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ENHANCING INDOOR ENVIRONMENTAL QUALITY THROUGH IOT: A REVIEW OF APPLICATIONS AND CHALLENGES

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SUMMARY: *Indoor Environmental Quality (IEQ), which encompasses thermal comfort, indoor-air quality, visual comfort, and acoustic comfort, directly influences health, well-being, and productivity inside buildings. This narrative review synthesises peer-reviewed studies retrieved from Scopus and Web of Science (2015 to June 2025) to assess how Internet-of-Things (IoT) technologies are being used to sense, analyse, and actively regulate the four IEQ domains. The evidence shows that IoT-enabled systems consistently outperform conventional controls: they narrow temperature and humidity fluctuations, deliver ventilation precisely when pollutant loads rise, modulate daylight and electric lighting to balance brightness and glare, and dynamically mask or cancel disruptive noise, all of which translate into measurably healthier, more energy-efficient spaces and higher occupant-satisfaction ratings. Yet adoption is still tempered by sensor drift, platform incompatibilities, cybersecurity vulnerabilities, and the e-waste and standby-energy burdens of dense device networks. Overcoming these barriers will require durable, self-calibrating sensors, open communication standards, privacy-by-design governance, and circular deployment models, supported by long-term field trials and interdisciplinary collaboration among building scientists, computer engineers, and behavioural researchers. Taken together, the findings confirm IoT's substantial promise for next-generation smart and sustainable buildings while charting a clear agenda for future research and practice.*

KEYWORDS: *Internet of Things (IoT), Indoor Environmental Quality (IEQ), Smart Building Systems, Occupant Comfort, Environmental Monitoring.*

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1. INTRODUCTION

Indoor environments have a profound impact on human health, comfort, and productivity, especially given that individuals spend nearly 90% of their time indoors (Thneibat, 2024). Indoor Environmental Quality (IEQ) encompasses indoor air quality (IAQ) along with thermal, visual, and acoustic comfort—critical, measurable components that influence occupant well-being and performance (Mujan et al., 2021). These elements not only affect physical health but also shape emotional and cognitive experiences, directly influencing satisfaction, mental health, and work efficiency (Al Horr et al., 2016). As such, IEQ is gaining increased recognition in architectural design and facility management, particularly amid growing interest in sustainability and occupant-centered environments.

Poor IEQ has been consistently linked to adverse health and productivity outcomes. Sick building syndrome (SBS), for instance, is characterized by symptoms such as headaches, dizziness, respiratory irritation, and fatigue—conditions often resulting from inadequate ventilation and low air quality (Niza et al., 2024). In addition to physical ailments, environmental stressors such as temperature fluctuations, noise disturbances, and insufficient lighting have been shown to impair focus, elevate stress, and reduce cognitive performance (Seppänen & Fisk, 2006). Research further indicates that poorly ventilated offices increase the risk of cognitive function decline due to elevated CO_2 and VOC levels, while high noise levels are associated with stress and decreased job satisfaction and productivity (Felgueiras et al., 2023, Park et al., 2020, Tsang et al., 2024). In healthcare settings, suboptimal IEQ has been linked to prolonged recovery times and higher incidences of hospital-acquired infections, highlighting the need for proactive environmental management (Ackley et al., 2024).

Traditional IEQ monitoring often involves independent sensors measuring variables such as temperature, humidity, CO_2, light, and sound. These systems tend to be expensive, intrusive to install, and limited to local data storage, which results in fragmented and low-resolution assessments (Geng et al., 2022). The emergence of IoT and big data technologies has significantly improved these tools by integrating sensor networks, enabling wireless transmission, and leveraging cloud-based platforms (Karami, McMorrow, & Wang, 2018, Martín-Garín et al., 2018). These advancements reduce the time and effort required for manual assessments and allow rapid responses to deteriorating environmental conditions (Schiavon & Lee, 2013). Moreover, IEQ monitoring has become increasingly embedded in sustainable building rating systems such as Leadership in Energy and Environmental Design (LEED) and WELL Building Standard (WELL), reflecting the critical role of responsive and data-driven management (Tsang et al., 2024).

The Internet of Things (IoT) has introduced real-time data analysis, predictive maintenance, and adaptive automation into IEQ monitoring. IoT-enabled systems—using smart thermostats, air quality sensors, and acoustic monitors—dynamically adjust indoor conditions to optimize comfort and health (Parkinson, Parkinson, & de Dear, 2019, Popescu et al., 2024, Yang et al., 2019). Wireless sensor networks (WSNs) facilitate remote tracking and control, reinforcing stable, healthy, and productive indoor environments (Sarkar & Gul, 2024). Continuous IEQ data collection and processing have become central to contemporary environmental management strategies (Broday & Gameiro da Silva, 2023).

Although several studies have explored the relationship between IoT applications and IEQ, a comprehensive review that synthesizes their collective impact on environmental conditions and occupant well-being remains limited. This paper addresses that gap by reviewing existing research on how IoT enhances IEQ through intelligent sensing, real-time monitoring, and automated building controls. It further examines the role of these technologies in promoting health, comfort, and operational efficiency. In doing so, the review identifies ongoing challenges and offers strategic recommendations for integrating IoT solutions into future-ready, occupant-centered indoor environments.

2. INTERNET OF THINGS (IOT): DEFINITION, ARCHITECTURE, AND EVOLUTION

IoT is a transformative paradigm characterized by a pervasive network of interconnected physical objects embedded with sensors, actuators, and communication technologies. These components enable seamless data collection, exchange, and analysis with minimal human intervention (Biagini, Bongini, & Marzi, 2024, Deng, Menassa, & Kamat, 2021, Tezel & Aziz, 2017). The concept of IoT originates from Mark Weiser's vision of ubiquitous computing and was formally introduced by Kevin Ashton in 1999.

At its core, IoT integrates a wide array of "smart" objects—from basic radio-frequency indentification (RFID) tags to advanced Artificial intelligence (AI)-driven systems—into a unified digital-physical ecosystem. This infrastructure allows devices to detect environmental parameters (e.g., temperature, light, humidity), communicate through standardized protocols (e.g., ZigBee, Message Queuing Telemetry Transport (MQTT)), and autonomously optimize operations. As a result, IoT has become indispensable in a variety of domains, including smart buildings, construction management, and energy-efficient facility operations (Biagini, Bongini, & Marzi, 2024, Floris et al., 2021).

2.1 IoT Architecture and Layers

To ensure interoperability and scalability, IoT systems are commonly organized into layered architectural frameworks. A widely adopted model divides IoT systems into three primary functional tiers (Kuchuk & Malokhvii, 2024), as illustrated in Figure 1.

The first tier, known as the Perception Layer (also referred to as the *Objects Layer*), comprises devices such as sensors, actuators, and RFID tags that collect real-time environmental data—including temperature, humidity, and occupancy (Al-Fuqaha et al., 2015, Kuchuk & Malokhvii, 2024). The second tier, the Network Layer (or *Transmission Layer*), is responsible for transmitting the collected data using communication protocols such as Wi-Fi, ZigBee, Bluetooth, or IPv6. This layer may also integrate edge computing technologies to process data closer to the source, thereby minimizing latency and reducing bandwidth demands (Čolaković, Džubur, & Karahodža, 2021, Parisi, Fanti, & Mangini, 2021).

Finally, the Application Layer converts the transmitted data into actionable insights by interfacing with platforms such as Building Management Systems (BMS), Energy Management Systems (EMS), and AI-driven dashboards. This layer provides users with tools and interfaces for environmental monitoring, control, and decision-making (Chamari, Petrova, & Pauwels, 2023).

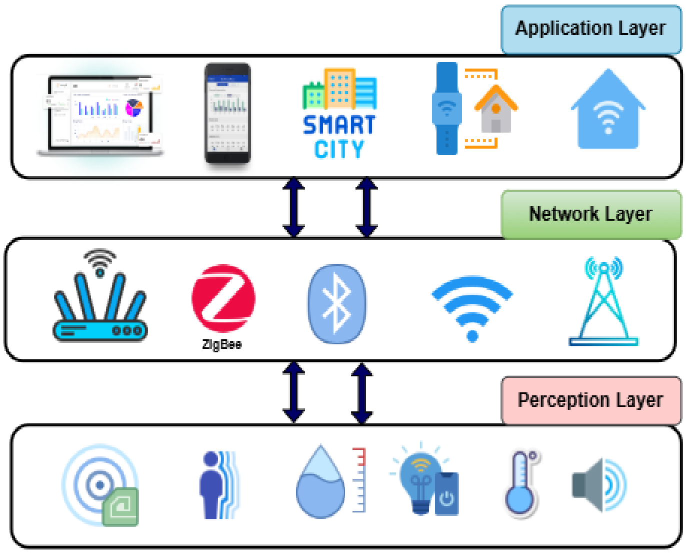

Figure 2: IoT Architecture Layers.

IoT architectures may vary depending on the specific application. Some frameworks incorporate additional layers, such as a middleware layer dedicated to data processing, storage, and system integration. Advanced IoT models—such as the Cisco-IBM-Intel seven-layer architecture—further extend this structure by integrating fog and cloud computing, along with semantic web technologies (e.g., RDF, Brick Schema). These enhancements enable seamless interoperability with Building Information Modeling (BIM) platforms and support the creation of dynamic Digital Twins for real-time predictive analytics in construction (Biagini, Bongini, & Marzi, 2024).

2.2 Evolution of IoT in Smart Buildings and Interior Design

1980s–2000s (Foundation of Automation): In the 1980s, early Building Automation Systems (BAS) introduced centralized control of heating, ventilation, and air-conditioning (HVAC) and lighting, along with basic sensor networks to monitor environmental parameters such as temperature, occupancy, and energy use. These systems laid the groundwork for today's smart buildings. However, they were primarily reactive—responding to environmental changes only after preset thresholds were reached (So, Chan, & Tse, 1997, So, Chan, & Wai, 1998). Although the term "Internet of Things" (IoT) was not yet in use, the foundational principles of automation and remote environmental monitoring emerged during this period.

2010s (Integration and Intelligence): The widespread adoption of cloud computing, affordable sensors, and wireless communication protocols (e.g., ZigBee, Wi-Fi) marked a new era of integrated BAS. During this period, building subsystems—such as lighting, security, and HVAC—began communicating within unified IoT platforms. Predictive maintenance, occupant-centered automation, and machine learning–based control strategies became increasingly prevalent (de las Morenas et al., 2019, Haidar, 2020). Concurrent developments in smart grids and renewable energy integration further enhanced adaptive, sustainable building operations (Floris et al., 2021).

2020s–Present (AI and Interoperability): Recent advancements focus on the integration of artificial intelligence for autonomous environmental adjustments (e.g., lighting), and the use of blockchain for secure and transparent data exchange (Ma et al., 2023, Opoku, Louafi, & Mouhoub, 2024, Saeed, Al-Hamoud, & Adam, 2024). The convergence of IoT with Building Information Modeling (BIM) enables real-time synchronization between digital building models (using IFC standards) and on-site conditions, improving cost management, safety, and construction timelines (Carlo Biagini et al., 2020, Toyin et al., 2024). In interior design, IoT-enabled furnishings and wearable technologies offer personalized comfort experiences (Sokienah, 2023). Furthermore, sensors embedded in construction tools (e.g., pneumatic breakers) allow for remote equipment monitoring and accident prevention, illustrating the ongoing shift toward holistic, data-driven building life cycles (Wang & Liu, 2024, AL Bardan, S., 2025).

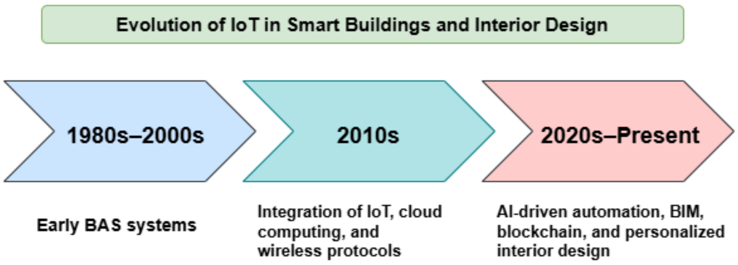

Figure 2: Evolution of IoT in Smart Buildings and Interior Environment.

3. METHODOLOGY

This study explores the integration of Internet of Things (IoT) technologies into Indoor Environmental Quality (IEQ) systems in buildings, with a focus on four key parameters: thermal comfort, IAQ, lighting, and acoustics. The research was guided by two primary questions:

1. How effectively does IoT improve different aspects of IEQ?
2. What types of IoT devices and technologies are most effective in enhancing IEQ, and how do they function

To address these questions, a comprehensive literature search strategy was developed. Two major academic databases—Scopus and Web of Science—were selected due to their robust coverage of interdisciplinary research spanning technology, environmental science, and smart building systems. The following Boolean search string was used to identify relevant studies at the intersection of IoT and IEQ:

("Internet of Things") AND ("Indoor Environmental Quality")

The review focused on peer-reviewed publications between 2015 and June 2025 that specifically investigated how IoT technologies are applied to measure, monitor, and enhance IEQ which led to 478 records from two databases.

As the first step towards exclusions, all 60 duplicated articles were removed, followed by eliminating any non-English-language and non-peer-reviewed publications. Next, all the titles and abstracts were screened to ensure that studies which mentioned IoT only tangentially or addressed exclusively outdoor environments were excluded. Finally, an in-depth study of remaining 87 records led to a total of 38 articles that were included in the scope of this study.

To enhance clarity and replicability, a research mapping approach was adopted. This framework visualizes the entire review process, from literature selection to thematic synthesis, and is illustrated in Figure 1. The overall structure of the paper follows the methodological steps outlined in this map.

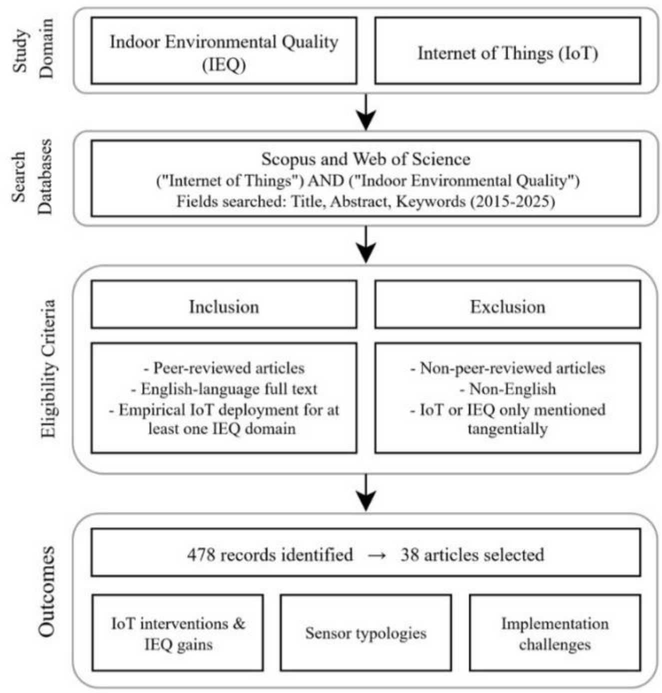

Figure 3: Workflow illustrating database search (2015-2025), eligibility screening, and thematic grouping of 38 IoT–IEQ studies.

The initial phase of the review provided an overview of IoT development and its relevance to indoor environments, establishing the technological foundation for its applications in building performance and occupant well-being. Subsequent analysis was organized around the four core domains of IEQ: thermal comfort, IAQ, visual comfort, and acoustic comfort. Each domain was examined in terms of how IoT has been utilized to assess and regulate environmental conditions. Special emphasis was placed on the role of IoT sensors—including sensor types, operational mechanisms, and their effectiveness in maintaining desirable IEQ levels. In addition, the review identified and categorized key implementation challenges such as sensor calibration and accuracy, data interoperability, user interaction, and system scalability. These issues were examined in relation to both technological limitations and practical deployment.

4. INTERNET OF THINGS AND INDOOR ENVIRONMENTAL QUALITY

Integrating IoT into indoor environments presents a transformative approach to enhancing IEQ. By deploying networks of interconnected sensors and intelligent devices, IoT-enabled systems allow for continuous monitoring and dynamic regulation of key IEQ parameters—including air quality, temperature, humidity, lighting, and noise.

These systems provide real-time environmental feedback and support automated adjustments to building operations, helping to maintain optimal indoor conditions that promote occupant health, comfort, and productivity. In addition to improving well-being, IoT integration enhances energy efficiency and advances the broader objectives of sustainable and responsive building management.

4.1 IoT and Thermal Comfort

Indoor thermal comfort plays a critical role in supporting energy efficiency, occupant well-being, and productivity. However, conventional HVAC systems—typically operating on fixed schedules and preset temperature points—often fall short, leading to inefficient performance and frequent occupant complaints (Marques & Pitarma, 2019, Ulpiani et al., 2021). Comfort is shaped by both physical and psychological factors and is influenced by variables such as air temperature, humidity, radiant temperature, airflow, clothing insulation, and metabolic rate (Tomat et al., 2020).

Recent advances in IoT technologies have significantly transformed thermal comfort management in buildings. IoT-enabled HVAC systems continuously monitor indoor environmental conditions and dynamically adjust operations to maintain comfort (Tomat et al., 2020). These systems leverage intelligent algorithms that learn from occupant behavior and fine-tune their performance accordingly. For example, smart thermostats have been shown to reduce energy consumption by 15% in residential settings without compromising thermal comfort (Pan et al., 2015). In commercial buildings, IoT integration has led to 22% energy savings and a 30% improvement in perceived comfort (Gao, Li, & Wen, 2020).

One of the key strengths of IoT-integrated systems is their ability to reduce temperature variability. Compared to traditional systems, IoT-enabled HVAC solutions can lower temperature fluctuations by 2.8–4.5°C (Huang, 2024, Ulpiani et al., 2021). This effect is particularly notable in office and healthcare environments, where improvements in thermal stability of 3.2°C and up to 4.5°C, respectively, have been documented (Mujan et al., 2021, Broday & Gameiro da Silva, 2023). In educational settings, human-centric frameworks that combine environmental sensing with occupant feedback have also demonstrated effectiveness in maintaining consistent thermal conditions (Lee & Zhang, 2024).

Another major benefit of IoT-based systems is the ability to provide personalized thermal control. Unlike conventional systems that deliver uniform temperatures across zones, IoT solutions support occupant-specific adjustments (Marques & Pitarma, 2019). This personalization has measurable impacts on user satisfaction. For instance, Kim et al. (2019) reported a 25% increase in satisfaction when employees were allowed to fine-tune their thermal settings. Similarly, Salamone, Sibilio, and Masullo (2024) observed a 24% reduction in complaints in co-working spaces. Smart zoning and predictive control strategies have consistently improved thermal satisfaction across residential and commercial settings (Pan et al., 2015, Gao et al., 2020, Huang, 2024), emphasizing the importance of integrating subjective feedback with objective environmental data (Lee & Zhang, 2024).

Beyond comfort, IoT-driven HVAC systems contribute significantly to energy efficiency. By utilizing predictive analytics and real-time data, these systems reduce unnecessary energy consumption while maintaining comfortable conditions (Salzano et al., 2025). Reported energy savings range from 15% to 30%, depending on system sophistication (Huang, 2024). For example, implementing a Digital Twin framework in educational facilities reduced HVAC energy use by 15% (Salzano et al., 2025), while dynamic setpoint adjustments based on occupancy and weather reduced cooling loads in office spaces by 18% (Huang, 2024). AIoT frameworks, although not always quantified, have also shown promise in promoting smart energy use in schools (Lee & Zhang, 2024).

Humidity control—an equally essential component of thermal comfort—also benefits from IoT integration. Inconsistent humidity can cause discomfort, dryness, or microbial growth (Ulpiani et al., 2021). Traditional systems often struggle to maintain the ideal 40–60% range, particularly in densely occupied spaces (Marques & Pitarma, 2019). IoT-based solutions offer greater precision: one study found that humidity could be maintained within ±3% of setpoints, compared to ±7–10% in conventional systems (Broday & Gameiro da Silva, 2023). In high-occupancy areas such as classrooms and auditoriums, this improved control led to a 12% reduction in excess moisture and better overall air quality (Huang, 2024). Incorporating real-time humidity feedback also enhanced occupants' perception of comfort (Lee & Zhang, 2024).

An additional advantage of IoT systems lies in their capacity for predictive maintenance, which extends equipment lifespan and minimizes operational disruptions. Traditional maintenance models rely on scheduled inspections or reactive servicing—both of which can increase costs and downtime (Mujan et al., 2021, Salzano et al., 2025). In contrast, IoT-enabled monitoring allows early fault detection: AI-powered diagnostics have identified HVAC issues 27% earlier and reduced downtime by 35% (Huang, 2024, Salzano et al., 2025). Moreover, integrating Digital Twin models has been shown to extend system life by 22% (Lee & Zhang, 2024). These proactive strategies enhance reliability, support building resilience, and align with long-term sustainability goals (Broday & Gameiro da Silva, 2023).

To clarify how Internet-of-Things interventions translate into tangible comfort gains, Table 1 aligns building type, IoT strategy, and the core thermal indicators that authors report (temperature stability, humidity regulation, occupant satisfaction). By presenting this information side-by-side, the matrix shows at a glance which digital-twin, predictive zoning, or personalized control approaches have delivered the most consistent performance across educational, healthcare, office, and residential settings.

Table 1: IoT-enabled thermal-comfort interventions: building type, smart technology applied, and principal comfort outcomes.

Study	Building Type	IoT Integration	Temperature Stability Improvement	Humidity Control	Occupant Satisfaction
Ulpiani et al. (2021)	Educational	Smart HVAC	Reduced fluctuations by 2.8°C	IoT humidity tracking improved comfort	Improved learning conditions
Marques & Pitarma (2019)	Residential	Smart Thermostats	Smart thermostats improved stability by 15%	N/A	15% increased comfort perception
Salzano et al. (2025)	Commercial	Digital Twin & HVAC Control	Reduced deviations by 15%	N/A	Optimized energy & comfort
Lee & Zhang (2024)	Educational	AI-Driven HVAC Zoning	Temperature deviations reduced by 2.8°C	Humidity adjusted within ±3% optimal range	Higher student satisfaction
Broday & da Silva (2023)	Healthcare	Occupancy-Based Climate Control	4.5°C reduction in temp deviations	12% reduction in excess moisture	Enhanced patient comfort
Mujan et al. (2021)	Office	AI Predictive HVAC	3.2°C reduction in temp variability	N/A	18% workplace satisfaction boost
Huang (2024)	Mixed-Use	AIoT-Based Climate Control	Adaptive control reduced fluctuations	N/A	Improved adaptability & comfort
Salamone et al. (2024)	Co-Working	Personalized Temperature Adjustment	24% fewer thermal complaints	N/A	24% reduction in complaints

4.2 IoT and Indoor Air Quality

IAQ is a core component of IEQ, directly affecting occupant health, cognitive performance, and overall well-being. Poor IAQ—characterized by elevated levels of carbon dioxide (CO_2), particulate matter (PM), volatile organic compounds (VOCs), and humidity imbalances—has been linked to respiratory conditions such as asthma and COPD, as well as symptoms like headaches, fatigue, and reduced cognitive function (Leung, 2015, Salamone, Sibilio, & Masullo, 2024, Ulpiani et al., 2021). These risks underscore the importance of maintaining high IAQ standards across residential, commercial, and institutional buildings.

Traditional ventilation and filtration systems operate based on static thresholds and often lack responsiveness to changing indoor conditions. In contrast, IoT-based IAQ systems leverage real-time sensing and automated environmental adjustments to manage air quality dynamically (Lee & Zhang, 2024, Mujan et al., 2021). Smart sensors monitor key pollutants such as CO_2, VOCs, and PM2.5, and respond by adjusting HVAC settings, activating filtration, or increasing ventilation rates as needed (Taştan, 2022). These systems also raise awareness of invisible pollutants, supporting proactive environmental health strategies.

A major benefit of IoT-enabled IAQ systems is the ability to optimize ventilation based on real-time pollutant concentrations and occupancy. For instance, commercial buildings have reported 20–30% CO_2 reductions with IoT-driven systems (Jiang, Jung, & Boor, 2021). Demand-controlled ventilation (DCV) has achieved up to 40% CO_2 reductions in offices (Mujan et al., 2021), 55% in schools (Lee & Zhang, 2024), and 30% in healthcare settings with AI-assisted systems (Broday & Gameiro da Silva, 2023). These results demonstrate how smart ventilation not only enhances air freshness but also improves energy efficiency through data-informed control.

Beyond reactive adjustments, predictive modeling further improves IAQ. AI-integrated IoT systems anticipate pollutant buildup and initiate preemptive actions, reducing CO_2 prediction errors by 8–10% (Huang, 2024, Marques & Pitarma, 2019a) and misclassification rates by 12% in school environments (Lee & Zhang, 2024). These approaches support more intelligent ventilation strategies that balance health and energy goals.

IoT-enabled filtration systems also play a critical role in managing indoor particulate pollution. Sources such as cooking, office equipment, and outdoor infiltration contribute to PM2.5 and PM10 exposure (Salamone, Sibilio,

& Masullo, 2024, Ulpiani et al., 2021). In contrast to fixed-speed purifiers, IoT-enhanced high-efficiency particulate air (HEPA) systems adapt in real time based on particle concentrations. In offices, they have reduced PM2.5 levels by 42% (Mujan et al., 2021), and in classrooms, by 38% (Lee & Zhang, 2024). Additional studies confirm 10–15% improved performance over conventional systems, correlating with better respiratory health (Jiang, Jung, & Boor, 2021).

In residential settings, smart home systems equipped with multisensory IAQ monitoring have also shown health benefits. Using data fusion, these platforms coordinate HVAC and filtration responses, reducing pollutant concentrations by up to 30% and supporting long-term wellness (Chang et al., 2019, Marques & Pitarma, 2016).

Controlling VOC exposure is another critical function of IoT-based IAQ systems, especially given common sources like furniture, finishes, and cleaning products. VOCs are linked to symptoms such as headaches, nausea, and eye irritation (Broday & Gameiro da Silva, 2023). Unlike conventional systems, IoT-enabled VOC sensors continuously monitor concentrations and trigger ventilation or purification when thresholds are exceeded (Salamone, Sibilio, & Masullo, 2024). These strategies have reduced VOC levels by 29% in commercial buildings (Huang, 2024) and by 25% in hospitals with IoT-integrated air exchange systems (Broday & Gameiro da Silva, 2023).

Although temperature often dominates comfort discussions, indoor-air quality is the clearest link between IoT and occupant health. Table 2 therefore groups the most recent studies that targeted CO_2, fine particulates, and VOCs, and it maps each pollutant to the sensing suite, analytics layer, and adaptive ventilation or filtration strategy applied. Taken together, the evidence shows that real-time, demand-controlled operation consistently drives reductions, confirming the central role of IoT in health-centred IEQ management.

Table 2: Comparative overview of IoT-driven IAQ studies: building context, target pollutant, smart technology, and measured improvements.

Study	Building Type	IoT Integration	CO2 Reduction	PM Reduction	VOC Reduction	Occupant Satisfaction
Salamone et al. (2024)	Office	Smart CO2 & PM Sensors	40% reduction with adaptive ventilation	42% decrease in PM2.5 with IoT-controlled filtration	29% VOC reduction with IoT-driven ventilation	Enhanced worker concentration and alertness
Ulpiani et al. (2021)	Educational	IoT-Driven VOC & CO2,, Monitoring	55% reduction in high-occupancy classrooms	N/A	Early VOC detection improved air exchange rates	Improved student performance with better IAQ
Lee & Zhang (2024)	Educational	AI-Based Smart Ventilation	CO2,, misclassification errors reduced by 12%	PM2.5 levels lowered by 38%	VOC-controlled ventilation improved air freshness	Classroom IAQ monitoring improved student health
Mujan et al. (2021)	Office	HEPA Air Filtration with IoT Control	30% lower CO2 levels in offices	Airborne PM exposure reduced by 35%	N/A	Higher workplace satisfaction with cleaner air
Broday & da Silva (2023)	Healthcare	Hospital Air Quality Monitoring	Hospital CO2,, reduced by 30%	N/A	25% decrease in VOC accumulation	Hospital air quality control benefited patients
Marques & Pitarma (2019)	Residential	IoT-Enabled Ventilation Control	Improved IAQ perception by 17%	N/A	IoT air quality tracking improved VOC management	Better perceived air quality in homes
Huang (2024)	Commercial	AI-Powered CO2 Prediction	AI-based prediction reduced CO2 errors by 10%	IoT-enabled filtration improved air quality	AI-optimized air purification controlled VOC exposure	IAQ predictions led to proactive air control
Salzano et al. (2025)	Mixed-Use	IoT-Based Adaptive Air Purification	N/A	PM control adapted based on real-time monitoring	IoT-driven air exchange reduced VOC levels	Optimized air quality reduced health complaints

4.3 IoT and Indoor Visual Comfort

Visual comfort is a key dimension of IEQ, directly influencing occupant well-being, productivity, and spatial perception. It involves factors such as adequate illuminance, uniform light distribution, glare control, and color temperature appropriate to both visual tasks and psychological needs (Carlucci et al., 2015). Poor lighting—characterized by excessive glare, insufficient brightness, or uneven daylight—can lead to visual discomfort, eye strain, and diminished performance (Lee & Zhang, 2024, Mujan et al., 2021). Traditional lighting systems, typically controlled manually or by static schedules, often lack responsiveness to real-time conditions or occupant needs.

IoT-based lighting systems address these limitations through continuous sensing, adaptive daylight integration, and AI-enhanced artificial lighting control (Broday & Gameiro da Silva, 2023, Salzano et al., 2025). These technologies dynamically adjust illumination based on occupancy, daylight availability, and user preferences, simultaneously improving visual comfort and energy efficiency. Smart lighting also optimizes brightness and spatial distribution in response to behavioral and contextual cues, helping to reduce eye fatigue and enhance task performance (Putrada et al., 2022).

Studies have consistently shown that IoT-integrated lighting systems enhance lighting quality while reducing energy use. For example, adaptive lighting improved illuminance and reduced glare by 21% in indoor settings (Marques & Pitarma, 2019a). In office environments, dynamic façades and automated shading systems effectively regulate daylight and minimize visual discomfort (Giovanardi et al., 2024). Putrada et al. (2022) highlighted the importance of real-time adjustments in task-intensive spaces, while Huang (2024) reported a 15% increase in visual comfort in classrooms with sensor-based lighting. Smart lighting also reduced eye strain complaints by 18% in educational settings (Lee & Zhang, 2024).

Table 3: IoT solutions for visual comfort: lighting/shading approach, study setting, and performance indicators.

Study	Building Type	IoT Integration	Glare Reduction	Illuminance Optimization	Occupant Satisfaction
Giovanardi et al. (2024)	Office	Daylight Sensors & AI-Based Lighting	25% glare complaints reduction with automated shading	21% improvement in indoor lighting conditions	Higher visual comfort ratings among employees
Lee & Zhang (2024)	Educational	Adaptive Classroom Lighting	IoT-controlled blinds reduced glare by 30%	18% better classroom lighting adaptation	Improved student learning environment
Huang (2024)	Commercial	Automated Blinds & Dynamic Shading	Electrochromic glass optimization reduced glare by 22%	Real-time daylight tracking improved indoor illumination	Office users reported better lighting control
Mujan et al. (2021)	Office	Smart Lighting Personalization	N/A	15% increase in workplace visual comfort	19% increase in workplace satisfaction
Broday & da Silva (2023)	Residential	IoT-Driven Lighting Preferences	Adaptive daylighting minimized brightness discomfort	IoT-adjusted brightness for energy efficiency	Better lighting adaptation for home users
Marques & Pitarma (2019)	Smart Homes	IoT-Based Mood Lighting	N/A	Smart home lighting enhanced user satisfaction	Personalized lighting enhanced relaxation
Salamone et al. (2024)	Mixed-Use	AI-Powered Daylight Optimization	AI-driven daylight control balanced illumination	Adaptive lighting ensured consistent indoor brightness	IoT-driven lighting control improved perception
Salzano et al. (2025)	Smart Buildings	IoT-Enabled Energy-Efficient Smart Lighting	Automated window coatings mitigated glare	Energy-aware lighting reduced over-illumination	Enhanced occupant experience in smart spaces

A distinct advantage of IoT lighting systems is their ability to manage daylight and mitigate glare, especially in spaces with large glazing surfaces or direct sun exposure. Automated shading systems—including motorized blinds and electrochromic glass—respond to solar intensity, reducing glare by up to 30% and improving visual comfort ratings by 20% (Huang, 2024, Salamone, Sibilio, & Masullo, 2024).

These systems also provide activity-specific lighting by adjusting brightness and color temperature using motion sensors, daylight tracking, and AI-based learning. Salzano et al. (2025) reported energy savings of 15–30%, along with increased occupant satisfaction. In offices, smart lighting reduced artificial lighting use by 22% without compromising comfort (Broday & Gameiro da Silva, 2023), while in homes, dimming controls improved perceived comfort by 17% and cut electricity costs by 20% (Lee & Zhang, 2024). Smart home lighting also enables automation based on time of day or user routines, supporting both visual comfort and psychological well-being (Gade, 2019).

Personalization is another key feature of IoT-based lighting. These systems allow users to control brightness, color temperature, and distribution via intuitive apps or interfaces (Huang, 2024). Personalized lighting environments have been linked to improved satisfaction and mood. Mujan et al. (2021) observed a 19% increase in workplace satisfaction, while Broday and Gameiro da Silva (2023) noted a 22% improvement in residential mood and comfort. In educational settings, adaptive lighting aligned with instructional tasks has enhanced focus and learning outcomes (Gade, 2019). These findings emphasize the value of occupant-centered lighting in creating adaptive and health-supportive visual environments.

Lighting research has shifted rapidly from static schedules to sensor-integrated ecosystems. Table 3 summarizes recent work that combines daylight-responsive façades, networked luminaires, and AI control algorithms, detailing their effects on glare suppression, illuminance balance, and user satisfaction across workplaces, classrooms, and homes.

4.4 IoT and Indoor Acoustic Comfort

Acoustic comfort refers to the regulation of indoor sound levels to maintain a favorable auditory environment. It is essential in settings such as homes, schools, hospitals, and offices, where excessive noise can impair concentration, disrupt communication, and negatively impact health and productivity (Lee & Zhang, 2024, Mujan et al., 2021, Riffelli, 2022). Traditional passive noise control methods—such as insulation or fixed white noise generators—often fall short in addressing the dynamic nature of indoor acoustics. The integration of IoT technologies represents a shift toward responsive and adaptive sound management. Smart acoustic systems now use interconnected sensors and algorithms to continuously monitor, analyze, and respond to sound conditions with minimal human intervention (Riffelli, 2022).

IoT-based acoustic systems combine real-time noise sensors, machine learning algorithms, and active sound masking to deliver dynamic acoustic management across building types (Broday & Gameiro da Silva, 2023, Salzano et al., 2025). These systems detect fluctuations in ambient noise and regulate sound pressure levels to support comfort and concentration. In open-plan offices, IoT-enhanced systems have reduced background noise by up to 15 decibels, significantly improving the acoustic environment (Marques & Pitarma, 2020).

A key innovation is the integration of real-time acoustic tracking with adaptive sound control. These systems assess noise intensity, frequency, and source, enabling them to initiate background masking or active noise control (ANC) when disturbances occur. Studies show 85–92% accuracy in detecting and mitigating disruptive sound events (Huang, 2024, Marques & Pitarma, 2019b). In offices, sound masking reduced perceived acoustic disturbances by 28% (Mujan et al., 2021), while in hospitals, noise levels dropped by 15–20% in intensive care units and patient rooms, supporting improved sleep and recovery (Broday & Gameiro da Silva, 2023).

IoT-enabled active noise control (ANC) technologies offer real-time noise cancellation that adapts continuously to the environment. In office spaces, AI-driven ANC has reduced speech intelligibility by 35%, improving focus and task performance (Lee & Zhang, 2024). Similar systems reduced ambient noise by 22% in shared workspaces (Mujan et al., 2021) and improved sleep quality in residential settings by 17% (Huang, 2024). Smart home systems further enhance acoustic comfort by adjusting masking and volume based on room function and occupant activity.

Educational spaces also benefit from IoT acoustic strategies. Beyond passive treatments like acoustic panels, smart classrooms use real-time feedback to modulate speech reinforcement and suppress disruptive sounds. These systems have achieved 20–30% reductions in environmental noise (Lee & Zhang, 2024), while Salzano et al. (2025) reported a 15% improvement in student attentiveness with intelligent sound control.

In addition to noise mitigation, IoT-enabled platforms offer personalized soundscapes based on user preferences and context. In homes and commercial buildings, systems create auditory profiles for focus, relaxation, or social interaction by adjusting sound modes in response to occupancy and ambient noise (Broday & Gameiro da Silva, 2023). In residential settings, personalized acoustic environments increased occupant satisfaction by 19% (Marques & Pitarma, 2019b). In hospitality venues, adaptive music systems improved guest experience by 22% by aligning sound settings with crowd levels and acoustic conditions (Salamone, Sibilio, & Masullo, 2024).

The acoustic domain is newer but evolves quickly. Table 4 aggregates implementations of IoT systems such as real-time sound sensing, active noise control, and context-aware masking, mapping decibel reductions against behavioral or well-being metrics and illustrating the move from passive insulation to responsive, data-driven soundscapes.

Table 4: IoT applications in indoor acoustic comfort: sensing/actuation scheme, noise-mitigation performance, and occupant response.

Study	Building Type	IoT Integration	Noise Reduction	Active Noise Control (ANC)	Occupant Satisfaction
Lee & Zhang (2024)	Educational	Adaptive Noise Monitoring & ANC	Speech noise reduction by 35% in classrooms	Real-time adaptive ANC in classrooms	15% increase in student focus & engagement
Mujan et al. (2021)	Office	Smart Noise Masking & Sound Sensors	28% lower background noise in offices	IoT-managed ANC in open offices	Higher workplace satisfaction with less auditory distraction
Broday & da Silva (2023)	Healthcare	Hospital Acoustic Tracking	15-20% noise level reduction in hospitals	Smart ANC reduced hospital noise disturbances	Better patient sleep & comfort with reduced hospital noise
Salzano et al. (2025)	Classroom	IoT-Based Classroom Noise Control	Disruptive noise reduced by 30%	Noise cancellation improved student concentration	Improved teacher & student perception of classroom sound
Huang (2024)	Residential	Home Sound Optimization	IoT-driven nighttime noise control improved sleep	IoT-integrated ANC in home environments	19% better auditory satisfaction in home environments
Marques & Pitarma (2019)	Retail & Hospitality	IoT-Enabled Dynamic Soundscapes	Background sound adjusted based on occupancy	Dynamic ANC for enhanced customer experience	22% improvement in customer experience
Salamone et al. (2024)	Mixed-Use	AI-Powered Noise Prediction & Mitigation	AI-predicted noise reduction of 22% in public spaces	AI-enhanced ANC for real-time noise adjustments	IoT-driven noise control improved perceived acoustic comfort

5. IoT SENSING SYSTEMS FOR IEQ MONITORING

Recent advances in IoT technologies have redefined how buildings monitor and manage IEQ. Moving beyond traditional, siloed approaches, IoT-enabled systems enable continuous, multidimensional monitoring of key parameters—including thermal comfort, IAQ, lighting, and acoustics—through networks of environmental and physiological sensors. These platforms support real-time decision-making and occupant-centered strategies for optimizing indoor environments (Broday & Gameiro da Silva, 2023).

In the thermal comfort domain, IoT systems primarily monitor indoor air temperature and relative humidity, essential inputs for predictive models like Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD) (Geck et al., 2024). Advanced configurations also capture air velocity, mean radiant temperature, and surface temperature using tools such as infrared thermography (Lee et al., 2022, Marques & Pitarma, 2019b). Wearable and intelligent sensors further enhance thermal assessment by integrating physiological data such as skin temperature, heart rate, metabolic rate, and clothing insulation (Alsaleem et al., 2020, Geck et al., 2024, Salamone, Sibilio, & Masullo, 2024). For practical deployment, low-cost sensor nodes based on platforms like Arduino and Raspberry Pi—such as those in the PROMET&O framework—have shown reliable performance (Calvo et al., 2022, Fissore et al., 2024).

IAQ monitoring builds on this foundation through sensors that detect key pollutants, including CO_2, PM2.5, PM10, VOCs, formaldehyde (HCHO), ozone (O_3), NO_2, and CO, as well as ambient temperature and humidity (Bobulski, Szymoniak, & Pasternak, 2024, Dai et al., 2023, Mujan et al., 2021, Ulpiani et al., 2021). Integrated sensor networks, as demonstrated in PROMET&O, support high-resolution, real-time surveillance (Fissore et al., 2024). Platforms such as ENVIRA and iAQ+ enable scalable deployment in schools and commercial buildings, enhancing environmental control and health outcomes (Marques & Pitarma, 2019a, Mujan et al., 2021). Studies show that pairing CO_2 monitoring with adaptive ventilation can significantly reduce indoor concentrations of pollutants like

CO_2 and O_3 (Felgueiras et al., 2024). To maintain accuracy, sensors should be recalibrated or replaced every 4–6 months (Dai et al., 2023).

Visual comfort is typically assessed using photometric or illuminance sensors that track light intensity (lux), helping maintain standards such as the 500 lux threshold recommended for office work (Dong et al., 2019). These sensors are particularly useful in classrooms and workplaces where lighting quality influences well-being and cognitive performance (Hernandez & Cañas, 2024). Advanced systems incorporate dynamic lighting control using image or infrared sensors to adjust for occupancy and daylight availability (Lee et al., 2022). Some platforms also integrate physiological feedback—such as pupil dilation data from mobile pupillometers—to optimize lighting conditions (Dong et al., 2019, Salamone, Sibilio, & Masullo, 2024).

Acoustic comfort is addressed through sensors that measure sound pressure levels (SPL), along with microphones and sound event detection (SED) algorithms. These tools help identify noise sources and assess subjective acoustic experiences, especially in noise-sensitive spaces like schools and offices (Mujan et al., 2021, Salamone, Sibilio, & Masullo, 2024). Wireless Acoustic Sensor Networks (WASNs) extend this capability by analyzing ambient noise patterns and predicting occupant comfort with up to 85% accuracy (Bonet-Solà, Vidaña-Vila, & Alsina-Pagès, 2024). Multifunctional IEQ loggers integrate acoustic, thermal, lighting, and air quality data to support comprehensive environmental management (Dong et al., 2019).

The potential of IoT sensor networks is further enhanced by integration with Artificial Intelligence of Things (AIoT) and Digital Twin technologies. AIoT systems fuse sensor data with occupant feedback to enable predictive, human-centric control (Lee & Zhang, 2024). Meanwhile, Digital Twin platforms synchronize real-time sensor inputs with virtual building models to improve HVAC maintenance and optimize energy performance (Salzano et al., 2025). Together, these innovations position smart buildings as adaptive ecosystems that respond in real time to both occupant needs and operational goals.

6. CHALLENGES FOR IoT-DRIVEN IEQ MONITORING

While the IoT technologies into IEQ management offers transformative potential, its implementation presents a range of technical, organizational, behavioral, and ethical challenges. Buildings are inherently dynamic systems, influenced by fluctuating occupancy patterns, seasonal variability, and individual comfort preferences—all of which complicate the continuous optimization of environmental parameters through automated sensing and control. One primary challenge concerns sensor reliability and measurement accuracy. Effective IEQ regulation depends on the precision of data collected by sensors monitoring factors such as carbon dioxide, particulate matter, temperature, and humidity. However, many low-cost sensors degrade over time, leading to performance issues and requiring regular recalibration. For instance, non-dispersive infrared (NDIR) CO_2 sensors must be recalibrated periodically, a process that becomes logistically complex and resource-intensive at scale (Dai et al., 2023). Although high-end sensors offer greater accuracy, their cost remains a barrier to widespread implementation (Lawal & Rafsanjani, 2022).

Another persistent issue is system fragmentation. Many buildings adopt smart technologies incrementally, resulting in isolated subsystems built on proprietary platforms and incompatible communication protocols (Whaiduzzaman et al., 2022). This lack of interoperability hinders integrated analytics, intelligent environmental control, and predictive modeling, as noted in foundational studies of smart infrastructure. Privacy and cybersecurity concerns further constrain adoption. The collection of granular occupant data raises ethical issues related to surveillance, consent, and data ownership (Lawal & Rafsanjani, 2022). Empirical research shows that trust in smart building systems hinges not only on technical performance but also on transparent data governance and responsible handling practices (Mazhar et al., 2023). Additionally, many IoT devices operate on unsecured wireless networks, increasing their vulnerability to cyberattacks (Sicari et al., 2015). While AI-driven intrusion detection systems are advancing, maintaining cybersecurity requires proactive, ongoing monitoring and system resilience strategies (Mazhar et al., 2023).

Occupant behavior introduces another layer of complexity. Even in highly automated buildings, users frequently override default settings—adjusting thermostats, disabling sensors, or opening windows—based on personal comfort preferences (Bonilla et al., 2018). Systems that fail to account for this behavioral variability may be underutilized or ignored. Effective IoT integration must therefore prioritize flexible, occupant-centered design that accommodates a range of user interactions (Mazhar et al., 2023, Metwally, Ismail, & Farid, 2024). Infrastructure-related limitations, particularly dependence on cloud-based systems, can also affect performance. Cloud platforms are vulnerable to latency and connectivity disruptions, especially in areas with poor internet access (Marques & Pitarma, 2019a). Edge computing—where data processing is localized at the sensor or gateway level—offers an alternative that reduces latency, enhances privacy, and improves system robustness (Salamone, Sibilio, & Masullo, 2024).

Capital outlays span roughly US \$10 m² for basic BLE sensor grids to > US \$45 m² for AI-enabled multi-sensor nodes, and retrofits often require middleware that bridges legacy BMS protocols, adding a further 10–15 % to project cost (Chamari et al., 2023). Large campuses report devoting ≈ 12 person-hours per month solely to battery swaps and firmware updates (Calvo et al., 2022), while continuous calibration is needed to prevent sensor drift (Dai et al., 2023). User-acceptance studies reveal that perceived intrusiveness can trigger manual overrides, wiping out up to 30 % of predicted energy or comfort gains (Bonilla et al., 2018). Rigorous cost–benefit modelling, participatory design workshops, and transparent feedback dashboards are therefore indispensable to ensure long-term performance and occupant trust.

Sustainability represents another often-overlooked dimension. IoT devices contribute to environmental burdens through energy-intensive manufacturing, short product life cycles, and electronic waste (Bonilla et al., 2018, Pandiyan et al., 2024). Mitigating these impacts requires the adoption of sustainable IoT practices, including modular hardware design, low-power communication protocols, extended device lifespans, and end-of-life materials recovery (Abdul-Qawy et al., 2023, Pandiyan et al., 2024). Ultimately, realizing the full potential of IoT in IEQ monitoring and control requires a comprehensive, interdisciplinary approach. Beyond technological innovation, successful deployment must integrate human-centered design, ethical data governance, sustainability principles, and adaptive cybersecurity frameworks (Asaad & Maghdid, 2022).

At the privacy front, the high-resolution thermal, acoustic, and occupancy "fingerprints" generated by dense sensor networks can expose daily routines and health cues, making privacy-by-design safeguards—on-device encryption, differential identifiers, and explicit consent dashboards—non-negotiable (Mazhar et al., 2023). Environmentally, short sensor life cycles translate into an under-appreciated e-waste stream: replacing a low-cost CO_2 node every four years yields almost one kilogram of electronic scrap and can erode up to one-third of the HVAC energy it was meant to save (Pandiyan et al., 2024). Nor is operational energy trivial, a 500-node office deployment can draw ≈ 6 MWh/yr in standby power—roughly the annual lighting load of a 900 m² modern workspace (Lawal & Rafsanjani, 2022). Responsible roll-outs must therefore be a couple of low-power communication protocols and edge processing (to curb cloud traffic) with modular, repairable hardware and circular take-back schemes, ensuring that IoT gains in indoor environmental quality are not offset by hidden social or ecological costs.

7. DISCUSSION

This review highlights the transformative potential of IoT technologies in managing IEQ, encompassing thermal comfort, IAQ, visual comfort, and acoustic comfort. Across these domains, IoT-enabled systems consistently outperform traditional, manually controlled approaches by enabling real-time monitoring, predictive analytics, and adaptive environmental control. These capabilities support dynamic responses to environmental fluctuations and occupant needs, offering a pathway toward smarter, healthier, and more energy-efficient buildings.

A consistent finding across the literature is IoT's ability to maintain stable indoor conditions and minimize fluctuations that contribute to discomfort. In thermal comfort management, IoT-based HVAC systems reduce temperature variability and enable zone-specific adjustments informed by occupancy and user feedback. In IAQ, pollutant-specific sensors integrated with demand-controlled ventilation effectively reduce concentrations of CO_2, VOCs, and PM2.5—key contributors to health issues and cognitive decline. Visual and acoustic comfort—often underemphasized in conventional IEQ strategies—also benefit from IoT innovations. Smart lighting systems equipped with occupancy and daylight sensors regulate illuminance, reduce glare, and respond to task-specific requirements, while intelligent acoustic systems use real-time monitoring and adaptive control to reduce disruptive noise, enhancing focus and restfulness. Collectively, these findings confirm the multidimensional nature of IoT-based IEQ management, integrating environmental sensing with behavioral responsiveness.

The ability to personalize environmental conditions is another key advantage. Systems that allow user-specific adjustments are consistently associated with higher satisfaction and lower complaint rates. This shift toward occupant-centered environmental control reflects broader trends in health-supportive architecture and human-centric building design. However, despite these advantages, several limitations hinder broader adoption. Sensor inaccuracy, reliability issues, and calibration drift remain common, especially in low-cost devices. Many studies report that while these sensors improve accessibility, their limited lifespan and maintenance needs create challenges in large-scale deployments. Emerging solutions such as self-calibrating sensors and AI-based error correction are promising but not yet widespread.

Building on these technical limitations, a broader literature scan reveals several open research gaps. Despite the breadth of work surveyed, few studies track IEQ outcomes for longer than a full year, leaving seasonal variability, occupant churn, and sensor drift under-examined. Acoustic comfort remains notably under-represented—only eight of the 38 core papers conduct controlled noise-mitigation trials, and none pair sound data with physiological or cognitive indicators, as summarized in Table 4. Cross-domain interactions are seldom modelled, most projects optimize a single IEQ parameter in isolation, overlooking trade-offs such as glare reduction versus daylight autonomy or fresh-air gains versus heating penalties. Equity is another blind spot, with virtually no fieldwork in low-income housing or deep-retrofit buildings. Future investigations should therefore prioritize multi-season, multi-metric studies in diverse socioeconomic contexts and develop integrated comfort models that balance all four IEQ domains.

Fragmentation of IoT systems is another barrier. Many deployments operate on proprietary platforms with limited interoperability, restricting integration, coordination, and scalability. Without open communication standards, it becomes difficult to merge environmental data streams or enable cross-system responsiveness. Likewise, privacy and cybersecurity challenges remain significant. IoT systems often collect detailed behavioral and environmental data, raising concerns about surveillance, consent, and data ownership. Without transparent data governance and privacy-by-design principles, occupant trust may decline, undermining system effectiveness. Ensuring secure architectures and ethical data handling is essential for long-term adoption.

Behavioral variability adds another layer of complexity. Even highly automated systems can be undermined when users override controls due to discomfort or preference. Research emphasizes the importance of adaptive systems that incorporate feedback loops, allow for manual intervention, and learn from user behavior over time. Balancing automation with user autonomy is vital for both comfort and continued system engagement.

From a research standpoint, the field faces challenges related to methodological inconsistency. Studies differ widely in metrics, sensor types, sampling rates, and outcome indicators, making cross-study comparison and meta-analysis difficult. Standardized protocols, shared datasets, and benchmarking frameworks would significantly improve research rigor and comparability. Sustainability considerations also deserve closer attention. While IoT systems can improve energy efficiency, they also introduce new environmental burdens through frequent device replacement, short product life cycles, and e-waste. Future efforts should embrace life-cycle thinking—prioritizing low-power systems, modular hardware, and circular design principles.

Table 5: Summary of Key Themes in IoT-Enabled IEQ: Domains, Benefits, Challenges, and Future Research Directions.

Category	Summary
IEQ Domains	Thermal, air quality, visual, and acoustic comfort
IoT Benefits	Real-time sensing, adaptive control, predictive analytics, energy efficiency, and personalized comfort
Domain Applications	- Thermal: Stable temperatures, zone-level control - IAQ: Pollutant detection, smart ventilation - Visual: Adaptive lighting, glare control - Acoustic: Dynamic noise mitigation
Challenges	Sensor limitations, fragmented systems, privacy concerns, and user behavior inconsistencies
Future Priorities	Durable, self-calibrating sensors, interoperable platforms, ethical data use, lifecycle-aware design
Institutional Needs	Clear policy standards, certification mechanisms, and user-centered frameworks
Goal	Smart, inclusive, and resilient environments that enhance human well-being

Looking forward, advancing IoT-enabled IEQ management will require progress across technical, behavioral, and institutional domains. Priorities include improving sensor durability, developing edge computing for real-time processing, and creating plug-and-play systems for easier deployment. On the behavioral side, smart environments must be transparent, inclusive, and adaptable to diverse occupant needs. Institutionally, regulatory standards, certification mechanisms, and clear policy frameworks are needed to support safe, ethical, and scalable implementation. Ultimately, this review underscores the potential of IoT to redefine how indoor environments are monitored, controlled, and experienced. By shifting the focus from system efficiency to occupant-centered well-being, IoT-enabled solutions can help create buildings that are not only smarter, but also healthier, more inclusive, and more sustainable. Fully realizing this potential will require bridging the gap between technological innovation and human-centered design to ensure that smart environments truly serve the people they are designed for.

Table 5 provides an integrated summary of the key themes, benefits, challenges, and future directions discussed in this review, offering a concise framework for both researchers and practitioners engaging with IoT-based IEQ strategies.

8. CONCLUSION

This review has critically examined the integration of IoT technologies across four key domains of IEQ: thermal comfort, IAQ, visual comfort, and acoustic comfort. The findings demonstrate that IoT-enabled systems significantly enhance environmental monitoring and control through real-time sensing, predictive analytics, and adaptive feedback. These capabilities contribute to improved occupant comfort, cognitive performance, and energy efficiency, while also supporting the operational goals of building owners, designers, and facility managers across diverse typologies.

A clear shift is emerging from static, one-size-fits-all environmental controls to responsive, occupant-centered systems. Smart HVAC configurations, adaptive lighting, pollutant-specific ventilation strategies, and intelligent acoustic control represent integrated, real-time approaches that align indoor environments with dynamic occupancy patterns. These developments not only enhance occupant well-being but also reflect the broader evolution of construction practice toward data-driven, human-centric design and operations.

Nevertheless, critical challenges remain. Sensor degradation, system fragmentation due to proprietary platforms, and persistent concerns about data privacy and cybersecurity continue to limit large-scale adoption. Additionally, occupant behavior—especially the tendency to override automated systems—introduces complexity that requires adaptive, user-informed design strategies. Sustainability concerns, including electronic waste and the energy demands of continuous sensing and data transmission, also call for more holistic, lifecycle-aware approaches.

Future research should prioritize the development of robust, self-calibrating sensors, interoperable systems built on open standards, and privacy-preserving data architectures. Longitudinal field studies are needed to assess the long-term effectiveness of IoT-enabled environments on health, performance, and behavioral adaptation. In parallel, sustainable design practices—including modular hardware, low-power edge computing, and circular lifecycle models—should guide the next generation of IoT applications in the built environment.

Delivering occupant-centric, data-secure, and resource-efficient smart buildings is inherently interdisciplinary. Architectural and building-services engineers must work in tandem with computer, electrical, and data scientists to embed edge-AI processors into façades, HVAC, and lighting networks, while behavioural scientists and environmental psychologists evaluate how these adaptive environments affect comfort, cognition, and well-being.

Ultimately, IoT technologies offer transformative opportunities for construction professionals, building managers, and policymakers to design and operate spaces that are not only smart but also adaptive, inclusive, and resilient. Realizing this potential will require an interdisciplinary framework that integrates engineering innovation with human-centered design, ethical data use, and environmental responsibility. By embedding these principles into construction research and practice, the built environment can evolve into a responsive ecosystem that actively supports the health, productivity, and well-being of its occupants.

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