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IMPACT OF INDOOR AIR COMPOUNDS ON PERFORMANCE, INCLUDING THE RELATION BETWEEN AIR COMPOUNDS AND COGNITIVE PERFORMANCE

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Abstract
Indoor air quality (IAQ) is identified as a primary determinant of cognitive performance, psychological well-being, and academic success among students. A comprehensive systematic review of literature published between 2000 and 2026 evaluated the accumulation of anthropogenic and ambient-derived pollutants, including carbon dioxide (CO2), particulate matter (PM2.5/PM10), volatile organic compounds (VOCs), and carbon monoxide (CO). Evidence showed that educational environments characterized by high occupancy and inadequate ventilation frequently lead to elevated CO2 concentrations exceeding 1500 ppm, which are robustly associated with diminished executive functions. Analysis revealed that particulate matter significantly increases error rates in attention-intensive tasks, while subclinical CO exposure is linked to heightened psychological distress and emotional lability. Furthermore, high TVOC levels were found to reduce task precision by approximately 5%. The integration of strategic environmental interventions, such as high-efficiency filtration and optimized air exchange, effectively mitigates these risks and enhances standardized assessment scores. Standardized IAQ monitoring remains essential as a cost-effective strategy to improve students' learning trajectories and ensure long-term academic competitiveness in higher education admissions.
Keywords: Cognitive performance; Indoor air quality; Particulate matter; Student health; Ventilation

INTRODUCTION

Concerns about the impact of poor indoor air quality have increased in recent decades, with common complaints including eye irritation, respiratory problems, headaches, fatigue and lethargy, and its impact on children's growth, particularly in school classrooms. Broader concerns about the health of school-age children are often attributed to poor indoor environments, which affect activity and can have substantial potential for adverse effects on productivity. Indoor Air Quality (IAQ) plays a vital role in shaping cognitive performance, emotional well-being, and educational success among students. Given that children spend many hours indoors at school, maintaining good IAQ is crucial for their educational experience. Numerous physical environmental factors may influence students' academic performance, but the indoor environmental quality of classrooms has been shown to impact both teaching and learning outcomes significantly (Hooper et al., 2005). The World Health Organization (WHO) estimates that over 90% of children worldwide live in environments where air pollution exceeds the annual mean PM2.5 limit of 10 μg/m³ (WHO, 2018). Short-term exposure to particulate matter can cause coughing, worsen asthma, and trigger other immediate breathing or heart problems (WHO, 2018). Improving indoor air quality through effective ventilation and pollutant control measures can enhance cognitive performance and reduce health risks for students (Carton et al., 2023; Hoek et al., 2026). Core indoor air pollutants, including carbon dioxide (CO_2), carbon monoxide (CO), particulate matter (PM2.5/PM10), volatile organic compounds (VOCs), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and ozone (O_3) are likely to build up in environments lacking

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adequate ventilation (Allen et al., 2016; Wargocki et al., 2000) This condition results in both acute and chronic health consequences (Mendell & Heath, 2005)

The indoor environment of schools has been a particular public concern for several reasons. First, schools are seen as particularly vulnerable to environmental deficiencies due to the large expenditures on operation and maintenance of inadequate facilities and their constant use throughout the week. Second, school-age and growing children are more vulnerable to some environmental pollutants than adults because they breathe higher volumes of air relative to their body weight and their tissues and organs are actively growing. Third, children spend more time at school than in any indoor environment other than the home. Adverse environmental impacts on student learning and performance in schools can therefore have direct consequences for both students and the school community.

The concentration of particulate matter is frequently elevated in educational settings such as classrooms and laboratories, often surpassing established safety limits due to high occupancy rates, insufficient ventilation, or emissions from construction materials (Cedeño Laurent et al., 2021; Dorizas et al., 2015). These pollutants are associated with diminished attention spans, slower cognitive response times, impaired memory functions, and heightened psychological distress (Toftum et al., 2015; Tsai, 2021). Furthermore, poor IAQ leads to increased absenteeism and lower performance on standardized assessments, which significantly affect students' academic pathways (Chinazzo et al., 2019; Shendell et al., 2004). Carbon monoxide poisoning also poses a considerable hazard because it can lead to enduring neurocognitive impairments if exposure occurs (E. Kim et al., 2021).

METHOD

A comprehensive systematic review was conducted to evaluate the impact of indoor air compounds on cognitive performance and student health. The literature search was executed across major academic databases including Consensus, Semantic Scholar, and PubMed, targeting studies published between 2000 and 2026. The search strategy utilized eight unique search groups to ensure broad coverage of foundational concepts, pollutant-specific impacts, and academic outcomes. Key search terms included *indoor air quality* (IAQ), cognitive function, particulate matter (PM2.5/PM10), volatile organic compounds (VOCs), carbon monoxide (CO), and student academic achievement

RESULTS AND DISCUSSION

There are many ways, both directly and indirectly, in which IAQ aspects can affect building occupants. IAQ factors can, in turn, affect student and teacher health outcomes, which can affect performance directly or through effects on attendance, disruption to instruction, as well as discomfort or other physiological processes. Students spend a large amount of their time learning indoors, and when numerous students occupy a classroom or educational space, ensuring proper ventilation can become challenging, resulting in higher levels of indoor air pollutants. Poor IAQ negatively impacts both teaching effectiveness and students' academic performance, underscoring the essential need to ensure good IAQ for optimizing the performance and productivity of both students and teachers.

Characterization of Indoor Air Compounds and Accumulation Dynamics

The diagnostic synthesis of educational environments reveals that a complex mixture of anthropogenic and ambient-derived pollutants predominantly compromises indoor air quality (IAQ) (Allen et al., 2016; Fisk, 2000). Primary constituents include carbon dioxide (CO_2), carbon monoxide (CO), particulate matter (PM2.5/PM10), and volatile organic compounds (VOCs) (Mendell & Heath, 2005; Wargocki et al., 2000). Empirical data suggest that nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and ozone (O_3) infiltration from outdoor sources further exacerbates the chemical load within classrooms (Gullan & Craske, 2020; Tsai, 2021). The fundamental mechanism driving pollutant concentration is the misalignment between high occupancy density and inadequate volumetric air exchange (MacNaughton et al., 2015). While CO_2 frequently serves as a reliable proxy for ventilation efficiency, it is insufficient as a standalone indicator for the comprehensive spectrum of chemical risks present in academic settings (Persily & de Jonge, 2017).

Cognitive Performance and Neurocognitive Impairments

Systematic exposure to elevated CO_2 concentrations exceeding 1500 ppm is robustly associated with diminished executive functions, including attenuated reasoning capabilities and protracted reaction latencies (Haverinen-Shaughnessy & Shaughnessy, 2015; Tsai, 2021). Intriguingly, controlled chamber studies suggest that moderate pure CO_2 levels below 2100 ppm may not induce significant cognitive deficits in isolation, highlighting the synergistic toxicity of co-occurring pollutants in real-world scenarios (Allen et al., 2016; Wargocki & Wyon, 2017). Particulate matter (PM2.5), however, demonstrates a more aggressive impact; longitudinal observations indicate a 26% escalation in error rates during attention-intensive tasks for every 10 $\mu g/m^3$ increase in concentration (Foong, 2022; Qin, 2022). Additionally, neurocognitive accuracy is compromised by high TVOC concentrations (>2000 $\mu g/m^3$), which correlate with a 5% reduction in task precision (J. Kim et al., 2020; Lee et al., 2026; Zhao et al., 2025).

Psychosocial Well-being and Longitudinal Academic Trajectories

The nexus between IAQ and student outcomes extends beyond immediate physiology to encompass broader psychological and academic metrics (Chinazzo et al., 2019; Shendell et al., 2004). Chronic subclinical exposure to CO at levels below 1 ppm is statistically linked to heightened psychological distress and emotional lability among students in laboratory settings (E. Kim et al.,

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2021). Conversely, strategic environmental interventions such as high-efficiency air filtration and optimized ventilation have been shown to catalyze significant improvements in standardized reading and mathematics assessments (MacNaughton et al., 2015; Oberdörster et al., 2005) Specifically, the mitigation of CO_2 from levels exceeding 2000 ppm to a threshold below 1000 ppm corresponds with a performance enhancement ranging from 5% to 12% [2](Haverinen-Shaughnessy & Shaughnessy, 2015; Shendell et al., 2004). These findings underscore the criticality of environmental optimization as a determinant of students' long-term academic competitiveness and success in higher education admissions (Pegas, 2012).

Impact of Particulate Matter and Volatile Organic Compounds

Beyond CO_2, particulate matter (PM2.5/PM10) and volatile organic compounds (VOCs) exert a more aggressive influence on neurocognitive stability (Foong, 2022; Qin, 2022). Longitudinal observations indicate that every 10 μg/m³ increase in PM2.5 concentration corresponds to a 26% escalation in error rates during attention-switching tasks (Qin, 2022; Raz, 2020). These microscopic particles can infiltrate the blood-brain barrier, potentially causing neuroinflammation that disrupts memory consolidation and reasoning speed (Maher, 2016; Persily & de Jonge, 2017). Similarly, total VOC (TVOC) levels exceeding 2000 μg/m³ reduce cognitive accuracy by approximately 5% while also diminishing student motivation due to sensory discomfort (J. Kim et al., 2020; Lee et al., 2026; Zhao et al., 2025). These findings suggest that monitoring PM and VOC levels is as critical as monitoring ventilation rates for maintaining an optimal learning environment (Beko, 2016)

Neurocognitive Risks of Carbon Monoxide Exposure

Carbon monoxide (CO) represents a critical chemical hazard within educational environments even at subclinical levels (E. Kim et al., 2021). Chronic exposure to CO at concentrations below 1 ppm is statistically linked to heightened psychological distress and emotional lability among students, particularly in laboratory settings where combustion-related activities occur (E. Kim et al., 2021; Schiavon et al., 2017). The physiological mechanism involves hypoxia-induced cellular stress, which can lead to enduring neurocognitive impairments such as attention deficits and memory loss (E. Kim et al., 2021; Schiavon et al., 2017). The long-term sequelae of even moderate exposure can significantly undermine a student's academic trajectory and learning progress (Beko, 2016; Chinazzo et al., 2019). Consequently, the integration of CO monitoring and rigorous source control is an essential component of holistic indoor environmental management for educational institutions (MacNaughton et al., 2015; Wargocki et al., 2000).

CONCLUSION

This review demonstrates that *indoor air quality* (IAQ) is a primary determinant of cognitive function, psychological health, and long-term academic success among students. The empirical evidence reveals a clear dose-response relationship where elevated CO_2, particulate matter (PM2.5/PM10), and volatile organic compounds (VOCs) significantly impair executive functions such as reasoning, memory, and attention-switching tasks. Furthermore, even subclinical levels of carbon monoxide (CO) are linked to heightened psychological distress and potential neurocognitive sequelae. These pollutants accumulate primarily through inadequate ventilation and high occupancy, highlighting a critical need for standardized environmental monitoring in educational institutions. The findings of this review provide evidence suggesting that low ventilation levels have adverse effects on students' health and academic performance, providing a strong rationale for targeted and immediate prevention and mitigation measures in school settings. These measures include ensuring adequate indoor ventilation, humidity control, and avoiding indoor exposure to commonly occurring microbiological and chemical substances throughout the life of each school room. Implementing strategic interventions such as high-efficiency filtration and optimized air exchange rates is essential to mitigate these risks and improve students' learning trajectories.

This review identified several factors in the school environment that may reduce children's performance and attendance. However, researchers have not fully characterized the range of environmental risks and exposures in school settings associated with these outcomes; even for those initially identified, the relationships and underlying teaching and learning processes involved in these adverse effects remain inadequately measured and understood. Part of this difficulty stems from the limited techniques available to assess risk factors, exposures, performance outcomes, and instructional processes. Consequently, many critical gaps in the research persist. A related gap is the limited representative data available to characterize the IAQ currently experienced by children in schools, alongside other documented risk factors affecting symptoms and classroom conditions. The findings of this review should therefore be interpreted with caution and not be generalized beyond the scope of the studies examined.

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