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Review Article

Impact of Indoor Air Quality and Multi-domain Factors on Human Productivity and Physiological Responses: A Comprehensive Review

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Indoor environmental quality (IEQ) significantly impacts human health, well-being, and productivity. However, a comprehensive and in-depth review of the combined effects of IAQ and other multi-domain factors on human productivity is lacking. There has not been any prior review that encapsulates the impact of multi-domain factors on productivity and physiological responses of occupants. To address this gap, this review paper investigates and highlights the impact of IAQ and multi-domain factors (thermal, visual, and acoustic) on human productivity and occupant well-being in the built environment. The review explores various research methods, including evaluation of human productivity and creativity, data collection, and physiological signal analysis. We also examined the interactions between IAQ and multi-domain factors, as well as strategies for optimizing productivity through integrated building design and smart systems. The key findings from this review reveal that IAQ significantly impacts human productivity and occupant well-being, with interactions between IAQ and other IEQ factors further impacting these effects. Despite advances in the field, there are several limitations and gaps in the current research methods and study designs, including small sample sizes, limited and insufficient experimental design and control, reliance on laboratory or simulated environments, lack of follow-up and long-term data, and lack of robust performance metrics. The review proposes future research directions, including specific applications, and follow-up work to address these limitations and further advance the understanding of IAQ and multi-domain factors in the built environment. The implications of this review for policy and practice include the need for holistic and integrated approaches to IAQ and IEQ management, with a focus on creating healthy and productive indoor environments. This review emphasizes the importance of considering the complex interplay between IAQ and multi-domain factors, as well as the potentials of adopting smart control systems and sustainable design strategies to optimize productivity and occupant well-being in the built environment. By addressing these critical issues, we can enhance the overall quality of life for building occupants and contribute to a more sustainable future.

1. Introduction

1.1. Background. The concept of indoor environmental quality (IEQ) has become pivotal in the discourse of the built environment, reflecting its profound influence on the health, well-being, and productivity of building occupants [1]. This heightened relevance is attributed to the modern lifestyle trend where individuals spend a substantial portion of their day indoors. IEQ is a multifaceted construct, encompassing elements such as thermal comfort, indoor air quality (IAQ), acoustic comfort, and visual comfort, each playing a vital role in optimizing the performance and satisfaction of occupants, particularly in office environments [2], as illustrated in Figure 1.

These elements are not only individual factors but are interacted in a complex system that collectively shapes the experience of the indoor environment. For instance, thermal comfort is not just a matter of temperature regulation but is intrinsically linked to factors like humidity and air movement, directly impacting occupant comfort and productivity [3]. Similarly, IAQ, which includes parameters such as CO_2 concentration, particulates, and volatile organic compounds (VOCs), is a critical component of IEQ. For example, CO_2 levels have been associated with increased workplace stress

Figure 1: Overview of indoor environmental quality.

when concentrations surpass 2000 ppm [4]. Furthermore, the presence of VOCs and particulates in the air has been linked to a range of health issues, from respiratory problems to cardiovascular risks, thereby influencing both the well-being and efficiency of individuals [5].

The significance of IAQ extends beyond physical health. Studies have demonstrated a correlation between poor air quality and reduced cognitive function, highlighting the importance of maintaining optimal air quality for enhancing productivity [6]. This is particularly crucial in settings like schools and offices, where cognitive performance is directly tied to success and efficiency. Moreover, the broader spectrum of IEQ factors, including layout, biophilia, aesthetics, and location, also contributes significantly to human productivity and satisfaction [7]. These factors, often overlooked in traditional building management strategies, are essential for a holistic understanding of the impact of IEQ on human health and productivity.

IEQ represents a multidimensional concept, intricately linked to various environmental factors and their interactions with human health, comfort, and productivity [8, 9]. The growing body of research in this area underscores the need for an integrated approach in building management, one that acknowledges and addresses the complex interplay of these diverse factors to enhance both occupant well-being and environmental sustainability [10–13].

Human productivity is influenced by various factors, including physical and mental well-being, work environment, and available resources [14]. The impact of IEQ on worker productivity has garnered increasing attention, with studies demonstrating that poor IEQ can negatively affect worker productivity [15–18]. Factors such as air temperature [18–20], lighting [21, 22], and IAQ [23] play significant roles in determining workers' well-being and productivity. Thus, human productivity is directly influenced by the IEQ of the workplace. Creativity, a complex asset in various disciplines, is influenced by factors including the physical and social environment [24]. IEQ can significantly foster or hinder creativity, making it a crucial element in environments where innovation is key to economic growth and social progress.

1.2. Problem Statement and Significance. The impact of IAQ and multi-domain factors on productivity and occupant well-being is a significant area of study. Poor IAQ can lead to various health issues reducing human productivity. However, the relationship between IAQ and human productivity is complex and multifaceted, necessitating further research to understand the underlying mechanisms [14, 17, 18, 22, 23]. Additionally, the optimal range for thermal, acoustic, and visual comfort varies among individuals, posing challenges in building system design. The multi-domain impact of IAQ on other IEQ factors has not been thoroughly studied, highlighting the need for comprehensive research in this area.

Therefore, we suggest the following important research questions for IAQ on human productivity and occupant well-being:

(i) What is the relationship between IAQ and human productivity, and how does this vary based on different IEQ factors?

(ii) How can we effectively control IAQ with other factors to enhance occupant comfort and productivity while minimizing energy consumption and carbon emissions?

These research questions are critical for advancing the field and have practical implications for improving building design and operation. Given the complexity of these multi-domain factors, it is important to take a holistic approach to designing and managing indoor environments.

IAQ can significantly impact on occupant health, productivity, and creativity. Several studies have shown that poor IAQ can lead to respiratory problems, allergies, headaches, and fatigue, which can ultimately lead to reduced human productivity. However, the relationship between IAQ and human productivity is complex. Therefore, further research is needed to understand the mechanisms through which IAQ affects human productivity. What is more, several studies have shown that poor lighting, thermal discomfort, and noise can lead to distraction, discomfort, annoyance, and reduced productivity. However, the optimal thermal, acoustic, and visual comfort range varies between individuals making it challenging to design the building system. The multi-domain impact of IAQ on other IEQ factors was not well studied.

1.3. Scope and Purpose. The scope of this literature review is on the topic of IAQ and its multi-domain factors on human productivity and occupant well-being, which were lacked in previous reviews. Recently, several previous review papers have discussed the importance of multi-domain factors. Mendell and Heath [25] examined the relationship between IEQ and thermal on academic performance in schools. It discussed the adverse effects of poor IEQ, including indoor pollutants and thermal conditions, on student performance and attendance. Haynes [26] evaluated the impact of office comfort on office occupiers' productivity. It discussed the complex nature of evaluating office comfort, the lack of a universally accepted definition, and the need for a common measurement. It concluded that office comfort can affect productivity. Shishegar and Boubekri [27] reviewed literature on the impact of natural light on the health, satisfaction, attention, and performance of office workers and students. The review highlighted the positive effects of natural light on individuals in both work and educational settings. Rasheed and Byrd [28] examined the reliability of self-evaluation as a method for measuring the effect of IEQ on office workers' productivity. It identified the insufficiencies and biases prevalent in self-evaluation and concludes that it is not reliable for accurately measuring occupant productivity. Esfandiari et al. [29] conducted a literature review on the impact of IEQ factors on occupants' behavior and work productivity in green offices. The study emphasized the importance of factors such as lighting, noise, thermal quality, and IAQ in enhancing occupants' productivity and satisfaction. The review by Wu et al. [30] focused on the interaction between different environmental factors, such as acoustic, thermal, and illumination, in affecting overall human comfort. It emphasized the one-vote veto power of each kind of human perception on overall human comfort. Kapoor et al. [31] conducted a systematic review of the existing practices of IEQ in naturally ventilated school buildings. The review discussed components of IEQ, impacts of COVID-19, and the importance of concerned issues and factors for future research direction. Bueno et al. [32] conducted a systematic literature review on the correlation between thermal comfort and human productivity in buildings. The review focused on understanding the relationship between thermal comfort conditions and occupants' productivity and listed all the productivity calculation based on various comfort indices. Schweiker et al. [11] reviewed scientific papers on interactions and cross-domain effects that influence occupants' indoor environmental perception and behavior. Zhao and Li [33] conducted a thorough review of multi-domain IEQ on occupant satisfaction, especially the weighting on different factors. Finally, Dong et al. [34] also reviewed the effect of thermal, acoustic, and visual environment in underground space on human comfort and work efficiency.

While numerous previous studies have examined temperature, visual, and acoustics, IAQ has often been overlooked. A recent review by Torresin et al. [35] revealed that there were very few studies investigating the interaction between IAQ and other environmental factors. For instance, 29% of prior research examined the interaction between temperature and lighting, 24% looked at temperature and noise, and 9% explored the relationship between temperature, noise, and lighting. However, only 18% of these studies focused on temperature and IAQ. Furthermore, less than 10% of previous research considered the combined effects of IAQ with noise and lighting. This paper is aimed at exploring the relationships between IAQ and other multi-domain factors on human productivity. Furthermore, there has not been any prior overview that encapsulated the influence of multi-domain on human productivity and physiological signals. Consequently, this review contributes to several areas:

(1) It provides an extensive review of evaluating methods for productivity and creativity

(2) It compiles a comprehensive summary of participant characteristics

(3) It offers a thorough analysis of IAQ and the impact of multi-domain factors on physiological signals

The purpose of this literature review is to provide a comprehensive analysis of the existing research on the impact of IAQ and multi-domain factors on occupant well-being and productivity. Finally, it discussed the implications of the findings for the design, operation, and management of sustainable buildings and the future research directions in this field. With this review, it answered the above research questions and contributed to the fields. We would also suggest directions for future research.

Here is a brief overview of the main sections. Section 2 provides a review of research methods that are relevant to the study of IAQ and its impact on human productivity. The sections include data collection methods, questionnaire survey design, evaluation of human productivity, evaluation of creativity, and the use of physiological signals. Section 3 discusses the impact of IAQ and multi-domain interactions on human productivity. It also discusses strategies for optimizing these factors, including integrated building design, smart systems, and occupant feedback. Section 4 presents a discussion of the studies conducted on IAQ and human productivity. It provides an overview of the studies and their limitations. Section 5 provides a conclusion to the study. It summarizes the key findings and their implications for future research.

2. Review of Research Methods

2.1. Literature Search. Figure 2(a) shows the flow chart of the literature review. To conduct the review step-by-step, the first step is to identify the research questions. The next step is to define the scope of the review paper. Then, we conducted a comprehensive literature search on the topic using

(a)

(b)

Figure 2: (a) Step-by-step process for conducting the review. (b) Word cloud of the reviewed papers.

academic database Google Scholar. Keywords used for the search included IAQ, thermal comfort, visual comfort, acoustic comfort, productivity, creativity, questionnaire, and physiological signals. Next, we screened the studies by reviewing their abstracts and full text to determine whether they meet the inclusion criteria. Finally, we draw conclusions based on the synthesis of the findings and provide recommendations for future research and summarize the implications of the findings for policy and practice. Figure 2(b) shows the word cloud of the reviewed papers' abstracts. This involved text preprocessing steps such as tokenization, removing stop words, and lemmatization.

After careful selection, we reviewed a total of 420 research papers. Figure 3 illustrates the sources and publication years of the papers reviewed. The majority of these papers were published in the journal "Building and Environment." After the year of 2017, there was a substantial increase in the number of papers published. These papers were categorized based on the influence of individual IEQ factors on human productivity and physiological responses and the combined effects of IAQ and other multi-domain factors.

2.2. Research Design. To collect data and analyze the impact of IEQ on human productivity, researchers designed various test conditions. After literature review, we found that the research design can be categorized into the following types: chamber experiments, case studies, field studies, and longitudinal study, etc.

2.2.1. Chamber Experiments. Chamber experiments involved manipulating one or more variables to observe the effect. They could provide strong evidence of causality but can be challenging to design and implement. For example, Yang and Moon [36] studied cross effects of sound and illuminance on 60 students, discovering that illuminance had no effect on acoustic perception; relaxation was influenced by sound. Gender-based sensitivity differences were noted. Pellerin and Candas [37] studied the trade-off between noise and temperature and their combined effects on discomfort. They found that noise might alter thermal pleasantness in warm conditions. Yang et al. [38] studied the effects of thermal and acoustic environments on stress in underground spaces, finding that low relative humidity could counteract discomfort from high temperatures. Lastly, Fan et al. [39] examined thermal comfort and physiological reactions at different temperatures and humidity levels, suggesting that heat acclimatization could raise thermal discomfort thresholds. These studies underscored the multi-domain nature of IEQ, necessitating an integrated approach encompassing individual physiological attributes, and regional climate factors.

2.2.2. Case Studies. Case studies focused on a specific instance or scenario in depth. They could provide detailed insights but may not be generalizable to other situations. For instance, Lin et al. [10] proposed a comprehensive data analysis method to assess multi-domain drivers of occupant comfort, productivity, and happiness. The study implies that facility management should focus on key domains impacting overall satisfaction. Collinge et al. [40] introduced a framework integrating IEQ and dynamic life cycle assessment at a building level. The study identified overlaps between internal impact categories, suggesting that more research is needed. Andargie and Azar [41] demonstrated that environmental conditions and personal characteristics significantly influence occupants' indoor environment perception. Hong [42] underscored spatial features like visibility and accessibility as crucial for user productivity in open-plan commons. Another study [43] compared indoor environments in naturally and mechanically ventilated offices, indicating that CO_2 concentration negatively impacted task scores and duration. Hence, these case studies revealed the relationship between IEQ and human productivity, satisfaction, and well-being on specific scenarios.

2.2.3. Field Studies. The field studies involved making observations in a natural setting rather than a controlled laboratory environment and comparing conditions before and after an intervention or event. Juslén et al. [44] focused on the impact of a controllable task-lighting system on productivity in a luminaire factory. The study revealed that within the test group, productivity saw a 4.5% increase when users chose the preferred illuminance levels. Thatcher et al. [45] aimed to replicate the psychological benefits of indoor plants observed in laboratory studies in real work contexts. The laboratory study showed that indoor plants led to better work performance. A field study conducted by Xu et al. [46] found that higher air temperature, CO_2 concentration, and noise level led to poor sleep quality. The study also observed gender differences, and noise level had a greater impact on females' sleep quality. Haddad et al. [47] focused on secondary school classrooms and investigated the impact of a demand-controlled mechanical extract ventilation system on IAQ and thermal comfort. The study found that the system effectively reduced CO_2 concentration and improved air quality, leading to better student comfort and adaptability to indoor temperature changes. Ali [48] explored the importance of physical environment comfort in workplaces and its relationship with employee performance and productivity. The study used field surveys and questionnaires of three institutional buildings. It found correlations between room temperature, lighting, relative humidity, and employees' health-related issues, highlighting the impact of physical comfort on productivity and absenteeism rates. Witterseh et al. [49] found that noise distraction and warm air temperatures in open offices increased fatigue and reduced performance, emphasizing the importance of private offices and air temperature control. These studies reinforced the critical role of IEQ in designing sustainable, comfortable, and productive built environments.

2.2.4. Longitudinal Studies. Finally, there were also longitudinal studies. They involved repeated observations of the same variable for a long time. Midouhas et al. [50] analyzed outdoor and IAQ in relation to cognitive ability in children aged 3 years in England and Wales. The study found that consistent exposure to high levels of NO_2, damp/condensation, and secondhand smoke in the home were associated with lower cognitive abilities. Woods et al. [51] acquired data periodically before and after interventions in six elementary schools in Montgomery County, Maryland. This study is aimed at quantifying the effects of controlling indoor environmental factors on human response, student and teacher performance, and productivity in elementary

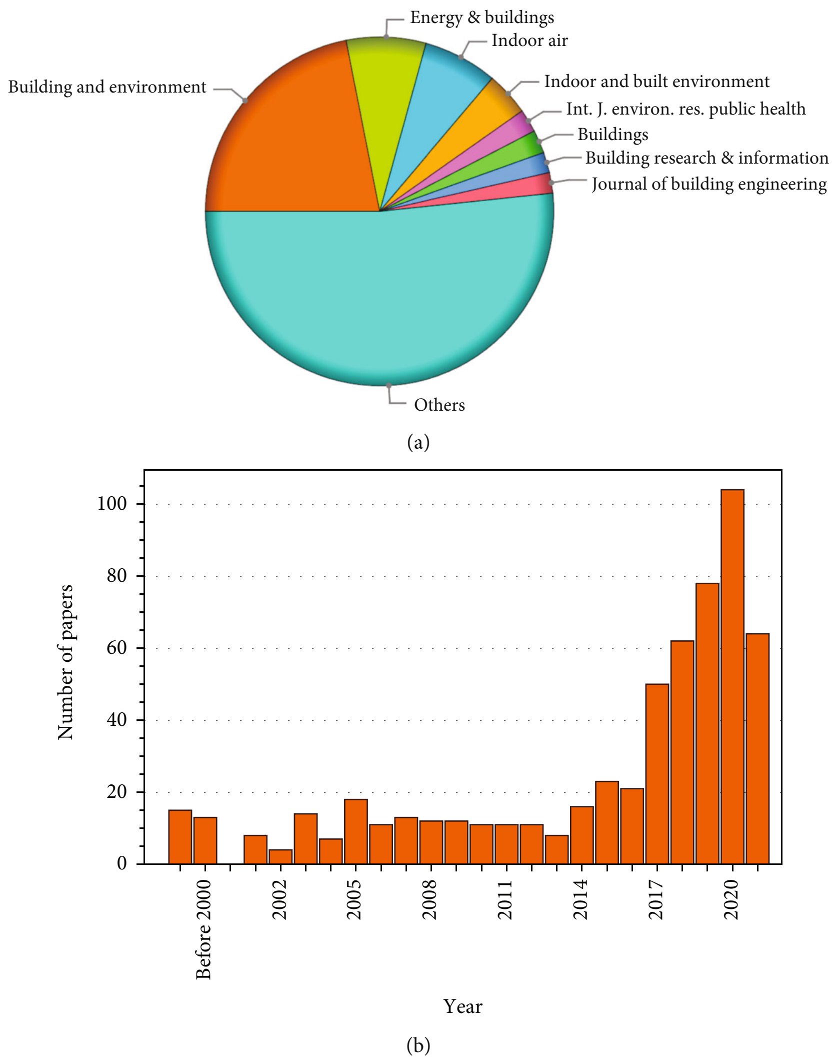

Figure 3: (a) Pie chart of sources of the reviewed papers. (b) Year of publication of the reviewed papers.

schools. They validated the hypotheses that the return on investment for additional costs to enhance IEQ, or even IAQ alone, was significant enough to warrant a shift in budget allocation towards education. Gupta et al. [43] investigated the relationship between indoor environment and workplace productivity in naturally ventilated and mechanically ventilated office. The study found that higher CO_2 concentrations were associated with lower task scores and longer task durations, highlighting the importance of good ventilation in workspaces. The longitudinal study by Wålinder et al. [52] examined the relationship between classroom noise and stress reactions among primary school children. The study found that higher sound levels were associated with symptoms of fatigue and headache, reduced diurnal cortisol variability, and emotional distress. The reviewed longitudinal studies provide valuable insights into the relationship between IEQ and various outcomes, including cognitive ability, academic performance, workplace productivity, and occupant comfort.

We can see that the research in the field employed a variety of study designs, from case studies to experiments. Each of these approaches had its strengths and weaknesses, and the choice of design depends on the specific research questions. Chamber experiments are valuable when precise control of IEQ variables is necessary to observe the effects, compared to uncontrolled real-world settings. However, limited human subjects can be involved usually due to site constraints. If focusing on a specific scenario like offices and schools, case studies and field studies prove more effective. Yet, accurately managing various IEQ factors and setting up data collection devices remains challenging, which affect result scalability. Long-term hypotheses necessitate longitudinal studies, constrained significantly by cost and time. In dynamic environments when occupants enter and exit or even be absent, consistent observation and gathering data stability over extended periods poses significant difficulty.

2.3. Evaluation of Human Productivity. Office productivity refers to the efficiency and effectiveness with which tasks, processes, and goals are accomplished within a work environment. It involves the optimal use of resources, including time, personnel, technology, and materials, to achieve maximum output and enhance overall performance [53]. Ilgen and Schneider [54] categorized productivity evaluation methods into three groups: physiological, objective, and subjective. Wyon [55] further divided objective and subjective methods into six categories: simulated work, diagnostic tests, embedded tasks, existing measures, absenteeism, and self-estimates. Each evaluation method naturally comes with its own advantages and drawbacks [56].

Specifically, human productivity is often measured by task speed and accuracy. Task speed is generally determined by examining the completing time for a task, while the number of errors or correct answers indicated the accuracy of performance. Past research has noted speed-accuracy trade-offs in various tasks, which could have conflicting impacts on the overall performance assessment. The combined productivity, referred to as the performance index (PI) or efficiency score (ES), can be expressed as [57]

$$\mathrm{PI}(\mathrm{ES}) = \frac{\mathrm{AC}}{\mathrm{RT}} = \frac{1 - \mathrm{PE}}{\mathrm{RT}}, \tag{1}$$

where AC, RT, and PE represent accuracy, response time, and proportion of error, respectively.

There are four cognitive functions of the brain: perception, memory and learning, thinking, and expression [58]. To evaluate the cognitive functions, researchers have used many representative tests [59, 60]. By employing a diverse array of cognitive tests listed in Table 1, researchers can better understand the various dimensions of cognitive functioning that contribute to an individual's performance and productivity in complex and multifaceted tasks. For example, text typing is a measure serving as a proxy for information processing efficiency. Number calculation addition test can assess cognitive flexibility, attention, and numerical processing. Schulte table is a test of visual attention, speed, and concentration, providing insight into an individual's ability to process information and maintain focus. Bourdon test is a measure of sustained attention and concentration, relevant for tasks that require extended focus and mental effort. Proofreading task is an evaluation of an individual's attention to detail, grammar, and syntax, crucial for high-quality literature production. NASA Task Load Index is a self-report measure of cognitive workload, providing insight into an individual's perceived effort and strain during various tasks. In psychomotor vigilance task, participants are required to respond to a visual stimulus. The task is designed to assess the ability to maintain vigilance over an extended period. Operation span task is a measure of working memory capacity to solve simple arithmetic problems while simultaneously remembering a sequence of letters. The N-back test is in which participants are presented with a sequence of stimuli and asked to indicate when the current stimulus matches the one presented N steps earlier. This task assesses the ability to update and manipulate information in working memory. In the Stroop test, participants are asked to identify the color of a written word while ignoring its semantic meaning. Walter Reed Performance Assessment Battery test is a comprehensive battery of cognitive tests designed to assess various aspects of cognitive function, such as attention, memory, and problem-solving. Summary extraction test evaluates the ability to extract relevant information from complex textual data. Receipt classification task measures the ability to organize and analyze data. Continuous performance test assesses sustained attention and vigilance by requiring participants to respond to specific target stimuli presented among distractors. In magnitude-parity test, participants are presented with pairs of numbers and are asked to determine which one is larger and whether they are odd or even. This task measures the ability to process numerical information and make rapid judgments. Therefore, these cognitive tests provide valuable insights into the human cognitive processes underlying the management and control of building systems and indoor environments.

2.4. Evaluation of Creativity. IEQ can affect the mood of people in a space. This can influence the level of neural processing in the anterior cingulate cortex, which has been associated with gaining insights. Creativity, an essential skill for innovative problem-solving and the development of sustainable technologies, is a multifaceted construct that can be assessed through various means. There are several creativity test methods in the literature [103], as listed in Table 2. Compound Remote Associate Task is a classic measure of convergent thinking, which requires participants to identify a single word that forms a valid compound word or phrase with three other given words. This task assesses an individual's ability to identify connections between seemingly unrelated concepts. Guilford Alternative Uses Task involves presenting participants with a common object and asking them to generate as many alternative uses for the object as possible within a given time frame. In Toy Construction Task, participants are provided with a set of simple materials and asked to create a novel toy within a specified time limit. The resulting creations are then assessed based on criteria such as novelty, usefulness, and complexity. Divergent Association Task is a unique approach that focuses on an individual's ability to generate multiple associations between unrelated concepts. Participants are presented with two or three seemingly unrelated words and asked to list as many words or phrases as possible that connect or relate to the given words. By employing these techniques, we can better understand the creativity for the built environment. However, evaluating creativity remains a complex and challenging task. Despite its importance, there is no universally accepted framework for assessing creativity, as it is a multifaceted and context-dependent construct that involves various cognitive, affective, and social dimensions.

2.5. Characteristics of Participants. The characteristics of participants are critical to assessing IEQ on human productivity. From the histogram in Figure 4, we can see that most of the studies involve a relatively small number of participants below 50. This can be seen from the high bars on the left side of the histogram. However, there were also a few studies that involved a very large number, as indicated by the long tail on the right side of the histogram. These studies have a significant impact on the mean value (544), which is

Table 1: Cognitive test method for evaluating human productivity in literature.

Test	Brief description	Duration	Reference
Text typing	Measure of speed, accuracy, and fluency for typing a given text	Around 5 min	[61–63]
Number calculation addition test	A series of addition problems with two digits to more	5-10 min	[59, 61, 62, 64, 65]
Bourdon test	Monitor gauge and respond whenever the needle reaches a specific target zone	10-20 min	[66–68]
Schulte tables	Identify a specific sequence of numbers or letters within the grid	—	[69–71]
NASA Task Load Index	Evaluation of workload across six dimensions: mental demand, physical demand, temporal demand, performance, effort, and frustration	Around 5 min	[72–75]
Psychomotor vigilance task	Respond as quickly as possible by pressing a button when see the stimulus such as number or light on screen	3-5 min	[76–78]
Operation span task	Solve math equations or remember letter sequences while simultaneously performing a secondary task	—	[79–82]
N-back	Presented with a sequence of stimuli and asked to indicate when the current stimulus matches the one presented N steps earlier	—	[83–87]
Stroop	Identify the color of a written word while ignoring its semantic meaning	—	[43, 61, 62, 73, 81, 86, 88, 89]
Deary-Liewald simple reaction	Presented with a visual stimulus, and quickly respond to it by pressing a button	—	[90–93]
Walter Reed Performance Assessment Battery test	Included simple reaction time, code substitution, continuous performance test, math processing, card rotations, match to sample	—	[61, 64, 94, 95]
Proofreading task	Review document and correct errors in grammar, spelling, formatting of text	—	[75, 96–98]
Summary extraction	Read and comprehend a passage and then provide a concise summary of its main points	—	[53, 56]
Receipt classification task	Categorize receipts into different predefined groups or labels based on the information	30 min	[53, 56, 99, 100]
Continuous performance test	Presented with a series of visual or auditory stimuli, and respond to specific target stimuli while ignoring non-target stimuli	—	[55, 101]
Magnitude-parity test	Observe the numbers and determine magnitude and parity (odd or even)	—	[81, 89, 102]

Table 2: Test methods for evaluating creativity in literature.

Test	Brief description	Duration	Reference
Compound Remote Associate Task	Identify a single word that forms a valid compound word with three other given words	20 min	[104–106]
Guildford Alternative Uses Task	Generate as many alternative uses for a common object as possible	10 min	[107–109]
Toy Construction Task	Create a novel toy with a set of simple materials	15 min	[110–112]
Divergent Association Task	List as many words as possible that connect or relate to the given words	4 min	[113–115]

much higher than the median (42). The following studies are notable for their substantial sample sizes:

Kim et al. [116] examined gender differences in occupants' perceptions of IEQ, with a large sample size of 38,257 predominantly North American participants. The study found that female occupants consistently reported lower satisfaction levels across fifteen IEQ factors. The most significant dissatisfaction was observed in thermal environment, IAQ, and workspace cleanliness. Midouhas et al. [50] focused on the impact of outdoor and IAQ on the cognitive abilities of young children. The study analyzed data from 8198 children in England and Wales. It was found that consistent exposure to high levels of NO_2 at an early age was associated with lower verbal ability. Newsham et al. [117] analyzed the effect of green building certification on organizational productivity metrics. With a large sample of 14,569 employees, it was observed that green-certified buildings performed better on certain productivity outcomes such as job satisfaction, engagement, and performance. Jensen et al. [118] developed a Bayesian network approach to evaluate building design and its impact on employee performance. Data from 12,000 office occupants from different parts of the world were used to establish a performance index to compare different building designs. Göçer et al. [119] studied the differences in occupants' satisfaction and perceived productivity in high- and low-performance offices, using data from 2133 postoccupancy evaluation surveys from Australian offices. The study found that building

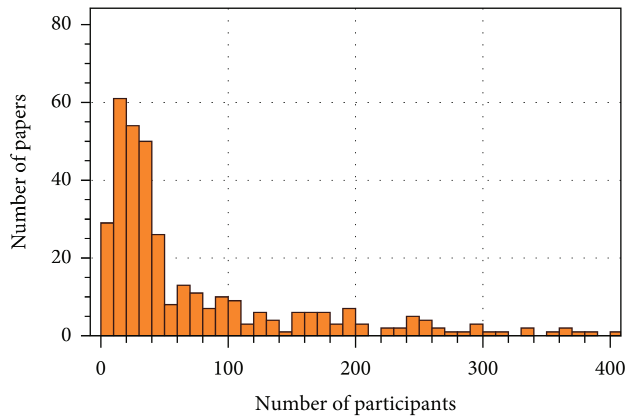

FIGURE 4: The number distribution of participants below 400 in the literature.

aesthetics and noise distraction were the strongest predictors of perceived productivity in low-performance offices. Lukcso et al. [120] conducted a comprehensive study in a federal government building complex with 7637 participants. The study found that physical comfort, odor, job stress, and glare were consistently associated with building-related health complaints. Sakellaris et al. [121] studied the effect of personal control over various indoor environment parameters on occupants' comfort, health, and productivity. The study, involving 7441 occupants from 167 office buildings across eight European countries, found that most occupants had no or low control over noise, temperature, and ventilation. This study also suggested that more personal control could lead to fewer building-related symptoms.

In terms of the age demographic, we discovered that 244 out of the 420 research papers mentioned the ages of the participants. Figure 5 illustrates the distribution of age and the number of participants across these 244 studies. It is evident from the data that a significant proportion of the participants were young office workers and university students, mostly falling within the 18 to 30 age brackets. Notably, certain studies [50, 122–127] exclusively centered on the performance and productivity of children and school students. Some investigations [128–131] focused on the elderly population.

In examining the demographic aspects, we discovered that 93 out of 420 papers included data on participant gender. Among these, 18% (e.g., [132–144]) were exclusively male, while 6% (e.g., [94, 145–148]) were solely female-focused. The remaining majority (e.g., [37, 149, 150]) carried out research involving both genders. We believe that studies with a large participant base—exceeding 100, for example—should ideally incorporate both genders, unless the research requires otherwise. The sample size can significantly influence the robustness of the findings, as a smaller size might not yield solid conclusions [151]. Some studies [140, 152, 153] also furnished additional information such as height, weight, and BMI.

Concerning the health status of participants, numerous studies [140, 142, 146, 154–158] have underscored the good health of their subjects. This factor is particularly pertinent for cognitive tests. Absence of respiratory diseases, smoking habits, and vision and hearing impairments are critical in studies related to IAQ, lighting, and acoustics, respectively. Some research specifically centered on certain populations or conditions, such as chess players [128], mild asthmatics [159], and respiratory allergies [160].

As for racial demographics, only a handful of studies [148, 161] have specified this information. Since many studies recruit their participants locally, we also examined regional distribution, as depicted in Figure 6. China has the highest number of studies, followed by the US, Japan, South Korea, the Netherlands, the UK, and Denmark.

2.6. Questionnaire Survey Design. There has been a growing interest in studying the effects of IEQ on occupant well-being, productivity, and overall satisfaction. To gain insights into these aspects, researchers have employed questionnaire surveys as a valuable tool for collecting data directly from building occupants. The typical questionnaire survey is as follows:

Participant Demographics. Many surveys begin by collecting demographic information such as age, gender, occupation, and education level [41, 162, 163].

Subjective Perception of Indoor Environmental Factors. Several studies focused on gathering participants' perceptions of various IEQ factors [17, 155, 164, 165]. Many surveys are aimed at evaluating participants' thermal comfort and sensation in different indoor environments [124, 166]. Participants were asked to rate their thermal perception, comfort, and acceptability on scales. In studies examining the influence of noise on well-being and productivity [167], participants were asked about their sensitivity to noise, annoyance levels, perception, and performance. Questionnaires were also used to assess responses to different lighting conditions and their effects on visual performance [95, 168]. Lastly, surveys can be focused on participants' perceptions and satisfaction regarding IAQ factors, such as ventilation, odors, and pollutants [169, 170]. They assessed participants' comfort and perception related to insufficient IAQ.

Perceived Symptoms. Questionnaires could inquire about perceived symptoms, such as fatigue, eye irritation, respiratory issues, and other health-related effects [7, 61].

Psychological and Physiological Responses. Some studies employ questionnaires to assess occupants' psychological and physiological responses to the indoor environment, including stress, mood, and arousal [171].

Impact on Performance. Surveys are aimed at measuring the impact of the indoor environment on occupants' performance, productivity, concentration, and cognitive abilities [172, 173]. Several studies investigated the relationship between IEQ and occupants' productivity and performance [14, 17]. Questionnaires included items related to self-rated performance, workload, motivation, and overall satisfaction with the indoor environment. Surveys may also investigate work-related factors, including the influence of work tasks, job roles, and remote working on occupants' perception and productivity [174].

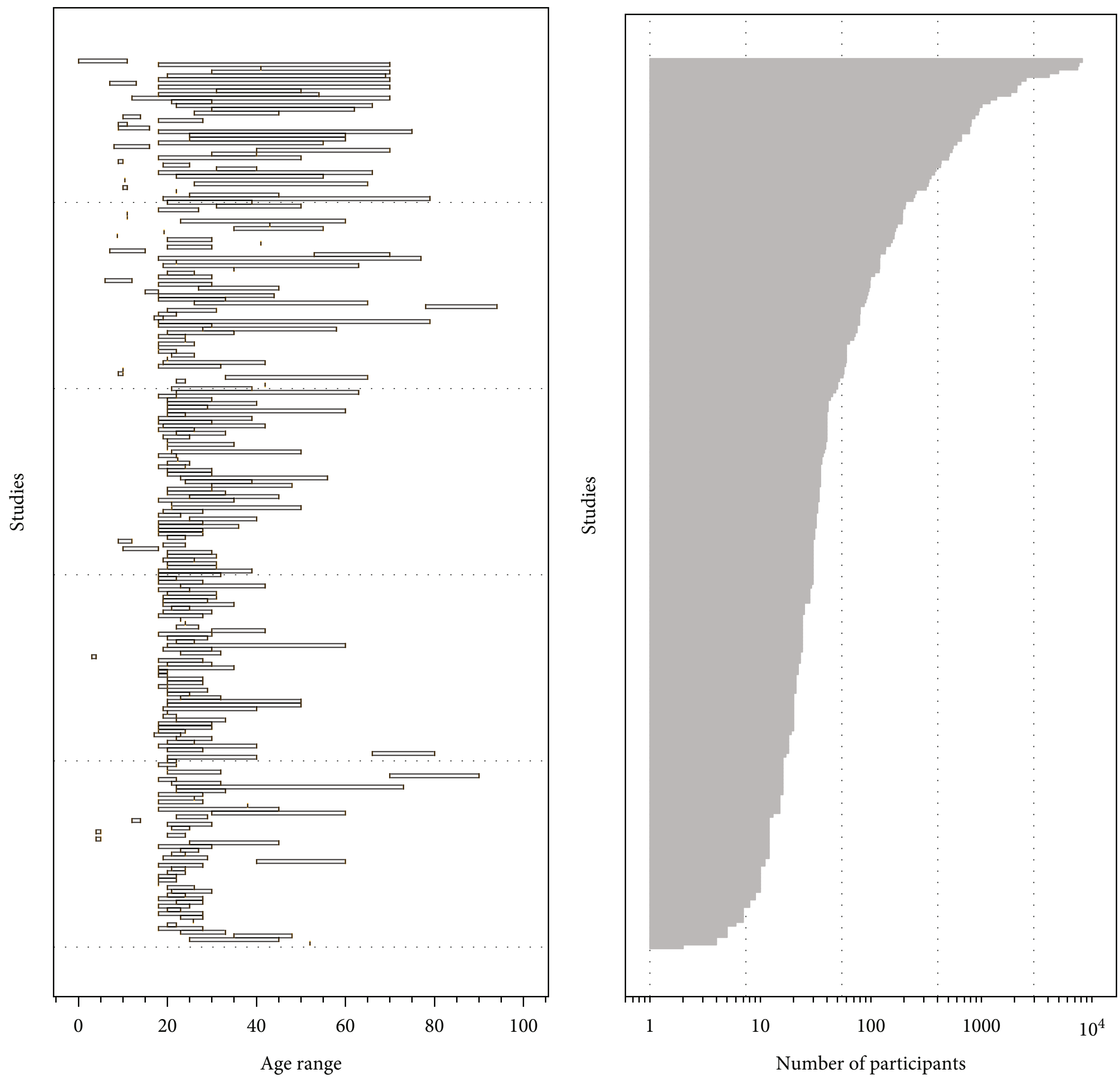

Figure 5: Age range and distribution of population.

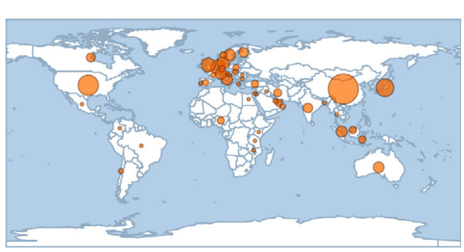

Figure 6: Regional distribution of various studies.

Overall Satisfaction and Well-Being. Questionnaires were used to assess occupants' overall satisfaction, comfort, and well-being in various indoor environments [1, 175, 176].

By well-designed questionnaire surveys, researchers can gain valuable insights into occupant experiences, preferences, and perceptions related to IEQ. These findings can contribute to the development of strategies and interventions aimed at creating healthier, more sustainable, and productive built environments.

2.7. Physiological Responses. The human body is made up of intricate systems. Diverse IEQ factors can influence our biological signals in unique ways. These signals provide us with the means to comprehend the physiological aspects of indoor comfort, which can enhance the resilience of buildings and human health [177]. Specifically, the skin has thermoreceptors that relay temperature data to the brain. High heat prompts an increased heart rate as our body works to cool down. IAQ is not only related to the respiratory system. Poor IAQ can lead to symptoms like headaches, breathlessness, and mental and physical fatigue. Lighting conditions directly impact the eyes [178], with light exposure influencing brain function by regulating our circadian rhythms, which in turn manage sleep, mood, and cognitive function. Table 3 provides an overview of how different IEQ factors influence physiological signals and the sensors used to measure them. Certain factors can be influenced by a combination of IEQ factors. For instance, skin moisture can be linked to thermal, IAQ, and noise. Oxygen saturation is associated with IAQ, thermal, and lighting. The respiration rate can be impacted by noise, temperature, and IAQ. Other physiological parameters such as heart rate, heart rate variability, blood pressure, and EEG can be influenced by all IEQ factors, which makes it complex to analyze the impact of multi-domain factors.

In addition, affordable, nonintrusive, and contact-free sensors play a vital role in detecting physiological signals [177]. Unlike heavy, complex, and invasive medical machinery, the focus is increasingly shifting towards lightweight, user-friendly wearable devices and noninvasive measurements [179]. Recently, wristbands and smartwatches are used to monitor skin-related parameters and heart rate [180]. Infrared cameras can measure the skin temperature of different body parts [181]. More sophisticated cameras, employing computer vision, are being developed to measure additional parameters such as respiration, pulse rate, and eye activities [182].

2.8. Structural Equation Modeling. While traditional methods in investigating IEQ often isolated single variables, structural equation modeling (SEM) offered a more sophisticated approach for complex interaction among multiple factors. SEM's strength lies in its capacity to analyze both observed and latent variables, providing a comprehensive understanding of the dynamics within the built environment, IEQ, and their influence on human productivity and well-being. This technique has been instrumental in dissecting the intricate connections among key elements such as thermal comfort, IAQ, lighting, and their collective impact on human productivity and well-being [210–212].

The advantage of SEM is its adept handling of latent variables like well-being, productivity, physiological responses, self-reported comfort, and work output [213, 214]. SEM's ability to model these latent constructs offers a more nuanced comprehension of the IEQ's effects on human health and productivity [215, 216]. Furthermore, the flexibility of SEM in model specification is critical, allowing the integration of mediating and moderating variables. This aspect is important for understanding how personal attributes, such as gender or age, conditionally affect the relationship between IEQ and outcomes like productivity or satisfaction [217, 218]. SEM's capacity to concurrently analyze multiple variables provides a layered understanding of the factors influencing IEQ and occupant productivity and well-being [219, 220]. For example, SEM's role has been pivotal in identifying the complex relationships between thermal environments and perceived productivity [221] and in assessing the impact of smart and sustainable building technologies on building professionals' intentions [222]. The inclusion of latent variables, such as occupants' perceptions or subjective norms, which are challenging to measure directly, is a unique advantage of SEM [223, 224]. By encompassing both observed and latent variables, SEM offers a holistic model for evaluating IEQ [225, 226]. Its application extends to understanding psychological and physiological responses in various settings, enriching our comprehension of IEQ and guiding targeted improvements in indoor environments [227–229]. Graves and Sarkis [213] and Yan et al. [214] extend SEM to psychological factors, highlighting the importance of a holistic approach that SEM facilitates. Tekce et al. [210] integrates building design with physical comfort dimensions, showcasing SEM's capacity as a multifaceted analytical tool. For IAQ and productivity, several studies [220, 221] have utilized SEM to uncover significant insights. For instance, Kawakubo et al. [217] elucidate the nuanced relationship between thermal comfort and productivity, considering gender-specific responses, while Liu et al. [230] differentiate the impacts of IEQ on staff and postgraduate students in university workplaces.

However, there were several limitations of SEM. The requirement for large sample sizes for robust results [212], the potential bias from subjective measures [219], and challenges in comprehensively integrating objective and subjective data [225] need careful consideration.

SEM offers a robust, flexible, and comprehensive approach for studying the complex relationships of IEQ and productivity. Its ability to handle multiple variables and their interrelations makes it an indispensable tool. Further research is needed on SEM for IAQ and multi-domain factors on human productivity and physiological responses.

3. Interactions between IAQ and Other Multi-domain Factors on Human Productivity

3.1. IAQ and Thermal. IAQ and thermal comfort significantly impact human productivity in various environments. High or low air temperatures can cause thermal discomfort, negatively affecting office workers' well-being, motivation, and productivity [16]. Poor IAQ and uncomfortable thermal conditions can lead to increased health symptoms, discomfort, and reduced cognitive performance [183, 231]. Research shows that the satisfaction levels of both temperature and noise have a one-vote veto power over the satisfaction level of the indoor environment as a whole [164]. Moreover, when the thermal environment is unsatisfactory, it weakens the comfort expectation of other IAQ factors, leading to less dissatisfaction with other factors. Conversely, when the thermal environment is quite satisfying, it raises the comfort expectation of other IAQ factors, which lowers the evaluation of the real performance of other factors retroactively [19]. Choi et al. [232] found that occupants' stress was maximized when they were exposed to a temperature of 30°C, odor irritants, and road traffic noises. They also found that when nature sounds were heard in the chamber, though, odor irritants were seen to be second to nature sounds in affecting the occupants' stress; stress was lower in the non-air-polluted environment when compared to the air-polluted environment. Liu et al. found that exposure to high temperatures, such as 35°C, can lead to increased discomfort, sleepiness, and acute health symptoms [183]. Physiological responses, such as eardrum temperature, skin temperature, heart rate, and body weight loss, can increase significantly under these conditions, indicating elevated

Table 3: Summary of physiological signals for various IEQ factors.

Parameters	Measuring sensor and example	Indicator for IEQ factors	Ref
Skin temperature (Tskin)	iButton (LDS1992L), infrared camera, resistance temperature sensor, wristband	Thermal, visual	[13, 37, 63, 80, 155, 183–185]
Skin humidity/moisture	Wristband, interdigital capacitance (IDC), polymer optical fiber sensor	Thermal, IAQ, acoustic	[63, 180, 186]
Heart rate (HR)	Heart rate monitor (SUUNTO Dual Belt), wristband, smart watch	Thermal, IAQ, acoustic	[13, 129, 155, 183, 185]
Heart rate variability (HRV)	Heart rate monitor (SUUNTO Dual Belt), wristband, smart watch	Thermal, visual, acoustic	[16, 38, 145, 187]
Blood pressure (BP)	Electronic sphygmomanometer	Thermal, IAQ, visual, acoustic	[4, 13, 60, 166, 188]
Systolic blood pressure	Electronic sphygmomanometer (HEM-7132, OMRON)	Thermal, IAQ, visual, acoustic	[4, 92, 184, 188] [185]
Diastolic blood pressure	Same above	Thermal, IAQ, visual, acoustic	[185]
Oxygen saturation (SpO_2)	Blood oxygen saturation monitor (Heal Force Prince-100H) Wristband (Fitbit)	Thermal, IAQ, visual	[183, 189–191]
Eardrum temperature	Infrared thermometer (TH839S OMRON)	Thermal	[39, 183]
Body core temperature	CorTemp HT150001 with capsule sensor	Thermal	[133, 135]
End tidal partial CO_2	LifeSense LS1	Thermal	[39, 192]
Respiration rate (RR)	Electromagnetic sensing system, ultrasonic proximity sensor	Acoustic, thermal, IAQ	[84, 137, 158, 189, 192, 193]
Respiration flow rate	Gas flowmeter	Acoustic, thermal, IAQ	[137, 190]
Muscle activity	Physiometer (PHY-400)	Visual	[146]
Electrodermal activity (EDA)	Wristband (Fitbit), Ag/AgCl disc electrodes, galvanic skin resistance (GSR)	Acoustic	[193–195]
Electroencephalogram (EEG)	Headband (Muse), EEG 8 channels of MP150, dry electrodes, passive electrodes	IAQ, acoustic, thermal, visual	[16, 90, 137, 141, 142, 196, 197]
Electrocardiogram (ECG)	PPG sensor, smart watch (Apple watch), wristband (Fitbit Charge 2-4)	Acoustic, visual, Thermal, IAQ	[84, 129, 130, 137]
Pulse rate	Wristband, optical sensor	IAQ, thermal, visual	[192, 198, 199]
Polysomnography (PSG)	Electroencephalogram devices	Acoustic	[200]
Cortical arousals	Electroencephalogram devices	Acoustic	[200]
Rapid eye movement (REM)	Electrooculography	Acoustic	[201]
Pupil diameter/size	Camera, eye tracking systems	Visual, thermal	[157, 202]
Skin capillary blood flow (SCBF)	Infrared camera, laser Doppler flowmetry	Thermal	[186]
Transepidermal water loss (TEWL)	Capacitive TEWL sensors	Thermal	[186]
Metabolic rate	Wearable multiparametric device, metabolic cart with facemask or canopy	Thermal, visual, IAQ	[192, 203, 204]
Forced vital capacity (FVC)	Spirometer	IAQ	[140]
Sweat loss	Sweat absorption pad, hydration sensor	Thermal	[49, 135, 184]
Eye tracking	Desk mounted eye tracking system (TOBII T60), desktop mounted eye gaze tracking (EGT) instrument	Visual	[205]
Electromyography (EMG)	Capacitive electrodes, surface EMG channels	Acoustic	[194, 195]
Sensory nerve conduction velocity (SCV)	Surface active electrode, subcutaneous needle electrodes	Thermal	[154]
Skin resistance	Galvanic skin response sensor	Visual	[206]

Table 3: Continued.

Parameters	Measuring sensor and example	Indicator for IEQ factors	Ref
Pupillary unrest index	Infrared video pupillography, rye-tracking instrument	Visual	[202]
Blink rate	Headband, eye tracking instrument, Doppler sensor, electrooculography, camera	Visual	[146, 202]
Average fixation duration	Eye tracking instrument	Visual	[202]
Grip strength	Dynamometer, flex sensor	Thermal	[207]
Urinary melatonin	Urine sampling	Thermal, visual	[208]
Salivary alpha-amylase	Kit, biosensor	Thermal	[209]

stress. In office environments, the effects of thermal discomfort on health and human performance have been investigated, and it has been found that when subjects felt warm, they assessed IAQ to be worse, reported increased intensity of sick building syndrome symptoms, expressed more negative mood, and were less willing to exert effort [190]. Moreover, cognitive performance was found to decrease at moderately raised indoor temperatures even when clothed for comfort [189]. During the COVID-19 pandemic, maintaining optimal indoor air conditions for SARS-CoV-2 inactivation has been critical. Spena et al. [233] found that proper HVAC settings can create indoor comfort conditions with a specific enthalpy, which may be adverse to the virus. These findings suggest that maintaining appropriate humidity and temperature levels can help reduce the spread of the virus in indoor spaces and potentially improve productivity during the pandemic. To solve the hot environment and IAQ issues and provide better environment for chefs and housewives in kitchen, Liu et al. [234] developed a new ventilation system and validated the measuring skin temperature and environmental parameters (CO, CO_2, TVOCs, and PM2.5). Hence, a comfortable indoor environment, encompassing thermal comfort and IAQ, plays a vital role in enhancing occupants' well-being and productivity [16].

3.2. IAQ and Visual. Both IAQ and lighting can impact human productivity. The quality of the visual and thermal environment is the most critical factor affecting IEQ, followed by IAQ and acoustics in university classrooms [235]. Moreover, integrating daylighting with artificial lighting in schools and office buildings has been found to have positive impacts on occupant health and performance. Students' progress in math and reading tests was 20-26% faster when classrooms were primarily illuminated by daylight [236]. High illuminance, uniformity of illuminance, and correlated color temperature have been found to improve perception, learning, and memory function, while lower levels of these factors can improve thinking and executive performance [237]. Finally, personal control over indoor environmental conditions has been found to be an influential factor for user satisfaction and environmental comfort [238]. Higher controllability of environmental factors leads to more satisfaction in terms of thermal and visual comfort.

3.3. IAQ and Noise. IAQ and noise have significant impacts on human productivity in various work environments. High levels of noise and poor IAQ can lead to discomfort, annoyance, and health issues among workers, ultimately affecting their performance and productivity. The combined effects of noise and air temperature on human neurophysiological responses have been shown to disturb working memory and other neurophysiological responses, with noise having a more significant impact on working memory [158]. In university open-plan research offices, the acoustic environment has the greatest influence on human productivity, with occupants having higher requirements for acoustics than in other types of open-plan offices [239].

Clausen et al. [240] found that a 1°C change in operative temperature had the same effect on human comfort as a change in perceived air quality of 2.4 decipol or a change in noise level of 3.9 dB. Furthermore, Pan et al. [241] concluded that noise and odor cause discomfort in humans and that the addition of noise may reduce the perception of discomfort from odor. A pilot experiment by Pellerin and Candas [37] showed that thermal strain can decrease acoustic perception, potentially reducing acoustic discomfort. High noise levels were found to increase thermal discomfort, suggesting additive effects in such cases. Choi et al. [232] found that when nature sounds were heard in the chamber, though, odor irritants were seen to be second to nature sounds in affecting the occupants' stress; stress was lower in the non-air-polluted environment when compared to the air-polluted environment. Noise increased fatigue and difficulty in concentrating but did not interact with thermal effects on subjective perception. Lastly, our previous studies mainly focused on the multi-domain impact of IAQ and noise on office productivity. We determined the effects of a portable air cleaner on IAQ and noise level by questionnaire survey and physiological signals from wristband and headband [242]. In conclusion, both IAQ and noise play crucial roles in affecting human productivity across various work environments. Ensuring optimal levels of IAQ and noise control can lead to improved comfort, health, and, ultimately, productivity among workers [231].

To summarize this section, Figure 7 shows the chart of impact between IAQ and other multi-domain factors including thermal, visual, and acoustic from literature. Quantitatively assessing the impact of IAQ in conjunction with other multi-domain factors remains complex and warrants additional investigation. Despite Bueno et al.'s efforts [32] in consolidating modeling equations for thermal comfort and productivity, the same comprehensive understanding

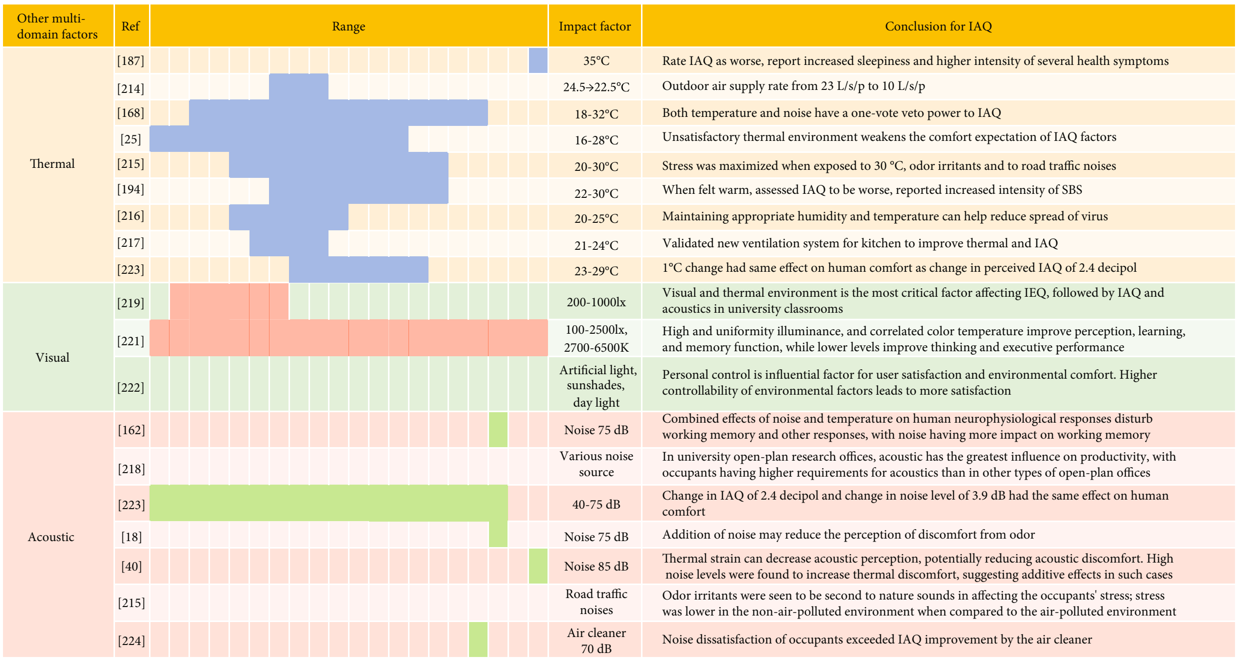

Figure 7: Summary of impact between IAQ and other multi-domain factors including thermal, visual, and acoustic from literature.

is yet to be achieved for IAQ and multi-domain factors. Presently, much of the ongoing research relies heavily on statistical analysis, lacking the necessary quantitative outcomes.

3.4. Strategies for Optimizing Human Productivity

3.4.1. Integrated Building Design. Integrated building design plays a crucial role in improving IAQ and various multi-domain factors that influence human productivity. To assess a building's energy performance and indoor comfort, building information modeling can be used as a base, allowing for the integration of different analysis models, such as building architecture, indoor comfort conditions, and energy performance [243, 244]. This method helps eliminate the complexity of software integration and ensures interoperability during the design process. An integrated approach to building design can help balance energy efficiency and IEQ objectives, preventing unintended consequences of underperformance in either domain [245]. Utilizing building information modeling and focusing on different aspects can contribute to improved building design and better occupant well-being and productivity [246].

3.4.2. Smart Systems and Occupant Feedback. Smart systems and occupant feedback are essential for improving IAQ and multi-domain IEQ factors. IoT-based sensory technology plays a vital role in monitoring and maintaining IAQ by ensuring the proper deployment of sensors and devices [247]. Smart technologies, such as advanced air distribution, air cleaning, modularization of indoor environmental devices/systems, and sensing systems, help optimize IAQ alongside conventional performance indicators [6]. Smart building sensing systems can manage energy saving, thermal comfort, visual comfort, and IAQ in the built environment, thus influencing occupant productivity and well-being [248]. Occupant engagement and feedback, when integrated with innovations in indoor environmental systems, contribute to achieving better IEQ tailored to individuals' preferences [249].

The use of smart monitoring and user feedback can help investigate the impact of indoor environments on learning efficiency, revealing potential spatial and temporal variations in comfort parameters and their correlation with students' assessments [250]. Similarly, smartwatches have been used to predict occupants' thermal comfort by measuring both environmental parameters and heart rate variability, with machine learning techniques providing accurate predictions of thermal sensation vote [251]. Longitudinal indoor comfort models that involve human feedback can evaluate and optimize human comfort within the built environment [252]. These models can also enhance comfort preference prediction and contribute to the evaluation, control, and design of indoor environments that balance the measurement of variables with occupant preferences. Hence, smart systems and occupant feedback are crucial for improving IEQ and leading to increased occupants' productivity and well-being.

4. Discussion

4.1. Limitations of Conducted Studies. Through the literature review, the above-mentioned current studies and methodologies investigating the impact of IAQ and multi-domain factors on human productivity face several limitations. They can be grouped into several categories:

Limited Research on the Multi-domain Combined Effects. Some research did not consider the multi-domain interaction between multiple environmental factors or only focuses on a limited number of factors. As shown in Figure 7, there is very limited research on the combined effects of IAQ with different environmental factors on occupants' productivity and comfort [19, 36]. These papers provided a narrow understanding of the impact of indoor environments on human productivity [34, 235].

Small Sample Sizes and Unrepresentative Samples. Many of the previous studies had a small number of participants less than 50. Many studies have unbalanced samples in terms of age, gender, and occupation, or focused on specific demographics (e.g., young, healthy college students, or female subjects) that did not represent office workers as a whole, which can introduce bias and limit the applicability of results [36, 132, 191, 203, 253, 254]. These studies limited the generalizability of their findings [145, 148]. The proper simple size depends on several factors including number of impact factors, variability, level of significance, and feasibility of resources. Thus, it must be determined carefully.

Limited and Insufficient Experimental Design and Control with Confounding Factors. Some studies lacked experimental control, relied on self-reported data, or used uncontrolled or anecdotal field studies. Others had cross-sectional designs, which limited the possibility of observing true effects. Some studies have been criticized for lacking experimental control or not accounting for confounding factors [22, 255]. For example, poor air quality may have been confounded with other negative aspects in one study [255]. Studies lack control groups or robust controls, making it difficult to draw reliable conclusions. Some studies also relied on subjective evaluations or self-reported productivity measures. Lack of control groups, real-world data, and preoccupancy information, which can affect the validity of the results [254].

Reliance on Laboratory or Simulated Environments. Some studies use laboratory settings, virtual reality, or climate chambers, which may not accurately reflect real-world conditions and occupant experiences [158]. Some studies do not manipulate or control indoor environmental factors, resulting in limited variations and difficulty in establishing causal relationships between factors and outcomes.

Short-Term Effects and Lack of Follow-Up and Long-Term Data. Many studies only looked at short-term effects and did not consider long-term impacts. Studies often use short-term exposure to environmental conditions, which may not accurately reflect the long-term effects of indoor environments on occupants. Cross-sectional designs can only establish associations, not causation, between factors and outcomes. Many studies did not consider the dynamic nature of the indoor environment and only investigated short exposure times or specific conditions, which may not be representative of real-world scenarios [39, 90]. Short adaptation times, exposure durations, or study periods, which may not provide a comprehensive understanding of the long-term effects of IAQ and multi-domain factors on human productivity [125, 158]. It left questions about the long-term impact of indoor environmental factors on human productivity [44, 62].

Lack of Robust Performance Metrics. Some studies have not collected data on crucial performance indicators but relied on subjective evaluations. These issues limit the ability to accurately assess human productivity. Many studies often focus on specific cognitive tasks or physiological measures, which may not fully represent the range of tasks and physiological responses experienced in real-world settings. Inconsistencies in experimental conditions and methodologies make it difficult to compare results across studies [95, 256]. Studies often face data scarcity, short study durations, and the inherently complex nature of the indoor environment and human responses, making it difficult to draw conclusive results.

Incomplete or Uncertain Data. A few studies had limitations in their data collection or analysis, such as incomplete data sets, limited statistical power, or high degrees of uncertainty. A lack of objective measurements or reliance on self-reported data may introduce biases and limit the validity of the findings [121, 122]. Many studies rely on subjective evaluations, questionnaires, or self-reported data, potentially introducing bias and limiting the robustness of findings [257]. Many studies rely on self-reported data and subjective opinions, which can be influenced by individual perceptions, expectations, and recall biases.

Lack of Consideration for Individual Differences. Many studies do not account for individual differences in terms of sensitivity to environmental factors, personal characteristics, or lifestyle, which can affect occupant responses and outcomes. Some studies had difficulty isolating the effects of individual factors on human productivity or determining the magnitude of their impact [197]. Several studies did not consider the effects of individual preferences, gender differences, or other personal factors that may influence the relationship between indoor environment and human productivity [80, 258].

The limitations of current studies and methodologies on the impact of IAQ and multi-domain factors on human productivity include small and homogenous sample sizes, controlled settings, participant bias, limited test configurations, lack of control groups and real-world data, inadequate measures or methodologies, short study periods, and limited research on combined effects of environmental factors. These limitations make it difficult to draw definitive conclusions about the impact of various indoor environmental factors on worker productivity. They indicate a need for more robust research designs, larger and more diverse samples, and comprehensive evaluations of the various indoor environmental factors that may influence productivity.

4.2. Unsolved Problems and Research Questions. Through literature review, it is evident that numerous unsolved problems and research questions still exist in this field.

Integration of Different Research Studies. One of the challenges is the lack of baseline and reference cases, making it difficult to integrate and compare different research findings and results. Figure 7 shows that the range of multi-domain factors varies widely across studies. Future studies should strive to establish standardized conditions and cases, allowing for more accurate comparisons between different interventions, building types, and occupant profiles. This will facilitate the identification of optimal strategies for improving IAQ and multi-domain factors to enhance human productivity.

Long-Term Studies. Most studies reviewed were short-term in nature, which limits our understanding of the long-term effects of IAQ and multi-domain factors on human productivity. Future research should focus on conducting long-term studies in real-world environments to better capture the chronic exposure to these factors and their impact on health and productivity of occupants over time.

Representative Study Populations. Many studies primarily involved young students as participants, which may not be representative of broader populations in different workplaces. Future studies should aim to include diverse occupant profiles, considering factors such as age, gender, cultural background, and job type. Understanding how these individual differences moderate the relationship between IAQ, multi-domain factors, and human productivity will provide valuable insights for tailored interventions and building design.

Advanced Control Systems. The potential of advanced control systems, such as AI and machine learning, to optimize IAQ and multi-domain factors is promising but requires further exploration [259]. Intelligent systems that adapt to occupants' preferences and dynamically optimize the indoor environment can enhance their productivity.

Biophilic Design Integration. Integrating biophilic design principles in the built environment is an emerging field. Future research should investigate how these principles can improve human productivity in different building types and workplaces, by incorporating natural elements and processes.

5. Conclusion

5.1. Summary of Key Findings. IEQ is a complex factor that can be influenced by many factors. Past approaches neglected the interactions between these factors. Research on temperature and IAQ interaction is limited, with even fewer studies on IAQ combined with noise and lighting; thus, IEQ has been overlooked. Poor IAQ and uncomfortable temperatures increase health symptoms and discomfort and reduce cognitive performance. Satisfaction with temperature and noise significantly influences overall indoor environment evaluation. Unsatisfactory thermal conditions affect comfort expectations of other IEQ factors, leading to more dissatisfaction. Satisfying thermal conditions raise comfort expectations, influencing performance evaluation.

IAQ and other IEQ factors could affect human productivity. Noise has the most substantial impact on human productivity in open-plan offices, while thermal conditions are crucial in classrooms. Personal control over ventilation and lighting enhances satisfaction with comfort. High noise and poor IAQ may cause discomfort, annoyance, and health issues, lowering performance. Relationships between perceived air quality, noise, and dissatisfaction exist, showing potential cross effects and interactions.

5.2. Implications for Future Research. First, there is a need to explain the causal relationship between multi-domain factors and human productivity through experimental and longitudinal field studies, which can lay a scientific groundwork for healthier and more productive indoor environments. Second, exploring interactions among multi-domain factors is critical for holistic, integrated solutions optimizing IEQ and enhancing human productivity. The complexity and dynamism of these factors necessitate in-depth investigations. Third, advancements in energy-efficient technologies and smart control systems promise sustainable indoor environments while boosting human productivity. Exploring the efficacy of advanced energy technologies like smart sensors, automation systems, and energy-efficient HVAC solutions in achieving better indoor quality is critical. In addition, occupant-centric design approaches, focusing on individual preferences and biophilic elements, can promote occupants' health, well-being, and satisfaction, thereby enhancing their productivity. This approach requires comprehensive understanding for developing adaptive built environments. Lastly, comprehensive health and well-being assessments are imperative to evaluate the impact of indoor environmental factors on human productivity. Standardized assessment tools quantifying the influence of these factors will guide evidence-based decision-making for healthier, productive built environments.

5.3. Implications for Policy and Practice. Establish Comprehensive Indoor Environment Standards. Develop and enforce comprehensive indoor environment standards and guidelines for multi-domain conditions. These standards should be based on rigorous scientific research, including the latest findings on the impact of IEQ factors on human productivity, and should be periodically updated as new evidence emerges.

Promote Green Building Design. Promote green building principles and certifications to prioritize IEQ in new and retrofitted buildings. Endorse biophilic design elements to improve well-being and productivity.

Implement Smart Control Systems. Promote the use of smart control systems that can optimize indoor environmental conditions in real time. These systems should be capable of monitoring and adjusting various IEQ parameters to maintain optimal conditions for human productivity while minimizing energy consumption.

Foster Interdisciplinary Collaboration. Encourage collaboration among architects, engineers, environmental scientists, and public health experts to develop innovative solutions for improving IEQ. This can lead to the development of new technologies and control strategies that can enhance both productivity and sustainability.

By implementing these policy and practice implications, we can effectively address the impact of IAQ and multi-domain factors on human productivity, ultimately enhancing the well-being and performance of building occupants while promoting a more sustainable built environment.

Additional Points

Practical Implications. Interactions between IAQ and thermal, visual, and acoustic are examined, revealing complex interplay. Key findings emphasize IAQ and multi-domain factors' significant impact on human productivity and well-being. The review proposes future research directions, innovative ideas, and specific applications. Implications for policy and practice stress the need for integrated IAQ and IEQ management strategies.

Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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