Indoor air quality and thermal comfort in schools: comparative analysis of mechanical controlled and natural ventilation in northern and southern Italy

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Abstract. The "necessARIA" project addresses analysis, promotion, and coordination of indoor air quality issues. Objectives include data integration for evaluating sanitary and plant engineering aspects. This activity analyzes air change systems in existing school buildings based on 35 installations in Bolzano, Abruzzo, and Apulia regions. Monitoring provides reliable data for future school installations. Results show optimal indoor air quality in classrooms with mechanical controlled ventilation (VMC) versus naturally ventilated classrooms, which present humidity and microbiological challenges. Continuous monitoring used CO_2 indicators, temperature, relative humidity, and microbiological analysis during winter 2025–2026. The project is funded by the Ministry of Health under the National Complementary Plan "Health, Environment, Biodiversity, Climate" (PREV-A-2022- 12377013).

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1 Introduction

Indoor Air Quality (IAQ) and thermal comfort represent critical factors for occupant health, cognitive performance [1], and well-being in educational environments [2]. The concentration of students and staff within constrained classroom volumes creates significant challenges for maintaining adequate ventilation and thermal comfort simultaneously, particularly in response to varying external climatic conditions [3]. The three primary dimensions of IEQ - thermal comfort, indoor air quality, and acoustic comfort - are scientifically established to influence classroom cognitive performance [4], student learning outcomes, and teacher effectiveness [5]. Elevated CO_2 concentrations (>1000 ppm) are associated with measurable cognitive impairment in decision-making and strategic thinking tasks, while thermal discomfort diverts cognitive resources away from learning tasks [6].

The COVID-19 pandemic has fundamentally reshaped perspectives on IAQ in schools, accelerating adoption of mechanical ventilation systems and strengthening European regulatory frameworks for ventilation standards [7].

The PNRR-PNC necessARIA project, which will run for four years (2023-2026), aims to analyse the issue of air quality in Italian schools by evaluating possible technical and technological solutions to be tested in pilot cases by Di loreto and Peretti et al. [8]. The solutions analysed include manual window opening and Controlled Mechanical Ventilation (VMC) systems.

One of the "necessARIA" project's objectives is the analysis and integration of data for the assessment of health, engineering, air quality and cost aspects in support of policies and regulations [9]. This activity involves the analysis of VMC systems that can be installed in existing school buildings, with specific characteristics determined on the basis of the experience of the operational units involved [10,11]. To date, all the installations have been completed in 35 classrooms located in the Province of Bolzano, the Abruzzo Region and the Puglia Region. These installations, which are currently being monitored, are examples of best practice for future installations in Italian schools [12].

A tender model was produced for the installations, which specified the characteristics of the air exchange systems, including the installation of VMC systems outside the classroom and the installation of an effective distribution system that allows air exchange throughout the classroom. Preliminary results show optimal air quality levels in classrooms with VMC compared to similar classrooms without it. Air quality surveys involve continuous monitoring of CO_2 levels, temperature and relative humidity, subjective assessments by occupants of their state of health, and microbiological analyses, which will be conducted during the winter of the 2025-2026 school year.

It should contain the general background information, a description of the existing literature and/or the events that resulted in the production of the paper.

2 Controlled Mechanical Ventilation requirements

In order to ensure that VMC installations are repeatable, a tender model has been drawn up with specific technical and installation requirements. The criteria for VMC management, monitoring and control systems have been classified as “bonus criteria”. The characteristics of the VMC systems included in the tender document template, which was applied to ten schools in the three Operational Units involved, in a total of 35 school environments, are listed below.

Technical requirements:

- One VMC (Controlled Mechanical Ventilation) unit serving one, two (or more) classrooms: in the case of multiple classrooms, these must have the same orientation.

- Ventilation flow rate: application of the Minimum Environmental Criteria - UNI EN 16798-1 standard [13]. The flow rate must be guaranteed with the head necessary to ventilate the classroom.
- Position of the machine: in the corridor or technical rooms (bathrooms/storage rooms/etc.)
- Exhaust: in a different direction from the intake or at least at a distance defined by the manufacturer
- Distribution and extraction ducting in the classroom: avoid bypassing flows, comply with acoustic requirements
- To ensure acoustic comfort and the smooth running of lessons, low-noise systems must be installed to guarantee that the noise produced by the system is acceptable, in accordance with technical standards and legislation on system noise.

Monitoring and control system: award criteria detailed below.

- Electrical connections functional to the installation.
- Regulation: these criteria were considered as award criteria in the evaluation.
- System designed for integration and management based on regulation and control logic.
- Machine connection – regulation system: bus (via cable).
- Modbus protocol or other protocol.
- Possibility of manual switching on and off for holiday weeks.
- Flow rate adjustment
- Panel in the classroom (connected to the machine via bus or other wireless means): adjustment via operating levels.

2.1 VMCs installation of the necessARIA project's

As part of the necessARIA project, innovative VMC systems were installed in the following regions/autonomous provinces, as described in Table 1.

The eleven schools were chosen to be representative of the building types and crowding levels of schools in the regions and autonomous provinces involved, as well as to represent, from a geographical point of view, a representative distribution of the different average seasonal weather conditions of the Italian regional areas.

Table 1. Installation of the necessARIA project's

	Details about the installation	**Number of schools**
VMCs in Bolzano	Two types of installation. In one school, VMCs are installed in bathrooms or other ancillary rooms and ducted to classrooms. In the second school, a centralised VMC system is installed outside, serving four classrooms and a canteen.	2
VMC in Abruzzo	VMCs installed in bathrooms or other ancillary rooms and channelled towards the classrooms.	4
VMC in Apulia	VMCs installed in the ceilings of corridors and channelled towards the classrooms.	5

Figures 1 to 4 show some of the different installations of VMC systems. The different configurations (type of VMC machine, flow rates, types of air distribution systems, size and orientation of classrooms) will be analysed during the 2025-2026 school year, both in terms of IAQ, comfort and consumption, and in terms of occupant health, through the administration of a questionnaire.

Figure 1. Distribution system in the classroom (left) and VMC installed in the bathroom (right). One machine dedicated to each classroom. Primary school in Bolzano.

Figure 2. Distribution system in the classroom (left) and VMC installed outside (right). The machine serves four classrooms and a canteen. Primary school in Bolzano.

Figure 3. Distribution system in the classroom (left) and VMC installed in the bathroom (right). One machine dedicated to each classroom. Primary school in Abruzzo.

Figure 4. Distribution system in the classroom (left) and VMC installed in the corridor (right). One machine dedicated to each classroom. Secondary school in Bari.

3 Controlled Mechanical Ventilation and airing: a comparison

For a comparative analysis, six classrooms were selected in three schools: two in Bari, two in Bolzano and two in Nereto. Figures 5 to 7 show the CO_2 concentrations in the three schools (Bari, Bolzano and Nereto). For each school, one classroom with VMC and one classroom with manual window operation (airing) are shown.

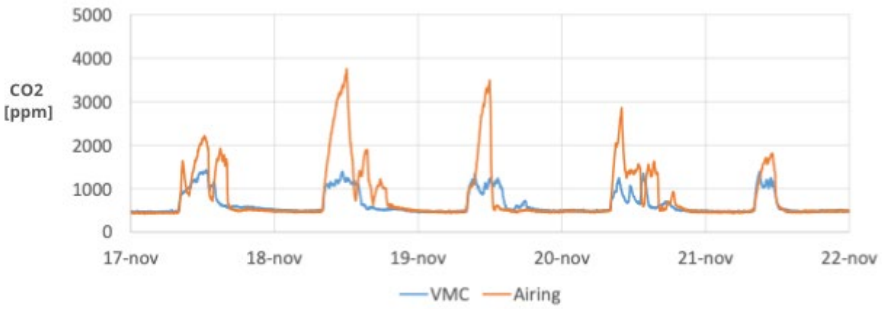

Figure 5. CO_2 (ppm) concentration during a school week. Comparison between a classroom with VMC and a classroom with airing (manual opening of windows) in Bari

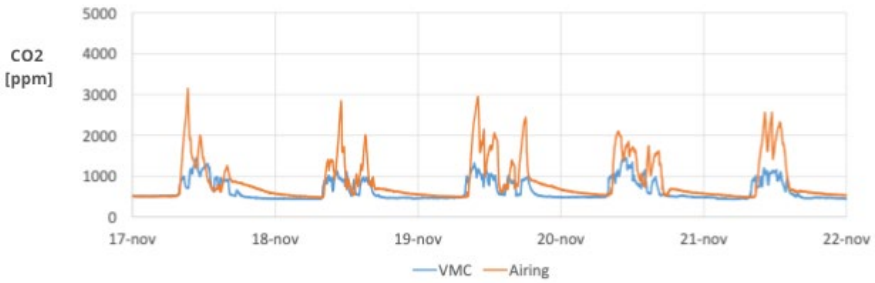

Figure 6. CO_2 (ppm) concentration during a school week. Comparison between a classroom with VMC and a classroom with airing (manual opening of windows) in Bolzano

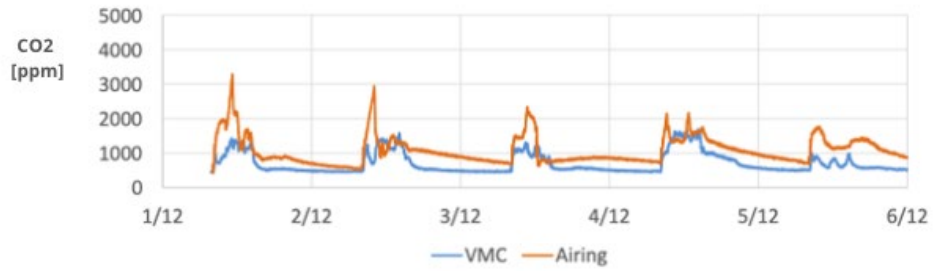

Figure 7. CO_2 (ppm) concentration during a school week. Comparison between a classroom with VMC and a classroom with airing (manual opening of windows) in Nereto (Teramo, TE)

In order to compare the performance of ventilation systems (VMC) with classrooms that are not equipped with them, the hours of occupancy (from 8:00 a.m. to 1:00 p.m.) were selected and the categories of the UNI EN 16798-1 standard were determined for these hours.

EN 16798-1:2019 specifies four categories of IAQ for non-adapted occupants, based on CO_2 concentration above outdoor concentration (Table B.9). The categories assume a standard CO_2 emission of 20 L/(h per person):

- Category I (High Quality): ≤ 550 ppm CO_2 added
- Category II (Medium Quality): 550–800 ppm CO_2 added
- Category III (Moderate): 800–1350 ppm CO_2 added
- Category IV (Low Quality): > 1350 ppm CO_2 added

For schools and other sensitive occupancies (hospitals, healthcare facilities, nurseries), Category II is the recommended target. This represents outdoor CO_2 baselines (typically 450 ppm) plus an added maximum of 800 ppm, resulting in absolute indoor CO_2 concentrations not exceeding approximately 1250 ppm under standard reference conditions.

The results are summarised in the histograms shown below in Figures 8 and 9.

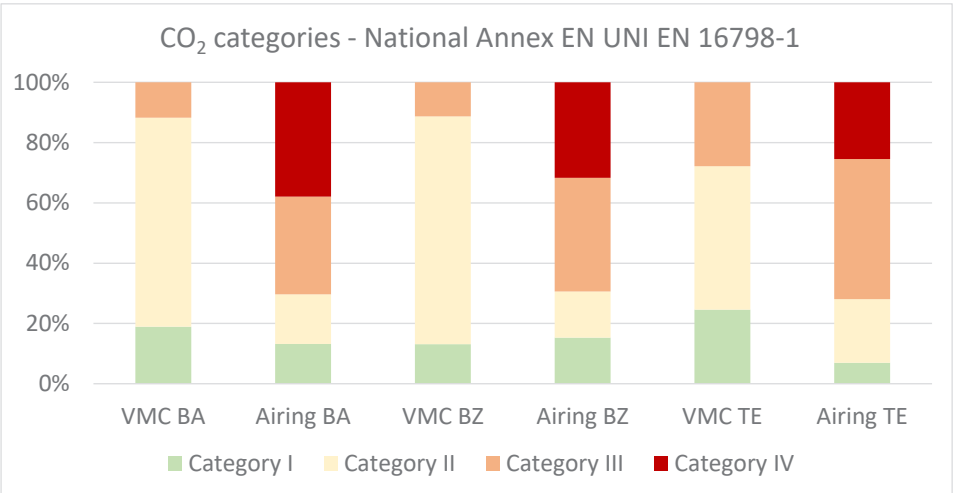

Figure 8. UNI EN 16798-1 categories for CO_2

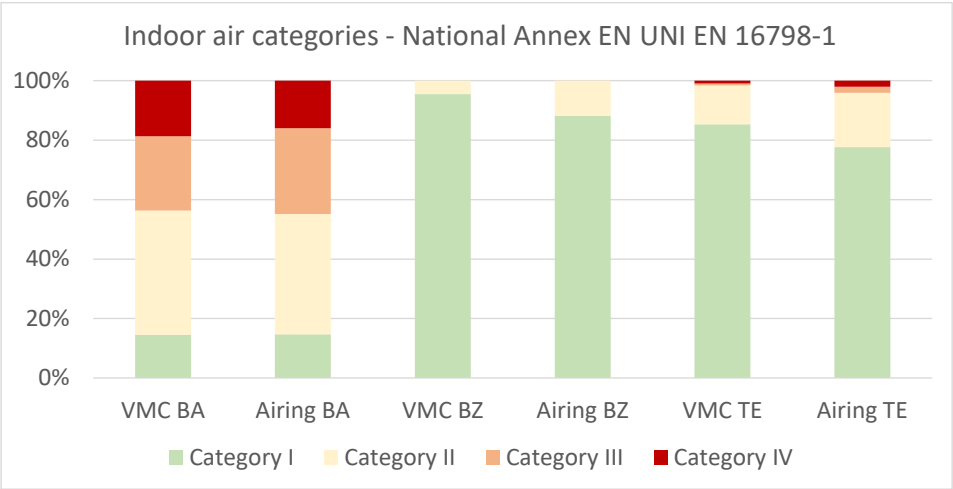

Figure 9. UNI EN 16798-1 categories for air temperature

When comparing mechanical ventilation (VMC) and airing, the clearest benefit concerns indoor air quality in terms of CO_2, while the effect on temperature depends more on the local climate and on how the emission systems are controlled.

In Bolzano, mechanical ventilation (VMC) brings a clear improvement in CO_2 levels compared with natural airing. With airing, the classrooms spend most of the occupied time in Categories III and IV, meaning CO_2 concentrations frequently exceed the recommended ranges. When VMC is used, time in the lowest categories (III–IV) is strongly reduced and the distribution shifts towards Categories I and II, indicating consistently better air quality. For indoor temperature, both strategies already perform very well. With airing alone, almost all the time falls within Categories I and II, and VMC only slightly increases the share of time in Category I. This suggests that in Bolzano the building and climate context allow good thermal comfort even with window airing, while VMC mainly adds value on the CO_2 side. Given that VMC, despite heat recovery, also reduces air temperatures, the difference must be sought in the different system configurations (number of radiators, distance from the generator) and classrooms (heat loss surfaces, orientation).

In Bari, the contrast between airing and VMC is very pronounced for CO_2. With natural airing, the classrooms spend a large portion of time in Categories III and IV, signalling insufficient ventilation and frequent CO_2 exceedances. When VMC is introduced, the distribution inverts: most of the time moves into Categories I and II, and Category IV conditions are virtually eliminated. This shows that, in this context, VMC is essential to reach acceptable indoor air quality classes. For temperature, however, the difference between airing and VMC is limited. In both cases, time is spread across all four categories, with only about half of the time in Categories I and II and a significant fraction in III and IV. This indicates that thermal discomfort in Bari is influenced more by climate and building/system design than by the type of ventilation alone, and that VMC does not by itself resolve the thermal comfort issues.

In Nereto under airing, the majority of the time is spent in Categories III and IV, reflecting inadequate air renewal. With VMC, Category IV essentially disappears and the time is redistributed mainly into Categories II and III, with some increase in Category I. For indoor temperature, both airing and VMC deliver generally good performance. Most of the time falls

within Categories I and II in both cases, and VMC only slightly reduces the already low occurrence of Categories III and IV. As in Bolzano, this indicates that the building and local climate support good thermal comfort with simple airing, while VMC provides a modest additional benefit on temperature but a more relevant one on CO_2 control.

4 CONCLUSIONS

The necessARIA project has defined and tested replicable Controlled Mechanical Ventilation (VMC) solutions in 35 classrooms across three Italian climatic contexts, supported by a standard tender specification. The comparative analysis between VMC-equipped classrooms and those relying solely on manual window opening shows a clear and systematic improvement in indoor air quality in terms of CO_2 concentrations. In all three case-study schools, VMC markedly increases the share of time in UNI EN 16798-1 Categories I–II and almost eliminates Category IV, which can reach up to 60% of occupied hours with airing only. For indoor air temperature, the difference between VMC and airing is less pronounced and strongly influenced by the local context. These findings highlight that VMC is a key tool to guarantee adequate IAQ in schools, but must be integrated with careful design of envelope, heating system and control strategies. Ongoing monitoring, including microbiological analyses and occupants' health questionnaires, will allow a more comprehensive assessment of global IEQ, energy performance and health outcomes, providing an evidence base for future technical guidelines and regulatory measures.

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References

1. A. Latini, S. Di Loreto, E. Di Giuseppe, M. D'Orazio, C. Di Perna, V. Lori, F. Serpilli, Assessing People's Efficiency in Workplaces by Coupling Immersive Environments and Virtual Sounds, in: 2023: pp. 120–129. https://doi.org/10.1007/978-981-19-8769-4_12.
2. S.S. Korsavi, A. Montazami, D. Mumovic, The impact of indoor environment quality (IEQ) on school children's overall comfort in the UK; a regression approach, Building and Environment 185 (2020). https://doi.org/10.1016/j.buildenv.2020.107309.
3. C. Balocco, L. Leoncini, Energy cost for effective ventilation and air quality for healthy buildings: Plant proposals for a historic building school reopening in the covid-19 era, Sustainability (Switzerland) 12 (2020) 1–16. https://doi.org/10.3390/su12208737.
4. C. Peretti, W. Pasut, G. Emmi, M. De Carli, Comfort and perceived air quality in refurbished social houses with mechanical ventialtion system: The impact of occupants behaviour, in: 2015: pp. 2887–2892. https://doi.org/10.1016/j.egypro.2015.11.659.
5. S. Di Loreto, M. Cantarini, S. Squartini, V. Lori, F. Serpilli, C. Di Perna, Assessment of speech intelligibility in scholar classrooms by measurements and prediction methods, Building Acoustics 30 (2023) 165–202. https://doi.org/10.1177/1351010X231158190.
6. A.M. Coggins, V. Hogan, A.K. Mishra, D. Norton, D. Foster, N. Wemken, H. Cowie, E. Doherty, Corrigendum to "Energy retrofits: Factors affecting a just transition to better indoor air quality" [Indoor Environ. 1 (4) (2024) 100058] (Indoor Environments (2024)

1(4), (S2950362024000559), (10.1016/j.indenv.2024.100058)), Indoor Environments 1 (2024). https://doi.org/10.1016/j.indenv.2024.100067.

7. S. Di Loreto, M. Falone, M. Pierantozzi, S. Montelpare, Field Measurements of Indoor Environmental Quality in School Buildings Post-COVID-19: Systematic Review, Applied Sciences 15 (2025). https://doi.org/10.3390/app15105692.
8. S. Di Loreto, C. Peretti, L. Verdi, M. Pierantozzi, A. Marcon, S. Montelpare, Development of an Informative Protocol for Environmental Assessment in Schools: A Comparative Case Study Between North and South Italy, in: C. Zilio, F. Busato, L. Mazzarella, M. Noro (Eds.), Proceedings of the 15th REHVA HVAC World Congress - CLIMA 2025, Springer Nature Switzerland, Cham, 2026: pp. 400–410.
9. M.F. Rossi, F. Beccia, R. Leone, C. Peretti, L. Verdi, C. Di Perna, S. Montelpare, G. Caggiano, U. Moscato, necessARIA Working Group, Impact assessment of Controlled Mechanical Ventilation systems for air quality in school buildings: a study protocol, Epidemiology, Biostatistics, and Public Health 20 (2025). https://doi.org/10.54103/2282-0930/28136.
10. D. Colarossi, S. Di Loreto, E. Tagliolini, P. Principi, F. Serpilli, Multi-Objective Optimization Of Thermo-Acoustic Comfort Of School Buildings, Building Simulation Applications 2022-June (2022) 59–67. https://www.scopus.com/inward/record.uri?eid=2-s2.0-85176499177&partnerID=40&md5=871487bffd54a6312daf188db9b990f5.
11. F. Serpilli, S. Di Loreto, V. Lori, C. Di Perna, The impact of mechanical ventilation systems on acoustic quality in school environments, in: 2022. https://doi.org/10.1051/e3sconf/202234305002.
12. C. Peretti, L. Verdi, G. Fulici, U. Moscato, C. Di Perna, S. Montelpare, Dall'esperienza locale a quella nazionale: il progetto necessARIA e la condivisione delle competenze., in: C. Zilio, F. Busato, L. Mazzarella, M. Noro (Eds.), Atti Di Ecomondo 2024, Rimini., Maggioli S.p.A., 2024.
13. U. EN 16798-1:2019, Energy performance of buildings - Ventilation for buildings - Part 1: Internal environment input parameters for the design and assessment of the energy performance of buildings in relation to indoor air quality, thermal environment, lighting and acoustics - Module M1-6, UNI (2019).