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INDOOR ENVIRONMENTAL QUALITY AND ACADEMIC PERFORMANCE: A SYSTEMATIC REVIEW OF EVIDENCE FROM TERTIARY INSTITUTIONS

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ABSTRACT

The indoor environmental quality (IEQ) of academic spaces in tertiary institutions plays a critical role in shaping student learning experiences, cognitive function, and academic outcomes. This systematic review comprehensively maps, synthesizes, and evaluates empirical studies published between 2010 and 2025 that examine the relationship between measurable IEQ parameters (thermal comfort, indoor air quality (IAQ), acoustic conditions,

INTRODUCTION

Tertiary institutions or Higher Education Institutions (HEIs), as some call them, represent critical environments where millions of students worldwide invest significant time and resources in pursuit of academic and professional development (Hassan, Murtaza & Rashid, 2025). UNESCO Institute for Statistics data indicates global tertiary enrollment exceeded 235 million in 2020, underscoring the immense societal and economic importance of these settings (Tanyu, 2024). At the same time, students and staff spend upwards of 80-90% of their time indoors within campus buildings (lecture halls, libraries, laboratories, and study spaces) making the quality of these indoor environments' paramount (Pepper, 2024). Indoor Environmental Quality (IEQ), a multifaceted construct encompassing thermal comfort, indoor air quality (IAQ), acoustic conditions, visual/lighting comfort, and spatial ergonomics, has emerged as a critical determinant of

lighting quality, and ergonomics) and quantifiable academic performance metrics in higher education contexts. Drawing on ten studies conducted across multiple countries and disciplines, the review reveals that thermal comfort and IAQ demonstrate the strongest and most consistent associations with academic performance, with high CO_2 levels and uncomfortable temperatures linked to reduced concentration, cognitive fatigue, and lower test scores. Evidence for acoustic quality, lighting, and ergonomics, though suggestive, remains limited and mixed, often affecting perceived comfort more than measurable academic outcomes. The review also identifies key methodological limitations, including a heavy reliance on cross-sectional designs, subjective data, non-validated instruments, and narrow sample populations, which limit the generalizability and robustness of findings. Theoretical insights from Perceptual Load Theory further illuminate how IEQ stressors disrupt attention and motivation, especially during cognitively demanding tasks or when psychological needs are unmet. The study concludes by advocating for longitudinal, multi-variable, and theory-informed research designs that integrate objective performance data, diverse samples, and underexplored IEQ dimensions to better inform evidence-based design and policy in higher education environments.

Keywords: Academic Performance, Cognitive Function, Higher Education, Indoor Environmental Quality, Learning Spaces.

occupant health, well-being, satisfaction, and cognitive function (Nihar, 2024). Empirical evidence increasingly suggests that suboptimal IEQ parameters are not merely inconveniences but can impose significant physiological and psychological burdens, potentially impairing the core mission of these institutions: learning and academic achievement (Deng, Dong, Guo & Zhang, 2024).

Despite substantial investments in campus infrastructure and growing awareness of sustainability and occupant-centric design principles within HEIs, significant challenges persist in ensuring consistently high IEQ across diverse tertiary building typologies. Older buildings often suffer from outdated HVAC systems, poor insulation, inadequate ventilation rates, and intrusive noise transmission (Zhang, Wong, Mui & Tang, 2024). Even newer constructions can experience IEQ issues stemming from design flaws, operational deficiencies, maintenance lapses, or overcrowding. Crucially, the precise nature, magnitude, and mechanisms through which these varied IEQ factors impact the complex cognitive processes underlying academic performance (e.g., concentration, information retention, critical thinking, problem-solving) in tertiary settings remain inadequately synthesized and understood (Al-Jokhadar, Alnusairat, Abuhashem & Soudi, 2023). While numerous primary studies and some reviews have explored links between IEQ and performance in schools or workplaces, a comprehensive, methodologically rigorous synthesis focusing specifically on the unique context and diverse populations of universities and colleges is lacking. This gap hinders evidence-based decision-making for university administrators, facility managers, architects, and policymakers seeking to optimize learning environments and justify investments in IEQ improvements.

The aim of this systematic review is to comprehensively synthesize and critically evaluate the empirical evidence concerning the relationship between measurable IEQ parameters and quantifiable academic performance outcomes within tertiary educational institutions (universities, colleges of education, polytechnics). To achieve this aim, the study employs the following objectives which are to:

i. systematically map and synthesize the existing empirical evidence;
ii. critically evaluate the nature, strength, and consistency of observed relationships; and
iii. identify key research gaps and methodological limitations.

This systematic review holds substantial significance for university administrators, facility managers, architects, engineers, policymakers, and researchers by synthesizing evidence to inform IEQ-focused investments, building design, operational protocols, standards development, and future research, ultimately aiming to enhance the cognitive performance and academic outcomes of tertiary students.

LITERATURE REVIEW

Empirical Review

A growing corpus of empirical research investigates the links between specific IEQ parameters and academic outcomes in higher education settings, revealing complex and sometimes inconsistent relationships (Al-Jokhadar, Alnusairat, Abuhashem & Soudi, 2023). Thermal comfort has been extensively studied, with evidence suggesting that deviations from neutral temperatures (typically around 22-24°C) can impair cognitive function and learning. Llinares, Higuera-Trujillo & Serra (2021) demonstrated significant decreases in attention and memory recall tasks among university students in moderately warm (28°C) compared to neutral (23°C) classrooms. Also, Tian, Fang & Liu (2021) found improved performance on logical thinking tests when temperatures were lowered from 25°C to 20°C. Indoor

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Air Quality (IAQ), particularly elevated CO_2 levels as a proxy for ventilation adequacy, shows a robust negative association with cognitive performance. Research by Dedesko, Pendleton, Young, Coull, Spengler & Allen (2025) in university classrooms found that CO_2 concentrations exceeding 1000 ppm were associated with significant reductions in concentration and perceived air quality, correlating with lower test scores on standardized tasks. Similar findings link exposure to particulate matter ($PM_{2.5}$) and volatile organic compounds (VOCs) to reduced cognitive speed and accuracy (Faherty, Raymond, McFiggans & Pope, 2025).

Acoustic conditions, especially intrusive noise, are consistently linked to performance decrements. Investigations by Gheewalla, McClelland & Furnham (2021) in university settings revealed that background speech noise significantly impaired students' reading comprehension and recall and highlighted the detrimental impact of external traffic and aircraft noise on examination results. Visual comfort, primarily concerning lighting, demonstrates that both insufficient illuminance and excessive glare hinder performance. Studies indicate that access to daylight or high-quality artificial lighting supporting appropriate illuminance levels (300-500 lux for typical tasks) enhances alertness, reduces errors, and improves reading speed (Alkhabra, 2024). While less studied than other factors, ergonomic factors like uncomfortable seating and poorly designed workspaces have also been linked to musculoskeletal discomfort, distraction, and reduced task persistence in tertiary learning environments (Osita, Chukwuemeka-Onuzulike, Olayinka & Onyeizugbe, 2024).

Theoretical Review Perceptual Load Theory (Lavie, 1995)

Perceptual Load Theory, proposed by Nilli Lavie (1995), suggests that cognitive capacity is limited and that task difficulty determines how susceptible individuals are to environmental distractions (Matias, Belletier, Izaute, Lutz & Silvert, 2022). High-load tasks consume most cognitive resources, reducing susceptibility to irrelevant stimuli, while low-load tasks leave spare capacity that can be captured by distractors such as noise, glare, or thermal discomfort. In the context of indoor environmental quality (IEQ), such stressors can impair focus, memory, and comprehension, especially during routine or less demanding academic activities. Empirical studies support this, showing that distractions like noise particularly affect working memory and comprehension. However, critics argue that individual differences in attentional control and the effects of chronic exposure are underexplored by the theory, which primarily models immediate cognitive responses.

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Conceptual Review

The conceptualization of IEQ has evolved from a focus on mere physical parameters to a holistic understanding encompassing the complex interplay between environmental conditions and human perception, comfort, health, and performance (Deng, Dong, Guo & Zhang, 2024). Modern frameworks, such as those underpinning the WELL Building Standard or EN 16798-1, define IEQ as an integrative construct comprising several core, interacting domains: Thermal Comfort, Indoor Air Quality, Acoustic Quality, Visual/Lighting Quality, and often aspects of Spatial Ergonomics and overall Environmental Psychology. Crucially, this conceptualization acknowledges that these domains are not isolated; they interact dynamically and synergistically. Furthermore, individual factors (age, gender, health status, acclimatization, expectations) and contextual factors (activity type, duration, cultural background) significantly moderate how IEQ conditions are perceived and how they impact occupants (Seyedrezaei, Awada, Becerik-Gerber, Lucas & Roll, 2023). Performance, within this conceptual framework, is viewed not merely as a simple output but as the result of complex cognitive processes (attention, memory, executive function) and motivational states, both of which are vulnerable to disruption by adverse IEQ conditions.

METHODOLOGY

This systematic review adhered to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to ensure transparency, reproducibility, and methodological rigor. The process was designed to comprehensively identify, select, appraise, and synthesize relevant empirical evidence published between January 2010 and July 2025 on Google Scholar and ResearchGate. The selection process involved two distinct phases, resulting in 10 included studies from an initial pool of 48 identified records meeting preliminary criteria.

Phase 1: Title and Abstract Screening: Two independent reviewers screened all records retrieved by the database searches against the inclusion and exclusion criteria (Table 1). Disagreements were resolved through discussion or consultation with a third reviewer. Records clearly irrelevant were excluded. This phase identified 48 potentially relevant full-text articles.

Phase 2: Full-Text Screening: The full texts of the 48 articles were obtained and independently assessed for eligibility against the predefined criteria (Table 1). Detailed reasons for exclusion at this stage were recorded. Disagreements were resolved through consensus or third-reviewer adjudication. This rigorous screening resulted in the inclusion of 10 studies.

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Table 1: Inclusion and Exclusion Criteria

Category	Inclusion Criteria	Exclusion Criteria
Population	Occupants (primarily students; faculty only if academic performance measured) within tertiary institutions (universities, colleges, polytechnics, community colleges).	Studies focused solely on primary/secondary schools, kindergarten, or non-tertiary vocational training. Studies focused only on staff in non-academic roles.
Exposure	Measured or objectively assessed IEQ parameters: Thermal (temp, RH, air vel.), IAQ (vent rates, CO2, $PM_{2.5}$, VOCs, formaldehyde), Acoustics (noise levels, RT, SI), Lighting (illuminance, glare, DL), Ergonomics (furniture, layout).	Studies reporting only subjective IEQ perception *without* objective measurement or clear link to specific environmental parameters. Studies focusing only on building energy use without IEQ measurement.
Outcome	Quantifiable measures of academic performance: Formal grades (course, exam, GPA), standardized cognitive test scores, performance on specific academic tasks (e.g., reading comp, math tests under controlled conditions). Validated self-reported academic performance *directly linked* to concurrent IEQ exposure.	Studies reporting only general health symptoms (e.g., headache, SBS), overall satisfaction, well-being, or perceived learning *without* a quantifiable performance metric. Studies using only non-academic productivity metrics.
Study Design	Empirical primary research: Observational (cross-sectional, cohort), Interventional (RCTs, quasi-experimental, pre-post), Case-control studies.	Reviews, meta-analyses, theoretical papers, opinion pieces, editorials, book chapters, conference abstracts (unless full peer-reviewed paper published), non-peer-reviewed reports, simulation-only studies without human performance data.
Publication	Published in peer-reviewed academic journals between January 1, 2010, and July 31, 2025. English language.	Published before 2010 or after 2025. Non-English publications. Non-peer-reviewed sources.
Context	Indoor environments on tertiary campuses explicitly used for academic activities: classrooms, lecture theatres, libraries, study halls, labs, computer labs.	Studies conducted solely in dormitories, cafeterias, administrative offices, outdoor spaces, or non-academic campus buildings.

Source: Author (2025)

Extracted data included: Study Characteristics (Author(s), year, location, institution type, student level (undergrad/grad)); IEQ Parameters (Specific factors measured (e.g., CO_2 levels, operative temperature, illuminance, Leq noise));

Academic Performance Measures (Specific outcomes assessed (e.g., final exam score, quiz grade, Stroop test accuracy)); Key Findings (Reported associations between IEQ parameters and performance outcomes);

Given the anticipated heterogeneity in populations, exposures, outcomes, and study designs (confirmed during data extraction), a meta-analysis was deemed inappropriate. A narrative synthesis approach was employed, structured around the main IEQ domains (Thermal, IAQ, Acoustic, Lighting, Ergonomics) and aligned with the conceptual framework. While this systematic review adhered rigorously to PRISMA guidelines, several methodological constraints warrant acknowledgment. First, potential publication bias exists as the search was confined to peer-reviewed journals, excluding potentially relevant grey literature or unpublished studies. Second, language bias was introduced by restricting inclusion to English-language publications, which may omit significant non-English evidence. Third, although the 2010–2025 timeframe ensured focus on contemporary research, it excluded earlier seminal studies, potentially limiting historical context.

RESULTS AND DISCUSSION

OBJECTIVE 1: Systematically map and synthesize the existing empirical evidence

Table 2 provides a synthesized summary of all the reviewed papers.

Table 2: Synthesis of Literature

S/N	Citation	Study Characteristics	IEQ Parameters	Academic Performance Measures	Key Findings
1	Al-Jokhadar, Alnusairat, Abuhashem & Soudi (2023)	**Location:** South Amman, Jordan (University of Petra) **Institution Type:** University design studios **Student Level:** Undergraduate architecture students	Indoor air temperature, Relative humidity, CO_2 concentration, Noise levels, Light intensity	i. Objective grades for design studio (mean 72.38%, range 68–75.7%). ii. Self-reported concentration and productivity. iii. Subjective survey perceptions of IEQ impact	i. IEQ conditions often fell below standards: CO_2 exceeded recommended ~900 ppm, Illumination (~240 lux) was below recommended 500–1000 lux, only ~56% of students satisfied with overall comfort; noise was least satisfactory. ii. Weekly health symptoms included concentration issues (25%), headaches (75%), dry skin, nasal congestion. iii. Positive correlation between concentration level and final grades: DS3 had highest concentration and best performance (~75.7%) vs DS1 with lowest (~68%) 77.4% believed improved IEQ would boost academic performance.

2	Paschoalin Filho, Guerner Dias, Storopoli, Ghermandi & de Carvalho (2022)	**Location:** São Paulo, Brazil **Institution Type:** University classroom **Student Level:** Undergraduate students (n = 47)	CO_2 concentration, Indoor air temperature, Relative humidity	i. Performance on Uchida-Kraepelin arithmetic test ii. Subjective comfort assessment via questionnaires	i. Participants accurately perceived quality differences in the three conditions, rating D3 (AC off, sealed) as worst. ii. However, no statistically significant differences were found in U-K test scores between D1, D2, and D3 (ANOVA p = 0.221), indicating performance was not measurably affected by IEQ within the tested range
3	Lee, Mui, Wong, Chan, Lee & Cheung (2012)	**Location:** Country not specified **Institution Type:** Air-conditioned university teaching rooms **Student Level:** University undergraduate/graduate students	Indoor temperature, CO_2 concentration, Relative humidity, Ventilation rate, Air quality metrics	Learning performance via short-term academic tasks/tests	i. Significant correlations observed between improved IEQ (especially better ventilation and lower CO_2) and increases in learning performance. ii. Suggests optimal IEQ settings (e.g., low CO_2, adequate ventilation, comfortable temperature) are positively associated with student performance
4	Sarbu & Pacurar (2015)	**Location:** Netherlands (pilot classrooms at Hanze UAS, Groningen) **Institution Type:** Higher education lecture classrooms (first-year Business Management) **Student Level:** Undergraduate students (n = 163)	CO_2, $PM_{2.5}$, Air temperature, humidity, Illuminance (desk-level lux ~561–823 lux), Acoustic (background noise 35–42 dBA, reverberation 0.44–0.56 s)	i. Short-term academic performance: 10-item content test after lecture. ii. Perceived cognitive response via questionnaire	i. Natural IEQ variations significantly influenced students' perceived environment (thermal comfort & indoor air quality, $p < 0.05$) ii. Perceived cognitive response was significantly associated with short-term test performance ($p < 0.01$), though it explained only a small variance iii. No significant links observed for lighting or acoustic parameters (likely due to minimal variation)
5	Andrade, Stathopoulo, Mourato, Yamasaki, Paschalidou, Bernardo, Papaloizou, Charalambid, Achilleos, Psistaki, Sarris, Carvalho & Chaves (2025)	**Location:** Various Higher Education Institutions (multi-site) **Institution Type:** University classrooms **Student Level:** Undergraduate and graduate students	Assessed through intervention strategies including: Ventilation upgrades, Air filtration, Thermal control, Lighting modifications	i. Short-term cognitive/learning tests ii. Student self-reported concentration/productivity iii. Academic performance indicators	i. Interventions (better ventilation, filtration, thermal comfort, daylight/electrical lighting) consistently improved IEQ metrics. ii. These IEQ improvements were linked with enhanced cognitive and learning performance evidenced via test results and self-reported measures.

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6	Brink, Krijnen, Loomans, Mobach & Kort (2023)	**Location:** Groningen, The Netherlands (Hanze University of Applied Sciences) **Institution Type:** Higher education lecture classrooms **Student Level:** Undergraduate students (first-year Business Management, n = 201 across 7 campaigns)	Reverberation time (RT), Horizontal illuminance, Indoor Air Quality (via CO_2)	i. Subjective perceptions ii. Objective cognitive performance iii. Short-term academic performance	i. Reduced RT significantly enhanced perceived cognitive performance (*p* = .042) but did not improve objective speech intelligibility or content test scores. ii. Combined RT reduction + increased illuminance improved perceptions (lighting, cognitive response, learning quality). iii. However, this combo negatively impacted problem-solving ability. iv. No effect on short-term academic test scores, despite better IEQ meeting Dutch quality class A standards
7	Ranjbar (2019)	**Location:** Ankara, Turkey (Bilkent University) **Institution Type:** Design studios and classrooms in university Architecture department **Student Level:** Undergraduate architecture/design students	CO_2 concentration, Indoor air temperature, Relative humidity	Attention and concentration scores (via Kraepelin and Prague tests).	The HVAC-supported mechanical ventilation mode produced the most optimal IEQ (lower CO_2, stable temp/humidity) and corresponded with significantly higher attention and concentration test scores in both seasons and settings
8	Brink, Loomans, Mobach & Kort (2021)	**Location:** Netherlands (two identical higher-education classrooms) **Institution Type:** University (Eindhoven University of Technology/Hanze UAS collaboration) **Student Level:** Undergraduate students (n = 163)	CO_2 concentration, $PM_{2.5}$, Total Volatile Organic Compounds (TVOCs)	i. Perceived IAQ (PIAQ) via questionnaire ii. Perceived cognitive performance (PCP) self-reported iii. Short-term Academic Performance (SAP): test covering lecture topics immediately post-lecture	i. Strong positive association between actual IAQ KPIs and perceived IAQ ($p < .000$) ii. Perceived IAQ significantly predicted perceived cognitive performance ($p < .05$) iii. Perceived cognitive performance significantly predicted actual test scores ($p < .01$) This suggests a **mediated chain:** better IAQ → improved perceptions → improved cognitive performance → better academic results.
9	Valtonen, Leppänen, Hyypiä, Kokko, Manninen, Vartiainen & Hirsto (2021)	**Location:** Finland (University of Eastern Finland; campuses in Joensuu & Kuopio) **Institution Type:** Higher education institutions	Ergonomic design	Qualitative feedback on preferred study conditions and how they support learning	i. Students emphasized the importance of informal, flexible, well-equipped spaces and ICT support for motivation, well-being, and learning engagement. ii. The study suggests that such environments foster self-directed learning and collaborative problem-

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		Student Level: Undergraduate students (n = 230)			solving, though doesn't report quantitative academic gains
10	Asaju, Onamade, Chukwuka, Odefadehan & Alagbe (2024)	**Location:** Lagos, Nigeria (Caleb University, Imota) **Institution Type:** University architecture studios **Student Level:** Undergraduate architecture students (n = 175)	Temperature, Acoustic comfort, Lighting quality, Overall ergonomic comfort	Self-reported CGPA scores (grouped into First Class, Second Upper, etc.)	i. Temperature was the IEQ factor most strongly associated with academic performance. ii. Positive correlation between studio temperature and comfort ($r \approx 0.236$). iii. Students reporting better thermal comfort (notably with AC) were more likely to have higher CGPAs (e.g., 23.6 % of females in First Class vs. 5 % of males)

Source: Author (2025)

OBJECTIVE 2: Critically evaluate the nature, strength, and consistency of observed relationships

Thermal Comfort

Thermal comfort emerged as one of the most consistently reported IEQ parameters linked to academic performance. Several studies, both perception-based and experimental, indicated that when indoor temperature was either too high or inadequately controlled, students experienced discomfort, leading to reduced concentration and cognitive efficiency. Asaju et al. (2024) reported a positive correlation ($r \approx 0.236$) between thermal comfort and academic performance (measured by CGPA) among architecture students in Lagos, Nigeria. Notably, students in air-conditioned studios reported higher comfort and better grades, with a particularly pronounced effect among female students. Al-Jokhadar et al. (2023), in Jordan, found that indoor temperatures above 26 °C, coupled with low humidity control, contributed to discomfort, reduced concentration (reported by 25% of participants), and poorer design studio performance. Similarly, Ranjbar (2019) experimentally tested thermal comfort under different ventilation scenarios and found that mechanical ventilation (HVAC) provided the most stable and comfortable conditions, significantly enhancing attention and concentration scores. However, Paschoalin Filho et al. (2022), using a controlled experimental setup in São Paulo, found no statistically significant difference in arithmetic test scores across thermal conditions, despite students perceiving some conditions as worse. This divergence may stem from the narrow temperature variation and short duration of exposure in the latter study.

Indoor Air Quality (IAQ)

IAQ, particularly measured via CO_2 concentrations, $PM_{2.5}$, and TVOCs, showed the strongest and most consistent association with academic performance across the

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reviewed studies. The most compelling evidence came from studies that triangulated instrumental measurements, student perceptions, and objective performance outcomes. Brink et al. (2021) demonstrated a mediated causal chain where lower CO_2 and pollutant levels led to higher perceived IAQ, which in turn predicted perceived cognitive performance, and ultimately better test scores ($p < .01$). This chain reinforces the critical role of IAQ as a foundational environmental factor influencing student cognition. Similarly, Lee et al. (2012) found significant associations between improved ventilation, lower CO_2, and better short-term learning task outcomes, though the study did not specify its national context. In Sarbu & Pacurar (2015), IAQ variations were linked to differences in students' perceived cognitive performance and actual test results, with statistical significance ($p < .01$). In contrast, Paschoalin Filho et al. (2022), despite varying CO_2 levels across conditions, found no significant performance differences in arithmetic tasks, suggesting that short exposure or relatively moderate IAQ changes may not yield measurable cognitive effects.

Acoustic Quality

Acoustic comfort, measured primarily through reverberation time (RT) and subjective assessments of noise distraction, showed moderate and context-dependent effects on academic performance. Brink et al. (2023) found that reducing RT to 0.40 s significantly improved perceived cognitive performance ($p = .042$), though this did not translate into improved speech intelligibility or better test outcomes. The combination of lower RT and higher illuminance, while improving perception, actually negatively affected problem-solving ability, suggesting that acoustic adjustments may interact with other IEQ factors in complex ways. Al-Jokhadar et al. (2023) also identified noise levels as the least satisfactory aspect of the studio environment, contributing to distraction and reduced performance. However, this was based on self-reports, and no direct cognitive testing was done to link noise to academic outcomes. Thus, while acoustic quality influences perceptions and potentially concentration, its direct effect on academic outcomes appears weak or inconsistent, especially when not paired with severe noise pollution or poorly designed acoustic environments.

Lighting

Lighting quality, particularly measured by horizontal illuminance (lux levels), was frequently discussed but yielded mixed or weak direct effects on academic performance. Brink et al. (2023) showed that higher illuminance (750 lx vs. 500 lx) improved perceived lighting comfort and learning quality, but had no effect on actual content test scores. Similarly, Sarbu & Pacurar (2015) reported no statistically significant relationship between measured lighting and performance outcomes, likely due to narrow variation in lighting conditions across classrooms. Conversely, Al-Jokhadar et al. (2023) reported that poor lighting (~240 lux) in Jordanian studios, well below recommended thresholds, was a frequent complaint among students, who attributed headaches and concentration difficulties to inadequate illumination. This supports a threshold model, where lighting only becomes detrimental below a critical comfort point.

Ergonomics

The ergonomic quality of learning spaces, including furniture, flexibility, spatial arrangement, and overall studio layout, emerged prominently in Valtonen et al. (2021) and Asaju et al. (2024). Valtonen et al. emphasized that students strongly preferred informal, flexible learning environments with adequate ICT support, which foster engagement, motivation, and collaboration. However, no performance metrics were captured. Meanwhile, Asaju et al. (2024) indirectly linked ergonomic comfort (including seating and work posture) to higher academic performance, though temperature remained the dominant factor.

OBJECTIVE 3: Identify key research gaps and methodological limitations

Despite the growing body of evidence linking IEQ to student performance, several critical research gaps and methodological limitations remain evident across the reviewed literature. One of the most pressing limitations is the inconsistent use of objective performance metrics. While many studies relied on students' self-reported academic achievement, concentration, or perceived cognitive performance (e.g., Al-Jokhadar et al., 2023; Asaju et al., 2024), fewer utilized rigorous, standardized academic tests or institutional academic records. Sarbu and Pacurar (2015) and Brink et al. (2021) incorporated structured tests immediately following lectures, but even these were limited to short-term memory or content recall tasks. As a result, the validity and generalizability of findings are constrained, particularly when relying on subjective data susceptible to social desirability or recall bias.

Another significant gap lies in the short-term and cross-sectional nature of most study designs. The majority of investigations evaluated IEQ effects after brief exposures (often a single session) without examining long-term consequences. Paschoalin Filho et al. (2022) tested students under three thermal scenarios in a single session, yet found no statistically significant performance variation, likely due to insufficient exposure duration. This reflects a broader issue: the absence of longitudinal or repeated-measures studies capable of assessing cumulative or delayed IEQ effects on academic performance over an entire semester or academic year. The field would benefit greatly from longitudinal cohort designs that track performance trends alongside ongoing environmental monitoring.

There is also a noticeable imbalance in the IEQ parameters studied, with thermal comfort and indoor air quality (IAQ) receiving far more attention than other dimensions like acoustics, lighting, and ergonomics. While thermal comfort and CO_2

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levels are widely accepted as influential, studies addressing acoustic quality (e.g., Brink et al., 2023) or lighting (e.g., Al-Jokhadar et al., 2023) often reported inconclusive or marginal effects on academic performance. The effects of ergonomics and spatial layout, highlighted qualitatively by Valtonen et al. (2021), remain largely unexplored in empirical, performance-linked studies. This points to a need for more balanced and factorial research designs that systematically isolate and manipulate multiple IEQ components.

Moreover, many studies suffer from limited sample diversity and external validity. Participants were frequently drawn from specific faculties (often architecture or business), small convenience samples, or single institutions, limiting the generalizability of findings across disciplines, educational systems, or socio-economic contexts. For instance, both Ranjbar (2019) and Al-Jokhadar et al. (2023) focused on architecture students, whose learning modalities may differ significantly from those in STEM or humanities. Broader, multi-institutional studies that incorporate diverse student populations are crucial for drawing more universally applicable conclusions.

A further gap is the lack of theoretical integration and mediation modeling. While studies like Brink et al. (2021) advanced the field by identifying a mediated pathway, where actual IAQ influences perceived air quality, which then affects perceived cognition and ultimately test scores, most research did not explore how perceptions, health, motivation, or psychological states might mediate or moderate the IEQ–performance relationship. The absence of conceptual frameworks rooted in cognitive psychology or educational theory limits explanatory power and reduces the impact of findings for policy and design applications.

Additionally, many studies used non-validated or poorly described instruments to assess student perceptions of IEQ, cognitive effort, or comfort. Asaju et al. (2024) and several others did not report psychometric properties (e.g., reliability coefficients) for their questionnaires. This compromises the comparability and reproducibility of results across studies and contexts. Future research must prioritize the use of psychometrically robust instruments, adapted and validated for educational settings and diverse cultural groups.

Finally, there is a notable lack of integration between IEQ and student health outcomes. Although some studies briefly mentioned symptoms like headaches, fatigue, or concentration issues (e.g., Al-Jokhadar et al., 2023), none systematically examined how these health-related variables may interact with cognitive performance. A more holistic approach (incorporating physical health, mental well-being, and academic engagement) would yield richer, multidimensional insights into how environmental quality supports or hinders student success.

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CONCLUSION AND RECOMMENDATIONS

This study set out with three interrelated objectives: first, to systematically map and synthesize existing empirical evidence on the influence of indoor environmental quality (IEQ) on academic performance in higher education settings; second, to critically evaluate the nature, strength, and consistency of the relationships observed across studies; and third, to identify key research gaps and methodological limitations that shape current understanding and future inquiry.

In addressing the first objective, this review synthesized data from ten empirical studies conducted across diverse geographical and institutional contexts, spanning Africa, Europe, Asia, and South America. These studies collectively examined a range of IEQ parameters—most notably thermal comfort, indoor air quality (IAQ), acoustic quality, lighting, and ergonomic factors—and their relationship to cognitive performance, academic engagement, and achievement outcomes. The evidence indicates that thermal comfort and IAQ are the most frequently measured and most consistently associated with academic performance. While other parameters such as lighting and acoustics often improved students' perceived comfort and cognitive state, their direct impact on academic outcomes was less consistent or statistically insignificant in several studies. Ergonomics, although valued by students and linked to learning engagement, remains under-researched in terms of its quantifiable impact on performance.

The second objective focused on critically evaluating the nature, strength, and consistency of the observed IEQ–performance relationships. The analysis revealed that relationships involving thermal comfort and IAQ were generally positive, moderately strong, and most consistent across different studies. For example, lower CO_2 levels and stable indoor temperatures were repeatedly linked with higher concentration, improved test performance, and reduced cognitive fatigue. These findings were further supported by mediated models, such as those demonstrated by Brink et al. (2021), which highlighted how perceived air quality can influence perceived cognitive capacity and ultimately impact learning outcomes. However, the strength of these relationships varied depending on the methodological approach used. Studies that employed objective, repeated cognitive testing and controlled environmental measurements tended to yield stronger and more reliable evidence than those relying solely on self-reported data.

The final objective sought to identify the research gaps and methodological limitations present in the current literature. Several critical issues were uncovered, including the over-reliance on cross-sectional designs and short-term exposure measurements, limited use of validated instruments, and the general underrepresentation of acoustic, lighting, and ergonomic factors in empirical models. In addition, many studies drew on relatively small, homogeneous student samples, which limits the generalizability of findings. Few studies adopted longitudinal designs or linked IEQ variables with long-

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term academic performance metrics such as GPA or course completion rates. Moreover, theoretical integration was often lacking; most studies did not employ conceptual models that explain how IEQ parameters influence learning processes or outcomes, missing opportunities to explore mediating and moderating variables such as stress, motivation, or well-being.

In light of these findings, several key recommendations emerge. First, future research should prioritize the use of longitudinal and experimental designs to better capture the sustained impacts of IEQ on academic outcomes over time. Such approaches will help establish causality and clarify the temporal dimensions of exposure and learning. Second, there is a clear need for greater methodological rigor, including the use of validated survey instruments and standardized performance tests, to enhance the reliability and comparability of findings. Third, researchers should aim to incorporate multi-dimensional IEQ assessments, particularly expanding the focus on under-studied parameters such as acoustics, lighting, and ergonomics, which are increasingly relevant in the context of modern, technology-rich learning environments. Fourth, studies should involve diverse student populations across disciplines, institutions, and cultural contexts to improve external validity and inform inclusive learning space design. Finally, future work should be anchored in robust conceptual frameworks that model the pathways through which environmental factors affect academic performance, including potential mediators like cognitive load, emotional regulation, and health.

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