

CMV in school classrooms: installation and management for optimal speech intelligibility

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Abstract. Indoor air quality and speech intelligibility are key factors for comfort and learning effectiveness in school classrooms. The installation of Controlled Mechanical Ventilation Systems (CMV) ensures proper air exchange and reduces pollutant concentration, but it can affect acoustic conditions. This paper explores design and management strategies for CMV systems aimed at minimizing noise and optimizing speech intelligibility. Through technical solutions and case studies, practical solutions are proposed to balance environmental comfort and acoustic performance, with a focus on current regulations and the specific needs of educational facilities.

1. Introduction

The Ministerial Decree of 23 June 2022 [1] concerning the *Minimum Environmental Criteria (CAM)* for the awarding of design services and construction works for building interventions, as well as for the joint awarding of design and construction works, effectively requires the installation of controlled mechanical ventilation (CMV) systems in newly constructed school buildings and in those undergoing major renovations (paragraph 2.4.5).

In the same period, the Prime Ministerial Decree of 26 July 2022 [2] introduced guidelines on minimum indoor air quality standards in school environments. These guidelines, developed on the basis of the opinion of the *Istituto Superiore di Sanità*, aim to improve ventilation effectiveness, air exchange rates, and overall indoor air quality in educational buildings.

While the introduction of CMV systems is essential to ensure healthy indoor environments, their implementation in schools must be carefully evaluated from an acoustic perspective. Paragraph 2.4.11 of the CAM explicitly addresses acoustic comfort requirements and refers, for school buildings, to UNI 11532-2 [3]. This standard provides specific guidance on acoustic design and assessment in classrooms, including criteria related to noise generated by building services.

A growing body of literature highlights that acoustic comfort is a key factor influencing teaching effectiveness and learning outcomes [4, 5]. Children tend to be more vulnerable to poor acoustic conditions, showing higher levels of distraction and discomfort compared to adults. Adverse acoustic environments have been shown to significantly impair students' performance in complex listening tasks [6], memorisation processes [7], and reading abilities

[8]. Moreover, on an emotional level, excessive noise and inadequate acoustic quality may induce unpleasant states such as irritation, anxiety, or frustration [9], potentially affecting social interactions and shaping negative attitudes towards the school environment over time [11].

From a perceptual standpoint, speech intelligibility in classrooms is known to be more strongly affected by background noise than by reverberation phenomena [13, 14], particularly when the noise is unrelated to speech signals [12, 15]. This aspect is especially critical in learning environments, where continuous or intermittent noise can mask spoken communication and compromise verbal instruction. Consequently, although ensuring adequate indoor air quality is a primary objective, acoustic design must explicitly account for the noise introduced by the operation of ventilation systems [16, 17].

In practice, several studies report that ventilation systems are sometimes operated at reduced capacity or even switched off altogether due to the disturbing noise generated by fans and air-handling components [9, 18]. This behaviour clearly highlights the strong interaction between indoor air quality and acoustic comfort: if ventilation noise is perceived as intrusive, the intended benefits of CMV systems may be significantly undermined.

Previous experimental investigations have explored this interaction. A study conducted on university campuses in Granada (Portugal) and Minho (Spain) analysed the effects of ventilation operation on classroom acoustic conditions, observing an increase in background noise levels and a corresponding reduction in the Speech Transmission Index (STI) when mechanical ventilation was active [19]. The authors suggested that regulatory frameworks should be revised to better balance air quality requirements with acoustic performance criteria.

Similarly, [21], examined classroom acoustic parameters during the operation of a CMV system in a school building, testing three different acoustic treatment solutions to demonstrate that only the one configuration was capable of ensuring reverberation times compliant with applicable standards.

Within this framework, the present study investigates the impact of CMV systems on the indoor acoustic quality of school classrooms, with a specific emphasis on how CMV operation affects speech intelligibility, as quantified by the Speech Transmission Index (STI). Measurements were carried out in a sample of classrooms to explore potential relationships among system typology, operating modes, architectural features, and acoustic descriptors, with the ultimate aim of supporting integrated design solutions that safeguard both air quality and communication effectiveness.

2. Materials and method

The study, funded within the NecessARIA and Vitality project, surveyed a large number of classrooms belonging to school complexes of different educational levels, distributed across several Italian regions. The present paper focuses on a subset of over than 20 classrooms, selected to highlight in a targeted manner the issues introduced in the premises (i.e., the interaction between indoor air quality requirements and acoustic performance, with particular attention to speech intelligibility under CMV operation).

The measurement campaign yielded a substantial dataset describing both system operating characteristics and their effects on indoor acoustic quality. For each classroom, a complete set of contextual information was also collected, including: room geometry (plan layout, volume, and surface distribution), the presence and characteristics of acoustic suspended ceilings and/or other sound-absorbing treatments, the passive acoustic performance of the envelope and internal partitions, and the presence of additional noise

sources (e.g., external traffic, adjacent rooms, technical rooms, or non-HVAC building services).

Across the investigated classrooms, CMV systems could be grouped into three main configurations:

1. Standalone CMV unit installed inside the classroom, i.e., a self-contained device directly located in the occupied space.
2. Ducted single-classroom CMV unit, installed either above a suspended ceiling or in an adjacent service space, supplying and extracting air for one classroom only.
3. Centralised CMV system serving 2–3 adjacent classrooms, with a single ventilation unit connected to multiple rooms via ductwork.

Classroom acoustic characterisation was carried out in accordance with UNI 11532-2, adopting the measurement procedures and descriptors referenced by the standard. In all cases, measurements were performed under the different predefined operating conditions of the CMV system (as set by the designer), to quantify the acoustic impact associated with each ventilation mode (e.g., off/standby and one or more fan-speed settings).

The following acoustic quantities required by UNI 11532-2 were measured:

Reverberation time, T30: is the *reverberation time* derived from the decay slope between –5 dB and –35 dB of the sound energy decay curve (a 30 dB interval). The corresponding decay time is then extrapolated to 60 dB to obtain an estimate of the conventional reverberation time (RT). Practically, the reverberation time measured as T30 describes how long sound persists in the room after the source stops and is a key descriptor of room absorption and sound-field persistence.

Speech Transmission Index, STI: is an objective metric of speech intelligibility based on how the room and noise environment reduce the modulation depth of speech-like signals across multiple frequency bands. STI ranges from 0 (poor intelligibility) to 1 (excellent intelligibility) and is strongly influenced by background noise and, to a lesser extent, by reverberation and signal-to-noise ratio. In this study, STI was used to quantify how CMV operation affects the effectiveness of verbal communication in classrooms.

Background noise level with systems not operating, L_{r} : is the A-weighted sound pressure level measured in the classroom with the CMV system switched off (or in a non-operational condition), intended to represent the residual/background noise due to external sources (e.g., outdoors), adjacent spaces, and other building services not under investigation. This parameter provides the baseline noise floor against which the additional contribution of CMV operation can be assessed.

Overall internal noise level due to the CMV system, $L_{ic,int}$: is the overall A-weighted sound pressure level attributable to the CMV system as experienced inside the classroom. Operationally, it represents the sound level produced by the ventilation equipment (fans, airflow, duct terminals, vibration transmission, etc.) during operation, measured according to the UNI 11532-2–referenced procedure so as to characterise the global indoor acoustic impact of the system under the considered operating mode(s). The minimum time range of each measurement is specified in the standard.

Fig. 1 illustrates the measurement setup adopted in the investigated classrooms, as specified by UNI 11532-2, for the evaluation of the different acoustic parameters considered in this study. The Fig. 1 schematically shows the arrangement of the sound source and measurement microphone positions used for the assessment of reverberation time, background noise levels, and speech intelligibility descriptors.

The same measurement configuration was consistently maintained throughout the entire experimental campaign and applied to all classrooms and operational conditions of the CMV systems. This approach was intentionally adopted to ensure methodological uniformity, to minimise operator-dependent variability, and to guarantee the repeatability and

comparability of the results across rooms with different geometrical, architectural, and acoustic characteristics.

By preserving identical measurement positions and boundary conditions, potential biases related to changes in source–receiver geometry or spatial sampling were avoided.



Fig. 1. Measurement setup according to UNI 11532-2

In Fig. 2, examples of the investigated classrooms and the associated in-room measurement positions are shown; in all cases, measurement locations were selected in full compliance with the prescriptions of UNI 11532-2.

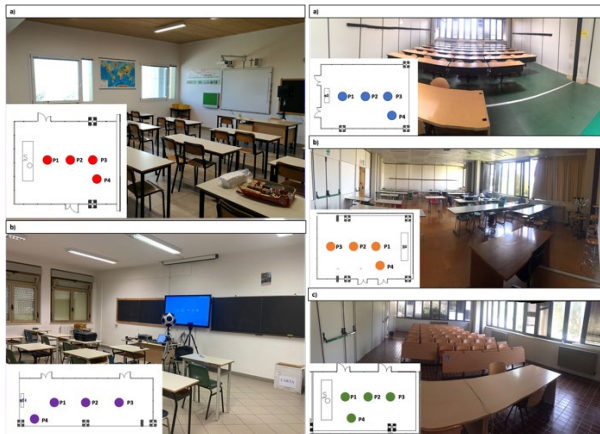


Fig. 2. Examples of the investigated classrooms and the corresponding acoustic measurement positions.

As mentioned before, STI is an objective measure to predict the intelligibility of speech transmitted from talker to listener by a transmission channel. The STI method applies a specific test signal to the transmission channel, and by analysing the received test signal, the speech transmission quality of the channel is derived and expressed in a value between 0 and 1. Subjective and objective intelligibility indexes are correlated through the discrete qualification given by the intelligibility rating (IR), as expressed in UNI EN ISO 99211 and incorporated by UNI 11532-1 with regard to STI in confined spaces belonging to several uses, including the educational destination [20]. In Table 1, the correlation between STI and IR is shown.

Table 1. Correlation between speech transmission index and intelligibility rating

STI values	IR
$0.00 < STI \leq 0.30$	Bad
$0.30 < STI \leq 0.45$	Poor
$0.45 < STI \leq 0.60$	Fair
$0.60 < STI \leq 0.75$	Good
$0.75 < STI \leq 1.00$	Excellent

During each measurement session, airflow rate measurements were also performed in order to characterise the operating conditions of the mechanical ventilation units and to verify the actual ventilation rates delivered to the classrooms. These measurements were essential to properly interpret the observed acoustic results, as airflow rate and fan operating point are directly related to noise generation mechanisms within CMV systems. Airflow rates were measured at the supply and exhaust terminals using procedures consistent with the relevant technical standards for ventilation systems. In particular, measurements were carried out in accordance with UNI EN ISO 12599, which specifies field measurement methods for ventilation and air-conditioning systems, and UNI EN 16211, which provides guidance on the measurement of airflows in ventilation ducts and terminals.

3. Result and discussion

The results presented in the following section represent a synthesised overview of a broader measurement campaign carried out within the project. For the purposes of this study, the data have been condensed so as to highlight the aspects most directly correlated with the measured Speech Transmission Index (STI) values in the investigated classrooms.

All acoustic measurements were performed under both inactive (CMV off) and active (CMV on) ventilation conditions. When the ventilation systems allowed for adjustable fan speed or airflow rate, measurements were systematically repeated under all available operating settings, in order to capture the full range of acoustic effects associated with different ventilation modes.

The analysis explicitly accounts for the minimum required air change rates prescribed for each classroom type, ensuring that all operating conditions considered in the results are compatible with the functional and regulatory requirements for indoor air quality. Consequently, the reported variations in STI are interpreted in relation to acoustically relevant changes in system operation, while maintaining compliance with ventilation performance targets.

Fig. 3 reports the internal noise levels generated solely by the CMV systems, measured under normal operating conditions for the different system typologies identified in the investigated classrooms. The reported values represent the net acoustic contribution of the ventilation systems, obtained by excluding the effects of background and residual noise originating from other internal or external sources (e.g., outdoor noise, adjacent spaces, and non-ventilation building services), in accordance with the measurement and data-processing procedures prescribed by the reference standard.

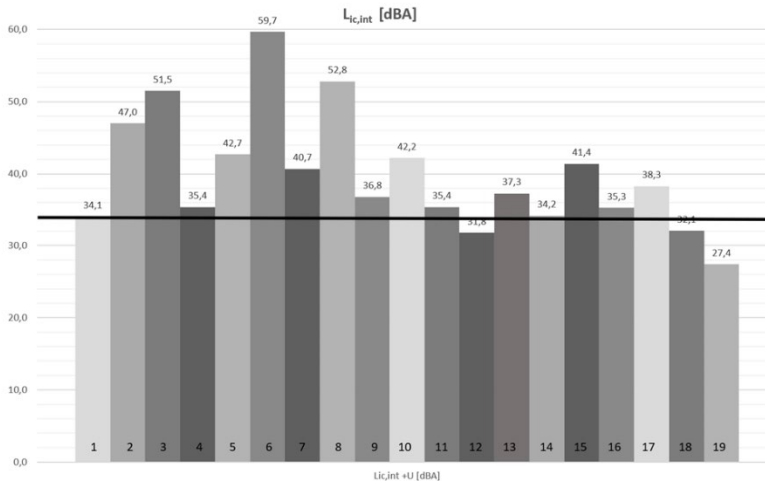


Fig 3. $L_{ic,int}$ measured

For each configuration, the analysed operating conditions correspond to ventilation modes that comply with the minimum air change requirements specified for the relevant classroom type. The black reference line indicates the upper limit value established by the applicable acoustic standards and guidelines previously introduced.

The results indicate that several classrooms–CMV system combinations generate system-related noise levels that approach or exceed the recommended limits, even after the removal of background and residual noise contributions. This outcome highlights that the observed exceedances can be directly attributed to the intrinsic acoustic emission of the CMV systems themselves, rather than to unfavourable external noise conditions. Such behaviour appears to be strongly dependent on system typology, installation configuration, and operating point, suggesting that fan characteristics, airflow velocities, and sound transmission paths play a decisive role in determining the final in-room noise level.

While compliance with noise limits represents an essential prerequisite for acoustic comfort, the functional relevance of these net CMV noise levels must be interpreted in terms of their impact on verbal communication. In learning environments, the critical issue is not only whether the CMV system exceeds a prescribed threshold, but whether its emitted noise results in a measurable degradation of speech intelligibility.

Accordingly, a key objective of the subsequent analysis is to investigate whether the CMV-only noise levels shown in Fig. 3 are correlated with variations in the measured Speech Transmission Index (STI). Given that STI is particularly sensitive to non-speech background noise, an increase in ventilation-related sound pressure levels may reduce the effective signal-to-noise ratio and thus impair speech perception in the classroom. Clarifying this relationship is fundamental to understanding whether acoustically critical CMV configurations also lead to a functional loss in speech intelligibility, even when ventilation requirements are fully satisfied.

A second key aspect that must be addressed at a preliminary stage is the classroom reverberation time, as it represents a primary descriptor of the room’s sound-field persistence and is therefore indicative of the overall sound absorption provided by interior finishes. In educational spaces, reverberation time is strongly governed by the presence of sound-absorbing treatments, most notably suspended ceilings, as well as by the acoustic behaviour (i.e., frequency-dependent absorption) of the materials employed. Because such treatments

typically exhibit a non-uniform absorption spectrum, their effectiveness may vary substantially across frequency bands, with potentially relevant consequences for both speech-related metrics and the perceptibility of building-service noise.

The measured reverberation times (Fig. 4) show a clear separation between untreated and treated classrooms. For rooms without acoustic treatment, the measured reverberation times are consistently well above the optimal range across the entire investigated frequency spectrum, indicating insufficient absorption and a highly reflective acoustic environment. Conversely, classrooms equipped with acoustic treatments exhibit reverberation times that generally fall within the compliance interval at mid-to-high frequencies, specifically for bands above 500 Hz, confirming the effectiveness of common ceiling-based solutions in the frequency range most relevant to speech clarity.

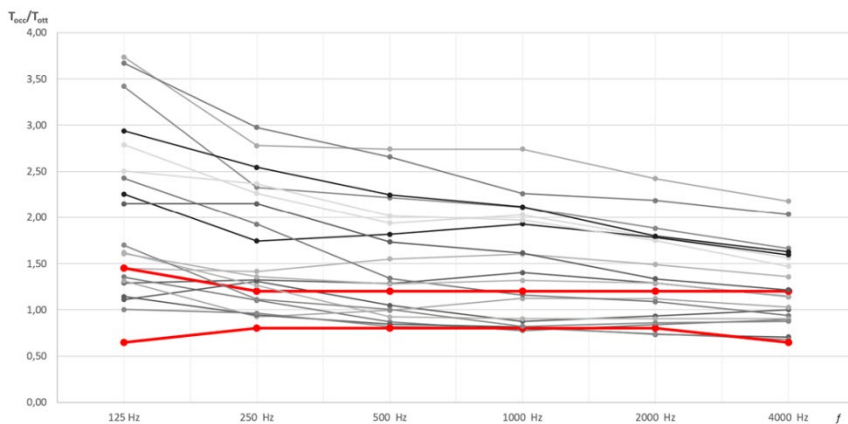


Fig. 4. Occupied classroom RT normalised with respect to the optimal reverberation time (red lines are the standard optimal values)

However, residual low-frequency criticalities remain evident in a subset of treated rooms, with reverberation times at frequencies below 500 Hz still exceeding desirable targets. These low-frequency deviations are closely linked to the type of acoustic treatment installed (e.g., porous absorbers, perforated panels, mineral-fibre tiles, or hybrid solutions), since many standard classroom treatments are primarily optimised for mid–high frequencies and provide limited absorption in the low-frequency region. Importantly, such low-frequency reverberation behaviour is not merely a room-acoustics detail: it can significantly affect the in-room sound level induced by the CMV system, because ventilation noise often contains tonal or broadband components with relevant energy at low and mid frequencies. As a result, classrooms characterised by insufficient low-frequency absorption may exhibit a greater build-up of CMV-related noise and a higher perceived intrusion, even when the same system operates under comparable airflow conditions.

Fig. 5 summarises the results of the STI measurements carried out in the investigated classrooms with the CMV systems switched off, i.e., under reference conditions without ventilation-related acoustic emissions. For each classroom, the STI reported in the Fig. corresponds to the mean STI value, calculated from the prescribed set of measurement positions and/or repetitions in full compliance with UNI 11532-2. In this way, the dataset provides a robust baseline of speech intelligibility that reflects the combined effects of room acoustics (including reverberation characteristics), residual environmental noise not associated with the ventilation system, and the architectural features of the space.

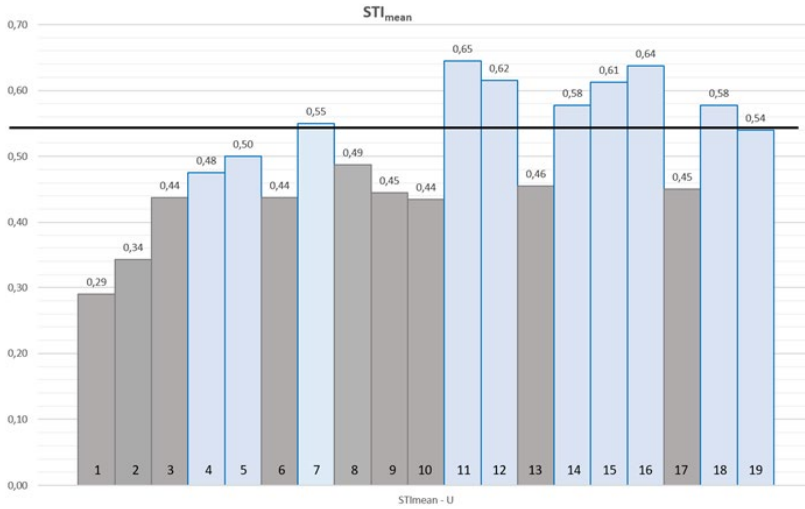


Fig. 5. STI values, CMV off (grey=with treatment; blue= no treatment)

Fig. 6 presents STI measurements obtained in the same classrooms and using the same measurement configuration, but with the CMV systems operating under their normal in-use conditions. As in Fig. 5, the STI associated with each classroom is reported as a standard-compliant mean value, determined by averaging the STI results according to the UNI 11532-2 procedure. Maintaining an identical measurement geometry (source–receiver arrangement and sampling positions) ensures that differences observed between Figs 5 and 6 can be interpreted primarily as the effect of CMV operation, rather than being attributable to changes in spatial sampling or experimental setup.

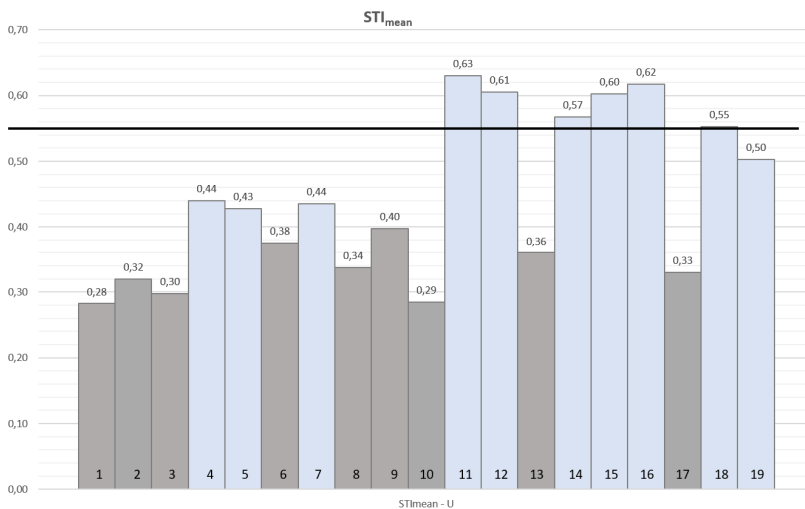


Fig. 6. STI values, CMV on (grey=no treatment; blue= with treatment)

In both Figs, the black horizontal line marks an STI value of 0.55, which UNI 11532-2 identifies as the minimum acceptable criterion for classroom environments. Accordingly, mean STI values falling below this threshold indicate potentially inadequate conditions for effective oral communication, whereas values above it correspond to progressively improved intelligibility.

Taken together, the paired representation in Figs 5 and 6 enables a direct assessment of the net impact of CMV operation on speech intelligibility. Specifically, it allows (i) identification of classrooms where the activation of CMV leads to a measurable reduction in mean STI—potentially shifting the room from compliant to non-compliant conditions—and (ii) recognition of configurations in which adequate STI is preserved despite active ventilation.

4. Conclusion

The measurements show that the overall noise level induced by CMV systems is frequently higher, and in some cases significantly higher, than the reference values prescribed by the applicable standards. A first important distinction emerges with respect to system typology. In the case of standalone CMV units installed directly inside classrooms, the highest noise levels are observed in a substantial number of cases. For this configuration, the sound pressure levels generated by the system exceed the prescribed limit already at air change rates slightly above 1 vol/h and increase markedly when the ventilation rate exceeds 3 vol/h, regardless of whether the classroom is equipped with acoustic treatment.

Conversely, in the case of ducted CMV systems, either serving a single classroom or operating in a centralised configuration, the noise levels induced by system operation are generally lower than those associated with standalone in-room units. In several cases, these systems are able to comply with the maximum noise limits specified in UNI 11532-2, even under operating conditions that satisfy the minimum ventilation requirements. For these system typologies, the presence of an acoustic suspended ceiling plays a decisive role, contributing to reduced in-room noise levels even at air change rates exceeding 4 vol/h. Additional, partly expected, benefits are observed when the CMV unit is located in spaces remote from the served classroom and/or when silencers are installed on the supply and exhaust ductwork, effectively attenuating fan and airflow-related noise before it enters the occupied space.

Within this general framework, the analysis of speech intelligibility highlights a strong interaction between CMV-induced noise and room acoustic conditions. In classrooms without acoustic treatment, STI values are consistently lower than the reference thresholds, even under non-operating ventilation conditions. When the CMV system is switched on in these untreated spaces, a significant reduction in STI is observed, indicating that the added non-speech noise exacerbates an already unfavourable acoustic environment. By contrast, in classrooms equipped with acoustic treatment, the degradation of STI associated with CMV operation is generally limited, suggesting that adequate sound absorption—particularly at mid and high frequencies—mitigates the impact of ventilation noise on speech intelligibility.

At this stage of the discussion, results have not yet been disaggregated in detail by CMV system typology. This is due to the fact that a portion of the dataset can only be partially disclosed, as the classrooms investigated were identified in advance and agreed upon with the relevant public administrations prior to the measurement campaigns. Under this framework, a fully explicit association between individual classrooms, system configurations, and measured outcomes cannot be presented.

Nevertheless, the experimental evidence collected in this study corroborates general trends widely reported in the scientific literature. In particular, the findings confirm that standalone CMV units installed within classrooms represent the configuration for which the greatest attention is required during both design and implementation. Owing to their proximity to occupants and the limited availability of spatial and structural attenuation mechanisms, these systems are more likely to generate perceptible noise levels that interact unfavourably with room acoustics, leading to elevated CMV-induced noise levels and, in several cases, to measurable reductions in STI.

Overall, the results underline the necessity of an integrated design approach, in which CMV system selection, airflow rates, installation layout, and room acoustic treatment are jointly considered. This is particularly critical for in-room ventilation solutions, where compliance with indoor air quality targets must be achieved without compromising acoustic performance and speech intelligibility, which remain fundamental prerequisites for effective learning environments.

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