ranked values, and is suitable for non-normally distributed data.

Spearman's correlation analysis revealed a strong, statistically significant positive relationship between CO<sub>2</sub> and PM. CO<sub>2</sub> with PM<sub>2.5</sub> ( $\rho = 0.656$ ,  $p < 0.001$ ) and CO<sub>2</sub> with PM<sub>10</sub> ( $\rho = 0.677$ ,  $p < 0.001$ ), as well as with TVOC ( $\rho = 0.489$ ,  $p = 0.002$ ) as detailed in table 3.

|                                            | AVG CO <sub>2</sub><br>(PPM) | AVG PM <sub>2.5</sub><br>(MG/M <sup>3</sup> ) | AVG PM <sub>10</sub><br>(MG/M <sup>3</sup> ) | AVG TVOC<br>(PPB) | RELATIVE<br>HUMIDITY (%) | TEMPERATURE<br>(°C) |
|--------------------------------------------|------------------------------|-----------------------------------------------|----------------------------------------------|-------------------|--------------------------|---------------------|
| Avg CO <sub>2</sub> (ppm)                  | 1.00                         | 0.66**                                        | 0.68**                                       | 0.49**            | 0.17                     | -0.68**             |
| Avg PM <sub>2.5</sub> (µg/m <sup>3</sup> ) |                              | 1.00                                          | 0.99**                                       | 0.59**            | 0.40**                   | -0.27               |
| Avg PM <sub>10</sub> (µg/m <sup>3</sup> )  |                              |                                               | 1.00                                         | 0.59**            | 0.39**                   | -0.029*             |
| Avg TVOC (ppb)                             |                              |                                               |                                              | 1.00              | 0.31*                    | -0.186              |
| Temperature (°C)                           |                              |                                               |                                              |                   | 1.00                     | 0.23                |
| Relative Humidity (%)                      |                              |                                               |                                              |                   |                          | 1.00                |

Table 3 presents strong positive correlations were observed between CO<sub>2</sub>, PM<sub>2.5</sub>, PM<sub>10</sub>, and TVOC, indicating co-accumulation under shared conditions such as occupancy and limited ventilation. Relative humidity showed a moderate negative correlation with CO<sub>2</sub>, while temperature exhibited weak associations with other variables.

**Interpretation:** These findings indicate that temporal concentrations of indoor pollutants correlate strongly, suggesting potential shared causes such as human occupancy, ventilation conditions, or air exchange dynamics. The pattern is consistent with indoor environments using RC systems, where limited fresh air exchange may contribute to the co-accumulation of exhaled gases, particulates, and volatile compounds.

## DISCUSSION

This study provides empirical evidence that indirect evaporative cooling systems can align with the IAQ Blueprint (Science, 2024), ASHRAE Standard 241 (Jones et al., 2025), and Lancet NADR in a canteen setting in conducive climate zones.

The IDEC system delivered 7,200m<sup>3</sup>/h of 100% outdoor air, achieving 13 ACH in a ~552 m<sup>3</sup> space, with a 4.6-minute air change time. Assuming a default 50-person occupancy under ASHRAE 241, this yields an ECAi of 40L/s per person, exceeding the 30L/s per person target for canteen and supporting Infection Risk Management Mode (IRMM) requirements for a ≤0.1% hourly infection probability (Jones et al., 2025). RC systems, limited to ~5.6L/s per person (2–5 ACH), aligned with ASHRAE 62.1 (Ventilation for Acceptable Indoor Air Quality), but not IRMM. The RC system met the IAQ Blueprint CO<sub>2</sub> target but did not meet the PM<sub>2.5</sub> or ventilation requirements. Indirect evaporative cooling systems improved CO<sub>2</sub>, PM<sub>2.5</sub> and TVOC levels compared to reverse cycle, meeting IAQ Blueprint targets for CO<sub>2</sub> and PM<sub>2.5</sub> (Science, 2024) and satisfying the Lancet NADR ventilation benchmark for infection control (Allen Joseph, 2016), resulting in comparatively better IAQ outcomes under indirect evaporative cooling operation.

Ventilation dilutes virus-laden aerosols, reducing airborne transmission risk (Gilkeson et al., 2013). The 100% outdoor air delivered by indirect evaporative cooling aligns with NADR's preference for minimising bioaerosol redistribution, achieving Re<1, which indicates that the effective reproduction number is below one, and transmission is not sustained within the space.



The 13 ACH delivered by indirect evaporative cooling exceeds the ventilation rates typically associated with ASHRAE 241 (4–12 ACH) and demonstrates the capacity to achieve high outdoor air exchange under the conditions tested. This level of ventilation supports applications in high-occupancy settings such as schools and gyms.



#### ASHRAE STANDARD 241

ECAi of 40 L/s/person achieved — exceeds the 30 L/s/person canteen target. Supports Infection Risk Management Mode (IRMM).



#### IAQ BLUEPRINT (SCIENCE, 2024)

CO<sub>2</sub> and PM<sub>2.5</sub> targets both met under IDEC conditions. RC met CO<sub>2</sub> target but not PM<sub>2.5</sub> or ventilation requirements.



#### LANCET COMMISSION NADR

Re < 1 achieved through high outdoor air delivery. Transmission not sustained within the conditioned space.

## LIMITATIONS AND SUGGESTIONS FOR FURTHER RESEARCH

This study was conducted in a single canteen under summer conditions in a warm, dry climate, and the findings should be interpreted within this context. System performance is climate-dependent, and outcomes may differ under more humid conditions. The reverse cycle system reflects the existing installed capacity, which may be lower than typically recommended for this space. Increasing capacity may improve thermal comfort, but would not improve ventilation or IAQ without additional outdoor air supply. Further research should assess both systems across different climates, occupancy levels, and configurations. Studies incorporating mechanical ventilation and humidity control would help identify where each system is most appropriate.

## CONCLUSION

Indirect evaporative cooling provides a viable option to achieve emerging IAQ and infection control standards.

Indirect evaporative cooling systems reduce CO<sub>2</sub>, particulate matter, and volatile organic compounds through high outdoor air supply, resulting in concurrent changes across multiple IAQ parameters rather than isolated effects. While the use of outdoor air introduces a potential pathway for external pollutants, this can be addressed through the integration of filtration and additional air treatment where required, enabling application in polluted environments without compromising energy efficiency or overall IAQ performance. The potential for increased indoor particulate concentrations during bushfire events reflects the use of high outdoor air ventilation rather than an inherent limitation of indirect evaporative cooling and can be effectively mitigated through established integration of filtration and recirculation strategies. Its ability to deliver high outdoor airflow, reduce pollutant loads, maintain relative humidity within ranges associated with occupant comfort and respiratory health, positions the technology as an alternative approach for healthy, low-carbon buildings. Where ambient humidity increases, indirect evaporative cooling can be complemented with control strategies such as hybrid configurations or desiccant-assisted systems, enabling humidity to be reduced if required while maintaining high outdoor air delivery and ventilation effectiveness.

Indirect evaporative cooling systems offer a scientifically and policy-aligned solution to improving IAQ while mitigating airborne infection risk. In this study, both indirect evaporative cooling and reverse cycle systems met CO<sub>2</sub> targets; when assessed over the full sampling period; however, during peak occupancy periods (e.g. lunchtime), higher CO<sub>2</sub> concentrations and greater variability were observed under reverse cycle conditions compared to indirect evaporative cooling. By delivering 100% outdoor air without recirculation, indirect evaporative cooling achieved lower CO<sub>2</sub>, PM<sub>2.5</sub>, PM<sub>10</sub>, and TVOC concentrations than reverse cycle under the conditions tested in this canteen. These findings support the potential relevance of indirect evaporative cooling for health-focused ventilation in similar high-occupancy indoor environments.

Future work should further explore testing in other types of facilities and other climate zones, as well as reverse-cycle systems that supply outdoor air. Evaluating additional outcome measures in indirect evaporative cooling ventilated environments may further inform long-term policy adoption.

### CONFLICT OF INTEREST

The authors declare that Sonali Deshmukh, Cyril Mathew, Patrick McCaffrey are employed by Seeley International, a manufacturer of direct and indirect evaporative air conditioning systems.

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S.D., C.M., H.W., K.E.R. and P.Mc.C. designed and participated in the study. S.D. drafted and edited the manuscript. C.M. designed and simulated the CFD model. H.W., K.E.R. and P.Mc.C. reviewed and edited the manuscript. All authors have read and agree to the published version of the manuscript.

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