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Variables Affecting Indoor Environmental Quality of Buildings: A Critical Review

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ABSTRACT

Indoor Environmental Quality (IEQ) is a critical determinant of occupant health, comfort, and productivity. As indoor environments become increasingly central to human activity, optimizing IEQ through design and operational strategies has become a pressing concern in building science. This paper presents a systematic and critical review of 51 peer-reviewed studies published between 2010 and 2024 to identify and categorize the key variables influencing IEQ. The analysis classifies 36 variables into six overarching categories: design features, building characteristics, occupant characteristics, environmental parameters, physiological responses, and outdoor conditions. Among these, operative temperature, clothing level, and age were the most frequently examined, underscoring their foundational role in thermal comfort, perceived air quality, and overall occupant comfort. Conversely, variables related to physiological responses and psychological well-being were underexplored. The review highlights a significant gap in integrated approaches that consider variable interactions and dynamic changes in indoor environments. Future work should focus on prioritizing high-impact variables using sensitivity and uncertainty analyses, developing context-specific standards, and balancing health and comfort outcomes. This study offers valuable insights for architects, engineers, and policymakers striving to design occupant-centric, health-promoting indoor spaces.

INTRODUCTION

Indoor environments, regardless of their purpose or location, are fundamentally designed to support occupant well-being. These environments cater to diverse needs, ranging from critical health-related conditions to general comfort and satisfaction (Bluyssen, 2009). The extent to which occupants perceive an indoor space to meet these needs defines Indoor Environmental Quality (IEQ)—a multidimensional concept encompassing physical conditions within buildings that influence occupant health, comfort, and overall experience (Deng et al., 2024). IEQ is typically characterized by four key parameters: indoor air quality (IAQ), thermal comfort, lighting quality, and acoustic conditions (ASHRAE, 2016; Korsavi et al., 2020; Wei et al., 2020; Akanmu et al., 2021). The importance of evaluating and optimizing IEQ is increasingly recognized in both research and practice. It enables the early detection of spaces requiring intervention, supports compliance with building performance standards, and contributes to improved physical and mental health outcomes (Fisk et al., 2007). Moreover, high IEQ is associated with enhanced productivity, reduced occupant complaints, and greater job satisfaction (Seppänen & Fisk, 2006), making it a key performance indicator in indoor spaces where people spend a significant portion of their lives.

Although sustainable building practices have traditionally emphasized energy efficiency and carbon reduction, ensuring optimal IEQ is equally essential. Poor indoor conditions have been linked to discomfort, reduced work performance, and adverse health effects (Al horr et al., 2016; Felgueiras et al., 2023; Mansor et al., 2024). Occupant satisfaction with indoor environments—the alignment between perceived and expected indoor conditions (Kallio et al., 2020)—serves as a valuable measure of IEQ. It reflects both the physical characteristics of the space and the subjective experiences of users (Kallio et al., 2020). Despite a growing body of literature addressing various aspects of IEQ (Bluyssen et al., 2016; Mendes et al., 2015;

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Carlucci and Pagliano, 2012; Xue et al., 2016a; 2016b), the field remains fragmented. Research has identified numerous IEQ influencing factors, including environmental conditions, seasonal variation, and user-specific attributes, making it a multidimensional aspect of sustainable building performance (Seppänen et al., 1999; Fisk et al., 2009). However, findings often lack consistency, and a clear consensus on which variables most significantly impact IEQ is still absent. To address this gap, the present study offers a critical and systematic review of the variables that affect IEQ in buildings. By synthesizing the available evidence, this review aims to clarify key influencing factors and support evidence-based strategies for architects, engineers, and policymakers. Ultimately, these insights will help guide the design, operation, and optimization of indoor environments, balancing health and comfort outcomes with broader sustainability and energy efficiency goals.

METHOD

This systematic review was guided by the following question: "What are the factors that affect the IEQ of buildings?" A systematic review was conducted following the Preferred Reporting Items for Systematic Reviews and Meta-analysis (PRISMA) guidelines (Nunayon et al., 2023). A comprehensive literature search was conducted using the Web of Science academic repository, covering publications from January 2010 to December 2024. The search employed combinations of the following terms and Boolean operators: (TITLE-ABS-KEY ("indoor environmental quality" OR "IEQ") AND TITLE-ABS-KEY ("variables" OR "factors" OR "parameters") AND TITLE-ABS-KEY ("buildings")). Various permutations of these keywords were used to refine and broaden the search scope. Studies were included if they met the following criteria: (1) reported empirical findings (e.g., primary studies and systematic reviews); (2) were published in English; (3) appeared in peer-reviewed journals; (4) explored or identified specific factors affecting IEQ or occupants' satisfaction with indoor environments. Excluded were non-peer-reviewed reports, editorials, case series, commentaries, and theoretical papers. As illustrated in Figure 1, the initial search identified 225 potentially relevant articles. After the title screening, 158 articles remained. Further abstract reviews reduced this to 92 papers, all of which were retrieved in full. Following a detailed assessment, 36 studies met the inclusion criteria. Given the relatively limited number of empirical studies on the topic, additional publications were identified through bibliographic tracing and included based on the same eligibility criteria, thereby enhancing the comprehensiveness of this review and supporting a more robust understanding of the factors affecting the IEQ of buildings. Therefore, the total number of publications included in the review is 51. The remaining studies were excluded due to irrelevance. Data were extracted using a structured template designed by the first author (SN). Extracted information included author(s), publication year, IEQ variable studied, and key findings. The second reviewer (LZ) checked the data for accuracy and completeness. Discrepancies were resolved through discussion. Due to heterogeneity in study designs and outcomes, meta-analysis was not feasible. Therefore, findings were synthesized thematically and presented using narrative summaries, tables, and figures to highlight recurring factors affecting IEQ.

Figure 1 Research methodology.

RESULTS AND DISCUSSION

The results are presented and discussed from two aspects: 1) the categorization of variables affecting IEQ, and 2) how each variable affects the IEQ.

Categorization of variables affecting IEQ

The identification and categorization of IEQ variables were based on a thorough content analysis of the selected literature. Each paper was carefully reviewed to extract and interpret the variables examined within its scope. In cases where different terminologies were used to refer to the same or closely related concepts, semantic reconciliation was performed to ensure

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consistency across the dataset. A total of 36 unique variables were identified and subsequently grouped into six broad categories: (1) design, (2) building characteristics, (3) occupants' characteristics, (4) environmental parameters, (5) physiological responses, and (6) outdoor conditions. While it is important to acknowledge that certain variables could justifiably belong to multiple categories due to their multifaceted nature, each variable was ideally assigned to a single category. To achieve this, a content-informed classification strategy, guided by the dominant context in which each variable was discussed across the reviewed literature, was employed. Specifically, variables were categorized based on their primary mode of influence. For example, daylight and glare were frequently associated with building orientation, window design, and façade configuration, factors rooted in architectural decisions, thus classified as "design variables." In contrast, parameters such as temperature, humidity, and indoor air pollutants were typically largely treated as ambient or operational conditions, and accordingly grouped under "environmental variables." In instances where overlap or ambiguity existed, the variable was placed in the category that best reflected its most consistent interpretation in the literature.

The design category includes variables related to architectural and engineering decisions, such as insulation, ventilation strategies, and system control levels. These elements shape the foundational structure and operational dynamics of the indoor environment. Building characteristics encompass the intrinsic qualities of the indoor space, including features like window area, presence of operable windows, finishes, and dampness or mold growth. These variables affect both the physical condition and functional performance of indoor spaces. Occupants' characteristics capture demographic, behavioral, and subjective attributes of building users, such as clothing insulation, metabolic rate, adaptation to local environments, and activity levels. These factors influence how individuals perceive and respond to indoor environmental stimuli. The environmental parameters group refers to measurable indoor conditions such as operative air temperature, relative humidity, noise level, lighting quality, and air pollutants. These variables are central to evaluating the performance of an indoor space in terms of comfort, health, and productivity. Physiological responses include quantifiable bodily reactions that reflect the occupant's internal state in response to environmental exposure. Examples include heart rate, skin temperature, blood pressure, and electrodermal activity—biomarkers that offer objective insights into human-environment interaction. Lastly, outdoor climatic conditions such as external temperature, humidity, noise, and seasonal variation are recognized for their indirect influence on indoor conditions, particularly in naturally ventilated or poorly insulated buildings.

Table 1 presents the categorization and corresponding references for each of the 36 identified variables. The categorization provides a structured framework for future studies aiming to evaluate or model IEQ and supports interdisciplinary collaboration by aligning variables with their respective domains of expertise.

Table 1. Categorization of Variables Affecting IEQ

Category	Variables	References
Design	Insulation	Mendes et al. (2015); Schweiker et al. (2020)
	Ventilation	Annesi-Maesano et al. (2013); Zhao et al., (2018); Ahmednur et al. (2022); Fritz et al., 2022; Földváry et al. (2017); Zhao et al. (2018)
	Systems control level	Park et al. (2018)
	Daylight	Giarma et al. (2017)
	Lighting level	Carlucci et al. (2015); Xue et al. (2016a)
	Uniformity of lighting	Carlucci et al. (2015); Xue et al. (2016a)
	Glare	Carlucci et al. (2015); Xue et al. (2016a)
	Outside view	Xue et al. (2016a)
Building characteristics	Indoor interior configuration	Syafei et al. (2020);
	Dampness & mold growth	Bluyssen et al. (2016); Ahmednur et al. (2022)
	Cleanness conditions	Ahmednur et al. (2022)
	Occupancy level	Ormandy and Ezratty (2012); Mendes et al. (2015); Bluyssen et al. (2016); Ahmednur et al. (2022)
	Lack of operable windows	Bluyssen et al. (2016); Castaldo et al. (2018); Park et al. (2018); Weerasinghe et al. (2024);
	Window area or aspect ratio	Vittori et al. (2021); Aries et al. (2010); Jamaludin et al. (2014); Xue et al. (2016a); Xue et al. (2016b); Vakalis et al. (2019)
	Finishes	Bluyssen et al. (2016)
	Contaminant load	Zhao et al. (2018); Ahmednur et al. (2022); Cao et al. (2012); Ramalho et al. (2013); Korsavi et al. (2021)

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Occupants' characteristics	Activities	Indraganti (2010); Luo et al. (2018); Mendes et al. (2015); Syafei et al. (2020); Xia et al. (2024)
	Clothing	Indraganti (2010); Mendes et al. (2015); Mishra et al. (2017); Patiño et al. (2018); Andargie et al. (2019); Brink et al. (2022); Shum et al. (2022); Weerasinghe et al. (2024); Oh et al. (2023)
	Age	Hwang and Chen (2010); Indraganti and Rao (2010); Bentayeb et al. (2013); Zalejska-Jonsson and Wilhelmsson (2013); Mendes et al. (2015); Lee et al. (2012); Xue et al. (2016a)
	Health status	Mendes et al. (2015)
	Gender	Indraganti and Rao (2010); Zalejska-Jonsson (2012); Mendes et al. (2015); Silva et al. (2017)
	Adaptation to the local environment	Mendes et al. (2015); Andargie et al. (2019)
	Metabolic rate	Indraganti (2010); Luo et al. (2018); Oh et al. (2023)
Environmental	Air movement or air speed	Andargie et al. (2019); de Oliveira et al. (2021)
	Operative air temperature	Bøkenes et al. (2011); Chatzidiakou et al. (2012); Wargocki and Wyon (2013); Chatzidiakou et al. (2015); Dorizas et al. (2015); Mendes et al. (2015); Park et al. (2018); Andargie et al. (2019); Korsavi et al. (2021); Schweiker et al. (2020); Ahmednur et al., 2022); Haroon et al. (2024)
	Relative humidity	Mendes et al. (2015); Andargie et al. (2019); Schweiker et al. (2020); de Oliveira et al. (2021); Fritz et al. (2022)
	Artificial lighting color temperature	Vittori et al. (2021)
	Air pollutants	Bentayeb et al. (2013); Mendes et al. (2015); Korsavi et al. (2021); Fritz et al. (2022)
	Noise level	Jeon et al. (2010); Xue et al. (2016b); Xia et al. (2024)
Physiological responses	Heart rate	Sun et al. (2020); Chauhan et al. (2023)
	Electrodermal activity	Chauhan et al. (2023)
	Skin temperature	Sun et al. (2020); Chauhan et al. (2023)
	Blood pressure	Sun et al. (2020)
Outdoor conditions	Season	Castaldo et al. (2018); Park et al. (2018); Schweiker et al. (2020)
	Outdoor temperatures	Zhao et al. (2018); Park et al. (2018)
	Outdoor noise	Andargie et al. (2019); Aguilar et al. (2022); Xia et al. (2024)

The bubble chart (Fig. 2) provides a visual representation of the frequency with which specific variables affecting IEQ have been investigated across the reviewed literature. The size of each bubble corresponds to the number of references citing each variable, offering insight into prevailing research priorities and potential knowledge gaps.

Among all variables, operative air temperature, clothing, and age emerged as the most frequently referenced, each appearing in 12, 9, and 7 studies, respectively. This prevalence underscores their foundational roles in determining thermal comfort and overall occupant satisfaction—two of the most widely studied dimensions of IEQ. The prominence of operative air temperature reflects its well-documented impact on thermal sensation, microbial growth, and airborne contaminant dynamics (ASHRAE, 2016). Similarly, the emphasis on clothing aligns with adaptive comfort theories, which recognize the influence of metabolic heat production and occupant behavior on perceived thermal comfort (Mendes et al., 2015; Oh et al., 2023). Furthermore, the repeated consideration of age highlights its broad influence across multiple IEQ domains (Hwang and Chen, 2010; Bøkenes et al., 2011; Bentayeb et al., 2013).

Variables such as ventilation, window area/aspect ratio, contaminant load, occupant activity, and relative humidity were also relatively well-represented, reflecting increased attention to IAQ and thermal comfort, and visual comfort as critical

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components of IEQ. These findings are consistent with broader trends in building science research that prioritize the optimization of airflow, natural lighting, and energy efficiency in building performance.

In contrast, several parameters, particularly glare, blood pressure, skin temperature, electrodermal activity, etc, were cited in only one or two studies. This suggests that physiological metrics and visual discomfort factors have not been extensively explored in the context of IEQ, despite their relevance in understanding nuanced occupant responses. Moreover, variables such as outdoor noise, artificial lighting color temperature, and seasonal influences, though critical in certain contexts, also appeared underrepresented, highlighting a potential area for future research, especially in longitudinal and cross-seasonal studies.

The chart also reveals a gap in the integrated treatment of psychological and behavioral factors, such as adaptation to the local environment, furniture arrangement, and emotional well-being, which were either absent or received minimal attention in the reviewed literature. While IEQ research traditionally emphasizes physical parameters, growing evidence suggests that subjective and psychosocial aspects significantly modulate occupant perception and comfort (Bluyssen et al., 2016; Sun et al., 2020; Chauhan et al., 2023). As such, future research should adopt more holistic approaches that encompass both objective and subjective dimensions of IEQ.

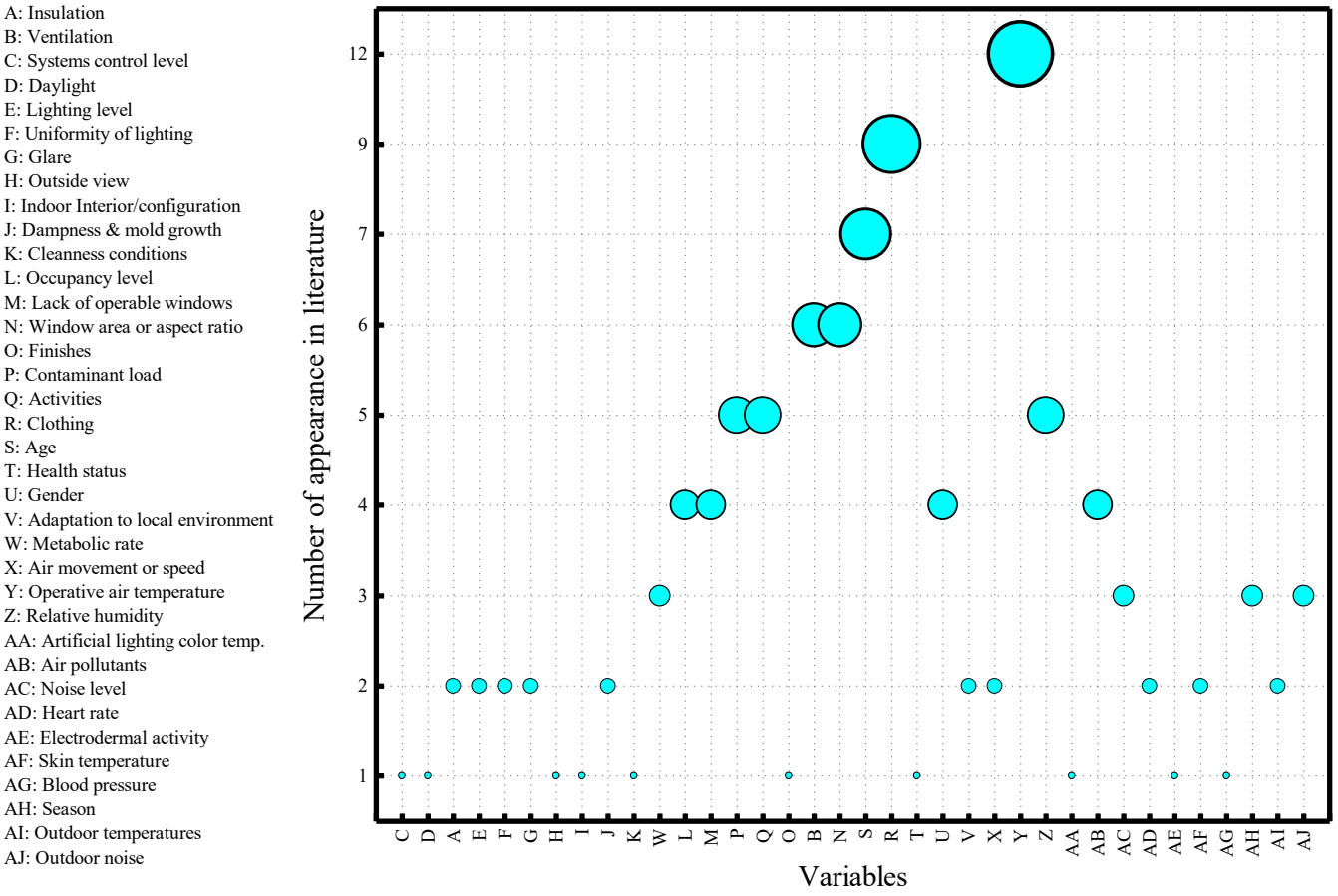

Figure 2 Frequency of appearance of variables influencing IEQ across reviewed literature. Note: while high-frequency variables indicate widely acknowledged factors, low-frequency variables, though cited only once, may represent emerging or context-specific influences on IEQ. Their inclusion helps identify areas underrepresented in current research and signals opportunities for future investigation.

Overall, the bubble chart supports the conclusion that while core variables influencing thermal, air quality, and lighting conditions have received significant attention, other domains, particularly those involving physiological and psychological responses, have not been rigorously investigated. Although only a few studies in the reviewed literature referenced physiological measures, these variables hold considerable potential for advancing occupant-centric IEQ research. Their underrepresentation may be attributed to several challenges, including the need for specialized instruments, ethical

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considerations (e.g., clearance, participant consent, etc.), controlled environments, and difficulties in isolating physiological responses directly attributable to environmental stimuli. Additionally, the lack of standardized measurement protocols and interpretive frameworks has hindered broader adoption. Nonetheless, with the increasing accessibility of wearable technologies and advances in data analytics, future studies could integrate physiological measures more effectively to offer objective and real-time insights into how indoor environments affect human comfort, health, and performance.

We strongly believe that variables that have received limited scholarly attention warrant closer examination rather than omission. These lesser-studied variables may capture emerging concerns, context-specific challenges (such as those relevant to specialized environments or populations), or novel research perspectives. Retaining such variables in this review enables a more holistic synthesis of the existing literature and highlights critical gaps that may shape future research agendas. Moreover, presenting the full spectrum of identified variables offers a broader, more inclusive understanding of the current knowledge landscape, reinforcing the importance of addressing both established and emerging determinants of IEQ. A more balanced investigation across all variable types is essential for advancing occupant-centric building design and policymaking. This approach aligns with the overarching aim of this review: to consolidate current insights while also charting a path forward for empirical, interdisciplinary, and application-oriented research in the evolving domain of IEQ.

Influence of variables on the IEQ of buildings

Various building design choices and operational strategies affect IEQ, making it a multidimensional aspect of sustainable building performance (Fisk et al., 2009). Key contributors to poor IEQ include inadequate ventilation, the presence of airborne pollutants, excessive noise levels, temperature fluctuations, and poor lighting conditions. These factors are influenced by architectural and engineering design choices, such as building orientation, material selection, HVAC system efficiency, and spatial configuration. However, despite the growing body of research on IEQ optimization, the relationships between design variables and IEQ outcomes remain insufficiently explored. Building design plays a fundamental role in shaping indoor environmental conditions throughout the life cycle of a building. For instance, ventilation strategies impact IAQ and pollutant dispersion, while thermal insulation and glazing specifications influence temperature stability and humidity control. Likewise, the choice of lighting systems and daylighting strategies affects visual comfort and circadian rhythm regulation.

CO_2 concentration is a well-established indicator of perceived IAQ and has a direct impact on occupants' perception of air freshness and stuffiness (Cao et al., 2012; Ramalho et al., 2013). Maintaining CO_2 levels below 1000 ppm and keeping the operative temperature (Top) within the thermal comfort band have been shown to improve air sensation votes by up to 43% (Korsavi et al., 2021). However, the strength of the correlation between occupants' air sensation votes and CO_2 levels varies by season, with stronger correlations observed during non-heating seasons and weaker associations in heating periods.

Thermal parameters, particularly air temperature and relative humidity, also influence IAQ both directly and indirectly. Wargocki and Wyon (2017) demonstrated that the mechanisms mediating the effects of IAQ and thermal environments on cognitive performance are remarkably similar. Elevated temperature and humidity levels can increase the concentration of pollutants, while lower temperatures are generally perceived as improving IAQ (Wargocki and Wyon, 2013). Specifically, cooler indoor environments enhance perceived air freshness, whereas warmer conditions are associated with greater sensations of stuffiness (Korsavi et al., 2021). This phenomenon can be attributed to the interaction between air temperature and the respiratory tract: when ambient temperature is significantly lower than mucosal temperature (30–32°C (86–89.6°F)), convective and evaporative cooling enhances thermal sensation (Chatzidiakou et al., 2015). In contrast, reduced respiratory cooling, regardless of air cleanliness, may lead to perceptions of poor air quality. Dorizas et al. (2015) found that a median indoor temperature of 22.3°C (72.14°F) was associated with high IAQ satisfaction, while discomfort was reported at temperatures exceeding 25°C (77°F). Thermal conditions further affect IAQ indirectly by modifying emission rates from indoor sources. Chatzidiakou et al. (2012) showed that variations in indoor temperature and humidity significantly influence pollutant release rates, including volatile organic compounds (VOCs). For example, Bentayeb et al. (2013) found statistically significant associations between symptoms such as breathlessness and elevated indoor concentrations of toluene and o-xylene among the elderly.

Age-related physiological changes, including reduced immune response and respiratory capacity, increase vulnerability to air pollution among older adults (Bentayeb et al., 2013). Age also influences thermal comfort preferences and tolerance. Bøkenes et al. (2011) reported associations between ambient indoor temperature and cardiorespiratory mortality. Hwang and Chen (2010) found that older adults prefer warmer indoor temperatures (by approximately +2°C (+35.6°F)) compared to younger individuals. For sedentary older occupants, optimal thermal comfort was observed at temperatures exceeding 25°C (77°F), higher than the standard 20–24 °C (68–75.2°F) thermal comfort zone. Thermal comfort is also influenced by variables such as activity level, health status, gender, and acclimatization to local environments (Ormandy & Ezratty, 2012). Clothing level is a critical determinant of thermal acceptability, especially in settings where individuals can freely adjust their attire based on metabolic activity. Indraganti (2010) and Patiño et al. (2018) observed residential clothing insulation values as low

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as 0.1 clo, significantly below the 0.4 clo typically recorded in office environments (ANSI/ASHRAE, 2017; Mishra et al., 2017; Brink et al., 2022; Shum et al., 2022). While flexibility in clothing adjustment improves comfort, such behavior is often limited in institutional settings due to normative constraints and lack of thermal variability.

Gender differences also influence thermal perception. Women generally exhibit higher neutral temperatures, prefer warmer environments, and wear more clothing layers (Silva et al., 2017). Reduced sweat rates among females further reduce their ability to adapt to hot conditions, potentially compromising thermal comfort. Time spent in residences may also shape adaptation; studies by Indraganti and Rao (2010) and Zalejska-Jonsson (2012) found that women reported higher IEQ satisfaction, possibly due to longer periods spent in indoor environments. Thermal comfort also varies with physiological responses such as heart rate, skin temperature, blood pressure, and electrodermal activity, all of which are influenced by environmental conditions and show varying degrees of correlation with thermal sensation votes (Sun et al., 2020).

Seasonal variation significantly influences thermal perception and IEQ. Castaldo et al. (2018) and Park et al. (2018) found that occupants report better visual and thermal comfort in fall and winter compared to spring and summer. Seasonal shifts alter thermal preferences, with cooler environments favored in autumn and winter, and slightly warmer conditions desired in summer. Seasonal fluctuations in IEQ parameters, such as PM_{10}, CO_2, total VOCs, and bacterial load, are often driven by behavioral adaptations like window opening and occupancy patterns (Annesi-Maesano et al., 2013).

High occupancy density and poor ventilation have been associated with elevated indoor pollutant concentrations. Buildings with inadequate ventilation may accumulate CO_2 and indoor pollutants due to insufficient air exchange, particularly during winter months when windows remain closed (Schweiker et al., 2020). These conditions underscore the critical need for dynamic building systems capable of maintaining consistent IEQ across seasons.

Despite these evident connections among extracted variables, a comprehensive understanding of how each of them affects multiple IEQ parameters is still lacking.

RECOMMENDATIONS FOR FUTURE WORK

The findings of this review reveal a wide range of variables influencing IEQ in buildings. To improve future research and practical applications in the IEQ domain, this section outlines key areas for further investigation, emphasizing prioritization of influential variables, development of context-sensitive standards, and integration of public health and comfort outcomes in variable assessment.

Identifying and prioritizing key IEQ-influencing variables

Given the large number of IEQ-influencing variables, evaluating every possible design or operational combination is infeasible. A promising approach is to focus on high-impact variables that most significantly affect IEQ. Identifying these requires estimating their relative importance, which can guide more efficient and effective indoor environmental design strategies. Recent studies have employed sensitivity analysis (SA)—a statistical approach to assess how variations in input variables influence model outcomes. Both local sensitivity analysis (e.g., one-at-a-time method) and global sensitivity analysis (e.g., Sobol or Morris methods) have been used to rank design and environmental variables in terms of their influence on comfort and health-related IEQ parameters (Nguyen et al., 2014; Ioannou et al., 2018). For instance, Pisello et al. (2014) identified ventilation rate, air temperature, and daylight availability as dominant variables affecting perceived IEQ using global SA techniques. However, several limitations in current SA applications must be addressed. First, most studies treat variables as static, whereas in reality, many operational variables (e.g., RH, CO_2 concentration) change dynamically over time. Second, design and operational variables are often analyzed in isolation, ignoring their interaction effects, which may produce nonlinear or synergistic outcomes (Hopfe and Hensen, 2011). These oversights can reduce the validity of variable prioritization and introduce uncertainties in model predictions. Thus, future research should integrate uncertainty analysis and coupled dynamic modeling to determine dominant variables under realistic conditions. While objective physical parameters (e.g., temperature, humidity, CO_2 levels, etc.) have been extensively modeled in IEQ research, subjective satisfaction and psychological well-being remain underrepresented in quantitative frameworks. However, there is growing recognition that occupant experience cannot be fully understood without considering perceptual and emotional responses. Integrating these subjective dimensions into IEQ modeling requires the development of hybrid approaches that combine environmental monitoring with real-time user feedback. Methods such as post-occupancy evaluations (POEs), wearable sensors, and mobile surveys can be used to capture occupants' thermal sensation, perceived air quality, mood, and overall satisfaction. Moreover, advancements in data analytics, particularly machine learning and data fusion techniques, provide promising avenues for modeling the complex, non-linear relationships between physical conditions and subjective responses. Structural equation modeling (SEM) and other psychometric approaches may also help to reveal latent constructs, such as stress or cognitive strain, that mediate the relationship between IEQ variables and well-being. Moving forward, research should prioritize the development of inclusive, occupant-centric models that explicitly account for both measurable environmental parameters and experiential data to support

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health-promoting and user-responsive indoor environments.

Establishing context-specific standards for IEQ-influencing variable value ranges

The review highlights that variations in the assigned values of IEQ-influencing variables can result in significantly different occupant outcomes. Therefore, defining appropriate value domains for each variable is essential for designing healthy, comfortable, and occupant-friendly indoor environments. While several technical standards provide recommended ranges—e.g., ASHRAE Standard 62.1 for ventilation (minimum 0.3–0.5 L/s·m² (0.059–0.098 cfm/ft²)), ASHRAE 55 for thermal comfort (acceptable operative temperature range 20–26°C (68–78.8°F)), and WHO (2021) guidelines for IAQ (e.g., $PM_{2.5} \leq 5$ μg/m³)—these recommendations are often based on general assumptions, and may not account for regional climate, occupancy density, cultural expectations, or building typologies. For instance, an acceptable relative humidity (RH) of 30–60% may be inappropriate in high-humidity climates, and lighting levels suitable for office work (500 lux (46.45 foot-candles)) may not align with residential or healthcare needs (CIBSE, 2015). Moreover, socioeconomic and behavioral factors influence occupants' perceptions and tolerances. To enhance real-world relevance, future studies should aim to develop adaptive standards based on occupant feedback and contextual variables, incorporate climate-responsive design guidelines, and propose locally validated IEQ benchmarks that align with health and comfort goals. This context-sensitive approach would allow the development of region-specific standards that better address the environmental and cultural diversity encountered in building use.

Balancing public health and comfort: dual-focus optimization of IEQ variables

A nuanced finding of this review is that IEQ-influencing variables affect two primary domains of occupant well-being: pleasantness (e.g., furniture layout, spatial configuration, color scheme) and public health (e.g., CO_2 levels, airborne pathogens, VOCs). Sometimes, variables that enhance one domain may negatively impact the other. For example, richly upholstered furniture may increase aesthetic appeal but also emit VOCs that degrade air quality. This duality presents two optimization paths: (1) single-objective optimization, where variables are tuned for either comfort or health outcomes, and (2) multi-objective optimization, where trade-offs are evaluated to minimize negative impacts and maximize total IEQ performance. Future research should focus on: (1) identifying conflicting variables (e.g., material finishes, ventilation vs. noise), (2) applying multi-criteria decision-making tools (e.g., TOPSIS, AHP, Pareto optimization) to model trade-offs, and (3) developing integrated evaluation frameworks that unify both subjective (comfort) and objective (health) metrics. Such frameworks can guide designers and facility managers in selecting evidence-based, balanced solutions that do not sacrifice health for aesthetics or vice versa.

CONCLUSION

This critical review examined variables influencing IEQ in buildings, categorizing them into environmental, design, physiological, and occupant-related groups. The study highlights the need for future research in three key areas: (1) determining the most influential IEQ variables, considering variable interactions and real-world uncertainties, (2) developing adaptive, context-sensitive standards to define optimal value ranges for IEQ-influencing variables, and (3) exploring trade-offs between comfort and public health impacts, and applying integrated frameworks to optimize indoor environments holistically. These directions will help create occupant-centric, health-promoting, and environmentally sustainable buildings, while also supporting evidence-based building policies and performance standards.

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