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Systematic Review

Indoor Air Quality in Naturally Ventilated Primary Schools: A Systematic Review of the Assessment & Impacts of CO_2 Levels

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Abstract: Indoor air quality (IAQ) in schools significantly impacts occupant health and academic performance, especially in naturally ventilated (NV) classrooms, where CO_2 levels are often elevated. This systematic review synthesises findings from 125 studies, examining CO_2 as an indicator of ventilation rates (VRs) and its impact on IAQ, health, and academic performance in NV primary school classrooms. This analysis highlights seasonal and temporal variations in CO_2 concentrations, revealing a median CO_2 concentration of 1487 ppm across 2444 classrooms, with 81% exceeding the recommended 1000 ppm threshold. Influencing factors include VR, occupant density, generation rates, and occupant behaviours. Increased VRs consistently lowered CO_2 levels and enhanced IAQ. CO_2 concentrations correlated with particulate matter, volatile organic compounds, bioeffluents, microbial concentrations, and bacteria and fungi levels, but not with traffic-related pollutants like NO_2, which is associated with asthma prevalence. Elevated CO_2 levels consistently correlated with fatigue, headaches, respiratory symptoms, reduced academic performance and absenteeism, suggesting potential socio-economic benefits of increased VRs. However, effective IAQ management requires balancing ventilation with considerations of thermal comfort, noise, and outdoor pollutants. The findings highlight the need for standardised IAQ indices and CO_2 monitoring protocols, offering insights for future research, intervention design, and investment aimed at enhancing classroom environments.

Keywords: carbon dioxide (CO_2); primary schools; classrooms; ventilation; indoor air quality; student health; cognitive performance

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1. Introduction

The primary function of the school building is to provide learners with an optimal indoor environment that facilitates learning and emotional, behavioural, and cognitive development [1]. Indoor air quality (IAQ) has emerged as a critical concern in indoor educational environments due to its significant implications on student health and academic performance [2–13].

On average, classrooms accommodate four times more people per square metre than typical office spaces [9]. The high occupancy densities (ODs) in school classrooms result in high internal gains and emissions of body odour together with various occupant-generated indoor pollutants [14]. Children are more vulnerable to indoor air pollutants than adults because their bodies and organs are actively developing [15]. Poor IAQ can negatively impact students' health and academic performance, leading to immediate and long-term consequences for their quality of life and economic implications for society [5]. Furthermore, children spend more time in school than in any other indoor environment, aside from the

home [16]. Primary schools were chosen as the focal point of this study as they present a unique worst-case scenario for IAQ challenges, given their high occupancy density (OD), younger occupants, and longer periods of classroom occupancy [10,17,18].

Classrooms worldwide are ventilated through either mechanical ventilation (MV), natural ventilation (NV), or a mix of both, depending on climate, building design, and infrastructure [19]. NV is prevalent in mild-temperate climates where temperature fluctuations are smaller and the reliance on outdoor air is a cost-effective strategy to manage IAQ [20,21]. Furthermore, school design guidelines in countries with mild climates often recommend NV [18,22,23]. Unlike MV, which uses fans and ducting systems to control airflow, NV relies on passive airflow through windows, doors, vents and leakage to introduce fresh air [19]. As a result, NV systems are more sensitive to external factors such as outdoor air temperature and wind speed, which can affect ventilation effectiveness and the stability of indoor air parameters [22]. By examining the unique challenges and potential IAQ management strategies for NV classrooms, this review provides context-specific insights for improving ventilation efficiency in mild temperate regions.

CO_2 levels are the primary metric for assessing VR and IAQ in classrooms [10,14] and are increasingly referenced in ventilation and IAQ standards [24]. CO_2 represents a practical and easily measured proxy for ventilation rates (VR) in occupied spaces [25,26]. CO_2 is a colourless, odourless, tasteless, and non-inflammable gas [24]. It is a natural constituent of the atmosphere, with normal outdoor concentrations ranging between 450 and 550 ppm and typical indoor CO_2 concentrations ranging between 500 to 1500 ppm [27]. CO_2 levels depend on the number of occupants, VR, outdoor CO_2 level, and room volume [28], and it is generally assumed that higher CO_2 concentrations indicate poor IAQ [6].

Research has indicated that classrooms with CO_2 concentrations exceeding 1000 ppm are potentially under-ventilated [28–33], with ideal VR maintaining indoor CO_2 concentration levels between 600 and 1000 ppm [34–36]. Elevated classroom CO_2 concentrations have been associated with increased concentrations of indoor pollutants [14,37], a decrease in occupant satisfaction with IAQ [38], an increase in the frequency of IAQ-related health symptoms [2,39], increased absenteeism [3,5], and a reduction in both learning performance and staff productivity [40,41].

The relationship between CO_2 levels and IAQ in NV classrooms is multifaceted [14] and influenced by VR [42], seasonal variations [43], OD [14], occupant behaviours [43], and the presence of other pollutants [14]. Understanding the correlation between these factors is imperative for devising effective strategies to enhance IAQ in educational settings that optimise learning conditions for students. Classroom ventilation can be evaluated through CO_2 monitoring [26]. However, CO_2 distribution varies spatially and temporally, particularly in NV classrooms [28,44–47]. Existing guidelines provide inconsistent recommendations for the location and height of CO_2 sampling points and little information regarding the number of sampling points [48]. The absence of clear standards for CO_2 monitoring may lead to inconsistent results due to the variability of classroom CO_2 concentrations [46]. Standardised CO_2 monitoring protocols specifically developed for NV classrooms are required for the accurate assessment and management of ventilation conditions [48].

The context, motivation, and scope of this review are detailed in a previously published review protocol [18]. This review aims to provide a unique and practical perspective on the existing literature, exploring the associations between CO_2, VR, and IAQ and their effects on health and academic performance through the lens of a CO_2 sensor. It presents an overview of CO_2-based ventilation standards and a thorough assessment of CO_2 sampling methods. The findings provide essential insights into the assessment of CO_2 levels, IAQ, and ventilation adequacy, highlighting their associations with student health and academic performance. This review objectively outlines the determinants, risks and challenges associated with elevated CO_2 levels in NV classrooms in regions with mild temperate climates. Evaluating the current state of IAQ and the effectiveness of ventilation strategies is crucial for informing future research directions, targeted interventions and investment decisions aimed at optimising these learning environments.

2. Methods

The methodology employed in this review, along with the research scope and rationale, is comprehensively detailed in a previously published protocol [18]. Figure 1 illustrates the PRISMA systematic review process followed in this study. The research was systematically divided into six key components (Supplementary Material, Table S1), each addressing a specific aspect of the study, which guided the formulation of the search terms. These search components included CO_2-based IAQ standards, measured CO_2 concentration, determinants of CO_2 levels, correlations with IAQ, CO_2 sampling methodologies, and CO_2 associations with student health and academic performance.

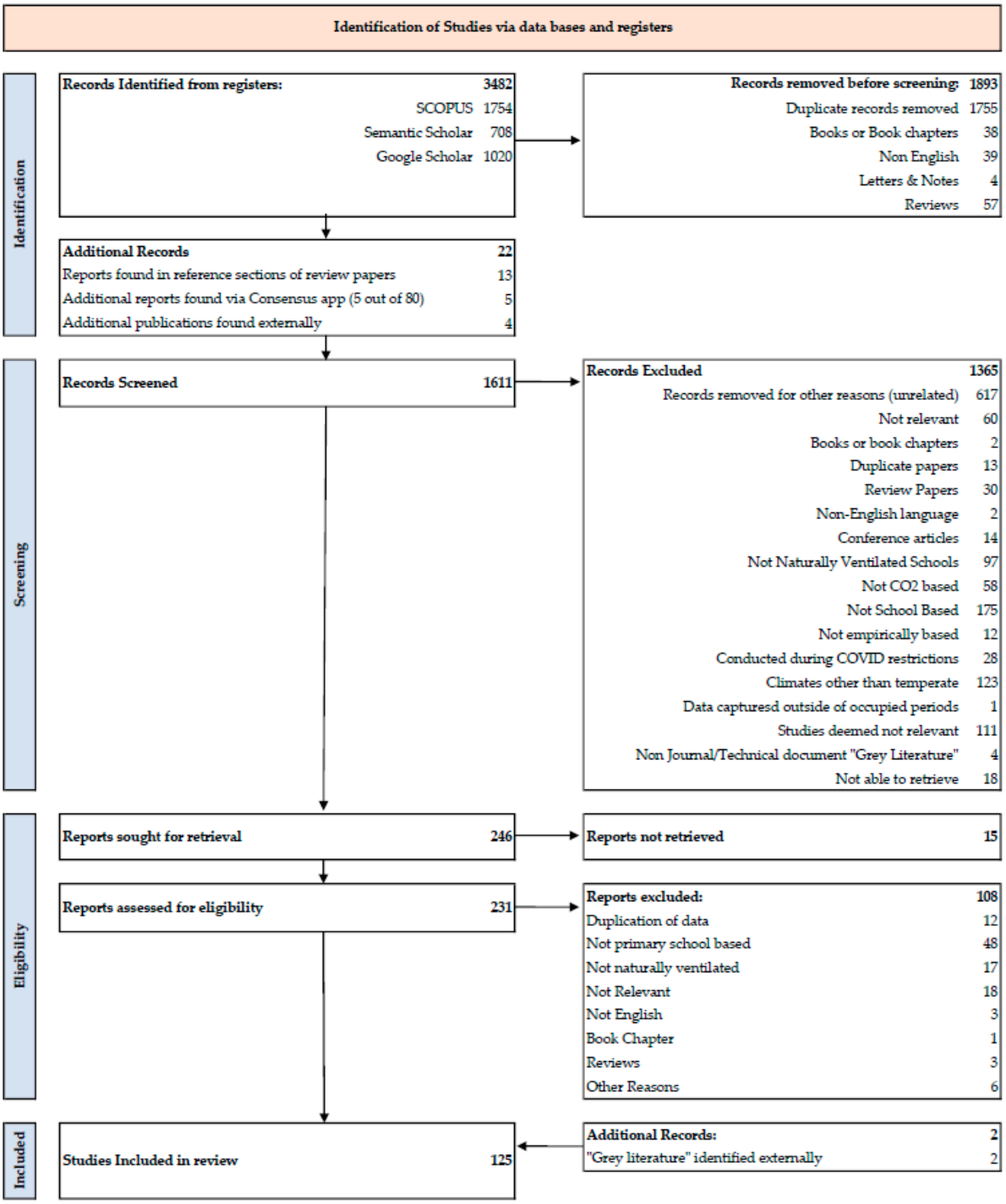


Figure 1. PRISMA flowchart of the systematic review process.

Publications related to classroom CO_2 concentrations, VR, IAQ, and their associations with occupant health and performance were identified through online searches of peer-reviewed journal databases and registers. These searches were conducted in February 2024 using various English-language search terms and Boolean search strings. The search terms for each research component were derived, tested, and optimised through scoping exercises, as detailed in the review protocol [18]. Additional records were sourced externally from government websites, the reference sections of review papers, and through the Consensus AI search engine.

Strict adherence to the predefined inclusion criteria (Supplementary Material, Table S2) was maintained throughout the screening process. Studies published in English that reported CO_2 measurements in NV primary schools located in mild temperate climates were included, irrespective of study duration, season, sample size, or year of publication. Data from day-care centres, preschools, secondary schools, colleges, universities, and laboratory-based studies was excluded. Studies relying on simulations or statistical models rather than actual measurements were also excluded. A complete list of included and excluded studies is available on request.

The methodology for data extraction, analysis, and synthesis is described in detail in the protocol paper [18]. Data extracted from the included studies encompassed the following: study title, author names, year of publication, geographical location, study duration, participant numbers and age, environmental conditions (e.g., season), air quality data and sampling methodology, any interventions implemented, and the methods and results for assessing student health, productivity, and performance in relation to IAQ.

In line with PRISMA guidelines, each study was evaluated to determine whether potential biases were addressed in its design, execution, and analysis. Studies employing longitudinal, cross-sectional, and intervention methodologies were included. Thematic coding was applied to identify and interpret patterns in the data relevant to each research component. To facilitate the synthesis of findings, tables summarising study characteristics and results were prepared, and visual representations of key findings were developed where appropriate.

The comparative analysis identifies current research gaps and offers valuable insights for future research directions. Significant findings within each classification will be discussed to inform the development of the future research agenda. The conclusions aim to underscore the consistency of findings across different studies, considering study quality and the management of potential confounding factors.

3. Results

3.1. CO_2-Based Air Quality Standards

CO_2 concentration is currently adopted by the most relevant international regulations and standards as a key parameter for IAQ evaluation [24]. Although it is widely researched, a common standard index for IAQ does not exist [27,49], and different standards prescribe different CO_2 limits and methods for the evaluation of IAQ [36]. Table 1 presents the CO_2 limits for classrooms from international standards and national regulations as presented in the included literature. In general, a CO_2 concentration exceeding 1000 ppm is an indication of insufficient ventilation [28] and reduced odour removal [49]. The current European standard (EN16798, 2019) Category 1 limit for CO_2 levels is 950 ppm, assuming a 400 ppm outdoor concentration [36]. The current UK standard, BB101 2018 [50], requires NV classroom daily average concentrations of CO_2 to be less than 1500 ppm (1000 ppm if MV) during the occupied period. Additionally, maximum concentrations should also not exceed 2000 ppm (1500 ppm if MV) for more than 20 consecutive minutes each day [50]. Both mean and maximum thresholds are specified to apply only when occupancy is equal to design occupancy or lower [36]. The 1000 ppm minimum requirement is recommended by most standards referred to in the literature [31,33,36,51–55], including the European Office of the WHO and ASHRAE [56].

Most standards, including the standards relevant to classrooms in Western Northern-hemisphere climates such as the European standard EN16798 [36], the British Building Bulletin 101-BB101 [50], and the ASHRAE 62.1 [53], are based on the findings of studies with adult subjects and assume that the determinants of IAQ are similar in children [36]. However, studies have reported systematic discrepancies between the actual perceptions reported by students and the predictions made according to the current comfort standards [53]. No standard proposes a combined IAQ and thermal comfort analysis for classrooms [36]. However, CO_2 and temperature are significant predictors of perceived IAQ, accentuating the need for an integrated approach to developing IAQ and thermal comfort standards simultaneously [10,38]. The perception of IAQ by classroom occupants is inversely proportional to the operative temperature and CO_2 concentration [38,57–59]. Korsavi et al. [35] surveyed air sensation votes of 805 primary school children from 29 NV classrooms across 8 UK schools. They found that perceived air quality improved by 23% when CO_2 levels were below 1000 ppm and by a further 20% when temperatures were maintained below 23 °C [35]. Further to this, the findings suggest that there are changes in the way students perceive IAQ depending on the season. During non-heating seasons, IAQ is more closely related to CO_2 levels than to operative temperatures, while during heating seasons, IAQ is more closely related to operative temperature than to CO_2 levels [35].

Occupant-generated CO_2 is also considered a good indicator of air stuffiness [34]. In 2008, the University of Paris-Est, Scientific and Technical Building Centre (CSTB) developed the ICONE (Indice de CONfinement d'air dans les Ecoles) air stuffiness index, which is used for the mandatory control of IAQ in schools and nurseries in France [34]. The index is calculated with the frequency of time spent in the concentration ranges between 1000 and 1700 ppm and above 1700 ppm. The scale of the index goes from 0 to 5, where 0 corresponds to no stuffiness and 5 corresponds to extreme stuffiness. The index reflects air change quality during occupancy only, and a building's overall score is determined by the highest value recorded from instrumented classrooms [34].

The proposal to integrate classroom IAQ and thermal comfort into a unified standard would enhance the ability to make informed trade-off decisions regarding IAQ management in classrooms. However, the differences in how a typical classroom is defined across different regions would pose a significant challenge to the implementation of such a standard. This diversity in classroom characteristics may contribute to the observed differences in the IAQ standards, as evidenced in Table 1.

Table 1. Comparison of standards for classroom CO_2 concentrations.

Location	Standard	CO_2 Level	Ref.
Ireland	Code of Practice for Indoor Air Quality—HSA, 2023	<1000 ppm ideal, above 1400 ppm action required	[55]
Europe	EN16798—Annex A, 2019	Cat1 < 550 ppm, Cat2 < 800 ppm, Cat3 < 1350 ppm, Cat4 < 1350 ppm. Above outdoor CO_2 levels	[36]
UK	BB101, 2018	NV classrooms: daily average < 1500 ppm and should not exceed 2000 ppm for more than 20 consecutive minutes each day.	[50]
New Zealand	NZ Ministry of Education guidelines 2017	Not above 1500 ppm	[51]
UK	ESFA, 2016	Mean CO_2 < 1500 ppm Tolerance up to 2000 ppm over 20 min	[52]
Switzerland	SN 520180 (2014)	2000 ppm	[60]
Portugal	Portatia no 353-A, 2013	Mean CO_2 < 1250 ppm	[52]
Portugal	RECS, 2013	1250 ppm	[53]
USA	ASHRAE 62.1, 2013	700 ppm above outdoor concentrations	[53]

Table 1. *Cont.*

Location	Standard	CO_2 Level	Ref.
Poland	PL-EN15251:2012	500 ppm + CO_2 of intake air	[54]
Russia	GOST 30494-2011	Optimal values: 500–800 ppm, Acceptable limit 1400 ppm	[54]
Ukraine	DDBN B.2.2-3:2018 with reference to DSTU B EN 15251, 2011	750–1200 ppm	[54]
Europe	EN15251, 2007	500 ppm above outdoor concentrations	[53]
Germany	DIN EN 15251, 2007	750–1200 ppm	[54]
Portugal	Decreto-lei n.o 78, 2006a; Decreto-lei n.o 79, 2006b	Maximum reference concentration < 984 ppm +/−10%	[52]
UK	"Ventilation in School Buildings. Standards and Design Manual", 2006	1500 ppm limit for a school day	[54]
UK	Building Bulletin 101, 2006	Mean CO_2 < 1500 ppm. 5000 ppm max should be able to achieve 1000 ppm	[31]
Germany	DIN1946-2, 2005	1500 ppm	[53]
Europe	EN 13779 classification of indoor air (IDA), 2004	IDA1 < 400 ppm, IDA2 400–600 ppm, IDA3 600–1000 ppm, IDA4 > 1000 ppm. Above outdoor CO_2 levels	[61]
Finland	Ministry of Health and Social Development Standard, 2003	Air quality: High—700 ppm, medium 900 ppm, satisfactory 1200 ppm	[54]
The Netherlands	Dutch Public Health Services (LCM, 2002)	1200 ppm	[61]
USA	Occupational Safety and Health Administration Recommendations 1994	800 ppm	[54]
New Zealand	Ventilation for Acceptable Indoor Air Quality" (NZS 4303, 1990)	<1000 ppm or less recommended	[51]
USA	ASHRAE 62-1989 Standards "Ventilation for Acceptable Indoor Air Quality"	1000 ppm	[54]
France	RSDT, 1978	Mean CO_2 < 1000 ppm. Tolerance up to 1300 ppm	[52]
Europe	World Health Organisation (European Office)	1000 ppm	[33]
Estonia	Standards of the Ministry of Social Affairs	1000 ppm—hygienic standard for schools	[54]
Finland	National Building Code—Part D2, 2010	1200 ppm	[53]
The Netherlands	"Overview of Indoor Air Quality Standards for Kindergartens in the Netherlands"	1000 ppm—hygienic standard for Kindergartens, 1200 ppm—hygienic standard for schools	[54]
USA	US Dept. of Health Reference Guide in Indoor Air Quality in Schools	limit: 1000 ppm	[54]

3.2. CO_2 Concentrations

A total of 75 studies, encompassing 1264 schools and 2444 classrooms, were included in this analysis. The European SINPHONIE study contributed the largest data set, consisting of 334 classrooms in 114 schools across 23 European countries. This extensive study was conducted by a consortium comprising 300 experts from 38 partners across 25 countries [33]. Additionally, several smaller studies that focused on CO_2 levels in individual schools were included [29,37,62–65]. One study, conducted in Turkey, measured CO_2 concentrations in a single classroom [64]. The most frequently observed pattern among the selected studies involved the assessment of 3 schools and 6 classrooms, representing the modal value.

Figure 2 illustrates the frequency distribution of mean CO_2 concentrations reported in the classrooms of studies included and analysed in this review. Only 8 of the studies

reported time-averaged CO_2 concentrations below 1000 ppm [10,66–72]. The mean CO_2 concentration across all analysed data sets was 1847 ppm, with a median value of 1487 ppm and mode of 1400 ppm being the most frequently occurring among these mean CO_2 concentrations. Figure 3 plots the mean, maximum, and minimum (where available) CO_2 concentrations measured in occupied school classrooms; for clarity, CO_2 values from the data sets of studies sampling multiple classrooms were averaged, reducing the number of data points in this graph. The highest mean CO_2 concentration, reaching 5346 ppm, was documented in a study examining 60 classrooms across 20 schools conducted during the heating season in Croatia [73]. The lowest recorded mean concentration was 644 ppm, identified in a study funded by the European Commission, which investigated the effects of IAQ on the respiratory health of schoolchildren in Norway, Sweden, Denmark, France, and Italy. However, this concentration was observed during the early summer period in School 4 Classroom B, a Swedish school equipped with mechanical ventilation [67]. The lowest mean CO_2 concentration recorded during the heating season in a NV classroom was 706 ppm, and this was recorded in a study involving 10 Portuguese schools [66].

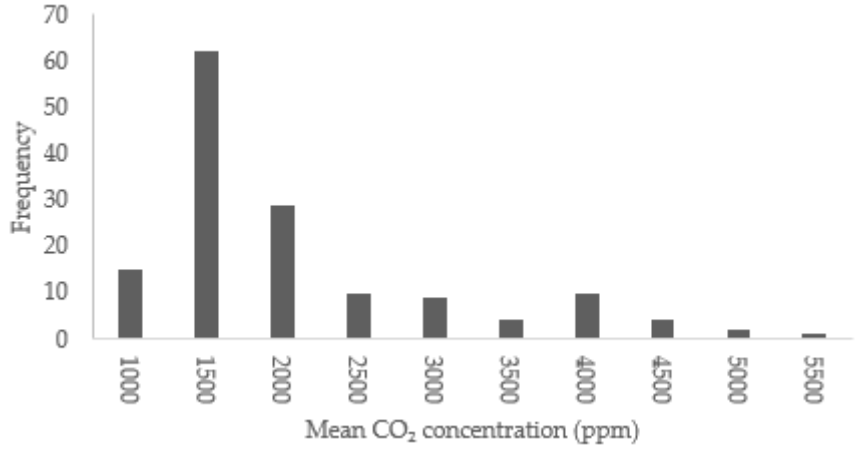


Figure 2. Frequency distribution of mean CO_2 concentrations (in ppm) observed in monitoring studies of classrooms identified in this paper.

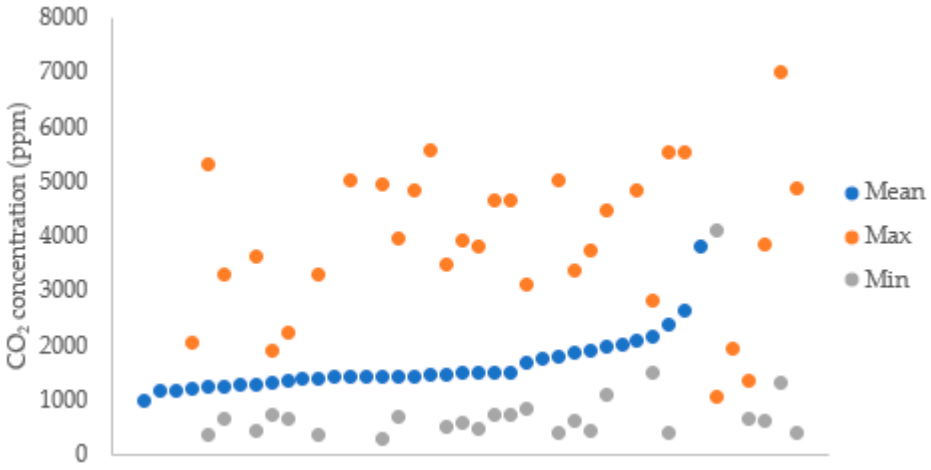


Figure 3. Plot of mean, maximum, and minimum CO_2 concentrations measured in classrooms where reported by the studies included in this analysis.

Eighteen different studies reported 25 instances where the CO_2 concentrations were greater than 4000 ppm [10,24,33,60,68,74–85], and 10 instances where CO_2 breached the 5000 ppm mark [10,68,76,81–85]. The average maximum CO_2 concentration documented across all data sets was 3136 ppm, with a median of 2831 ppm (and a mode of 5000 ppm be-

ing the most frequent concentration among these maximum values). The highest recorded CO_2 concentration, reaching 7000 ppm, was observed in a study examining eight classrooms within eight Portuguese schools during the winter [85]. Conversely, the lowest maximum CO_2 concentration reported for NV schools during the heating period was recorded at 1065 ppm. This finding stemmed from a study encompassing 60 classrooms across 30 schools conducted during the non-heating season (May–June) in Aberdeen [86].

Seventeen of the studies reported their results as the percentage of classrooms exceeding 1000 ppm [24,53,56,71,73,87–97], ranging from 41% [95] to 100% [24,53,71,73] and averaging 81%. Two studies, [75] and [97], reported mean CO_2 levels exceeding 1500 ppm in 85% and 61% of their sampled classrooms, respectively. Studies [56] and [97] reported mean CO_2 levels in excess of 2000 ppm in 66% and 43% of their classrooms, respectively. A further 8 studies presented their findings as a percentage of the time during which classroom CO_2 exceeded 1000 ppm [31,56,61,62,78,84,98,99]. The combined average of time above 1000 ppm for these studies was calculated as 83%, ranging from 64% [61] to 100% [98].

3.2.1. Temporal Variation

CO_2 concentrations increase rapidly from the start of the day [31], often exceeding 1000 ppm within the first hour of occupancy [58]. CO_2 build-up rates are inconsistent across classrooms [49], relating directly to the VR, number, and CO_2 generation rates of occupants [52]. Decay rates during unoccupied periods are typically slower, and, in some cases, minimal as a result of window closure and the airtight nature of new buildings [31]. Typically, two peaks of CO_2 concentrations were observed: one in the morning, coinciding with the start of the occupation period, and another in the afternoon, following lunchtime [30,31,52]. Data analysis revealed fluctuations in CO_2 concentrations at various time points throughout the school day, with levels increasing during teaching periods and decreasing during breaks [100,101], and declines during breaks were mainly attributed to brief periods of ventilation [70,84]. Using the data from the 62 classrooms, Santamouris et al. [101] determined that the CO_2 concentrations at the end of the break periods ranged between 400 and 2500 ppm with a median of 750 ppm, and that the corresponding concentration at the middle teaching period was found to vary between 650 and 2600 ppm, with a median of 1400 ppm; at the end of the teaching period, CO_2 levels varied between 750 and 3000 ppm, with a median value close to 1650 ppm. At the higher end of the scale, a pilot study conducted in 12 Bulgarian classrooms recorded a minimum CO_2 concentration of 572 ppm before students entered the classroom at 08:30, building to 4000 ppm before the 10:15 break, and subsequently reaching 5500 ppm when class resumed until the end of the school day [70]. These findings underscore the dynamic nature of indoor CO_2 concentrations and highlight the importance of considering temporal patterns when assessing and mitigating IAQ in educational settings.

3.2.2. Seasonal Variations

The findings highlight significant seasonal variations in indoor CO_2 concentrations in educational settings, with much higher mean CO_2 concentrations observed during the heating season [31,35,43,84,95,100]. A study of 92 German classrooms reported winter CO_2 levels exceeding 1000 ppm in 92% of classrooms, with 60% surpassing 1500 ppm [91,92]. Conversely, in the non-heating season, the percentage of classrooms with elevated CO_2 concentrations notably decreased, with only 28% exceeding 1000 ppm and 9% surpassing 1500 ppm [91,92]. The median CO_2 concentrations in winter and summer ranged from 598 to 4172 ppm and from 480 to 1875 ppm, respectively [91]. There appears to be no correlation between CO_2 concentrations measured in winter and summer, indicating distinct seasonal patterns [86,100]. Elevated CO_2 concentrations during the cold season have been attributed to poor VR in Albanian schools [84] and lower average window open areas during heating seasons (0.8 m^2) compared to non-heating seasons (2.4 m^2) in UK schools [43]. Dutton and Shao [102] reported CO_2 concentrations of over 1000 ppm for 10%, 4.7%, and

45.7% of the occupied time in a UK classroom for March, June, and October, respectively. Overall, these findings emphasise the importance of considering seasonal variations and ventilation practises when assessing and managing IAQ in educational environments.

3.3. Determinants of Elevated CO_2 Concentrations in Classrooms

3.3.1. Occupancy Density

A correlation was found between classroom occupancy and CO_2 concentrations across all studies. ASHRAE recommends an OD below 25 occupants per 100 m^2 (or 4 m^2 of floor area per person) for schools. Studies consistently reported significantly higher mean CO_2 levels from classrooms with high ODs (less than 1.5 m^2 of floor area per person) [33,43,76,84,90,92,103,104]. Rapid accumulation of CO_2 and a sensation of stuffy air was reported in densely occupied classrooms, highlighting the adverse effects of overcrowding [84]. Pegas et al. [32] found elevated CO_2 and bioaerosols in 28 overcrowded classrooms in Portugal. Korsavi et al. [43] found that OD (measured in m^2/p) explains 17% of CO_2 level variations in 29 UK classrooms. An Italian study observed lower concentrations of CO_2 in larger classrooms and classrooms with reduced occupancy, underlining the correlation between CO_2 levels and OD [36]. Statistical results present a significant correlation ($p < 0.001$) between CO_2 levels and OD [33,43]. A study of 92 German classrooms conducted by Fromme et al. [103] found that CO_2 was associated with low room volume. This finding suggests that considering height as a third dimension and calculating OD in terms of room volume per person (m^3/p) may provide a more accurate representation than the traditional metric of floor area per person (m^2/p).

3.3.2. Ventilation Rate

CO_2 is the most commonly used tracer gas for calculating ventilation rate [48], presenting a practical and simple proxy for ventilation adequacy in the presence of occupancy [26]. Research combining the experimental data from 287 naturally and 900 mechanically ventilated classrooms found that a CO_2 concentration equalling 1000 ppm represents an airflow of 8 l/p/s [101]. CO_2 levels of 800 ppm, 1250 ppm, and 2000 ppm correspond to fresh air supply rates of approximately 10, 6, and 4 L/s/person in a typical classroom [105]. Indoor CO_2 concentrations above 1000 ppm are widely regarded as indicative of unacceptable VR [28]. Thus, VRs in the order of 8 l/s per person are recommended in all teaching facilities [10]. The literature reveals significant concerns regarding VR in educational settings, with low ventilation levels identified as a primary factor contributing to elevated concentrations of CO_2 [29]. Inadequate ventilation was found to be the main contributing factor to increased levels of bioaerosols [32] and an increase in body odour complaints [28]. The SINPHONIE study [33] found a significant association between mean CO_2 concentrations and mouldy odour. The mean CO_2 concentration in classrooms with a mouldy odour was 1844 ppm, compared to 1436 ppm in those without [33]. The SINPHONIE study also reported that the majority of ventilation values fell below the desired standard of 4 litres per second per child, particularly prevalent in Western Europe [33]. A study by Mumovic et al. [68] found that all six classrooms with CO_2 levels exceeding 1500 ppm were in schools with natural ventilation. A Spanish study found that cross-ventilation is the most effective natural ventilation method for reducing CO_2 concentration levels in schools, as the airflow goes through the whole room [106]. Assuming 2000 ppm of CO_2 concentration, it would take 200 min with no apparent air ventilation (classroom closed) to achieve 1000 ppm, 47.62 min with only a door open, approximately 30 min with doors and windows open, and approximately 14 min with cross-ventilation [106]. However, current designs for natural ventilation in many schools do not appear to consider the use of openings or windows to improve classroom cross-ventilation [31].

3.3.3. CO_2 Generation Rates

Occupant generation rates (cm^3/s) were found to explain 14% of CO_2 variations in a study of 29 NV classrooms in the UK, underscoring the significance of human activity

in CO_2 accumulation [43]. Moreover, the age of the individuals in a room plays a crucial role in CO_2 production and vulnerability to poor IAQ, with children exhibiting higher metabolic rates and CO_2 exhalation compared to adults [106]. CO_2 spikes were particularly pronounced during physical activities, such as art classes or playground transitions, indicating the dynamic nature of CO_2 generation in educational settings [104]. These findings highlight the importance of considering human activity patterns and demographics when assessing and managing IAQ.

3.3.4. Occupant Behaviours and Adaptive Actions

Occupant behaviours such as window-opening can have a significant effect on indoor CO_2 concentrations in classrooms [90], potentially accounting for 63 to 87% of the total ventilation rate [107]. According to a study conducted in 29 classrooms in the UK, teachers are mainly responsible for opening and closing windows [43]. This study found that only 16% of window operations were carried out by children [43]. However, the study also reported that the upper limit of the thermal comfort band for the studied children is around 23 °C, while for their teachers, the upper limit is higher. In 20% of cases, teachers kept windows closed to avoid their own perception of thermal discomfort [43]. During the non-heating season, windows were predominantly left open, resulting in higher air change rates and lower CO_2 concentrations compared to the heating season, where window operation was less frequent due to concerns regarding cold temperatures and energy consumption [43,76,100]. Specific adaptive actions, such as window opening, were observed to improve indoor environmental quality, with a clear correlation between indoor temperatures and the resulting airflow rates [101]. However, statistical analyses revealed that there was no significant trend or preferred CO_2 level for window opening, with environmental factors such as temperature and humidity more likely to influence window interventions [101,102,108]; it would be counter-intuitive for teachers to open windows in winter to let in the fresh outside air with cold ambient temperatures [31]. A Canadian study found that the main reasons for using windows were to improve thermal comfort (81%) and IAQ (19%) [109]. The presumption that discomfort drives the majority of window interventions was found to be invalid in Dutton and Shao's case study [102]. Daily routines and habits were found to have a significant impact on the behaviour of occupants. The SINPHONIE study reported that 88% of window openings occurred during breaks [33], especially in the early morning [108]. During unheated periods, windows are most frequently opened in the early morning for ventilation and to prevent overheating later in the day [102]. Despite periodic window openings during breaks, particularly in unheated periods, such actions were often insufficient to maintain CO_2 concentrations below recommended thresholds [84,110]. Window opening for 15 min was found to reduce classroom CO_2 concentrations by 15% to 65% [111]. However, these values depend significantly on the indoor/outdoor temperature differential, window position, openable area, wind speed and direction [26,111]. The frequency of window opening was found to be influenced by various factors, including noise problems, weather conditions, and occupant behaviours, with occupants often relying on personal comfort rather than CO_2 levels to dictate window operation [60,64,102,108]. To effectively manage IAQ, strategies such as the use of signalling with CO_2 sensors or automated window-opening systems are recommended to ensure timely ventilation interventions [52,112,113]. Overall, these findings emphasise the importance of considering occupant behaviours and environmental conditions in promoting adequate ventilation and mitigating indoor CO_2 accumulation in educational environments.

3.4. Correlation Between CO_2 and IAQ

The correlation between CO_2 concentrations and IAQ in NV primary school classrooms can be influenced by various factors including, VR, occupancy, outdoor pollution, building materials, and cleaning practises [33,114,115]. Lowering CO_2 concentrations by increasing fresh air renewal rates is found to have beneficial effects on IAQ [31,42,66,85,91,116]. In-

door CO_2 concentrations are a useful proxy for IAQ investigations [14], and CO_2 levels (associated with VR) were a significant predictor of the concentration of particulate matter ($PM_{2.5}$) [85,91,115,117,118], total volatile organic compounds (TVOCs) [14,92,115,119], bio-effluents [59,85], microbial concentrations [7,14], and bacteria and fungi levels in schools [66,120]. While CO_2 did correlate with PM_{10} in some studies [37,42,91], this correlation was found to be inconsistent [79] or moderately linear [121] by others, with dust re-suspension due to occupancy being the most dominant factor influencing PM levels [37,52,79,100,115,116,122]. CO_2 levels were found to be a poor predictor for traffic-related pollutants [14], which increase with higher VR [94,104] and proximity to trafficked roads [90,122] and are linked to higher benzene and toluene concentrations [52].

Elevated CO_2, O_3, and $PM_{2.5}$ concentrations were observed in colder seasons, mainly due to reduced VR [31,94,95]. Outdoor sources of pollution, such as traffic, significantly influence IAQ, with schools near busy roads experiencing higher outdoor and sometimes lower indoor pollutant levels due to closed windows [52,90,104,122]. Outdoor NO_2 levels were found to be significantly higher during the heating season [14]. Urban schools were found to have NO_2 levels twice those of suburban schools [14]. Both NO_2 [33,94] and ozone [33] were lower than outdoor levels during the heating season, because windows and doors were more often closed during this period [32,95].

Behavioural interventions such as increased ventilation and cleaning practises have shown promise in reducing indoor PM and CO_2 concentrations [95,117,118]. A study conducted in Milan compared nine classrooms that implemented comprehensive daily cleaning practises, including HEPA-filtered vacuuming and regular ventilation through door and window opening, with those that did not. They found statistically significant differences ($p < 0.01$) between the two groups, with lower post-intervention indoor concentrations of $PM_{2.5}$ and CO_2 observed over a 5-day period in the classrooms that implemented cleaning practises. However, the interpretation of results was limited due to the absence of data on time-activity patterns [117]. Overall, these findings highlight the complex nature of the correlation between CO_2 and IAQ in schools and the importance of considering multiple factors, including ventilation, outdoor sources, and behavioural interventions, to promote healthier indoor environments for students and staff.

3.5. Measuring CO_2 Concentrations in Classrooms

Many national and international standards and guidelines on IAQ assessment have been developed worldwide. However, specific measurement protocols on CO_2 concentration levels that apply to NV classrooms are yet to be developed [28,47]. The method used to sample classroom CO_2 distribution is crucial to the accurate assessment of IAQ. The studies in this review used various approaches to the measurement of CO_2 based on the researcher's preferred sampling method, which can be compared with the findings of [47].

The average (median and mode) sampling duration across the relevant studies was 5 days. The longest sampling duration was 436 days, for a study examining the window opening behaviour in a NV school in the UK [102]. The shortest sampling duration was 5 min, recorded in a case study published in 2016 examining indoor environmental quality and its impacts on health in school buildings in Athens [123]; the sampling in this study was conducted across 4 schools during both heating and non-heating seasons. It must be noted that classrooms have large fluctuations in CO_2 concentrations throughout the school day, therefore single measurements are considered unreliable [124].

Approximately half of the studies recorded CO_2 concentrations during both heating (October to March) and non-heating (April to September) seasons, while 37% of studies took samples during the heating season only. The heating period is purported to provide a worst-case scenario of exposure for the most critical indoor parameters [87] and avoids the effects of pollen [88]. The remaining studies focused on the non-heating season due to the higher prevalence of window openings during this period [43,76,100] and the need to avoid municipal emissions [56].

Many studies followed the criteria set out in EN ISO 16000 [64,82,93,125] and ISO 7726 [35,43,72,83,123,126] when positioning their CO_2 sensors in classrooms. Sensors, typically non-dispersive infrared (NDIR) technology with reported accuracies falling within +/−50 ppm, were often located centrally in classrooms, away from walls, doors, windows, and active heating systems [10,82,85,87,102,118,127]. The most common CO_2 sensor position was wall-mounted, centrally, away from windows, doors, and active heating systems, and at least 1 m away from students [26,48,52,71,86,125,128,129]. One study [36] positioned CO_2 sensors in one of the four corners of the classroom so as not to disturb the normal operation of the classroom. Interestingly, in six out of eight classrooms, the CO_2 levels in this study were below 1000 ppm for most of the time and below 2000 ppm for over 95% of the time [36]. The median height of the CO_2 sensor was 1.1 m, to simulate the primary school children's breathing zone, which is considered to be between 1 and 1.5 m [93]. The minimum height of sensor placement was 0.2 m, which was in a study with 12 sensors positioned at 3 different sampling heights [47]. The maximum height of the CO_2 sensor was 2.2 m, and this location was considered child-proof [113].

Measuring concentrations at a single location or height may not be an accurate indicator or act as a representative for the whole measured space [47], as the highest CO_2 concentrations may result from persons breathing on the instruments [28]. A lab and classroom-based field study validation by Zhang et al. [48] positioned sensors at 1.1 m height on all 4 walls in their assessment of NV classrooms. They found that CO_2 concentrations in NV classrooms were always highest on the wall opposite windows, no matter the type of ventilation regime [48]. They recommend monitoring CO_2 concentrations in NV classrooms with two sensors, one positioned on the wall opposite windows and the other positioned on the front wall (nearest the teacher) [33].

A study conducted in three New Zealand NV primary school classrooms assessed whether the use of a single CO_2 monitor could predict the room's ventilation performance. The results indicated that a single CO_2 monitor placed at 1.5 m height on a wall, away from windows, doors, or air supply, and not directly under the breathing zone of occupants, produced a ±100 ppm temporal non-uniform variation of CO_2 concentrations. However, they concluded that using more than one sensor in an occupied space could significantly improve the accuracy of determining the average CO_2 concentration that is representative of the space [126].

Only 6 of the studies reviewed took CO_2 samples from multiple locations within the classroom. Mumovic et al. [68] and Ferrari et al. [125] took samples from 2 locations close to the occupied zone at the seated head height. Fernández-Agüera et al. [97] took 12 classroom CO_2 samples in a 3 × 2 matrix pattern at heights of 0.6 and 1.7 m. Muelas et al. [130] used 17 sensors positioned on walls and centrally on tripods at 3 different heights (0.75, 1.5, and 2.2 m) to provide a much higher spatial resolution, allowing the detailed characterisation of the CO_2 distribution in an NV classroom. The results of these tests consistently reported that CO_2 records were significantly lower for sensors installed on the walls [130]. Sensors installed at 0.75 m recorded lower than average CO_2 levels, sensors at 1.5 m yielded higher values, whereas sensors positioned at 2.2 m height produced results much closer to the room average [130]. Mounting sensors at a height of 2.2 m also has the advantage of being unobtrusive for both students and teachers and means the sensors are less prone to the effects of breath plumes [130]. Therefore, it can be considered to be a good option for sampling CO_2.

Mahyuddin et al. [47] utilised 12 CO_2 sampling points placed at 5 different locations with 3 different heights (0.2 m, 1.2 m and 1.8 m) in a university classroom in Reading. They observed great fluctuations in CO_2 concentration at different sampling points, particularly in NV classrooms. They concluded that placing only one sampling point in a specific location may produce an inaccurate mean value of the CO_2 concentration [47].

The outdoor CO_2 concentration should also be considered as part of the CO_2 sampling approach, as VR are often calculated based on the indoor/outdoor differential [37]. One outdoor sampling location is considered sufficient, and less than 50 ppm was found between

the two outdoor locations in Zhang, Ding, and Bluyssen's field study [48]. In this review, 14 studies measured external CO_2 concentrations as part of their sampling approach, and the time-averaged value for outside CO_2 was 422 ppm, ranging from 400 ppm [84] to 455 ppm [52]. However, the daily values for outside CO_2 during occupied hours can have high temporal variability [37]. A study conducted in Treviso, Italy recorded daily values ranging from 383 ppm to 560 ppm; these values indicate the necessity of using the measured values for outside CO_2 instead of daily or monthly averages [37]. It must be noted that air entering a classroom from neighbouring rooms may also influence measured CO_2 concentrations [68]. This potential influence should also be considered in the CO_2 sampling approach.

3.6. Associations Between Classroom CO_2 Concentration and Health

Table 2 provides an overview of the 15 studies, published between 1996 and 2022, that meet the inclusion criteria described in the methods section. These studies examined CO_2 levels in 572 classrooms across 258 schools during heating and non-heating seasons and reported their association with the health symptoms and absence rates of more than 8500 students and 400 teachers. Study features including location, CO_2 threshold, and sample size are included in the table. The associations of CO_2 concentrations with health symptoms were determined via questionnaires or surveys in 14 of the studies, with all studies reporting the prevalence of SBS symptomology with elevated CO_2 levels. Questionnaires and surveys on self-reported health symptoms were completed voluntarily, more often by parents or guardians for younger children [14,46,53,59,82], with responses from older children being considered more accurate [81]. Three studies assessed respiratory health symptoms, nasal patency, and inflammation markers through nasal lavage [104], spirometry [59,131], and exhaled nitric oxide tests [59], and they also reported improvements with lower CO_2 concentrations. Studies [24,104] evaluated the prevalence of IAQ-related health symptoms in teachers. Gaihre et al. [86] investigated the relationship between annual school attendance and average CO_2 concentrations.

Table 2. Association between classroom CO_2 concentrations and health.

Ref.	Study Location	NS [1]	NCR [2]	NP [3]	Association Between CO_2 Level and Occupant Health Effects
[86]	Aberdeen, Scotland	30	60		An increase of 100 ppm CO_2 was associated with a reduced annual attendance of 0.4 days of school per 190-day school year.
[67]	Norway, Sweden, Denmark, France and Italy	21	46	654	Schoolchildren exposed to CO_2 levels above 1000 ppm reported a significantly higher occurrence of dry cough at night and rhinitis with positive associations (5% increase in prevalence) for each 100 ppm rise in CO_2 concentration.
[97]	Andalusia, Spain	8	42	917	Dizziness, dry skin, headache and tiredness were found to correlate weakly with CO_2 concentrations. Greater symptomatology with open windows, while 72% of the measured values of CO_2 concentration levels were above 1000 ppm in these classrooms. However, itchiness and nasal congestion can be identified in periods when the windows are closed.
[123]	Athens, Greece	9	9	193	Significant increase in allergies, nose irritation, and fatigue with higher concentrations of CO_2. Girls seemed to be more sensitive to health effects than boys.

Table 2. *Cont.*

Ref.	Study Location	NS [1]	NCR [2]	NP [3]	Association Between CO_2 Level and Occupant Health Effects
[132]	Central Europe	64	64	1501	Positive associations were found between the occurrence of sore throat and higher CO_2 concentrations. The occurrences of headache and fatigue in children revealed significant positive associations with the levels of air stuffiness. A significant positive correlation was apparent between CO_2 concentrations and aldehyde concentrations, which are associated with respiratory, skin and eye irritation symptoms.
[131,133]	Coimbra, Portugal	51	81	1019	Children exposed to high CO_2 levels always have lower spirometric (lung function) values. Lack of concentration was also associated with elevated CO_2 concentrations.
[134]	London, UK	2	6	151	Higher indoor CO_2 levels were associated with general symptoms, fatigue, headaches, and muscle pain (Odds Ratio (OR): 1.1, 95% Confidence Index (CI): 1.0–1.2). Asthma prevalence in the school environment was associated with exposure to higher NO_2 levels (OR: 1.1, 95% CI: 1.0–1.2). Exposure to PM was associated with increased mucosal symptoms (OR: 1.4, 95% CI: 1.1–1.9) and eczema (OR: 1.3, 95% CI: 1.0–1.6).
[135]	Northern Portugal	25	69	882	This study found no evidence of a significant association between CO_2 and the prevalence of childhood asthma. However, reported active wheezing was associated with higher NO_2.
[124]	Norway	5	22	550	Symptoms including; headaches, tiredness, throat irritation, nose irritation, coughing, and irritations of the upper airway were found to increase significantly with rising CO_2 concentrations (1000–1499 ppm). Pupils in environments with CO_2 levels exceeding 1500 ppm were found to have a significantly higher grade of these symptoms.
[90]	Oporto, Portugal	11	76	177	Statistically significant correlation was found between central nervous system injuries (fatigue, headache, heavy headed, and concentration difficulties) and the levels of CO_2 and TVOC.
[87,92,93]	Porto, Portugal	20	73	1639	Positive correlation between CO_2 levels and bacteria concentrations. Higher levels of bacteria were significantly associated with higher odds of cough episodes. High levels of total VOC, acetaldehyde, $PM_{2.5}$ and PM_{10} were associated with higher odds of wheezing in children.
[88]	Uppsala, Sweeden	12	24	234	Air pollutants in the classroom air may influence nasal patency and inflammatory response in the nasal mucosa. Lower nasal patency (reduced nasal openness) was associated with higher CO_2 levels.

[1] Number of Schools. [2] Number of Classrooms. [3] Number of Participants.

Although the correlation between CO_2 levels and health may not be linear, the data in Table 2 overwhelmingly suggest that elevated CO_2 concentrations do impact the health of school occupants. The most commonly reported health issues associated with elevated CO_2 levels include increased levels of fatigue [90,97,123,124,132,134], lack of concentra-

tion [90,133], headaches [90,97,124,132,134], dizziness [97], dry cough [67,92,93,124], nasal patency [88,97] and nose irritation or rhinitis [67,123,124], and irritations of the upper airway [124] including sore throat [132] and lower spirometric (lung function) values [131].

Simoni et al. [67] found that schoolchildren across Europe who were exposed to CO_2 levels exceeding 1000 ppm exhibited a significantly higher risk for dry cough and rhinitis, with a 5% increase in prevalence reported for each 100 ppm rise in CO_2 concentration. Higher CO_2 concentrations were associated with increased allergies, nose irritation, and fatigue, particularly among girls in a cross-sectional study of nine NV schools in Greece [123]. High levels of CO_2 were associated with sore throat, headache, and fatigue in 64 Central European schools [132]. Elevated CO_2 levels have been observed to coincide with increased concentrations of bacteria [92], suggesting a potential linkage between CO_2 levels and microbial exposure within classroom environments. This association with higher bacteria concentrations may serve as an indirect measure of the risk of microbial exposure within educational settings. Elevated CO_2 levels correlating with higher bacteria concentrations have been associated with higher odds of cough episodes in Portugal [92]. Additionally, the correlation between elevated CO_2 levels and aldehyde concentrations has been linked to respiratory, skin, and eye irritation symptoms in a study across Central European schools [132]. Furthermore, there is evidence that high CO_2 concentrations are related to school absenteeism. A study involving 60 Scottish classrooms found that an increase of 100 ppm in CO_2 levels was linked to a reduced annual attendance of 0.4 days per school year [86].

A study involving 917 students across 8 Andalusian schools reported weak correlations between CO_2 concentrations and dizziness, dry skin, headache, and tiredness [97]. The same study reported a higher prevalence of itchiness and nasal congestion when windows were closed and CO_2 concentrations were above 1400 ppm (mean 1878 ppm). Interestingly, this study found that higher levels of perceived discomfort were reported when windows were open [97]. The authors attributed this finding to the possible presence of external contamination, which was not measured or incorporated into the study's analysis.

Branco et al. [135] used multivariate models to evaluate the associations between exposure to various indoor air pollutants and childhood asthma. After testing 882 primary school children in Northern Portugal, they found no significant link between classroom CO_2 levels and the prevalence of asthma [135]. However, the prevalence of asthma has been found to correlate significantly with high NO_2 concentrations [134,135] and traffic-related air pollutants [38] in urban UK schools. Increased concentrations of TVOCs and respirable particles were found to be associated with upper respiratory issues and mucosal irritation [90,134]. Madureira et al. [92] found that high levels of TVOC, acetaldehyde, $PM_{2.5}$, and PM_{10} were associated with higher reports of respiratory symptoms in Portuguese school children, with a twofold increased risk in asthma-related symptoms being attributed to higher TVOC levels.

While CO_2 levels can be considered a significant predictor of the concentration of TVOCs [14,92,115,119], $PM_{2.5}$ [85,91,115,117,118], bio-effluents [85,136], microbial concentrations [7,14], bacteria, and fungi levels in classrooms [66,120], studies investigating the association between indoor air pollutants' exposures in school indoor environments and children's respiratory health should not be limited to CO_2 as a global indicator of IAQ [135].

Air quality improvement represents an important measure for the prevention of adverse health consequences in children and adults in schools [137]. Efforts to improve the health of children and teachers should focus on the implementation of adequate ventilation [90]. CO_2 monitoring can be considered a cost-effective measure for the initial assessment of ventilation effectiveness. These findings suggest that modest increases in VR could significantly improve health outcomes for school occupants. Marginal reductions in CO_2 levels could have significant socioeconomic consequences, lowering student absences, leading to higher academic performance, and reducing the need for parents or guardians to miss work [113,138]. Moreover, improving air quality and working conditions should

result in improved teacher performance and the academic and economic benefits associated with lower rates of sick leave [6].

3.7. Associations Between Classroom CO_2 Concentration and Academic Performance

Four studies identified through the literature search met the inclusion criteria for this section of the review. Table 3 provides an overview of these studies, published between 2013 and 2022 [78,86,123,139]. These studies were conducted in 303 classrooms across 75 schools and involved over 8300 participants ranging in age from 5 to 13 years old. All 4 studies characterised IAQ in terms of measured CO_2. Measured CO_2 levels ranged from 350 ppm [139] to 4665 ppm [78] with a median value of 1400 ppm. Some studies [78,139] were performed during heating and non-heating seasons, while other studies [86,123] were performed during the non-heating season only. Studies [78] and [86] reported the results of national standardised tests, study [123] employed the SINPHONIE protocol for attention/concentration tests, and study [139] used standard progressive matrices for the assessment of cognitive function.

Table 3. Associations between classroom CO_2 concentrations and academic performance.

Ref.	Location	NS [1]	NCR [2]	NP [3]	Ventilation Method	Test Conditions	Cognitive Test	Sig	Magnitude
[78]	The Netherlands	27	216	5500	15% NV 85% MV	Mean CO_2 1495 ppm, range from 737 ppm to 4665 ppm. Heating and non-heating seasons.	National standardised tests	Yes	An increase in classroom CO_2 level during the school term by one standard deviation reduces subsequent test scores by 0.11 standard deviations
[123]	Athens, Greece	9	9	193	NV	High levels of CO_2. Non-heating season.	Attention/ concentration tests—protocol as per the SINPHONIE project	Yes	A negative correlation trend was found between the achieved scores and the CO_2 concentrations. An 17.01% increase in CO_2 concentrations lead to a 16.13% reduction in the performance.
[86]	Aberdeen, Scotland	30	60		NV	Average CO_2 1086 ppm. Non-heating season.	National standard for reading, writing, and numeracy	No	Time weighted average CO_2 concentrations were inversely associated with school attendance but not academic attainments.
[139]	Austria	9	18	436	NV	Average CO_2 1400 ppm, range from 350 ppm to 3300 ppm. Heating and non-heating seasons.	Standard Progressive Matrices	Yes	Cognitive function decreased significantly with increasing CO_2.

[1] Number of Schools. [2] Number of Classrooms. [3] Number of Participants.

The results from 3 out of the 4 included studies reported a significant inverse association between CO_2 levels and cognitive performance [78,123,139]. A 17.01% increase in CO_2 concentrations was reported to reduce student performance in attention/concentration tests by 16.13% in 9 NV Greek schools [123]. A longitudinal study conducted in the Netherlands, sampling 5500 pupils in 216 classrooms across 27 schools during heating and non-heating

seasons, found that an increase in classroom CO_2 levels by 1.0 standard deviation resulted in a subsequent reduction of 0.11 standard deviation in national standardised test results [78]. To underscore the significance of this finding, the researchers compared it against various other factors known to influence test scores. For instance, exposure to outdoor air pollution was associated with roughly half the baseline effect observed with elevated classroom CO_2 levels. Similarly, an 8-week interruption of in-person learning due to the COVID-19 pandemic resulted in an almost identical decrease in performance [78].

Gaihre et al. [86] did not find any significant association between time-weighted CO_2 levels and academic achievements in national standardised tests. This particular finding appears to be an outlier when compared to the results of the other studies listed in Table 3. It is possible that the unusual findings of this cross-sectional study could be attributed to the timing and duration of CO_2 measurements, which were conducted during May and June. During these months, classrooms tend to have greater levels of ventilation via open windows, which could also explain the lower-than-average reported CO_2 concentrations (1086 ppm) across the 60 schools surveyed in this study. The collective findings of the other studies offer persuasive evidence of a significant correlation between enhanced student performance and higher VR, as indicated by lower CO_2 levels.

4. Discussion

The impacts of short-term and chronic exposure to outdoor air pollutants are well-documented [140]. However, humans spend over 90% of their time indoors, where air pollution levels often far exceed those found outdoors [141]. IAQ has historically received less attention compared to environmental priorities like energy use, sustainability, and outdoor air quality [142]. With increasing evidence linking poor IAQ to adverse health outcomes, its importance has become more pronounced. This increasing body of research highlights the importance of understanding the determinants and effects of IAQ in different indoor environments. This review systematically evaluates the assessment of IAQ in NV primary school classrooms within mild temperate climates and its associated effects on students' health and academic performance through the lens of a CO_2 sensor. Only studies that utilised CO_2 as a metric were considered for inclusion in this review. Given that classrooms with students of similar age groups were chosen for analysis, it is reasonable to assume that their CO_2 generation rates remained relatively consistent across studies, although minor fluctuations in these rates cannot be entirely discounted. The findings should not be interpreted as indicating the direct influence of pure CO_2. In this study, CO_2 serves solely as an indicator of classroom air quality, reflecting variations in the concentrations of numerous other pollutants, including bioeffluents, which are the predominant air contaminants in occupied classrooms [143].

4.1. Air Quality Standards

While most IAQ standards recommend maintaining CO_2 concentrations below 1000 ppm, currently there is no universally accepted standard specific to schools [27,49]. Variances in IAQ standards can be attributed to regional factors such as building design, climate, and level of urbanisation. CO_2 and temperature are significant predictors of perceived IAQ [10,35,36,38]. However, current ventilation and IAQ guidelines often fail to integrate considerations for thermal comfort, which is critical for educational environments [36]. Ventilation guidelines adopted by schools are commonly based on findings from studies conducted in workplace settings involving adult participants and assume that similar IAQ determinants apply to children in classroom settings [36]. This presumption fails to address the specific requirements of school environments. Establishing a unified, holistic standard, specifically designed for schools, combining indoor air quality (IAQ) and thermal comfort, is essential. Such a standard should account for variations in classroom characteristics, ventilation procedures, and geographical factors, such as differences between urban and rural settings, and warm and cold climates. Establishing a universal standard specific to schools would facilitate the implementation of effective ventilation strategies and enable informed

decision-making regarding investments in ventilation within educational environments significantly improving classroom IAQ.

4.2. CO_2 Concentrations and Ventilation Strategies

A consistent pattern of CO_2 concentrations surpassing recommended thresholds (>1000 ppm) in NV primary school classrooms situated in mild temperate climates was documented in this review. Additionally, several studies reported instances of exceptionally high CO_2 levels (>5000 ppm) [10,68,76,81–85]. Analysis of the datasets highlights the considerable seasonal and temporal variability in CO_2 concentrations. This review collates and expands on the factors impacting classroom CO_2 levels, providing decision-making support to both educators and school building designers. In summary, these findings highlight the importance of considering factors such as room height for OD assessment [103], incorporating cross-ventilation in the design of NV classrooms [106], and acknowledging the impacts of occupant activities and behaviours when devising strategies to ensure sufficient ventilation and the mitigation of indoor CO_2 accumulation in classrooms [90,104].

Given the lack of a clear sensory perception of CO_2 levels [101,102,108] timely interventions such as CO_2 monitoring and alerting systems are essential for managing ventilation effectively [113]. Additionally, occupants should take the timing of interventions into account to maintain overall classroom comfort. For example, opening windows before class, during breaks, or at lunchtime facilitates the reduction of CO_2 levels without sacrificing thermal comfort. Developing an occupant awareness of the factors affecting IAQ, the consequences of insufficient ventilation, and how to address them is crucial. The modes for developing occupant awareness and prompting behavioural interventions require further examination to assess the potential efficacy of these interventions comprehensively.

4.3. CO_2 Monitoring

The lack of a universal approach for the evaluation and management of classroom VR through CO_2 monitoring poses challenges regarding the accuracy, reliability, and consistency of measurements concerning ventilation-related IAQ issues and their associated risks to student health and performance [28,47]. The findings of this review indicate that the assessment of ventilation adequacy through short-duration CO_2 sampling may be misleading. This is due to the variability in CO_2 concentrations linked to seasonal and temporal patterns, occupancy levels, occupant generation rates, and operational classroom behaviours. While infrequently utilised in studies, multiple sensor locations were found to enhance the accuracy of classroom CO_2 monitoring, capturing the considerable fluctuations observed across different spatial points in NV classrooms [47,48,144].

There is an apparent deviation between the guidance on sensor height and the findings in the literature. It is commonly suggested that sensors be placed at breathing zone height. However, studies that mounted sensors at different heights reported CO_2 levels lower than average at lower levels and higher than average at levels close to the breathing zone. However, sensors mounted at a height of 2.2 m were found to produce results closer to the room average, while also offering the benefits of being unobtrusive and less prone to the effects of breath plumes [130]. These findings also emphasise the importance of incorporating measured outdoor CO_2 concentrations as part of the sampling approach, given their significant regional and temporal variability. Additionally, the potential for air exchange from neighbouring rooms, which was not considered in any study in this review, should also be evaluated as part of the CO_2 sampling approach. Further experimental investigations aimed at establishing a more robust measurement protocol specifically tailored to classrooms, which integrates the aforementioned factors, are crucial for the accurate and consistent assessment of CO_2 levels. The development of such a protocol would facilitate the effective evaluation and management of classroom ventilation systems and enhance the validity and applicability of research findings across various educational settings.

4.4. CO_2 and IAQ

Lowering CO_2 concentrations through increased VR is consistently reported to have beneficial effects on IAQ. Behavioural interventions such as increased ventilation through scheduled window opening and cleaning practises have demonstrated promise in reducing indoor PM and CO_2 concentrations [95,117,118]. Conversely, CO_2 levels were found to be a poor predictor for outdoor sources of pollution such as traffic emissions, which increase with higher VR [94,104] and proximity to trafficked roads [90,122]. While CO_2 and VR are useful tools for IAQ assessment, it is evident that the consideration of other pollutants is necessary to ensure a healthy indoor environment [81]. Nature-based solutions present a compelling case for interventions, demonstrating promise in mitigating traffic-related pollutants. Tomson et al. [145] report that a green fence has the potential to reduce PM and NO_2 levels by up to 60% and 53%, respectively. Further investigations are needed to assess the acceptability of nature-based solutions in school environments to ascertain their feasibility as a mitigation measure.

These findings suggest that current ventilation and school design standards, designed to protect the health and well-being of students, are inadequate and contribute to significant IAQ issues. The presence of numerous harmful indoor air pollutants in NV classrooms suggests that an urgent revaluation of educational building design, procurement and air quality monitoring guidelines is needed [146]. Furthermore, an examination of the factors influencing the investment choices for school infrastructure development, especially concerning ventilation systems and air pollutant control, and establishing a framework for informed investment decisions concerning IAQ in educational settings, would constitute a critical first step toward fostering healthier environments that are more conducive learning environments.

4.5. CO_2 and Health/Absenteeism

The association between elevated classroom CO_2 levels (>1000 ppm) and occupant health is well-documented, particularly among young children, whose developing immune systems are more vulnerable to indoor air pollutants [10]. The findings of this review are consistent with those of Fisk [19] and Gangwar et al. [143], who also reported strong associations between CO_2 concentrations and the prevalence of respiratory disease in school children. The relationship between CO_2 concentrations and asthma prevalence exhibited some variability, while stronger associations were observed between asthma and traffic-related NO_2, as well as other indoor air pollutants like TVOCs [38,92,135]. This emphasises the importance of exploring diverse pollutants and mitigation strategies for the enhancement of IAQ and the quality of outdoor air sources.

Elevations in classroom CO_2 concentrations were also found to correlate with increased school absenteeism [86]. However, studies conducted in mechanically ventilated schools in the US have presented conflicting findings regarding the association between CO_2 levels and student absence rates [3,147]. The variability in results regarding this correlation highlights the need for further longitudinal investigations examining the relationship between CO_2 levels and illness-related absenteeism among school children. Additional studies of this nature, extended to include teachers, are essential for advancing the state of knowledge relating to this phenomenon in NV classrooms in mild temperate climates.

The findings indicate that improvements to school occupant health can be achieved through marginal increases in ventilation rate [67]. Decreasing CO_2 levels in classrooms is anticipated to yield significant health and socioeconomic advantages, including decreased student absences, leading to enhanced academic performance and reduced stress on parents or guardians, who may have to take time off work to care for sick children [113,138]. Moreover, enhancing air quality and working conditions can be expected to improve teacher performance and decrease sick leave rates, resulting in academic and economic benefits [6].

4.6. CO_2 and Performance

This review highlights a significant association between lower CO_2 levels and improved student performance, aligning with the findings of a review and meta-analysis conducted by Wargocki et al. [6] across classrooms with diverse ventilation methods. While the economic and social costs of performance declines linked to elevated CO_2 remain underexplored, preliminary estimates suggest that improving IAQ could be a more cost-effective approach for boosting standardised test scores than class-size reductions [148]. Addressing CO_2 levels in classrooms may therefore offer a practical intervention with broad educational and economic benefits.

Elevated CO_2 levels were reported to have a significant effect on the speed and accuracy at which students perform cognitive tasks. The requirement of additional time to complete tasks can also be quantified in monetary terms as redundant or unnecessary time for which teachers must be paid. While most studies to date have concentrated on the cognitive performance of students, it is reasonable to assume that inadequate classroom air quality will have detrimental effects on the performance of teachers, potentially contributing to an overall decline in learning outcomes.

Empowering teachers with an awareness and understanding of the fluctuating daily patterns of CO_2 concentrations would allow for tailored pedagogical approaches and strategic scheduling of learning tasks to periods of optimal environmental conditions, thereby mitigating the deleterious effects of elevated CO_2 levels on student learning outcomes. Such insights pave the way for low-cost interventions that enhance educational performance.

While the current results primarily concentrate on the cognitive performance of students, it is reasonable to assume that inadequate classroom air quality may also detrimentally impact the performance of teachers, thus potentially contributing to an overall decline in learning outcomes. Although there are studies investigating the effects of elevated CO_2 levels on office workers [149], there is a notable absence of research assessing the impact of classroom air quality on teaching performance [6].

4.7. Addressing the Challenge

Poor IAQ, indicated by high classroom CO_2 levels, emphasises the requirement for enhanced ventilation to promote student health and academic performance. While source control is the preferred method for reducing air contaminants, it can be insufficient, technically challenging, or economically unfeasible, especially in the context of NV classrooms [150]. Additional challenges include poor outdoor air quality, high OD, occupant behaviours, thermal comfort preferences, and energy efficiency regulations that promote airtight building designs. A holistic approach that combines prevention and mitigation strategies, supported by policy development, technological measures, and behavioural interventions is essential for addressing the challenge.

While there are many IAQ standards, there is a lack of consistent metrics or regulations for determining or assuring compliance in schools. Universal guidelines integrating IAQ and thermal comfort while accounting for classroom variability could bridge this gap [36]. These standards should mandate unified IAQ measurement protocols that reflect the specific needs of NV classrooms. Adherence to current IAQ guidelines is typically voluntary [151] and evidence shows that they are not being effectively implemented in schools. Establishing mandatory, evidence-based standards that are practical, acceptable, economically viable and readily enforceable would drive more consistent implementation and deliver measurable benefits to classroom IAQ.

Although outside the scope of this review, improved VRs can be achieved using MV or automated window-opening systems. Bakó-Biró et al. [10] found that MV systems can increase VRs from 1 l/p/s to 8 l/p/s, reducing CO_2 levels from 5000 ppm to 1000 ppm. Automated window opening systems have similarly maintained CO_2 levels below 1500 ppm, meeting the UK BB101 standard for NV classrooms [65]. In terms of improved building design for NV, cross-ventilation, as reported by Sánchez-Fernández et al. [106], can reduce CO_2 concentrations three times faster than single-sided ventilation.

However, these strategies can be cost-prohibitive and impractical for retrofitting in existing buildings, particularly in resource-constrained school settings [152]. Balancing intervention costs with their health and academic benefits is vital for effective implementation.

Occupant engagement is a critical yet unexploited strategy for improving IAQ in NV classrooms. Teachers generally employ an ad hoc approach to window opening that prioritises thermal comfort, frequently resulting in elevated CO_2 levels and poor IAQ [60]. Awareness campaigns, ventilation protocols, and CO_2 alerting systems have proven effective and affordable in addressing this issue. For example, Vasella et al. [60] found that awareness-raising reduced median CO_2 levels from 1600 ppm to 1097 ppm, increasing the percentage of teaching time with CO_2 below 1400 ppm from 40% to 70% across 100 NV classrooms. Continuous monitoring and visual alerting systems also show promise. Grimsrud et al. [153] reported sustained ventilation improvements with real-time CO_2 displays, while Avella et al. [112] observed CO_2 reductions of up to 42% using low-cost alerting systems. Such solutions are accessible and scalable, making them well-suited for resource-limited settings.

While the solutions outlined demonstrate promise, effective IAQ improvement strategies require careful planning and judicial implementation. The design and evaluation of ventilation enhancement measures must account for practicality, acceptability, and economic feasibility while addressing impacts on thermal comfort, energy consumption [101], and potential noise or pollutant infiltration [108]. An integrated approach that balances these factors can offer a sustainable and effective pathway to enhancing classroom IAQ.

4.8. Strengths and Limitations

As outlined in the review protocol [18], this study provides a comprehensive review linking CO_2 concentrations with VR, IAQ, health, and academic outcomes in NV primary school classrooms in mild temperate climates. Its strengths include its structured, multi-faceted approach covering six key areas, a rigorous literature search following PRISMA guidelines, and its reliance on peer-reviewed data. Several limitations include the reliance on data from cross-sectional studies with varied methodologies and sampling protocols across different durations and seasons, which limits generalisability and precludes a formal meta-analysis. The search scope for this review focuses exclusively on NV primary school classrooms in mild temperate regions. While this provides valuable insights specific to these conditions, it limits the generalisability of the findings to areas with different climate classifications, air quality standards, and school building design conventions.

5. Conclusions

CO_2 serves as a significant predictor of IAQ in classrooms. Classrooms often fail to meet recommended ventilation guidelines with CO_2 levels exceeding 1000 ppm in many cases, highlighting the inadequacy of current ventilation and school design standards. Factors such as seasonal variations, temporal patterns, VRs, and occupant generation rates and behaviours influence CO_2 levels in classrooms, highlighting the dynamic nature of this IAQ parameter. Monitoring CO_2 concentrations in classrooms offers valuable insights into ventilation efficacy and potential health and performance risks to school children. Establishing a unified measurement protocol tailored specifically to classrooms is required for accurate and consistent assessment of CO_2 levels. Given that human perception of CO_2 levels is negligible, monitoring and alerting interventions, together with the promotion of occupant awareness, should be integrated to school ventilation strategies. The evidence of associations between CO_2 levels and student respiratory health is compelling, as marginal increases in ventilation rate can yield significant improvements in school occupant health and improved academic performance. The findings of this review offer valuable insights that can inform future research directions, interventions, and investment decisions aimed at improving IAQ and school learning environments.

6. Recommendations for Future Research

- Research that examines the spatial and temporal distribution of CO_2 in a representative sample of NV classrooms would provide useful and novel information for optimal sensor placement and the development of accurate, consistent, and reliable CO_2 monitoring protocols.
- Longitudinal studies exploring the relationship between classroom CO_2 levels and illness-related absences among both students and teachers would advance the state of knowledge relating to the impact of CO_2 levels on attendance in NV classrooms.
- Research that evaluates the acceptability and efficacy of interventions for promoting ventilation awareness and enhancing ventilation practises in NV schools would provide useful information for the design of future ventilation enhancement measures.
- Research examining the impact of classroom air quality on teacher health and performance would provide valuable insights to the impact of CO_2 levels on teacher health and performance.
- Research that investigates the factors influencing investment choices for school infrastructure development would aid decision-makers in establishing frameworks for informed investment decisions that create healthier and more conducive learning environments.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/buildings14124003/s1, Table S1: Research framework, search terms, Boolean operation search strings, and keywords; Table S2: Inclusion and exclusion criteria.

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