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Tropical climates and the interplay between IEQ and energy consumption in buildings: A review

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ABSTRACT

Indoor environmental quality (IEQ) can impact human health, well-being, and productivity. This paper reviews the couplings between IEQ which consists of thermal, acoustic, visual comfort, and indoor air quality, and parameters such as human comfort and productivity, with the overarching aim of ensuring a healthy environment while reducing energy consumption in buildings. At current rates of population growth, it is anticipated that the tropics would be home to over half of the world's people by 2050, hence, special attention is paid to studies conducted in tropical climates to prepare a comprehensive review with a specific climatic context. Notably,we highlight the need for more data-driven IEQ research in tropical regions, the importance of broadening the scope of and maintaining uniformity in IEQ standards, and the significance of an adaptive and sustainable built environment as we move ahead. A discussion highlighting the existing challenges and opportunities – especially the integration of AI – for future research in the area is also presented.

1. Introduction

The tropics are currently home to 3.3 billion people (about 40% of the global population). The number of urban dwellers worldwide is projected to increase to 6.3 billion by 2050, with about 60% of this growth taking place in tropical nations [1]. Not only is the population growing at a considerable pace, but it is also becoming richer as more people rise out of poverty. The world's natural resources will be subjected to unprecedented stress as a result of these developments. Therefore, sustainable development in the tropics is one of the most crucial global concerns today.

In natural systems outside of the tropics, one can form a general notion of potential changes that may occur by looking at this region where temperatures are already warmer. However, there exist no precedents for the expected conditions in the tropics in the latter decades of this century. What is certain about tropical climate change is that a region with stable climate for the past three million years would be significantly impacted by increasing temperatures and shifting rainfall patterns.

To enhance energy conservation and create a sustainable environment for occupants, the International Energy Agency (IEA) is promoting energy efficiency in the building sector. Building operation is responsible for around 27% of all worldwide energy-related CO_2 emissions, in addition to constituting roughly 36% of the global energy demand. When emissions from the building construction sector are added, this proportion rises to 37% [2]. To permanently reduce CO_2emissions through energy efficiency, precise knowledge of how people and energy usage systems interact is required [3]. On average, 80%–90% of people's lives are spent indoors [4]; as a result of COVID-19, this percentage reached as high as 100% [3] between the years 2020 and 2021. However, interestingly, even after the pandemic started to recede, the retention of an indoor-centric lifestyle was observed, with 90% of our time still spent indoors [5]. Hence, the Indoor Environmental Quality (IEQ) – which consists of thermal comfort, Indoor Air Quality (IAQ), visual comfort, and aural comfort – in modern buildings is of crucial importance today [6]. In recent years, a lot of work has gone into developing effective and affordable technologies to ensure the built environment's sustainability. A critical contribution to combating climate change is through lowering energy demand and raising energy efficiency. [7].

There is evidence suggesting a potential conflict between strategies intended to decrease energy consumption and the ones necessary to create a pleasant and healthy indoor setting [8]. As a result, a balance between efficiency and comfort must be struck by forging synergies between building design, building temperature control, and occupant needs, with future buildings capable of promptly reacting and adapting to changing conditions [9].

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1.1. Novelty of this review

Though it has been widely acknowledged that IEQ affects human comfort, productivity, and energy consumption in the built environment, there is limited research that links all these variables together to present a holistic picture of their interaction, particularly in tropical climates.

Most existing studies limit their discussion to human comfort, or energy consumption in association with any one component of IEQ [3,10–12]. In the studies that analyze the interaction between human comfort, energy consumption, and IEQ, no specific climate is mentioned [8,13–16] as highlighted in Table 1. For instance Šujanová et al. and Horr et al. review the couplings between building design, IEQ parameters, and occupant comfort based on studies from across the globe [8,15]. Although some recent studies have taken climate into account, it does not employ sensor-based data or study all IEQ components [12,17]. The empirical study by Oluwatayo and Pirisola focuses on tropical climate [17]; Sakiyama et al. provide an insight into the global investigations focusing on thermal comfort, energy efficiency, and IAQ, but with limited consideration of the other aspects of IEQ [12]. The recent review article by O'Brien et al. provides insight into the state-of-the-art occupant-centric building design issues. However, they do not discuss individual components of IEQ, their interaction with other variables, or the climate context [10].

Considering the increasing global average temperatures, rapid urbanization, growing building stock, and varying socio-economic profiles in tropical climate regions, the need to examine the existing interconnections between IEQ, energy consumption, human comfort, and productivity is especially important [18,19]. Apart from addressing this gap, the paper attempts to provide insights into the various observations resulting from studies across the globe in this field, and also discuss the potential for future research.

1.2. Objectives of the review

This paper aims to review the available literature on the energy consumption-indoor environment-occupant comfort nexus in a specific climatic context. It begins with a brief overview of the involved variables, followed by a discussion on the interlinkages between these variables while presenting the similarities and variations between distinct climate zones and the spaces analyzed. It also discusses relevant modifications and recommendations that can be taken up for a more sustainable urban infrastructure system overall. Furthermore, it describes the research gaps that can be explored for future studies in the field.

1.3. Methodology

The presented literature review was systematically conducted following the well known methodology — Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) [20]. It consists of five main phases as demonstrated in Fig. 2: (1) identification, (2) screening, (3) eligibility, (4) inclusion and (5) snowballing. The figure briefly discusses the bibliographic flow followed to identify the studies appropriate to the scope of this paper.

For the initial search, the keywords were selected based on previous literature reviews conducted in the field [3,8,21–23]. A combination of phrases like 'Indoor Environmental Quality', 'energy efficiency/consumption/conservation', 'thermal comfort', 'acoustic comfort', 'visual comfort', 'Indoor Air Quality', 'tropics/tropical climate', 'optimization', 'productivity', 'performance' and 'occupancy' within the title/abstract/keywords were used to identify suitable studies. Additionally, keywords describing typical characteristics of tropical climate like 'hot', 'warm and humid', 'sub-tropical' etc. were also used. The literature search was performed using Scopus, Google Scholar, and Science Direct — some of the biggest and most prominent databases in the field of engineering academia. A manual search was also performed as more knowledge was gained during the process. The first round of searches yielded 2899 relevant documents published between 1994 and 2023. Fig. 1 illustrates a growing interest in optimizing IEQ and energy consumption and highlights its importance in the new studies.

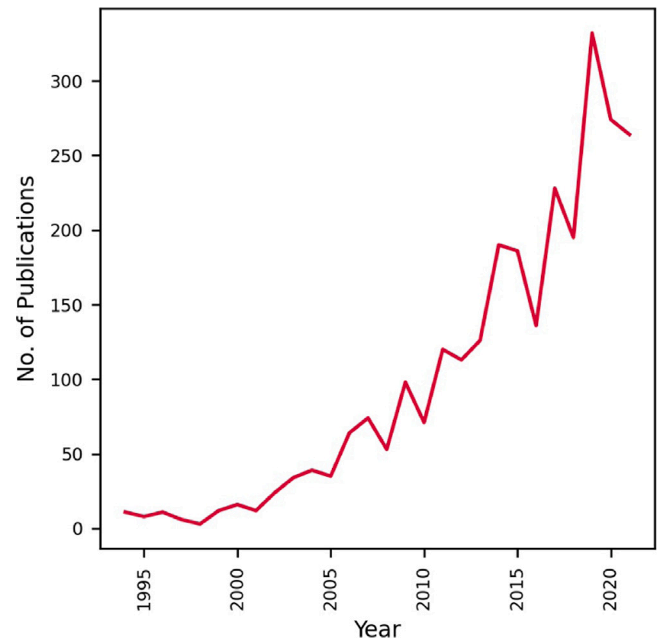

Fig. 1. Number of documents published per year.

During the screening phase, several publications based on title, article type, language and relevance to the scope of this study were excluded. Furthermore, studies that presented overlaps (based on same set of data, models and parameters considered) were also removed. It is to be noted that most of the studies conducted outside tropical climates were eliminated, however, a few representatives were retained for comparison with those conducted within tropical climates. A total of 554 abstracts were read, of which 338 were found appropriate for the scope of this paper and thus identified for a full review. Additionally, common references identified from the eligible literature were selected for further reading. It should be emphasized that the scope of the studies focused on IEQ was constrained to the investigations that assessed a minimum of two parameters within the domain. This allowed for an effective capture of the multifaceted nature of IEQ and its interconnected parameters.

2. Definitions and overview

This section describes the main aspects that are investigated for indoor environment and occupant comfort in buildings, along with their significance, while also offering a brief overview of the associated energy consumption. Occupant comfort and productivity are dependent upon IEQ, which can be altered by the amount of energy used. Climatic conditions play a significant role in influencing these factors. This interrelation will be discussed in the subsequent sections and can be depicted as in Fig. 3.

2.1. Indoor environmental quality

IEQ describes the characteristics of an indoor environment that should promote the health and well-being of building inhabitants [8]. A building is deemed "healthy and energy efficient" by Health Optimization Protocol for Energy-efficient buildings (HOPE) [24] if:

Table 1
Current state of play of existing studies.

Objective	Article type	Year	Variables considered	Limitations	Source
Critical review of the multi-domain literature in Indoor environment	Review paper	2022	IEQ, human comfort	No specific climatic context Does not discuss energy consumption and productivity	[16]
Review occupancy-based building energy and IEQ controls	Review paper	2022	Human comfort, energy consumption	No specific climatic context Does not consider productivity Individual IEQ components absent	[3]
Analyzing impact of passive design strategies on comfort and productivity of workers in Office building/spaces	Empirical study	2021	Human comfort, productivity, energy consumption	IEQ measurements not taken Specific to a location	[17]
Review of existing studies applying computer-based modeling and simulation to guide occupant-centric building design	Review paper	2020	IEQ, energy consumption, human comfort, productivity	No specific climatic context Connections are rarely discussed except for building energy performance Brief overview of IEQ	[13]
Review challenges and opportunities in the field of occupant-centric building design and operation	Review paper	2020	Human comfort, Energy consumption	No specific climatic context Individual IEQ components absent Does not consider productivity	[10]
Benefits of natural ventilation on thermal comfort, IAQ, and energy efficiency	Review paper	2020	IEQ (Thermal comfort, IAQ), human comfort, energy consumption	Does not consider productivity Other IEQ components are not discussed	[12]
Factors that limit the interactions between occupants, IEQ and building design	Review paper	2019	IEQ, human comfort, energy consumption	No specific climatic context Does not consider productivity	[8]
Analyze the relationship between thermal comfort and building control research	Review paper	2018	IEQ (Thermal comfort), Human comfort, energy consumption	No specific climatic context Other IEQ components are not discussed Does not consider productivity	[11]
Review the concept of occupant behavior and its relation with IEQ and building energy consumption	Review paper	2017	IEQ, energy consumption, human comfort	No specific climatic context Does not consider productivity	[14]
Establish links between IEQ and occupant well being and comfort	Review paper	2016	IEQ, human comfort	No specific climatic context Does not discuss energy consumption and productivity	[15]

"it does not cause or aggravate illnesses in the building occupants; it assures a high level of comfort for the building occupants; it minimizes the use of energy used to achieve desired internal conditions, taking into account available state-of-the-art technology and non-technical measures".

Inadequate indoor comfort affects productivity, performance, and health of inhabitants [25]. Recent research has focused on mitigating negative health effects in building environments [26], however, interactions at different scales (such as those related to building design, occupant level, and IEQ control) are often overlooked [27,28].

IEQ consists of a number of factors that can primarily be categorized into quantifiable physical variables that assess acoustical quality, physical, chemical, IAQ, and thermal comfort in an indoor environment. These aspects shape the health of building occupants [23].

2.1.1. Thermal comfort

ASHRAE 55 [29] defines thermal comfort as "that state of mind which expresses satisfaction with the thermal environment". It encompasses physiological and psychological factors [30,31] and describes an individual's degree of comfort. However, an individual often inhabits the built environment alongside other building occupants [32]. The indices predicted mean vote (PMV) and predicted percentage dissatisfied (PPD) from Standard ISO 7730 [33] estimate the thermal perception and satisfaction of a group.

The human body interacts thermally through convection, radiation, and evaporation, striving to maintain a consistent internal temperature [25,34,35]. Temperature, humidity, and air velocity are some variables that determine thermal comfort. HVAC systems significantly impact indoor thermal comfort [36], contributing to increased energy

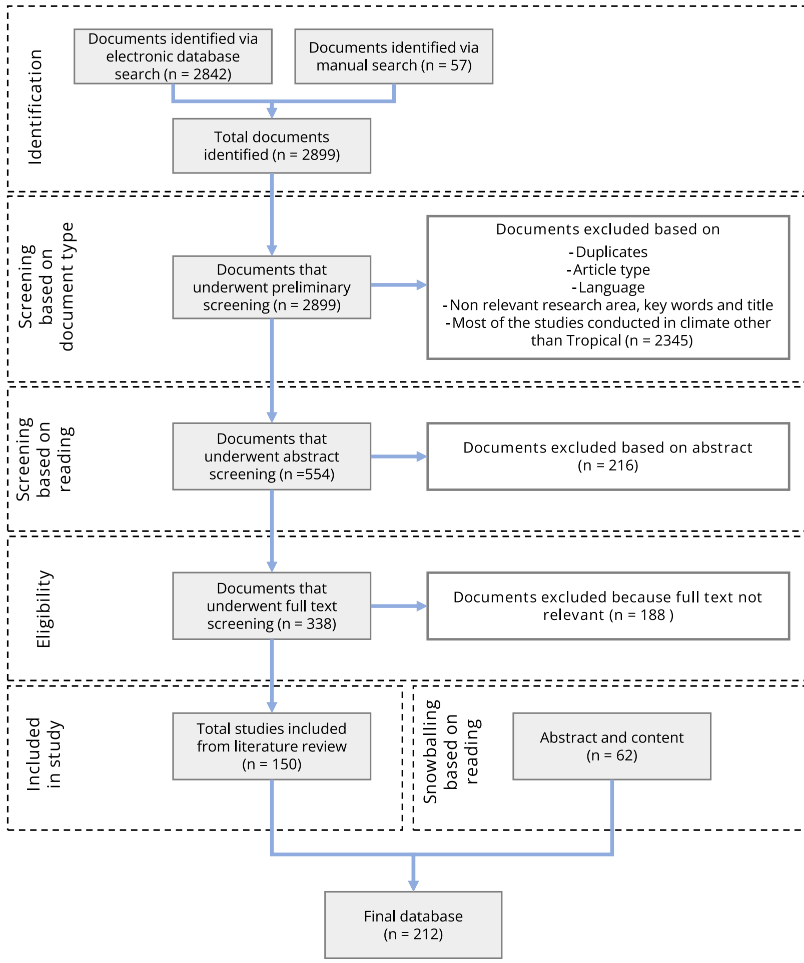

Fig. 2. Schematic of literature screening process based on PRISMA framework illustrating the number of documents at each phase.

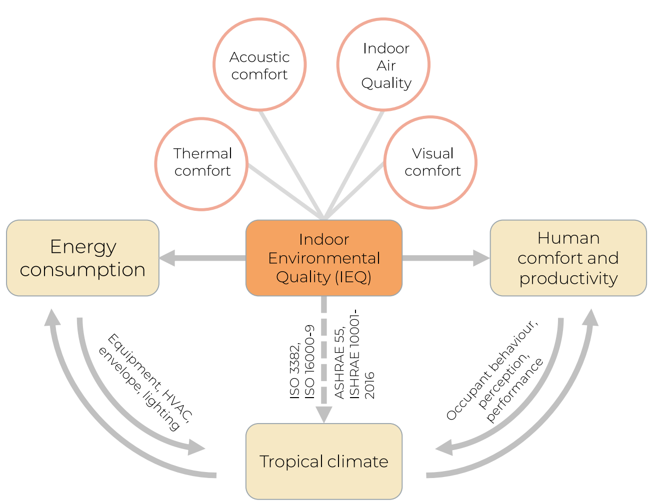

Fig. 3. Inter-linkages between IEQ, building energy consumption, human comfort and productivity.

consumption in buildings [37] as it is the most energy-intensive end-use in developed countries [38,39]. Optimal temperature plays a role in productivity [40,41]. Utilizing building automation and control can help regulate comfort levels and enhance energy efficiency [42].

2.1.2. Visual comfort

Visual comfort, defined by EN 12665 [43], refers to the subjective well-being induced by the visual environment. A lighting system should provide adequate illumination to ensure safety, movement, visual performance, and overall comfort. Monitoring quantitative measurements such as illumination, glare, daylight, and aspects of visual quality like distribution, homogeneity, and radiation spectrum composition is essential [8]. Daylighting, with views of the outdoors, contributes to occupants' psychological well-being and illuminates the room [44].

According to the last 30 years' worth of daylighting studies, it has been established that the visual environment influences human health on both a biophysical and visual level [45–47]. Insufficient light disrupts internal biological cycles, affecting performance, health, and safety [48]. Adequate light exposure synchronizes circadian cycles and hormone release.

Good lighting levels and visual comfort through efficient indoor design significantly affect productivity in offices, impacting financial performance [49,50]. The use of daylight sensors and photocells reduce energy consumption for illumination. Modern green buildings prioritize lighting and visual comfort to meet necessary requirements in enclosed structures [51].

2.1.3. Acoustic comfort

Acoustic comfort pertains to a building's ability to shield its occupants from external noise and offer them a smooth, unobstructed environment for tasks and interaction [21]. It considers factors that minimize discomfort [52], aiming for the absence of unwanted noises and presence of agreeable sounds.

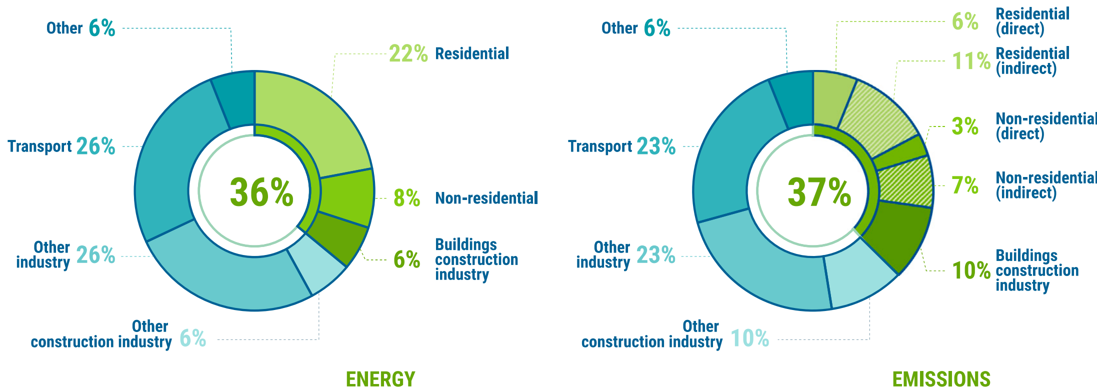

Fig. 4. The share of global final energy and related CO_2 emissions in buildings and construction industry, 2020.
Source: Reprinted from "2021 Global Status Report for Buildings and Construction: Towards a Zero-emission, Efficient and Resilient Buildings and Construction Sector", by United Nations Environment Programme (2021) [2].

The quality of the acoustic environment depends on sound pressure level, frequency, source distance, reverberation time, sound absorption, and insulation [32,53–56]. Better acoustics in offices and classrooms enhance focus, communication, and productivity [57–61]. Excessive noise in living spaces leads to irritation, disturbed sleep, and long-term health issues such as cardiovascular disease, hypertension, and psychological problems [48].

2.1.4. Indoor air quality

IAQ refers to the air quality within and around a building, focusing on the absence of discomfort from odor and sensory irritation. Acceptable IAQ means harmful contaminants are at safe levels, and that at least 80% of those exposed to the air do not express disapproval [32,62]. Factors like humidity, temperature, ventilation rate, biological pollutants, gases, and particulate matter influence IAQ [63–68]. Identifying IAQ-related issues is challenging due to the complex interactions among these physical, chemical, and biological components [69].

IAQ in naturally ventilated buildings is greatly impacted by outdoor pollutants [70], and it is mostly linked to Sick Building Syndrome (SBS) [71]. Ventilation plays a vital role in maintaining air movement and replacing contaminated indoor air with fresh outdoor air [72]. Enhancing air quality, reducing pollutants, or increasing ventilation rate can improve performance in simulated offices [73]. High indoor particle concentrations contribute to the spread of diseases and respiratory problems [22,74,75].

2.2. Detrimental effects of poor IEQ

The health of a building's occupants and the environment inside that building are closely intertwined. Issues like the building's age, inadequate IEQ, and poor maintenance can worsen its condition and affect residents' health [23]. IEQ has been connected in studies to mental health and physical illnesses that may not be immediately obvious but can create serious difficulties such as cardiovascular diseases, obesity, and asthma-related concerns, in the long run [76].

Sick building syndrome (SBS) and building-related illnesses (BRI) result from poorly designed or maintained structures [77]. SBS symptoms include headaches, dizziness, nausea, and exhaustion among others, while BRI symptoms include chest tightness, coughing, and fever. Both are tied to IEQ and require attention for occupants' comfort and well-being [23].

COVID-19, a highly infectious disease transmitted through inhalation or contact with contaminated droplets, spread globally in 2020. Fever, myalgia, dry cough, and pneumonia are some of its typical clinical symptoms; it can lead to gradual respiratory failure due to alveolar injury, and possibly even death. Improved building ventilation, filtration systems, quarantine, and social distancing were implemented to combat the spread. In arid Middle Eastern countries such as United Arab Emirates, Yemen, and Oman, which lie in the tropical zone, the severe climate prevents most buildings from using natural ventilation, leading to excessive use of air conditioning which increases the risk of viral transmission due to lower indoor air temperatures and inadequate indoor building ventilation levels. Also, it is a widespread cultural tradition here to burn incense in indoor spaces [78] which generates fine particulate matter (PM) [79]. Studies suggest a link between PM and propagation of COVID-19 [78,80]. Insufficient ventilation may facilitate the spread of the virus droplets in indoor environments [78].

Qian et al. (2020) argue that indoor settings are more susceptible to COVID-19 outbreaks compared to outdoor environments [81]. In their study of 318 outbreaks reported in 320 Chinese cities from 4 January to 11 February 2020, they discovered that all the outbreaks, except for one, transpired in indoor locations [82]. Due to building designs and sociocultural norms, SARS-CoV-2 virus preventive strategies must also take indoor local environmental factors into consideration [78]. Inadequate ventilation, overuse of air conditioning, poor IEQ, and PM accumulation increase the risk of contracting the virus. With this overview regarding the numerous components that add up together to inform the IEQ of a building and its importance from the perspective of the well-being of the occupants, we discuss how these factors influence energy consumption and why it is essential to explore the relationship between the two as we move towards a warming world.

2.3. Energy consumption in buildings

Buildings are dynamic systems, and occupants' interactions with the environment are bidirectional [83]. According to Humphrey's principle [84], "if a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort". Achieving a balance in the four components of IEQ ensures occupant comfort. However, buildings are typically designed for the average occupant, overlooking the complexity of occupant behavior (OB) [10]. This oversimplification leads to inconsistencies between predicted and actual energy performance [10,85,86]. Understanding occupant perception and influential factors is crucial for accurately predicting indoor conditions and energy usage.

The IEA identifies six variables impacting energy usage in buildings: climate, electrical and mechanical systems, building envelope, operation and maintenance, indoor design, and occupant behavior [87]. Research on occupant behavior is less extensive due to limited data availability and challenges in interpretation [88]. It is important to acknowledge that the active involvement of occupants has a notable effect on the energy consumption of a building, both directly and indirectly. Likewise, their passive engagement with building systems, such as HVAC, also has a considerable influence and affects thermal comfort and IAQ [3].

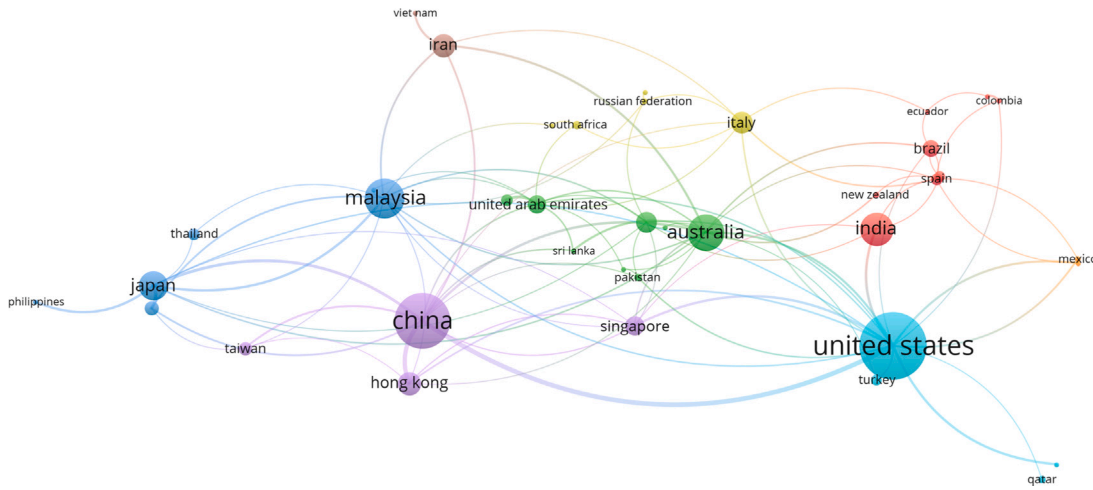

Fig. 5. Mapping the distribution of regions identified while investigating the interplay between energy, IEQ, human comfort, productivity and tropical climates.

HVAC, lighting, and equipment (Plug Loads) are the primary energy-consuming processes in an office building, accounting for approximately 85% of total energy usage [89]. The distribution may vary for different building types. Fig. 4 illustrates the proportion of worldwide final energy and associated CO_2 emissions attributed to the buildings and construction industry in 2020.

Several nations are increasing enforcement of energy regulations and mandates for various building types. These standards establish prerequisites for energy-efficient designs in new buildings, aiming to reduce overall energy usage and CO2 emissions [90].

Studies on energy and the built environment can be categorized into two scales: individual buildings and the urban scale. The individual building scale focuses on the building itself, while the urban scale considers the entire built environment system [7]. Urban energy models estimate building energy consumption using long-term relationships that incorporate physical, socio-econometric, and technical models [91]. In contrast, energy models for individual buildings use detailed physics-based or engineering models like multizone simulation and RC models [92,93]. These models provide versatility and enable detailed analysis for comparing retrofit scenarios [94–96].

The building industry has rapidly expanded in the past four decades, with significant growth in residential and commercial construction. Predictions suggest that global building energy demand could double or even triple by the middle of the century. Buildings play a crucial role in achieving a low-carbon future and meeting basic energy needs [97]. However, caution is needed to avoid oversimplifying energy demand reduction challenges [98]. It is difficult to separate energy consumption from global economic growth, which could have a detrimental impact on the economy [99,100].

In view of the aforementioned background regarding IEQ and energy consumption trends over the years, we dive deeper into the literature pertaining to these topics in the following section.

3. Literature review: A multi-domain analysis

The tropics experience a consistently warm climate with an average temperature range of 25 to 28 degrees Celsius (77 to 82 degrees Fahrenheit), owing to the region receiving the maximum intensity of solar radiation [101]. These are the areas lying between the northern latitude of the Tropic of Cancer at approximately 23°26′ North and the southern latitude, Tropic of Capricorn at 23°26′ South. The location not only affects the culture of tropical countries' citizens, but it also influences the way in which different types of buildings like residences, commercial buildings, factories, universities, and schools are constructed. Consequentially, this influences the energy requirements of these buildings. For instance, here, buildings with greater thermal mass, high-performance glass, shaded windows, and mixed-mode ventilation systems are preferred to reduce cooling loads [102,103]. Climatic conditions along with these variables play a vital role in determining the space thermal energy use in the tropics. It encourages carbon emission reductions in a cost-effective manner [104].

In tropical buildings, often closed rooms are air-conditioned due to higher air temperatures. The desire to conserve energy, coupled with a lack of understanding about the health and safety implications of IAQ, has led to room designs that permit the closure of all doors and windows, resulting in inadequate ventilation [105]. Inadequately ventilated enclosed spaces can allow gases to accumulate to hazardous concentrations, leading to adverse health outcomes [106], especially for office workers [107]. While leaving windows open or utilizing a ventilation fan can enhance IAQ, these approaches can also elevate energy consumption, as air conditioning systems must exert more effort to sustain a comfortable indoor temperature. As a result, maintaining good IEQ while consuming less energy is an important aspect of room and building design [94,108].

In view of the aforementioned, this section will discuss the research that has been conducted in this field in detail, while exploring the linkages between these variables. The network map illustrated in Fig. 5 highlights the distribution of countries with tropical climates where the included studies have been conducted. Based on the author's understanding, the research begins by reviewing the limited number of studies discussing three variables simultaneously.

3.1. IEQ, energy consumption, and human comfort

The realm of Indoor Environmental Quality (IEQ), energy consumption, and human comfort intertwines to create a human-centric and sustainable built environment. In their review, Šujanová et al. emphasized the significance of a human-centric built environment, where building design and working conditions are given due attention alongside quantifiable physical factors used to assess IEQ performance. They highlighted the importance of flexibility and adaptability in addressing energy consumption and conservation, as well as climate change impacts. The review concluded with recommendations focused on building automation to promote eco-friendly and people-focused building initiatives [8].

Building on the theme of building design, Oluwatayo and Pirisola examined how passive design strategies influenced worker productivity in office buildings. Their study in Lagos, Nigeria collected data through questionnaires and observation guides, focusing on the passive design features present in the buildings. The results indicated that strategies including building orientation and the utilization of shading devices for optimizing solar and ventilation played a significant role in predicting workers' productivity. The authors suggested the development of a rational model to assess the effects of various thermal climates on human performance [17].

Addressing the role of building control in the context of energy conservation, Park and Nagy reviewed the fields of thermal comfort and building control. They employed a data-driven approach to explore the relationship between the two areas and found that adaptive occupant behavior acts as a bridge between them. Interestingly, the emphasis in building control was primarily on energy conservation, rather than integrating findings on thermal comfort and occupant satisfaction [11].

Considering the measurement and simulation methods employed in studying IEQ factors, human behavior, and energy consumption, Asadi et al. highlighted a lack of comprehensive understanding. They observed that several studies used various simulation methods and software to estimate energy consumption, often taking into account only one or two specific IEQ parameters. This limited approach led the authors to infer a lack of relationship between overall IEQ parameters and energy consumption [14].

In a comprehensive review focused on thermal comfort, energy efficiency, and indoor air quality in the context of natural ventilation, Sakiyama et al. discussed the parameters and metrics used to assess natural ventilation performance. They identified a growing use of numerical models and efforts towards parametrization and optimization. However, most detailed studies on ventilation strategies have been conducted in hot and humid or tropical climates, suggesting the need for further exploration of natural ventilation in different climate conditions [12].

Finally, Azar et al. critically reviewed existing studies that applied computer-based modeling and simulation to address occupant-centric building design practices. They identified important barriers such as limited consideration of metrics beyond energy efficiency, limited implementation and validation of proposed methods, and a lack of integration of occupant behavior modeling in existing building performance simulation tools. The paper concluded by emphasizing the need for future research and applications to address these gaps and support an integrated occupant-centric design approach [13].

These studies collectively demonstrate the multidimensional nature of the relationship between IEQ, energy consumption, and human comfort. It is observed that building design and control strategies, occupant behavior, and the measurement and simulation of IEQ factors all play significant roles in optimizing energy consumption while ensuring human comfort and well-being. Also, it is clear that there is limited research that explores the interplay between these three closely-linked variables together. Further, to the best of our knowledge, there is no study that also incorporates productivity at the same time while taking the climatic context into consideration. Hence, we attempt to understand the individual interactions through the couplings of variables as discussed in the subsequent subsections.

3.2. IEQ and human comfort

For optimal occupant comfort and satisfaction, it is important that the occupant is simultaneously satisfied with all four aspects of IEQ [109]. However, existing studies have widely investigated the impact of one aspect at a time, including how occupants perceive thermal, visual, acoustic, or air quality stimuli [86,110,111]. Thermal comfort is frequently regarded as the most significant aspect in establishing overall satisfaction with IEQ [32]. For instance, consolidated efforts have been made to study thermal comfort internationally resulting in standards and a global database on field studies worldwide [111,112]. There is enough evidence reinforcing that physical environmental variables (temperature, air movement, humidity), ventilation strategies (NV, MM, AC) and personal demographics (age, gender, thermal history) influence the thermal comfort of occupants [12].

But occupants are exposed to different thermal, visual, acoustic, and air quality conditions simultaneously. Some studies have explored the correlation between multimodal environmental factors and the interaction of occupants with building systems [86,113,114]. Under simultaneous thermal and visual discomfort, the occupant preferred to control the blinds whereas the occupant adjusted the desk fans under thermal discomfort alone [113]. Additionally, although indoor and outdoor temperatures have been widely leveraged to develop models for window control to utilize NV, there is increasing evidence that aspects like noise levels, rain, and IAQ must be included in the models making window operation a multi-domain-triggered action [114,115]. Some studies have explored this interrelation between different components of IEQ and occupant comfort.

Frontczak & Wargocki conducted a literature survey based on indoor thermal, visual, acoustic, and air quality conditions to determine their importance as determinants of comfort as ranked by building users. In addition, factors not associated with the indoor environment, including occupant characteristics, outdoor climatic conditions, and building-related elements were also scrutinized. It was concluded that achieving thermal comfort is often viewed as the most crucial element. Based on the survey findings, it was suggested that indoor environmental control solutions should encompass regulation of the thermal environment, adaptations based on external weather conditions, and the provision of occupant-controlled customization options to meet individual needs [32].

Along similar lines, Ganesh et al. examined the literature to demonstrate the significance of IEQ and the factors that influence human thermal comfort. The authors also addressed the assessment of thermal comfort using various models and indexes as described in the literature. In addition, a discussion on a variety of IEQ-related problems was presented as well [22].

Focusing on a specific space, Kapoor et al. presented a review of studies conducted on IEQ variables in Indian school classrooms, which are indicated to be inadequate, tortuous, and unorganized. The authors inferred the lack of a well-established method to evaluate IEQ of classrooms in school buildings. They also discussed some key strategies and policies that will influence the future of IEQ research moving ahead [21]. As an extension of the previously mentioned work, Kapoor et al. presented the existing practices pertaining to IEQ components in naturally ventilated school buildings. The impacts of COVID-19 are discussed as well, along with related mitigating measures and factors for future research direction. The evidence suggests that more scientific efforts are urgently required to attain greater levels of comfort [23].

For an advanced understanding of the relationship between IEQ and human comfort, Mao et al. proposed a framework for collecting environmental and human-centric data, followed by an analysis of the relationship between the variables to build a scalable comfort model to detect the comfort level of occupants in buildings. The input for the machine learning model consisted of data obtained from IAQ sensors, while the output was considered to be the occupant's Blood Pulse Wave recorded via sensors. Based on the environment input, the model projected the comfort level, which aided in monitoring the comfort state of the occupants with the goal of preventing health problems in advance. The authors studied several regression models followed by evaluation using Support Vector Regression for optimum predictions [116].

To assess the role of gender and age in IEQ and thermal comfort assessment, Indraganti and Humphreys used a thermal comfort survey for offices in India, Qatar, and Japan. It was found that in addition to feeling colder than men did, women were less satisfied with all IEQ measures. The study advocates considerations for females in the design of workplaces, along with privacy concerns [117].

3.3. IEQ and productivity

Productivity is related to an individual's performance in relation to their goals. Currently, there is no established norm for evaluating productivity, and gauging the impact of the environment on human output in the workplace proves to be challenging due to numerous variables linked to particular tasks and distinct situations that cannot be precisely documented [118]. Different studies utilize different metrics and methods to measure productivity. According to Roelofsen, IEQ is more essential for the performance of office workers as compared to job satisfaction and stress. When working in environments with inadequate IEQ, individuals are likely to feel uncomfortable and may have reduced productivity even if they are only experiencing mild symptoms such as headaches and fatigue [102].

Lan et al. conducted a study to examine how temperature discomfort impacts health and human performance through neuro-behavioral tests in an office setting. The results showed that discomfort with higher temperatures is associated with the perception of inferior air quality, increase in severity of symptoms linked to sick-building syndrome, negative mood, and lower motivation to exert effort, ultimately leading to subpar task performance [103].

Tham performed a study in a call center, taking temperature and outdoor air supply rate in a blind intervention approach. Significant interaction effects were noted on workers' talk time due to the above-mentioned variables, highlighting their interdependence. Drawing on the results, the authors concluded that while maintaining a higher temperature within the thermal comfort range, increasing the outdoor air supply rate can enhance workers' performance. Also, reducing the temperature at a low ventilation rate leads to improvement in performance as well [104].

Acoustic comfort in commercial buildings is crucial for occupant productivity [119], but it has not often been prioritized in building design, leading to post-occupancy productivity issues [120,121]. However, there is a growing emphasis now on the overall impact of acoustics during the design of new buildings [122,123].

Occupants' well-being and productivity depend significantly on visual comfort [124]. Architectural design influences office lighting, which in turn influences well-being and productivity. The availability of both natural and artificial lighting is crucial for the occupants, particularly in areas where natural light is insufficient or during evening hours when natural light is scarce [125]. Because visual comfort is so important, buildings must avoid the overuse of artificial lighting while still maintaining some level of comfort [48].

According to Franke & Nadler, intangible factors (such as ergonomics and privacy) have a greater impact on workplace satisfaction, health, and productivity than tangible ones (room temperature, IAQ). The authors recommended employing a comprehensive approach that takes into account the interdependencies among various research dimensions, such as factors related to IEQ, outcomes, methods of assessment, and impacts to develop supportive workplace designs [126].

Sadick et al. evaluated variations in job satisfaction, IEQ satisfaction, and self-reported influence of IEQ on productivity among professionals and academics in a tropical African university setting. The study findings indicated that there were no notable differences in IEQ satisfaction factors among participants. Authors suggest that enhancing IEQ can lead to greater productivity and yield increased satisfaction with the job [127].

Despite the abundance of literature, little research has been able to measure real task performances in order to quantify productivity gains or losses [128,129]. The vast majority only show results based on perceived productivity [130,131]. There is a clear distinction between studies focusing on well-being and studies focusing on productivity.

3.4. Energy consumption and human comfort

Human comfort, as discussed previously, depends on the environmental conditions of temperature, air speed, thermal radiation, and humidity, in addition to personal factors. In contrast to human-related factors, these environmental factors necessitate design intervention through active and passive strategies to create the ideal conditions for thermal comfort and mitigate the likelihood of overheating, particularly in tropical regions [17,94,132,133]. Passive design measures or retrofits serve to be one of the most potent strategies to create an efficient building envelope design that can minimize energy consumption without compromising on human comfort [134,135]

Building envelope-related variables have been shown to produce significant impacts on efficient configurations between comfort and energy consumption of buildings [135]. Using a multivariate regression model, Juan Gamero-Salinas et al. determined that the most significant factors in reducing the risk of overheating and energy consumption in tropical areas are natural ventilation and the thermal characteristics of the building envelope [133]. Improvements in these variables can produce annual energy savings of more than 50% in the semi-arid conditions of Mexico. Passive design strategies can increase comfort hours by up to 45% [136]

Indoor air temperatures and cooling loads are impacted differently by physical variables such as window wall ratio (WWR), overhang depth, and thermal properties of construction materials, depending on the ventilation and air-conditioning scenarios employed [137,138]. As per Tong et al. natural ventilation can significantly decrease heat accumulation in tropical buildings, resulting in lowered indoor air temperatures and nighttime cooling loads [137]. Growing evidence suggests the potential of enhancing energy resource management in buildings, in reducing greenhouse gas emissions with improved overall operability of the control system based on user preferences for improved comfort [139].

Recent past experiences of building occupants with environmental exposures influence their preferences and expectations of thermal comfort [140]. In hot climates or during summer, these experiences tend to make occupants prefer warmer temperatures, while in cold climates or during winter, they tend to prefer cooler temperatures. This forms the basis of adaptive comfort, which could be leveraged to extract higher energy savings, particularly, while operating HVAC systems [141]. As per ASHRAE Standard 55, "An adaptive thermal comfort model is a model that relates indoor design temperatures or acceptable temperature ranges to outdoor meteorological or climatological parameters" [34].

Among the most developed adaptive models based on *right-here-right-now* thermal comfort questionnaires and field measurements to monitor primary environmental parameters, linear regression equations have been established for relating buildings' neutral operative temperature with an index of concurrent outdoor temperature with coefficient of determinations ($\hat{R2}$) up to 0.99 [34,142,143]. These linear models have achieved energy savings up to 70% [144]. To cite a few, Saber et al. [145] achieved 6%–41% energy savings in air-conditioned offices in Singapore, Attia and Carlucci [146] achieved savings of 16%–25% in Kairo-Egypt, Ismail and Ouahrani [147] saved 18% energy by conditioning an office building in Doha-Qatar, Bienvenido-Huertal et al. [148] achieved energy savings of over 70% by air-conditioning an 8-story building in Spain – all these studies employed adaptive approach to thermal comfort considering the thermal preferences of occupants in tropical areas. Currently, it is estimated that adoption of adaptive thermal comfort practices can result in a reduction of 8%–13% of the total cooling energy consumption in India alone in the building sector by 2030 [142]. Few studies have also quantified the impact of adaptive comfort models, combined with indoor air quality, on energy consumption, particularly while investigating passive ventilation systems [149,150]. For instance, Nihar et al. [150] assessed the impact of outdoor air quality on natural ventilation potential in informal settlements in India based on adaptive thermal comfort model for the Indian subcontinent [142]. They found that low-cost filtration provides both thermal comfort and exposure protection at 65% less energy intensity when compared with mechanical air conditioning systems operated full-time.

In some cases, however, enhanced human comfort may not always be associated with a reduction in energy consumption. Delgarm et al. conducted a study for a building in Iran and found that the optimal solution resulted in an increase in total building electricity consumption by about 2.9–11.3%, but significantly reduced the Predicted Percentage of Dissatisfied (PPD) by about 49.1–56.8% [151]. In a study by Scorpio et al. it was found that the use of a novel glass facade increased the demand for heating energy in January, but resulted in reduced demand for cooling energy reduced between 34.9% and 45.1% in July. The visual comfort, however, increased during both periods [152].

Maximized visual comfort and energy efficiency can be accomplished by effectively improving windows for natural ventilation and incorporating shading and lighting systems, resulting in significant energy savings. However, there have been few efforts to concurrently optimize thermal comfort, energy consumption, and daylighting [153]. Gabriel Carriço de Lima Montenegro Duarte et al. created a user-oriented model to optimize the three for a Brazilian educational building. The authors were able to attain energy savings of approximately 8 to 12% by effectively using artificial lighting as a complement to daylight and decreasing the duration of air conditioning usage [154]. Analogously, Wahid et al. minimized energy consumption and maximized occupants' comfort by optimizing illumination, air quality, and temperature, along with the parameters pertaining to the external environment. The optimized values were used to compute user comfort and adjust the systems for heating/cooling, illumination, and ventilation as per the occupant requirement [155].

Evidence suggests that only a few IEQ factors (thermal comfort and IAQ) appear to have received greater attention to simultaneously evaluating their impact on occupant comfort and energy consumption [14,37,156–158]. Visual comfort has started to gain attention only recently. It is studied mostly in silos in terms of glazing systems or with respect to thermal comfort and energy consumption only [153,154,159–162].

3.5. Energy consumption and IEQ

As a crucial component of the building services for contemporary office buildings, the air conditioning system is intended to maintain a secure, healthy, and tolerably comfortable indoor temperature. Ordinances and regulations typically set the minimum requirements for indoor safety and health. The level of occupant satisfaction (comfort) in relation to IEQ is, however, mostly a matter of choice for building designers, owners, and end users. Energy consumption, which represents a substantial portion of recurring costs, becomes a significant concern for creating sustainable buildings when viewed in the context of its association with IEQ [6].

Sekhar et al. introduced an integrated methodology for conducting IAQ-energy audits that offers a comprehensive approach to evaluating the "IAQ signature" of a building. In addition, the authors devised an indoor pollution standard index, along with a discourse on other metrics such as the energy index and ventilation index, among others. The outcomes suggested that the acceptability of IAQ, as determined by the measurement of indoor pollutants, varies significantly from the perceptions of occupants regarding symptoms experienced and overall environmental acceptability [163].

Wong and Mui investigated the link between thermal energy usage and the general occupant approval of IEQ in a selection of air-conditioned offices. Monte Carlo simulations were employed to construct distribution profiles for the environmental quality of office buildings and the corresponding thermal energy consumption, using survey data from the office building stocks of Hong Kong. The authors established an energy-to-IEQ improvement ratio and an energy-to-acceptance ratio to evaluate the efficacy of thermal energy utilization in upholding office IEQ [6].

In the subtropical Australian city of Brisbane, Quang et al. created a multi-component model to enhance IEQ while lowering energy usage in mechanically ventilated office buildings. There was a 77% decrease in the average indoor particle number concentration when operating the ventilation system, without any significant changes in indoor CO_2 concentration and energy consumption [164].

By implementing simple ventilation procedures and placing Sansevieria laurentii (mother-in-law's tongue plants) in the office, Pamonpol et al. sought to improve the IAQ of a poorly ventilated, air-conditioned office in Thailand, while also reducing its energy consumption [108].

Through their literature review, Anand et al. emphasized the reasons for discrepancies between the actual and intended performance of buildings. This disparity stems from the flawed assumption that interactions between building systems and occupants are either constant or inactive, while they are actually dynamic and intricate. Inaccurate occupant information may cause poor IEQ as well as energy wastage. In the post-COVID-19 era, innovative sustainable techniques like personalized ventilation, higher zone set-point temperatures, and improved ventilation with increased air movement must be evaluated for occupancy-based HVAC control systems [3].

Fig. 6 summarizes the existing couplings between energy consumption, IEQ, human comfort, and productivity investigated for the tropical climate. A major share of existing studies analyze interlinkages between energy consumption, IEQ (thermal comfort, IAQ) and human comfort. However, there is limited research that simultaneously explores energy consumption, acoustic and visual comfort, and productivity in tropical climates.

4. Discussion

The study provides a systematic literature review of existing intersections of IEQ components and energy consumption in buildings while maintaining a sustainable and healthy indoor environment, with occupant comfort and productivity at its core. Considering the increasing need for space cooling and the expected rapid development in the tropics, the study highlights research performed in this part of the globe. The type of climate, building design and operations, and occupant behavior are crucial in determining the amount of energy used. Building design with non-performing building envelopes, HVAC systems, and poor control of IAQ, ventilation, lighting, and acoustic systems may result in energy wastage along with poor IEQ. A sustainable and energy-efficient building thus requires an accurate understanding of the climate-induced interactions between occupants, their comfort with the indoor environmental quality, and the resulting building's energy use.

4.1. Findings of the review

Building design and operations impact IEQ, which can cause adaptive behaviors that, in turn, again influence IEQ [13]. Individuals engage with the building systems to regain their sense of comfort. As highlighted in the literature review, there have been numerous studies on investigating the impact of different components of IEQ in isolation on overall occupant comfort, particularly thermal comfort. However, studies investigating the combined effects of all IEQ components are still limited, especially in tropical climates. While there have been studies on the effects of IEQ and its impact on occupant well-being and health, the effects of IEQ on occupant behavior and productivity have been studied on a relatively smaller scale [10,86]. Moreover, such studies have attempted to monitor occupant comfort and behavior through surveys or lab experiments. These experiments have mostly been short-term and suffer from the Hawthorne effect wherein it is stipulated that subjects modify their behavior as a result of awareness

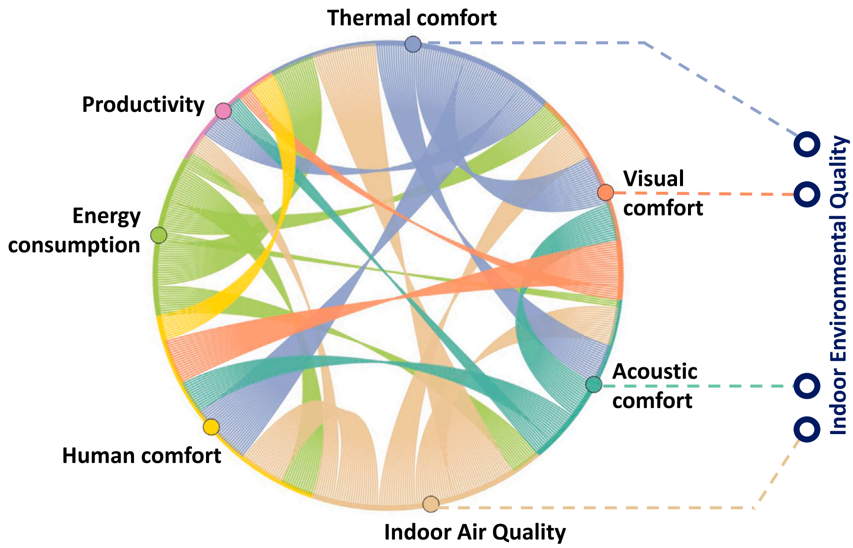

Fig. 6. Overview of the studies exploring couplings between energy, IEQ, human comfort, and productivity in the tropics. The length of the circle arc represents the percentage share of the selected studies considering the corresponding parameter. The color of the link represents the node of origin.

of being observed. Lab experiments are usually conducted on university campuses, wherein a young population of participants might not necessarily represent the entire population.

Although some research efforts have investigated the combined influence of multi-domain IEQ aspects on occupants' comfort and preferences, the results of such multi-domain research efforts have been inconclusive frequently and their overall benefit has been limited. For example, Nagano and Horikoshi [165] evaluated the influence of operative temperature on the acoustic comfort of participants but the evaluation of thermal sensation was observed to not be correlated with noise. Another study recognized the effect of noise on thermal comfort in warm situations, but the results did not support any correlation between temperature and acoustic comfort [166]. Azmoon et al. [167] and Yang and Moon [168] attempted to understand the interaction of thermal and visual conditions. The former observed that thermal comfort increased with increasing light levels while the latter reported no influence of lighting on the thermal sensation of occupants, thereby confirming the inconsistencies between thermal perception and visual perception.

Different expectations of comfort for each occupant consequently influence their interaction with building systems. In addition to environmental variables, occupants' interactions with buildings can also be governed by different personal and contextual factors physiological (such as clothing levels), contextual (such as building orientation, insulation levels, interior design), personal habits, and socio-economic factors to name a few [10], which are usually not accounted for and can potentially explain the inconsistencies in perception mentioned above. Furthermore, the proposed models to study occupant behavior have been validated for a particular context which highlights a major hindrance to assessing the accuracy and resilience of these models.

The literature states that there are numerous factors contributing to the dynamic growth in buildings' energy consumption [169]. However, there is limited consistent research on how this energy usage is changing globally and regionally, and how trends that affect energy use in buildings are evolving both historically and moving forward. A few studies have been carried out in response to this gap. According to the findings, the demand for residential cooling and heating energy is projected to stagnate or even slightly decrease in developed nations. However, the quantity of energy utilized for commercial heating and cooling is expected to rise worldwide [170]. Some studies have focused on examining areas and activities to see how they affect how energy loads are distributed spatially throughout the facility or building as a whole. Samples of premises were dissected into activity spaces to create comprehensive profiles of how these spaces were utilized within the overall facility [171]. However, there is a very small body of research that combines and contrasts variations in energy use among various types of spaces in this way. Understanding activities within facilities can help provide a more holistic interpretation of building energy consumption.

Recently, there has been increased interest in modeling high variability data using artificial intelligence-based methods. Some studies have focused on predicting room occupancy status, utilizing thermal comfort indices. This approach can facilitate more efficient resource utilization, resulting in energy conservation in buildings [172]. Analogously, Wei et al. concluded that incorporating the number of occupants as an input can enhance the accuracy of energy consumption predictions using a neural-network model [173]. However, no research has yet created a single model for diverse spaces to explain the interaction between energy and occupancy.

Also, there is little data on modeling how individual environmental conditions pertaining to acoustic, visual, and thermal comfort along with IAQ affect overall satisfaction with IEQ, especially in countries with tropical climate. This can be noted because very few research studies involving analysis of IEQ data obtained from installed sensors over a period of time have been reported in these tropical regions when compared to the number of studies conducted otherwise.

Real-time occupancy-based lighting control, which is a critical factor in determining the occupants' visual comfort, is well-established in commercial buildings. A space's lighting is often controlled by passive infrared (PIR) motion sensors that detect occupant movement. In order to offer higher energy efficiency, researchers have also considered the prospect of further optimizing lighting control in big open-plan rooms by restricting lighting to only those areas where people are present [174,175]. Nevertheless, the energy conservation benefits associated with this technique, as well as the savings linked to lighting optimization by limiting it solely to occupied areas, have yet to be recorded for institutional building spaces.

Many researchers have previously discussed the potential of reducing energy consumption in HVAC systems by using precise occupancy information to regulate the cooling needs of a space [176–181]. This will ultimately influence the thermal environment of the occupants, affecting their comfort levels. The majority of the reported energy savings come from restricting the supply of air during idle hours. However, these investigations are typically undertaken in small spaces with single or low occupancy in order to produce a controlled test setting. Very few studies have been conducted for bigger or multi-zone spaces, which demonstrate a considerable reduction in energy use when the HVAC system is controlled by real-time occupancy levels [182,183]. A more complex control method could be needed for institutional facilities like classrooms, which experience high occupancy variation during business hours. However, as far as we know, no studies have been done in these areas.

According to current research, a uniform technique is required, especially in developing nations, to standardize the process of maintaining and providing good IEQ conforming to all types of climates, while striving for maximum energy saving. A real-time evaluation of comfort and IEQ on a larger scale is necessary to achieve this.

4.2. Challenges

Although developed countries have implemented substantial energy conservation measures, the worldwide energy demand for buildings surged by over 20% between 2000 and 2017, owing to the rapidly growing floor area in developing countries, and rising energy requirements. To meet current climate commitments, new buildings should consume nearly zero energy while safeguarding occupants from extreme weather occurrences, promoting resilience, and ensuring the population's health and well-being. Future scenarios on building energy consumption propose techniques to decrease the sector's energy consumption by 2050 or later, primarily through improved energy efficiency measures and heightened deployment of renewable energy sources. Nonetheless, such a goal necessitates the implementation of comprehensive green policies as well as a significant increase in investment. Without strict regulation and monitoring processes keeping track of such policies, there is a genuine risk that the building sector will continue to use more energy and emit more greenhouse gases [184].

Gaining a more holistic interpretation of energy consumption in buildings is a challenge. This problem could be approached by understanding activities within the premises along with combining and contrasting variations in energy use of different types of spaces to determine the spatial distribution of energy loads. Furthermore, a comprehensive model can be developed to explain the interaction between occupancy and energy which will enhance our understanding of energy use in a facility.

Promoting zero-energy buildings mandatorily, while accounting for policy implications is necessary. The zero-energy buildings offer several advantages, including lower energy expenditures, enhanced occupant comfort, positive environmental impact, reliable and cost-effective operations, and improved energy security. As we expect the building stock to double over the next few years, zero-energy buildings with the above-mentioned benefits provide an essential sustainable solution as we move ahead.

Currently, monitoring the various variables contributing to IEQ is a challenge that affects both the overall comfort of occupants as well as an accurate prediction of building energy consumption. Suitable application of automated control systems for indoor environment monitoring along with regulation compliance would enhance the flexibility of the built environment to adjust to immediate performance needs and climatic conditions, which would be crucial to the future of building design [8].

A number of standards are available that provide guidelines for a healthy indoor environment. However, in many cases, a select few of these standards – which concentrate only on some specific aspects of IEQ, say IAQ or thermal comfort alone – are considered while designing and studying the IEQ of a particular building, not paying due attention to the other components that constitute the environment. As a result, there is a chance that the findings or the conclusions arrived at are flawed or incomplete. Thus, there is a need to broaden the scope of the standards to consider all components of IEQ and their monitoring methods. Future studies should cover a larger range of parameters to determine the overall health of the environment. Strict measures should be enforced to ensure that the indoor environment variables are in accordance with the specified thresholds.

Overall, there is a need to address the lack of availability of relevant real-time, in-situ data; this will lead to more robust research on interactions between IEQ, building energy consumption, and the holistic comfort of occupants with evidence-based policy-making implications. It will also help to advance the field with the integration of AI into the mix, which is expected to play a critical role as discussed in further sections.

4.3. Future potential — integrating IEQ & AI

An energy-efficient and occupant-centric design of the built environment requires technological interventions that can be efficiently measured and used for accurate predictions and successful implementations. Artificial Intelligence (AI) pertains to a machine's ability to imitate human cognitive intelligence. It provides the capability to solve intricate problems that are beyond the capacity of the human brain or are excessively challenging to solve. Implementing AI technology diminishes the necessity for manual computations. It can solve and process thousands of computations in seconds.

Leveraging AI to model high variability data has witnessed a growing interest in recent years [3]. It is being used in a variety of fields, including policy-making, economy, planning, energy efficiency, management, prediction, and optimization. The utilization of AI in sustainable architecture encompasses various areas such as designing energy-efficient buildings, devising strategies to alleviate environmental and climate impact, and forecasting and minimizing energy consumption, among others [185]. In their study, Kapoor et al. (2021) present an extensive summary of the utilization of AI techniques in prior research endeavors concerning energy consumption prediction and creation of models pertaining to thermal comfort, IAQ, visual comfort, and acoustic comfort [21]. It was observed that limited studies have developed models that evaluate complex relationships between building energy consumption, IEQ, and occupancy. A summary of AI studies in the realm of IEQ is provided in Table 2.

Considering the growing impact of climate change, and the need to conserve energy while preserving human comfort across the globe, the importance of flexible and adaptable systems is imperative. To foster a conducive environment for improving AI-driven building technology and operations that cater to user needs, swift data mining, optimal weighting of meteorological data derived from a range of sources, development of user-friendly interfaces that accommodate diverse user preferences and operating conditions, and utilization of AI and big data in smart homes and buildings that feature adaptable building components are some research directions that are recommended.

5. Conclusion

This paper presents a state-of-the-art review of research analyzing the interactions between all four parameters of indoor environmental quality (namely, thermal, acoustic, visual comfort and indoor air quality), and building energy consumption, while focusing on human comfort and productivity. Studying the interactions is crucial since it might have both immediate and long-term effects on people. It is clear that the issue of energy conservation is multifaceted given the constraints that indoor comfort conditions are satisfied, and studying this interconnection is vital if we are to achieve building decarbonization goals.

While numerous studies have been done to investigate individual parameters of IEQ, especially thermal comfort, and its impact on building energy consumption, we observed an absence of a holistic study that considers all the abovementioned factors simultaneously. We also observed that most of the review papers written in this domain have been agnostic to climatic conditions. In this paper, we particularly

Table 2
AI studies in IEQ.

IEQ Component	Method	Reference	Input/Output variables
Thermal Comfort	ANN	[186–192]	Indoor and Outdoor Temperature, Relative Humidity, CO_2 concentration, wind speed, metabolic rate, and clothing*
	MLP, RF	[193]	
	Reinforcement Learning	[194]	
	Fuzzy Logic	[195]	
	FNN	[196]	
	Decision Tree, Naïve Bayes, SVM, MLP, and DANN	[197]	
	KNR, SVR, LR, TR	[198]	
Indoor Air Quality	ANFIS, BP, MLRM	[199]	NH_3 concentration, Room temperature, barometer level pressure, wind direction, wind speed, global solar radiation, sea level pressure, temperature, Pasquill atmospheric stability class, relative humidity, outdoor pollutant concentrations, CO_2, VOC, fine dust, and Indoor PM2.5 and PM10 concentrations*
	ANN	[200,201]	
	MLP NN	[202]	
	Gated recurrent unit LSTM	[203]	
	DANN	[204]	
	Decision tree regression method	[205]	
	Extended fractional-order Kalman filter	[206]	
	Machine learning-based non-parametric forecasting	[207]	
	Multiple linear regression, non-linear ANN	[208]	
	Time slicer method, PAD method	[209]	
	ARIMA	[210]	
Visual Comfort	Fuzzy Rule Based	[211]	Building orientation, Sun position, illuminance level, glare, visual satisfaction, Overhang depth, Overhang tilt angle, Outdoor illuminance, Window width, Window length, Azimuth angle, and consumed energy*
	MOGA	[212]	
	NSGA-II	[213]	
	GA	[214]	
	LR, SVM	[215]	
	Python-based Method	[216]	
Acoustic Comfort	ANN, FFN, BP	[217]	Wall and ceiling materials, climatic zone, Total floor area, noise, number of storeys, and building envelope parameters*
	SVM, ANN, GBDT, RF	[218]	
	NSGA-II	[219]	

Notes: ANN = Artificial Neural Network, MLP = Multilayer Perceptron, RF = Random Forest, FNN = Deep-reinforcement learning, KNR = K-Neighbors Regression, SVR = Support Vector Regression, TR = Tree Regression, LR = Linear Regression, SVM = Support Vector Machine, DANN = Deep ANN, ANFIS = Adaptive Network-based Fuzzy Interface System, BP = Backward Progression, MLRM = Multiple Linear Regression Method, LSTM = Long Short-Term Memory, ARIMA = Autoregressive Integrated Moving Average, MOGA = Multi-Objective Genetic Algorithm, NSGA-II = Multi-Objective Non-Dominated Sorting Genetic Algorithm, GA = Genetic Algorithm, FFN = Feed Forward Network, and GBDT = Gradient-Boosting Decision Tree.
* Not all studies use each of the mentioned variables; they are listed together as per the literature reviewed.

focused on tropical climates because tropics are already home to 40% of the global population and another 60% growth is estimated to occur by 2050. Results of the few current studies investigating combined impact of multi-domain IEQ aspects on occupant comfort and energy consumption were observed to be inconclusive frequently and their overall benefit was found to be limited. Although research suggests that numerous factors are responsible for dynamic growth in energy consumption in the tropics, we observed a lack of consistency in understanding the global/regional change in building energy usage necessary for understanding the historical trends moving forward. Understanding these trends, combined with influence of multi-domain IEQ aspects on occupants' comfort and preferences, would be crucial in achieving the goal for sustainable development. Results of current studies investigating combined impact of multi-domain IEQ aspects on occupant comfort and energy consumption were observed to be inconclusive frequently and their overall benefit was found to be limited.

The benefits of understanding interconnections between IEQ, occupant comfort, and energy consumption in a specific climatic context extend to several key stakeholders. Firstly, academicians and researchers in the field of building science and automation and environmental engineering will find this study valuable as it synthesizes existing knowledge on these interrelationships while identifying critical research gaps, thereby guiding future research endeavors and facilitating the advancement of knowledge in this domain. High cooling demand in tropical climates poses challenges to energy efficiency, sustainability, and climate change. The hot and humid conditions in these climates can lead to indoor air quality issues, including high levels of moisture, mold growth, and the presence of pollutants. Recognizing these challenges is crucial for practitioners in the construction industry and HVAC sectors to ensure healthy and safe indoor environments. Furthermore, the projected exponential population growth in tropical regions calls for evidence-based decision-making and robust guidelines for the future. The findings can assist regulatory bodies in establishing effective standards and certifications. AI-based methods and modeling techniques can help policymakers to be informed about the data-driven strategies to promote energy conservation and sustainable building practices, while understanding the complex dynamics of building energy and occupant behavior.

In summary, by elucidating the interplay between IEQ, energy consumption, and productivity in tropical climates, the study provides a valuable resource for informed decision-making, knowledge advancement, and the development of sustainable practices and policies in the built environment.

CRediT authorship contribution statement

Ashutosh Verma: Conceptualization, Data curation, Resources, Writing – original draft. **Vallary Gupta:** Methodology, Writing – review & editing, Visualization. **Kopal Nihar:** Conceptualization, Writing – review & editing. **Arnab Jana:** Writing – review & editing, Supervision, Funding acquisition. **Rishee K. Jain:** Writing – review & editing, Supervision, Funding acquisition. **Chirag Deb:** Conceptualization, Resources, Writing – review & editing, Supervision, Funding acquisition.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Chirag Deb reports financial support was provided by TIH-IoT US–India Collaborative Research Program 2022.

Data availability

No data was used for the research described in the article

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