

Full Length Article

A multi-method approach to evaluating indoor environmental quality and energy performance in residential college buildings in a humid subtropical region[☆]

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ABSTRACT

Operational performance in built environments is mostly assessed through indoor environmental quality (IEQ), water consumption, and energy consumption data to foster improvement-oriented strategies. This study investigates the IEQ and energy performance of residential college buildings (RCBs), including a LEED Silver-certified building, at a Louisianan university in the United States. Variations in occupant satisfaction, hygrothermal conditions, air quality, and energy metrics were assessed across seasons. Comparative evaluations of LEED-certified and non-certified RCBs in humid subtropical climates are scarce, highlighting the need for further exploration. The study employs subjective, objective, and integrated IEQ evaluation models, alongside energy performance evaluations using conventional Energy Use Intensity (EUI) and a novel Energy Utility Quality (EUQ) metric developed for climates like Louisiana's. An extended IEQ model integrating energy performance with subjective and objective components is also introduced. Findings highlight significant underperformance in acoustic conditions and high humidity levels, posing risks to occupant comfort and health. While the LEED-certified building excelled in the various IEQ performance metrics adopted, its highest EUI attainment and intermediate EUQ ranking in relation to other buildings point to operational inefficiencies requiring targeted intervention. This research underscores the value of holistic IEQ and energy performance evaluations in enhancing occupant comfort, operational efficiency, and sustainability in student housing. The introduced metrics serve as an enhanced pre-audit tool, enabling facility managers to evaluate building performance effectively and make informed decisions. Future studies shall apply these metrics beyond RCBs.

1. Introduction

Sustainability in the twenty-first century continues to play an important role in how buildings are structured, operated on, and maintained. Two major drivers of this trend are incentives and the positive public image associated with adopting green building certification schemes like ENERGY STAR and Leadership in Energy and Environmental Design (LEED), which are widely recognized in the United States [1,2]. These certification systems emphasize the adherence to key criteria, including the incorporation of affordable, non-toxic, energy-efficient materials and appliances that enhance thermal comfort, air quality, and various indoor environmental quality (IEQ) aspects.

Across colleges and universities in the United States, the Association for the Advancement of Sustainability in Higher Education (AASHE) promotes sustainable practices through its Sustainability Tracking, As-

essment and Rating System (STARS) framework. This system guides institutions in fostering environmental and energy literacy while systematically documenting and reporting their environmental footprints [3,4]. Studies suggest that adherence to environmental sustainability principles has become a significant factor influencing college choices among young people [5]. In fact, Reams and Awolesi [6] reported that most university students are willing to pay more than their current rent to live in apartments that align with green building principles.

Residential college buildings (RCBs) are essential components of the campus environment. Beyond their primary housing function, they play a significant role in shaping social interactions and influencing academic performance. Extensive research has shown that occupant satisfaction is strongly associated with the four critical components (4CCs) of IEQ: thermal comfort (Tc), indoor air quality (IAQ), lighting comfort (Lc), and acoustic comfort (Ac) [7,8]. As the demand for accept-

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Nomenclature

Symbol/Abbreviation Definition Unit

Ac	Acoustic Comfort, -
AASHE	Association for the Advancement of Sustainability in Higher Education-
$\alpha, \beta, \gamma, \delta$	Weighting factors for IAQ, Tc, Ac, and Lc, respectively, in IEQ assessment models, -
ANSI	American National Standards Institute, -
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers, -
CBE	Centre for the Built Environment, -
CDD	Cooling Degree Days, Degree Days
C_{CO_2}	Indoor CO_2 concentration, ppm
C_{atm}	Outdoor reference CO_2 concentration, ppm
C_{HCHO}	Formaldehyde concentration, mg/m ³
$C_{PM_{2.5}}$	Particulate matter concentration ($PM_{2.5}$), $\mu\text{g}/\text{m}^3$
clo	Clothing insulation, -
dB	Decibel (sound pressure level), dB
EUI	Energy Use Intensity, kWh/m ² or MJ/m ²
EUQ	Energy Utility Quality, %
g/m ³	Absolute humidity, g/m ³
GSF	Gross square footage, ft ² $\approx$ 0.0929 m ²
HDD	Heating Degree Days, Degree Days
IAQ	Indoor Air Quality, -
IEQ	Indoor Environmental Quality, -
IEQp	Perception-based Indoor Environmental Quality, %
IEQo	Objective (sensor-based) Indoor Environmental Quality, %
IEQc	Convention-based (Subjective-Objective) Indoor Environmental Quality, %
IEQs	Sustainable Indoor Environmental Quality, %
kBTU/sf	Annual Energy Use Intensity (alternative: MJ/m ²), kBTU/ft ² or MJ/m ²
kWh/sf	Monthly Energy Use Intensity, kWh/ft ² ($\approx$ 10.764 kWh/m ²)
lbs of CO_2	Equivalent carbon emissions, lb ($\approx$ 0.4536 kg)
lbs of CO_2 /sf	Annual emission intensity, lbs/ft ² ($\approx$ 4.882 kg/m ²)
LEED	Leadership in Energy and Environmental Design, -
Lc	Lighting Comfort, -
$\log \frac{C_{CO_2}}{C_{atm}}$	Logarithmic ratio of CO_2 concentration to atmospheric concentration, -
Lx (LX)	Illuminance, lux
met	Metabolic rate, -
mg/m ³	Formaldehyde concentration, mg/m ³
MWh	Total energy consumption per annum, MWh
$PM_{2.5}$	Particulate matter smaller than 2.5 μm , $\mu\text{g}/\text{m}^3$
PMV	Predicted Mean Vote, -
PPDTc	Predicted Percentage Dissatisfied with Thermal conditions, %
PPDLc	Predicted Percentage Dissatisfied with Lighting conditions, %
PPDAc	Predicted Percentage Dissatisfied with Acoustic conditions, %
ppm	Parts per million (for CO_2 concentration), ppm
RfC	Reference Concentration, -
sf (ft ²)	Square footage (imperial unit of area), 1 ft ² $\approx$ 0.0929 m ²
SL	Sound Level, dB
STARS	Sustainability Tracking, Assessment & Rating System, -
Tc	Thermal Comfort, -
T (°C)	Temperature, °C

TSV	Thermal Sensation Vote, -
$\mu\text{g}/\text{m}^3$	Particulate matter concentration, $\mu\text{g}/\text{m}^3$
WHO	World Health Organization, -
W_i	Normalized weight for the i th IEQ factor, -
W_x	Weighting Factor or Coefficient, -

able IEQ—defined as the satisfactory performance across all four components—continues to grow, various IEQ models have been developed to assess and enhance building performance [8].

While spatial quality, which reflects how occupants perceive the aesthetics, cleanliness, and maintenance of indoor spaces [9], is occasionally considered in IEQ studies, it remains difficult to integrate systematically. This is primarily because such perceptions are inherently subjective and cannot be easily measured with sensors or quantified mathematically, as depicted in Fig. 1, which also illustrates the impacts and assessment approaches related to IEQ. The 4CCs have been well-defined in multiple reviews and case studies [10,11], and they have remained the focal point of IEQ research over the past decade. These components are particularly valuable because they can be evaluated through both environmental sensors and occupant surveys—capturing the “state of the mind” and the “state of the environment.”

Furthermore, sustainability practices, especially those promoting energy efficiency, have been shown to enhance occupant satisfaction [12,13]. In university settings, student performance—shaped in part by the indoor environment—affects institutional success, as seen in metrics such as academic rankings, enrollment rates, and retention [14,15]. At the same time, universities face the dual challenge of managing tight budgets and meeting ambitious sustainability goals, necessitating a thorough understanding of energy consumption patterns and the environmental impact of their facilities [16,17].

In regions like Louisiana, characterized by a humid subtropical climate [18], the design, operation, and maintenance of RCBs become even more critical due to heightened demands on heating, ventilation, air-conditioning (HVAC) systems, and the need for continuous comfort improvements. Given that people spend most of their time indoors and the pivotal roles of RCBs in students' lives, it is exigent to deploy temporal and longitudinal field measurements of indoor environmental conditions, alongside occupant satisfaction and energy performance data, to holistically evaluate building performance for comfort, health, safety, and sustainability assurance.

Numerous studies have explored the impact of various IEQ categories on occupant satisfaction and productivity across diverse settings [19–21]. In educational buildings, Tc and IAQ have been the primary focus, with fewer studies incorporating all the 4CCs [17,22,23]. However, discomfort from less-studied factors can also negatively affect productivity and increase health complaints. Most existing research has concentrated on classrooms and lecture halls, leaving RCBs relatively underexplored. When multiple IEQ factors are assessed together, the evaluation typically relies on subjective occupant surveys, sensor-based measurements of indoor environmental conditions, or an integrated approach combining both as earlier stated [8,24,25]. The resulting IEQ metric, represented in Eq. (1), integrates these components into a numerical score for performance assessment, where α , β , γ , and δ are weighting factors (W_x) for IAQ, Tc, Ac, and Lc, respectively:

$$IEQ = (\alpha \times IAQ) + (\beta \times Tc) + (\gamma \times Ac) + (\delta \times Lc) \quad (1)$$

The weighting factors are determined after normalizing mean response values or statistical regression results from survey questions related to the 4CCs [21]. These weightings reflect the significance of IEQ factors to building stakeholders, either based on their relative importance or satisfaction levels. A low score in any of the 4CCs signals poor performance, necessitating targeted improvements. For instance, a low IAQ score may indicate the building need for better ventilation or air purifiers [26–28]. Leccese et al. [21] previously reported on different

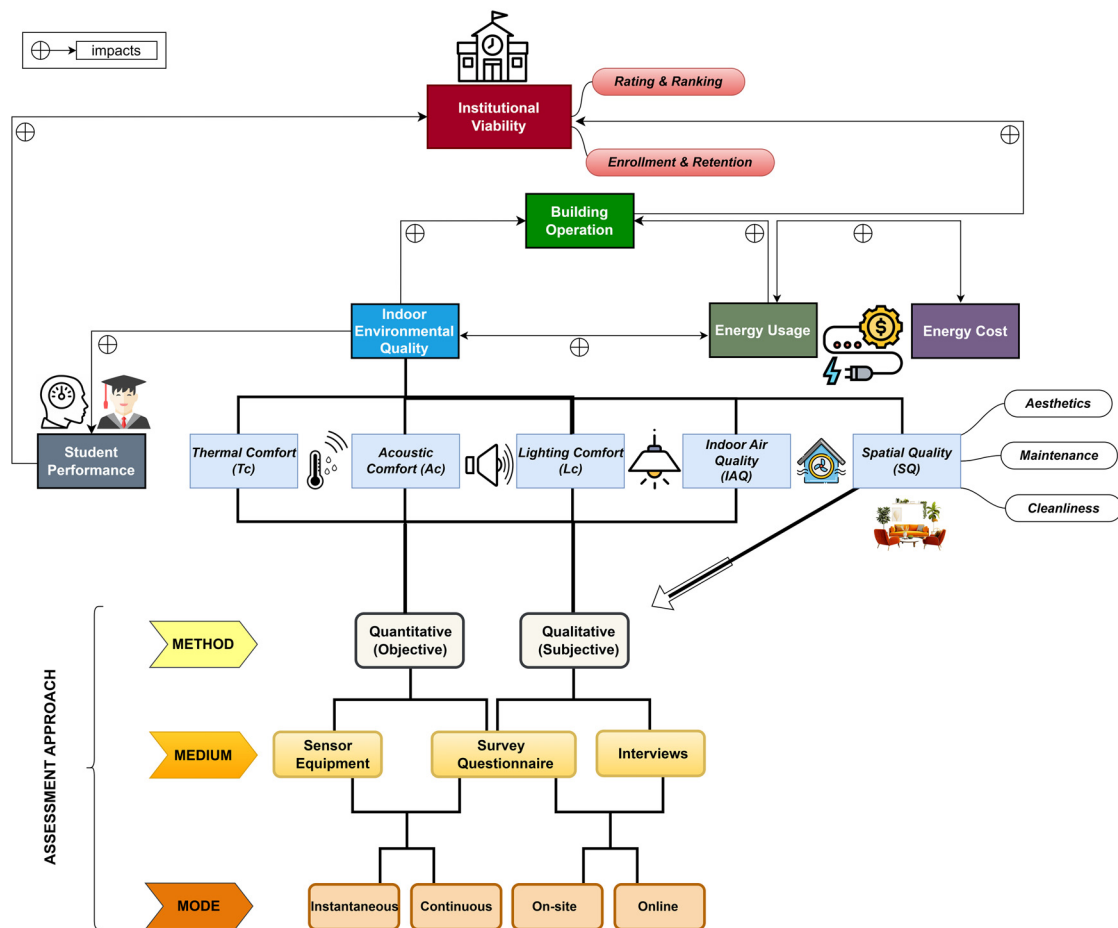


Fig. 1. Operational elements and impacts of buildings with assessment approaches.

weighting factors used in several case studies, stressing the uniqueness of buildings by type and occupant perceptions. Table 1 presents studies that have evaluated IEQ in university spaces; however, concurrent analysis of energy usage was rarely conducted.

Energy usage in university settings varies based on space design and functionality [37], with classrooms typically exhibiting higher occupant densities than dorm rooms. While research has tracked energy consumption in various climates [38,39], reports highlight that occupant behavior is critical, often highly variable among students [40]. Studies show that real-time energy monitoring and feedback can lead to significant reductions in consumption [41–43]. However, it is often difficult to live up to students' expectations of affordability and comfortability, while also remaining operationally efficient and financially viable as an institution [44].

As feedback to rising awareness about climate change, many universities have adopted or are considering green certifications [45], but achieving certification does not guarantee occupant satisfaction [46] or overall optimization of energy usage as recent case studies report mixed results. For example, Turner and Frankel [47] reported that LEED-certified buildings exhibit a 24 % lower energy usage intensity (EUI) compared to the national average. However, Vosoughkhosravi et al. [48] found that a LEED-certified RCB consumed more energy than non-certified counterparts but achieved higher occupant satisfaction with IEQ, with the former performing up to par with its certification score card.

Moreover, a recent study investigating green versus non-green buildings under current and future climate conditions reported that green buildings save 15.1 % of site energy under present conditions and up to 21.9 % under future scenarios [49]. Additionally, green buildings pro-

duced 15 % fewer greenhouse gas emissions under current conditions and up to 22 % fewer in future scenarios, while also prevailing with significantly higher thermal comfort levels.

A major limitation regarding the compared studies is either the failure to capture longitudinal field measurements (e.g., for weeks, non-stop) of indoor environmental conditions or evaluating energy performance in the studied buildings. This in turn leads to failure to adequately detect variations caused by changing weather conditions, occupancy patterns, and HVAC operational schedules which are important contributors to energy performance [50]. Besides, comparative assessments of LEED-certified and non-certified RCBs are rare, even within humid subtropical regions, as indicated in Table 1, necessitating further exploration.

Additionally, research reveals that energy utility bills strongly affect psychological, emotional, and physical well-being [51–53]. A study by Huh et al. [54] indicates that 59.4 % of building users express dissatisfaction with rising electricity costs, which directly influences occupant satisfaction and comfort. Although several studies address both energy efficiency and IEQ, these domains are largely explored independently. Even when examined together, they are rarely integrated into one comprehensive model, constraining a thorough understanding of how energy usage intersects with IEQ.

Few studies that have attempted such integration often fall short of a truly comprehensive approach. For example, Roumi et al. [55] developed a model to evaluate the cost-effectiveness of IEQ improvements relative to energy input but relied on expert opinions rather than direct occupant feedback. Similarly, Sun et al. [56] produced a matrix illustrating IEQ and energy usage in a hospital, yet their energy analysis only accounted for electricity consumption and excluded subjective evalua-

Table 1
Summary of published studies on IEQ evaluation in spaces within university settings.

Author	Space Type (No.)	Occupants Surveyed	Weighting Factor (W_x)				AT	Regional Climate	Energy Efficiency
			$\alpha = W_{IAQ}$	$\beta = W_{Tc}$	$\gamma = W_{Ac}$	$\delta = W_{Lc}$			
Tahsildoost and Zomorodian [29]	Classroom (9)	842	0.08	0.34	0.26	0.31	2 h ^a	Semi-arid	Evaluated
Mujan et al. [30]	Amphitheatre (1)	56	0.25	0.31	0.25	0.19	3 h	Temperate continental	Not evaluated
Leccese et al. [21]	Classroom (5)	1468	0.17	0.42	0.19	0.22	NOSS	Mediterranean	Not evaluated
Buratti et al. [31]	Classroom (7)	928	NWA	0.35	0.35	0.30	NOSS	Temperate continental	Not evaluated
Lee et al. [32]	Classroom (4); Lecture hall (4)	312	NWA	NWA	NWA	NWA	3 h 30 mins ^a	Humid subtropical	Not evaluated
Ricciardi and Buratti [33]	Classroom (7)	928	NWA	NWA	NWA	NWA	2 h ^a	Temperate continental	Not evaluated
Wang and Zamri [34]	Green educational building	179	0.27	0.16	0.19	0.19	NOSS	Humid subtropical	Not evaluated
Woo et al. [35]	Office (7) ^a	519	NWA	NWA	NWA	NWA	1 week ^a	Temperate oceanic	Not evaluated
Fassio et al. [36]	Classroom	17	0.12	0.30	0.28	0.30	2 h ^a	Mediterranean	Not evaluated

^a indicates that numeric value refers to building number, not spaces.

AT: maximum duration of uninterrupted data collection of environmental variables prior to any cessation.

NOSS: None; only subjective surveys.

NWA: No weight assigned.

^a indicates data collection periods spanning across different seasons or phases.

tions. These studies, while valuable, confirm the challenge of creating a holistic model that fully integrates IEQ and energy efficiency considerations. Accordingly, studies should integrate energy performance into IEQ as a single metric with both subjective and objective components. Such a model should be hinged on balancing trade-offs to maintain health and comfort without sacrificing sustainability.

This study aims to address some of the gaps in literature by investigating the operational performance of residential college buildings in a Louisiana university via IEQ and energy data. The main objectives are: (1) to ascertain the variations in hygrothermal conditions and air quality in several indoor residential college building spaces across two different seasons, (2) to explore the perceptions of building occupants and managers with respect to their satisfaction with IEQ and energy performance, respectively, (3) to compare and evaluate energy performance associated with RCBs, (4) to measure and compare building performance based on existing and proposed IEQ models, and (5) to evaluate the effectiveness of green certification on building performance. The results from this study would support recommendations that contribute to more sustainable student housing.

2. Methodology

The methodology consists of seven main steps: 1. Defining the climate of the study region, 2. Describing the buildings and study design, 3. Measuring environmental data using sensor devices, 4. Evaluating stakeholder perceptions of IEQ and energy performance, 5. Detailing the development and implementation of proposed IEQ model, 6. Describing the major IEQ and energy performance metrics adopted, and 7. Providing an overview of statistical resources employed for data analysis.

2.1. Climate of study region

Louisiana observes a humid subtropical climate, and the climatic conditions of the city of Baton Rouge generally vary seasonally. As in most regions in the United States, there are four major seasons observed in the city, annually [57]: the spring season often begins in March and last until May; the summer season mostly spans from June to August; the autumn season spans from September to November; and the winter season stretches from December to February. The daily mean outdoor ambient conditions [58] in Baton Rouge for a two-year period (April 2022 to

March 2024), are provided in Fig. 2. The year-over-year and month-to-month variations in external weather conditions can be attributed to climate change phenomena. Based on data retrieved from Wunderground [58], sourced from the weather station at Baton Rouge Metropolitan Airport, the months in Baton Rouge can be categorized into two predominant seasonal periods according to average hourly thermal conditions: the cool season, which spans from November to March, and the warm-hot season, which extends from April to October. In this study, the cool season is referred to as the heating season, emphasizing the increased use of indoor space heating due to cooler outdoor weather conditions, particularly during the winter months. Conversely, the warm-hot season is referred to as the cooling season, signifying the absence of heating requirements and the predominant reliance on indoor space cooling. During the study period, daily mean outdoor temperature and relative humidity ranged from 7.4 to 22.8 °C and 44.0–90.3 %, respectively, in the heating season, and 15.6–25.6 °C and 49.5–86.3 %, respectively, in the cooling season.

2.2. Building description and study design

This study examined eight RCBs at a Louisiana university, characterized by predominantly thick concrete envelopes, housing several spaces including dorm rooms, mini-libraries, conference rooms, and lounges. Table 2 provides detailed information about each building, including gross square footage (GSF), year of construction, number of dorm rooms (which are predominantly configured as either two-bed or four-bed occupancy spaces), floor levels, occupant capacity, dormitory type, and whether classrooms are present within the RCBs. Schematics illustrating both traditional and suite-style dormitory layouts are provided in Appendix A.

The buildings are categorized as follows: Old NL (non-LEED-certified, older construction), LEED (LEED Silver-certified, originally LEED BD+C: NC, v3, last certified in February 2021 with a score of 51/110, excelling in Sustainable Site (76.9 %), Indoor Environmental Quality (60 %), and Water Efficiency (60 %)), Modern NL (modern, non-LEED-certified building), and five additional non-LEED-certified buildings, referred to as Other NL I to Other NL V. Notably, Other NL I and Other NL II share a common lobby-lounge with a front desk but maintain separate energy-metering systems. Since their construction, most buildings have undergone at least one major renovation.

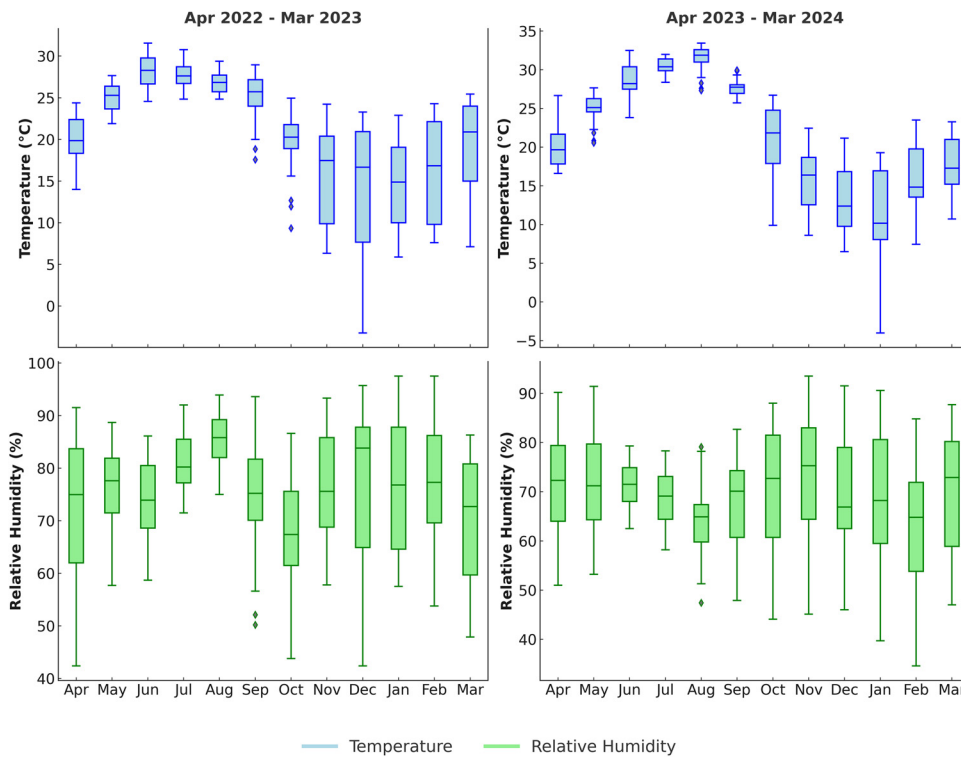


Fig. 2. Daily mean outdoor environmental conditions of Baton Rouge, Louisiana.

Table 2
Summary of investigated buildings.

Building ID	Gross Square Footage	Year Built	Floor Levels	Dorm Rooms	Capacity	Dormitory Type	Classroom
Old NL	102,129	1964	6	218	440	Traditional	Absent
Modern NL	67,695	2008	4	117	220	Suite Style	Present
LEED	109,446	2015	4	176	330	Suite Style	Present
Other NL I	91,071	1949	3	134	300	Traditional	Absent
Other NL II	81,900	1950	3	134	300	Traditional	Absent
Other NL III	48,825	1941	5	90	200	Traditional	Absent
Other NL IV	189,550	2006	3	186	490	Traditional	Absent
Other NL V	127,523	2021	5	208	400	Suite & Traditional	Present

All the buildings utilize mechanical systems for space cooling and heating. However, centralized air-conditioning systems with individual room controls are employed in each of LEED, Modern NL, Other NL I, Other NL II, and Other NL V buildings. Dorm rooms in LEED, Modern NL, and Other NL V are equipped with energy-efficient windows and blinds, while the remaining buildings use standard windows with blinds. Lighting, with motion sensors in common spaces, in all buildings is predominantly fluorescent, though there are plans to transition fully to LED lighting in the future.

Operational performance was assessed through energy use data, indoor environmental monitoring, and stakeholder surveys evaluating IEQ and energy utility satisfaction. Comparative analysis was conducted across the buildings. However, energy performance could not be evaluated for Other NL V due to inaccessible utility data.

For physical measurements on indoor environmental conditions, Old NL, Modern NL, and LEED buildings were selected based on their availability, accessibility, and relevance to a pilot comparison between pre-millennium and post-millennium RCBs within the university. In each of these buildings, two dorm rooms (coded A and B, respectively) and one corridor space (coded C) were monitored. The locations of these monitored spaces were as follows:

- **Old NL:** Room A (first floor), Room B (third floor), Corridor C (first floor)

- **Modern NL:** Room A (third floor), Room B (fourth floor), Corridor C (third floor)
- **LEED:** Room A (second floor), Room B (second floor), Corridor C (first floor)

The dorm rooms across the three buildings varied in both floor area and window size. Old NL rooms averaged 220 square feet, with a single window area of approximately 24.7 square feet. Modern NL featured larger rooms, averaging 305 square feet with window areas of around 21.3 square feet. In the LEED building, rooms had an average floor area of 290 square feet and window areas of approximately 27.8 square feet.

2.3. Sensor deployment

Low-cost, portable, real time, datalogging sensor devices with characteristics detailed in Table 3 were used for this study. Hygrothermal-IAQ sensor devices were installed at heights approximating the breathing zone of seated occupants in selected dorm rooms and at various heights on a surface or wall in corridor spaces to conduct long-term physical measurements.

The sampling frequency was set to 30-minute intervals, with continuous data collection conducted over 28 days during two periods: January 26, 2024, to February 22, 2024, representing the heating season,

Table 3
Information on sensor devices used for field measurements.

Device Weight	Device Price	Make	Device Dimension (mm)	Sensor Type	Measuring Range	Accuracy	Operation Environment
228 g	~\$200	Temtop M2000 2nd	223 × 73.5 × 37.5	Temperature sensor	0–50 °C	±1 °C	0–50 °C
				Humidity sensor	0–99.9 % RH	±5 % RH	0–90 % RH
				Laser PM sensor	0–999 µg/m ³	±10 µg/m ³	1 atm
				Non-Dispersive Infrared (NDIR) CO ₂ sensor	0–5000 ppm	±5 % ±50 ppm	
				Electrochemical HCHO sensor	0–2 mg/m ³	±0.03 mg/m ³	
489 g	~\$250	REED R8100SD	117 × 68 × 45	Photo diode & color correction filter	1–100,000 lx	±(4 % + 2 lx)	0–50 °C
							10–80 % RH
320 g	~\$400	REED R8070SD	245 × 68 × 45	Electret condenser microphone	30–130 dB	±3.0 dB - ±5.0 dB	0–50 °C
							0–85 % RH



Fig. 3. Example field measurement setups for hygrothermal-IAQ (left two images) and lighting and acoustic assessments (right two images). The rightmost image depicts a corridor space, while the remaining images show dorm rooms.

and April 5, 2024, to May 2, 2024, representing the cooling season. Both periods started on a Friday and ended on a Thursday.

Lighting (with ceiling lamps turned on) and acoustic measurements were taken once, instantaneously, and quasi-concurrently at the center of the monitored spaces. Devices were mounted on a tripod at a height of 75 cm for rooms and 155 cm for corridor spaces, reflecting conditions for standing or walking occupants, as these spaces are primarily traversed rather than used for seated activities. These measurements were conducted on the final day of the de-installation of the hygrothermal-IAQ devices.

For corridor spaces, caution notices were affixed to walls near the hygrothermal-IAQ devices to notify passersby of the ongoing research. Fig. 3 depicts example data collection scenarios, including a researcher in the field. Fig. 4 illustrates the schematic layout of a typical dorm room configuration used in the study, highlighting the representative placement of sensor devices in Rooms A and B across all buildings.

2.4. Survey distribution

2.4.1. Occupant satisfaction survey

With the assistance of the university housing administrative staff, survey questionnaire (**Appendix B**) modified from widely adopted templates from the database of the Center for the Built Environment (CBE) [59], was distributed electronically via Qualtrics to building occupants. The survey was open for response collection for six weeks. Reminder emails were sent once weekly, four times consecutively to the rest of the population of 2720 recipients yet to begin or finish up, but only 401 valid completions were finally analyzed. Using the Yamane formula

[60], the final sample size is above the minimum threshold for the general population of occupants. Meanwhile, users of Other NL I and Other NL II were unified inadvertently at the questionnaire distribution stage. Therefore, for the analysis of IEQ satisfaction, the two buildings are subsequently reported as Other NL I & II. This oversight makes the combination have the largest pool of participants ($n = 118$). The rest are 39 participants for LEED, 62 for Old NL, 31 for Modern NL, 31 for Other NL III, 64 for Other NL IV, and 56 for Other NL V.

The questionnaire emphasized the following: residence hall and weekly occupancy, ratings of each IEQ factors and overall experience, seasonal thermal sensation, discomfort issues, IEQ impacts on well-being and productivity, and an optional free text section for further comments and suggestions. To garner satisfaction ratings, a range of five responses (“Very Dissatisfied” to “Very Satisfied”) was used, whereas a 7-point scale with a latent range of −3 (extremely cold) to +3 (extremely hot) was used to stringently determine the thermal sensation of occupants during heating and cooling seasons.

2.4.2. University housing staff

Questionnaires—embedded with bar charts comparing season-based energy usage and associated costs for each building—were electronically distributed via Qualtrics to five university housing staff members. These individuals also served as key contacts for follow-up inquiries regarding the operation of the study buildings. Among the respondents were two directors, one supervisor, and two administrators. One director had over 15 years of experience in both the university housing office and their current role, while the other director had been in the position for less than a year. The supervisor and one of the administrators each

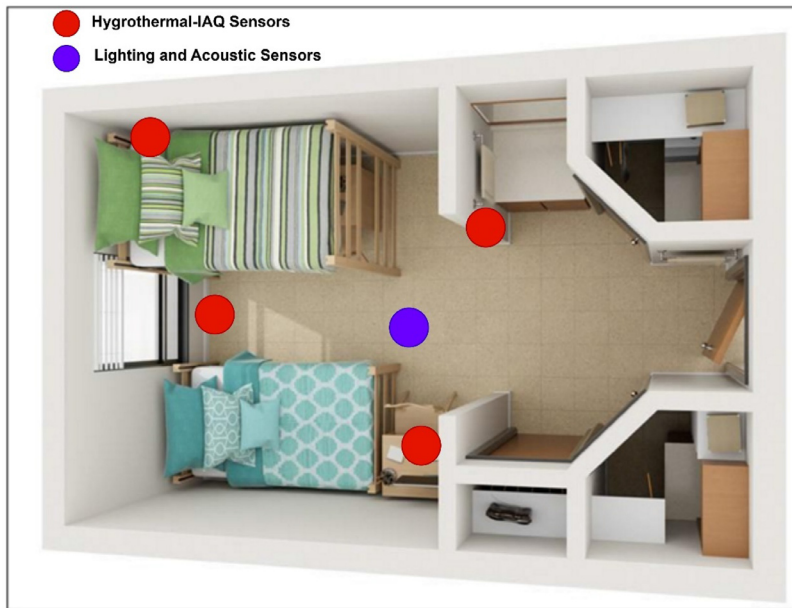


Fig. 4. Schematic of a typical dorm room layout with sensor placement overlay.

had approximately five years of relevant experience, while the second administrator had about ten years of experience in university housing and in their current role.

The diversity of roles and the collective experience of these staff members contributed to the reliability and depth of operational insights provided. Two fundamental questions were included in the questionnaire to assess their satisfaction with energy usage and cost during the heating season compared to the cooling season. Responses were captured using a Likert scale. As explained in Section 2.5.1, a positive response was ideally expected in cases where total energy consumption during the heating season was lower than that of the cooling season, regardless of building type.

2.5. Proposed model development and application

2.5.1. The extended IEQ model

In Louisiana and similar regions across the United States, historical data and climate model projections consistently show that significantly more energy—and, consequently, more money—is expended in both residential and commercial settings during the cooling season to meet indoor cooling demands [61–64]. This is largely due to the long, hot humid summer months, as opposed to the heating season, which is characterized by shorter, milder winters. This suggests that energy efficiency in a building is met when the average consumption in the heating season is lower than the average consumption in the cooling season.

Following preliminary consultations with building science and environmental policy experts—whose combined professional experience spans approximately 40 years—a scale for assessing Energy Utility Quality (EUQ) was developed to evaluate building energy efficiency. This EUQ scale is presented in Table 4. It covers a spectrum of extreme inefficiency to extreme efficiency. Higher levels of efficiency correspond with the paradigms in top-performing certified green buildings. For instance, studies show that LEED-certified buildings achieve 20–30 % energy savings on average compared to non-LEED-certified buildings [65–67], resulting in lower operational costs over time. The EUQ is computed using Eq. (2), where E_{HS} and E_{CS} represent average energy consumption in the heating and cooling seasons, respectively.

$$EUQ = \frac{E_{HS} - E_{CS}}{E_{CS}} \times 100\% \quad (2)$$

A positive EUQ value indicates higher energy consumption during the heating season compared to the cooling season, whereas a nega-

Table 4

Energy Utility Quality (EUQ) score scale.

Performance score	Measurement	Explanation
10	$\geq +20\%$	Highly Inefficient
20	$+15.0\%$ to $+19.9\%$	Very Inefficient
30	$+10.0\%$ to $+14.9\%$	Inefficient
40	$+5.0\%$ to $+9.9\%$	Slightly Inefficient
50	-4.9% to $+4.9\%$	Quasi-Neutral
60	-5.0% to -9.9%	Slightly Efficient
70	-10.0% to -14.9%	Efficient
80	-15.0% to -19.9%	Very Efficient
90	-20.0% to -24.9%	Highly Efficient
100	$\leq -25.0\%$	Extremely Efficient

tive value suggests greater efficiency during heating periods and potentially a higher level of climate resilience for the building. A quasi-neutral range, defined as -4.9% to $+4.9\%$, reflects a balanced energy use between the two seasons.

The extended IEQ model, herein referred to as Sustainable Indoor Environment Quality (IEQs), integrates EUQ as a fifth component. It is defined in Eqs. (3) and (4) as follows:

$$IEQs = IEQ + EUQ \quad (3)$$

such that:

$$IEQs = (\alpha \times IAQ) + (\beta \times Tc) + (\gamma \times Ac) + (\delta \times Lc) + (\epsilon \times EUQ) \quad (4)$$

where ϵ represents the weighting factor for EUQ.

2.5.2. Implementation steps

The following steps, including data collection, weighting factors, and analysis and evaluation, detail the implementation of the extended IEQ model. Fig. 5 summarizes the steps. The model attempts to offer significant advantages over existing IEQ models, by ensuring that energy costs and their impacts on stakeholders are adequately considered.

(a) Data Collection

Energy utility data covering April 2022 to April 2024 were collected from the university housing operations office, but the data for the periods, April 2024 to March 2024 were employed for EUQ computation,

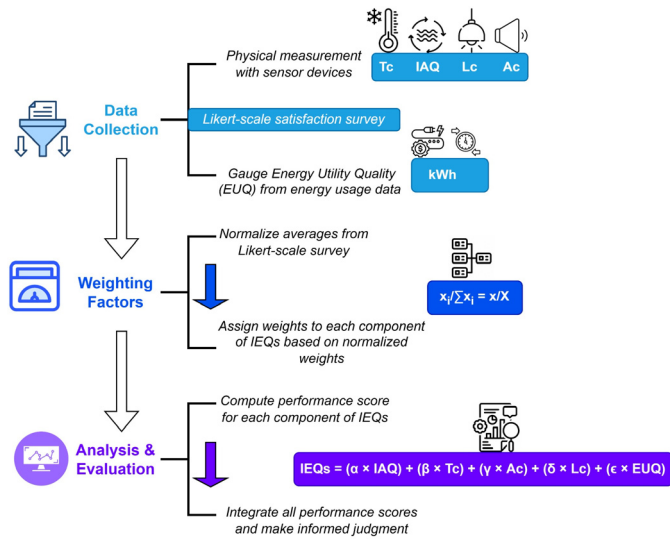


Fig. 5. Steps for implementing the extended IEQ model.

with averages of the months of November 2023 to March 2024 (heating season) compared against the averages of the months of April 2023 to October 2023 (cooling season).

The objective measurements of the 4CCs were carried out, modifying steps reported in Mujan et al. [30], summarized in Eqs. (5) to (14). Tc is often computed by researchers using metrics such as Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfied with the thermal conditions (PPD_{Tc}) [68]. PMV involves measuring environmental variables such as air temperature, radiant temperature, relative air velocity, and air humidity, as well as personal variables such as clothing insulation and metabolic rate. These variables are often computed based on Fanger's [69] comfort model. The PMV model predicts the average thermal sensation of a large group of people on a scale from −3 (cold) to +3 (hot), with 0 being neutral, and −0.5 to +0.5 being the optimum. The PPD_{Tc} is derived from the PMV and indicates the percentage of people likely to feel thermally uncomfortable, as represented in Eq. (5). Although Tc performance can be calculated from Eq. (6), we simply utilized the Tc software [70] developed by the researchers at the Centre for the Built Environment (CBE) by inputting the relevant values for the different parameters.

$$PPD_{Tc} = 100 - 95 \cdot \exp(-0.03353 \cdot PMV^4 - 0.2179 \cdot PMV^2) \quad (5)$$

$$Tc = 100 - PPD_{Tc} \quad (6)$$

The software is optimized to adhere to the latest version of ASHRAE Standard 55. The air temperature averaged at the end of each seasonal data collection period also represented the mean radiant temperature, thereby serving as the operative temperature in each building space. For the cooling season, 0.5 clo for dorm rooms and 0.54 clo for the corridors were used as the clothing insulation while 0.9 clo was used for the heating season in conformance with observations and existing literature [71]. Air velocity was assumed to be 0.15 m/s for all buildings throughout the study period [72]. We used 1.0 met and 1.2 met as metabolic rates for occupants in the dorm rooms and corridors, respectively, based on the range of predominant activities (e.g., eating, reading, sitting, and sleeping in dorm rooms, and ephemeral standing and sitting in corridor spaces) estimated to play out in those environments [73].

IAQ performance stems from the computed mean values of the performance indices of three main pollutant indicators (I_x , where $x = CO_2$, HCHO, $PM_{2.5}$), mostly emphasized in several green building schemes. The normalization procedures are presented in Eqs. (7) to (10).

$$IAQ = \text{mean}(I_{CO_2}, I_{HCHO}, I_{PM_{2.5}}) \quad (7)$$

$$I_{CO_2} = 100 - 70 \cdot \log \frac{C_{CO_2}}{C_{atm}} \quad (8)$$

$$I_{HCHO} = \begin{cases} 0, & \text{if } C_{HCHO} \geq 0.007 \\ 100 - 118 \cdot \log \frac{C_{HCHO}}{0.001}, & \text{if } C_{HCHO} < 0.007 \end{cases} \quad (9a)$$

$$I_{HCHO} = \begin{cases} 0, & \text{if } C_{HCHO} > 0.1 \\ 100 - 50 \cdot \log \frac{C_{HCHO}}{0.001}, & \text{if } C_{HCHO} \leq 0.1 \end{cases} \quad (9b)$$

$$I_{PM_{2.5}} = \begin{cases} 100, & \text{if } C_{PM_{2.5}} \leq 10 \\ 100 - 85 \cdot \log \frac{C_{PM_{2.5}}}{10}, & \text{if } C_{PM_{2.5}} > 10 \end{cases} \quad (10)$$

These indices are based on a logarithmic scale. For example, an upper limit of 15,000 ppm for CO_2 is established where $\log \frac{C_{CO_2}}{C_{atm}}$ denotes the logarithmic ratio of CO_2 concentration (in ppm) to the outdoor concentration of 415 ppm adopted (Eq. (8)). The U.S. EPA [74] noncancer reference concentration (RfC) for long-term exposure—0.007 mg/m³ HCHO—was applied as the threshold for dorm rooms (Eq. (9a)), while the WHO [75] short-term exposure guideline of 0.1 mg/m³ was used to indicate the permissible limit of HCHO in the corridors (Eq. (9b)). For $PM_{2.5}$, values at or below 10 µg/m³ as per WHO recommendations [76] were considered optimal, while values above underwent logarithmic adjustment (Eq. (10)). C_{HCHO} represents the concentration of formaldehyde measured in mg/m³ while $C_{PM_{2.5}}$ represents concentration of particles smaller than 2.5 measured in µg/m³.

Eq. (11) pertains to the illuminance (LX) at 140–1400 lx, the lower limit below the acceptable illuminance (200 lx) for visual comfort with respect to simple tasks [77–79]. It is based on a developed regression model associated with case studies reported in Refs. [80] and [81]. The derived numerical value is then subtracted from 100 to denote the percentage of people comfortable with the lighting condition in the building, according to Eq. (12).

$$PPD_{Lc} = \frac{100}{1 + \exp(-1.017 + 0.00558 \cdot LX)} \quad (11)$$

$$Lc = 100 - PPD_{Lc} \quad (12)$$

In Eq. (13), the sound levels (SLs) in both actual conditions and the design room conditions, while measured in decibels (dB), are differentiated and doubled, with the resulting value subtracted from 100 in Eq. (14), to determine the degree of acoustic comfort by percentage. Both equations are derived from Refs. [82] and [83]. In line with acceptable room sound levels derived from ANSI S12.2 (American National Standard Criteria for Evaluating Room Noise) [84], 40 dB and 45 dB were used as the design conditions for dorm rooms and corridors, respectively.

$$PPD_{Ac} = 2 \cdot (\text{Actual SL} - \text{Design SL}) \quad (13)$$

$$Ac = 100 - PPD_{Ac} \quad (14)$$

PPD_{Lc}, and PPD_{Ac} represent the predicted percentage of occupants dissatisfied with lighting, and acoustic conditions, respectively. Tc and IAQ performances for both heating and cooling seasons were computed and averaged to each have a single performance value.

(a) Weighting Factors

For each component of the IEQs, including the 4CCs and the EUQ, the average satisfaction score based on the survey responses was calculated. The weighting factors were determined by normalizing the average satisfaction scores (i.e., the percentage vote) associated with each of the subjective 4CCs and EUQ, ensuring that the sum of all weights equals 1. The normalized weight was calculated using the following equation:

$$W_i = \frac{AS_i}{\sum AS} \quad (15)$$

where W_i is the normalized weight for the i th factor, AS_i is the average score for the i th factor, and $\sum AS$ is the sum of all average scores.

(a) Analysis and Evaluation

Performance scores derived from measuring and scaling the five factors were calculated and integrated to derive a single value for the IEQs, ranging from 0 % to 100 %. The value conforms to pre-determined performance packet of scores, aiding in making an informed judgement on the qualitative status of the built indoor environment.

2.6. Major performance metrics

2.6.1. Comparative IEQ metrics

This study adopted four distinct performance metrics to evaluate overall IEQ in the studied buildings, derived from four models: IEQp, IEQo, IEQc, and the proposed IEQs. The performance results derived from the proposed IEQs model were compared with those from the three other IEQ models.

The IEQp model is perception-based, relying exclusively on the mean values derived from subjective satisfaction responses regarding IEQ factors, expressed as a percentage. This model focuses solely on subjective assessments via occupant surveys and does not incorporate physical, sensor-based measurements of the indoor environment.

The IEQo model is entirely objective, averaging the performances of the 4CCs based on Eqs. (5) to (14). It assumes equal weighting, which aligns with emphasis made by Piasecki et al. [24] regarding simplicity and equity across different IEQ components and building types.

The IEQc model integrates subjective occupant feedback with sensor-based objective measurements, employing variable weightings for the 4CCs. In this model, weighting factors using the formula in Eq. (15)—denoted as α , β , γ , and δ —are applied to objective performance of IAQ, Tc, Ac, and Lc, respectively, as defined in Eq. (1), and supported by Eqs. (5) to (14). In short, this conventional model emphasizes subjective-objective IEQ performance without the consideration of an energy-related variable.

To facilitate interpretation, a tiered evaluation system was employed to categorize IEQ scores into three performance levels:

- **Subpar:** $0 \% \leq IEQ \leq 50 \%$
- **Acceptable:** $50 \% < IEQ \leq 75 \%$
- **Optimal:** $75 \% < IEQ \leq 100 \%$

2.6.2. Energy performance metrics

For energy performance, this study employed the traditional, annual Energy Use Intensity (EUI) metric [85], supplemented with monthly EUI assessments to account for intra-annual trends. To provide deeper insights into seasonal performance variations and overall building efficiency, the Energy Utility Quality (EUQ) metric was used in tandem with the interpretation presented in Table 4.

2.7. Data analysis and statistical resources

Meticulous cross-checking of datasets was performed throughout the cleaning, exploration, exporting, and importing processes to ensure data integrity. EUI was calculated using standard conversion factors [86–88], ensuring consistency across measurements. Total energy consumption per annum is expressed in MWh. Annual EUI is reported in kBtu/sf. Monthly EUI is expressed in kWh/sf ($1 \text{ kWh/sf} \approx 10.764 \text{ kWh/m}^2$). Carbon emissions are expressed in lbs of CO_2 , while annual emission intensity is reported in lbs of CO_2 /sf ($1 \text{ lb/sf} \approx 4.882 \text{ kg/m}^2$).

In 2022, the emission rate of electricity supplied by the major utility provider in Louisiana (Entergy) was 743 lbs of CO_2 /MWh. In 2023, it was 766 lbs of CO_2 /MWh. Therefore, total equivalent carbon emissions were computed by multiplying the annual total energy consumption by the respective emission rate.

Data analyses were performed using Python and Excel environments to compare IEQ parameters, occupant satisfactions, and energy performance. Statistical analyses included Pearson's correlation, regression, and nonparametric tests viz Kruskal–Wallis test, Mann–Whitney U test, Wilcoxon signed-rank test, and Chi-square Test of Independence, to evaluate relationships and the significance of differences among variables.

3. Results

This section presents the findings from the study, focusing on IEQ and energy performance in the investigated RCBs. The results are structured to highlight subjective and objective evaluations of IEQ, including satisfaction votes, physical measurements, and integrated assessment metrics (IEQc and IEQs). Key discomfort factors and occupant satisfaction with overall building experiences are analyzed. Energy performance is reported through EUI and EUQ, alongside results on energy satisfaction. These findings provide a comprehensive overview of building performance, linking environmental quality and energy efficiency.

3.1. Indoor environmental quality

3.1.1. Satisfaction votes and subjective IEQ

The varied satisfaction levels of occupants across the RCBs for different IEQ factors are illustrated in Fig. 6. Among the factors assessed, natural lighting consistently received the highest positive satisfaction levels, while acoustics had the lowest satisfaction across all buildings. Results from Kruskal–Wallis test revealed statistically high significant differences in occupant satisfaction for most IEQ factors across buildings ($p < 0.001$), with the exception of acoustics, which showed a significant difference ($p = 0.002$).

The subjective performance of the 4CCs based on mean responses indicated that Modern NL outperformed all other buildings in thermal comfort, achieving 85.2 %, followed by Other NL IV (80.3 %) and Other NL V (81.1 %). Old NL exhibited the lowest performance in thermal comfort with a score of 63.5 %, while Other NL III (74.8 %), LEED (75.9 %), and Other NL I & II (77.5 %) were intermediately positioned. Similar rankings were observed for positive thermal satisfaction, except for a position swap between LEED and Other NL III.

For lighting comfort, which was assessed based on satisfaction with both natural and artificial lighting, Other NL V (85.0 %) and LEED (82.1 %) outperformed other buildings. Modern NL (78.7 %) and Other NL I & II (76.5 %) followed, while Old NL (68.4 %), Other NL III (70.6 %), and Other NL IV (63.5 %) scored lower. Acoustic comfort results were less variable, with most buildings scoring in the sixties, except for Other NL I & II (72.4 %) and Old NL, which had the lowest performance at 57.4 %. For indoor air quality, Other NL V scored the highest at 81.8 %, followed by Modern NL (76.8 %) and LEED (72.8 %). Old NL again performed the worst, scoring 54.5 %, with the other buildings scoring in the sixties.

Overall, the subjective IEQ performance (IEQp) ranked the buildings as follows: Other NL V (78.2 %) > Modern NL (77.4 %) > LEED (74.1 %) > Other NL I & II (72.7 %) > Other NL IV (70.9 %) > Other NL III (70.4 %) > Old NL (61.0 %). Across all buildings, satisfaction with air quality correlated most strongly by satisfaction with other IEQ factors ($0.40 \leq r \leq 0.43$), followed by satisfaction with natural and artificial lighting ($r = 0.40$).

Across all buildings and based on the overall sample population, 26 respondents did not indicate thermal sensation votes (TSV) for the heating season, while 48 respondents did not indicate votes for the cooling season. This resulted in 72 instances where TSV during both seasons were concurrently absent. Despite this, 67 % of occupants reported being thermally comfortable (i.e., voted neutral thermal sensation) apropos of the heating season, and 61 % indicated comfortable TSV during the cooling season. Notably, only 42 % of occupants felt thermally comfortable across both seasons.

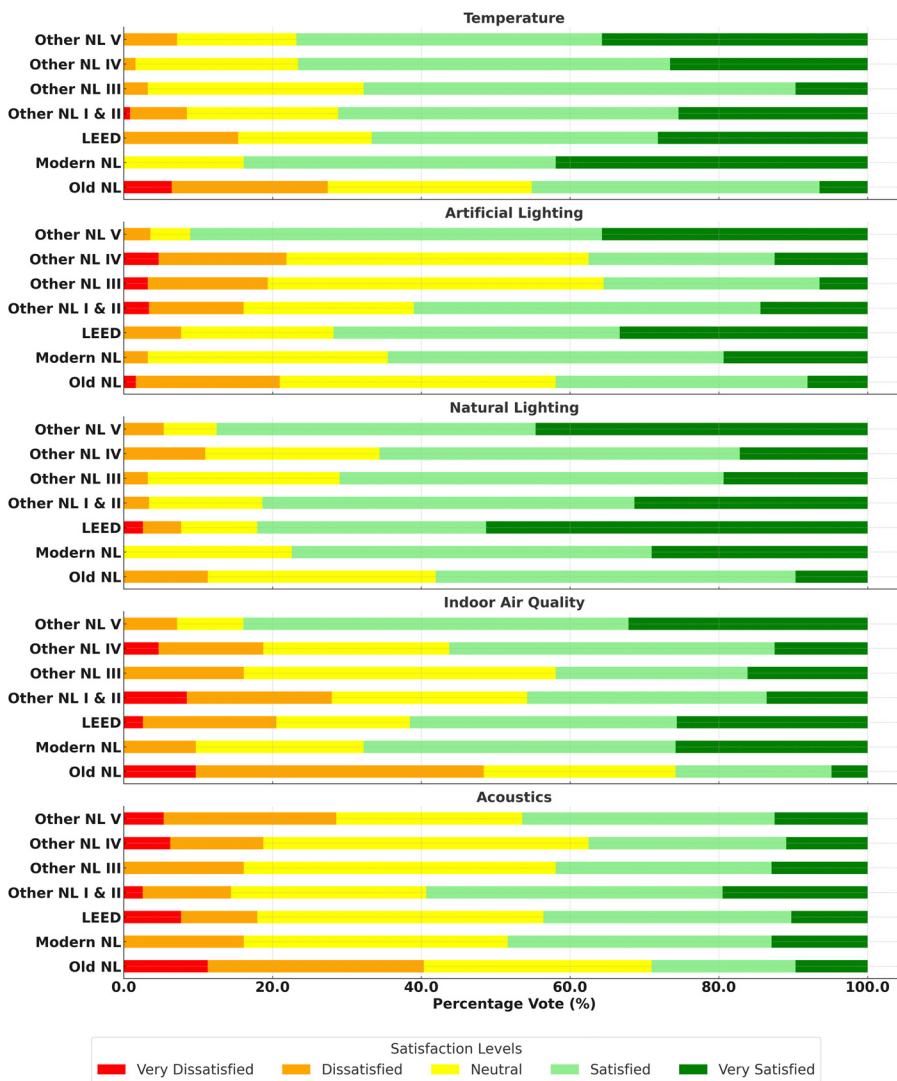


Fig. 6. Satisfaction levels across IEQ factors and buildings.

The voting pattern, summarized in Fig. 7, shows Modern NL emerging as the top performer with 70.0 % and 82.8 % comfortable TSV in the heating and cooling seasons, respectively. Other NL IV followed with 62.9 % and 73.3 % for the respective seasons. In contrast, Old NL consistently performed the lowest, with percentage comfortable TSV in the forties.

By averaging the TSV across seasons and comparing them to average PMV values, the following trends emerged: Old NL recorded a TSV of 0.22 in the heating season and -0.22 in the cooling season; Modern NL had TSVs of zero and 0.20, respectively; and LEED showed higher TSVs of 0.49 and 0.47 for the respective seasons. These results suggest that PMV overstates coolness in Old NL across both seasons. In Modern NL and LEED, PMV overstates coolness during the heating season and understates warmth during the cooling season.

Besides, occupant discomfort factors varied across the buildings, with issues such as foul odors, excessive noise, dirty or unclean areas, and poor ventilation emerging as the most common concerns. Nonetheless, specific complaints varied by building. In Old NL, structural and maintenance issues dominated, including thin walls that exacerbated noise pollution, malfunctioning AC systems, and mold growth. Modern NL had complaints about loud neighbors, marijuana smells, and high humidity levels. LEED occupants cited noise from neighboring rooms, inadequate water pressure, and limited control over room temperatures. For example, a respondent wished they “could all control the temper-

atures of their rooms at night.” Other NL I & II experienced a range of complaints, such as loud ventilation systems, ant infestations, and inconsistent room temperatures. In Other NL III and Other NL V, complaints centered on pests, disruptive noise, and uneven heating, while occupants in Other NL IV reported loud HVAC systems, excessively bright LED lights causing headaches, and plumbing issues. Issues with air freshness or odors were indicated by 56.5 % ($n = 32$) of occupants in Old NL, 38.7 % ($n = 12$) in Modern NL, 23.1 % ($n = 9$) in LEED, and at least 16.1 % in each Other NL.

Despite these discomfort factors, 41.1 % of the sampled population indicated that IEQ positively impacted their well-being and productivity, while 9.5 % reported a negative impact, with the remainder being neutral. Among those who reported positive impacts, satisfaction with natural lighting was the highest (85.6 %), followed by thermal satisfaction (83.2 %), while other factors ranged from 71.9 % to 79.3 %. For respondents indicating negative or neutral impacts, natural lighting still had the highest satisfaction, while air quality had the lowest rate. These variations are illustrated in Fig. 8.

Furthermore, satisfaction with overall building experience varied significantly across the buildings. Positive satisfaction rates were highest in Other NL V (94.6 %), Modern NL (87.1 %), and LEED (82.1 %), while Old NL recorded the lowest satisfaction at 41.9 %. Although most respondents occupied the buildings for six to seven days per week, the least reported frequency was one day per week. A Chi-Square Test of

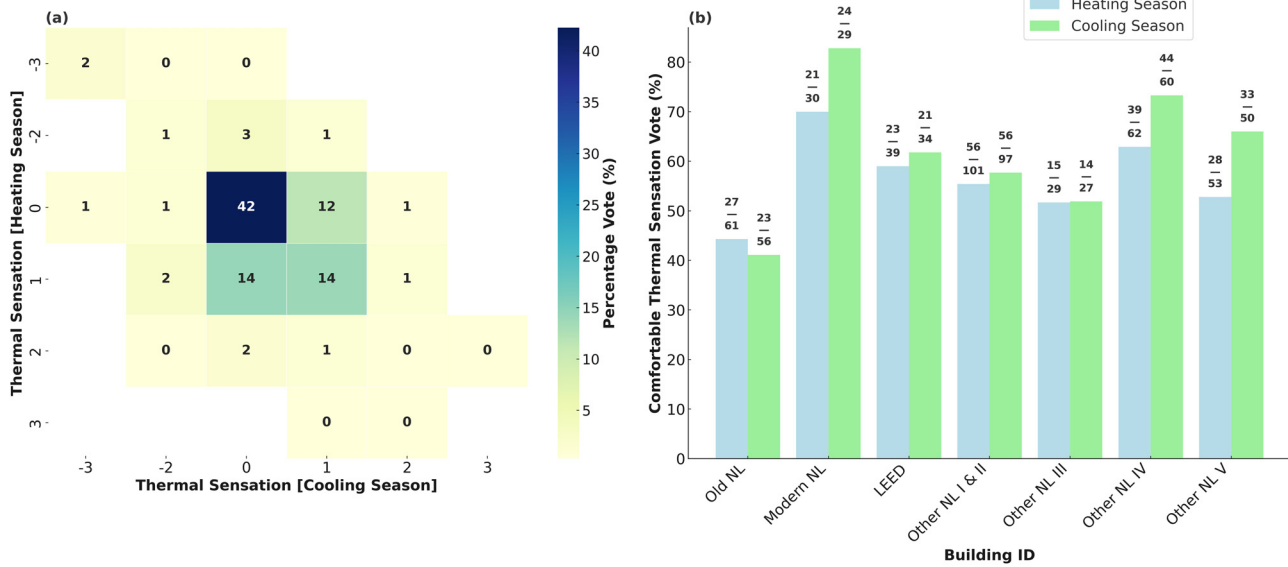


Fig. 7. Thermal sensation votes: (a) Overall distribution across buildings and (b) Specific voting pattern by building.

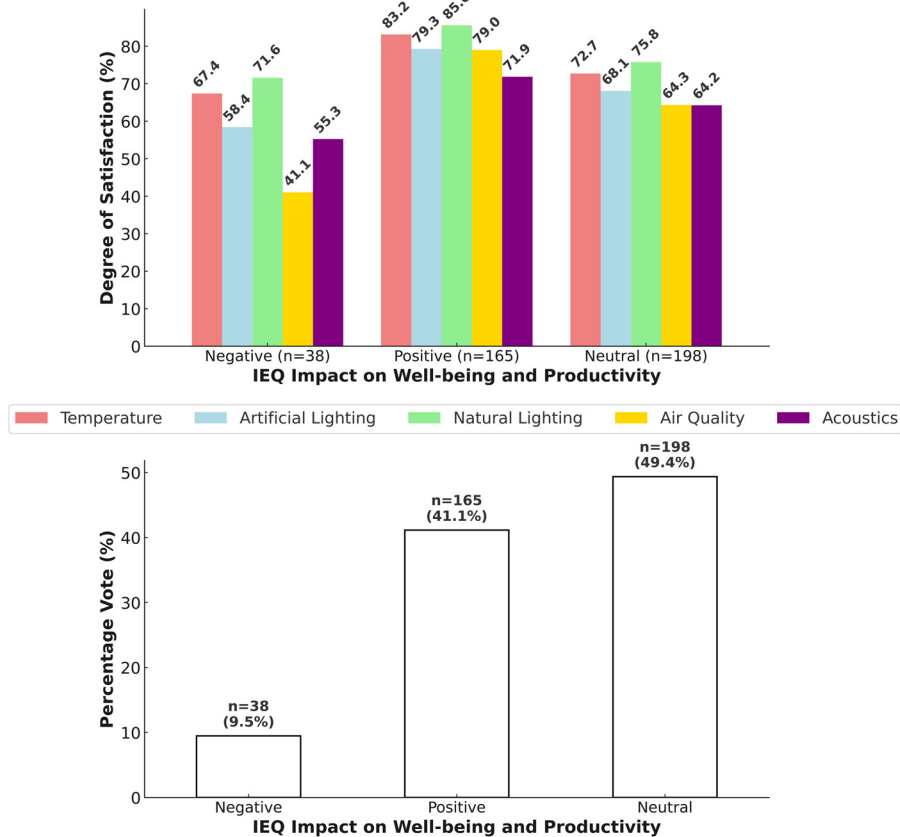


Fig. 8. IEQ impact analysis: Degree of satisfaction across IEQ factors and perceived impact on well-being and productivity.

Independence was conducted to assess whether weekly occupancy frequency and satisfaction with overall experience in the building were associated. Significant associations were found only for Old NL ($\chi^2(12) = 21.49, p = 0.04 < 0.05$), while no significant associations were observed for the other RCBs ($0.37 \leq p \leq 0.82$).

3.1.2. Summary of physical measurements of hygrothermal conditions and indoor air quality

As previously mentioned, the monitored spaces in Old NL, namely Old NL A, Old NL B, and Old NL C, were examined for indoor air quality

and hygrothermal conditions during both heating and cooling seasons. Similar assessments were conducted for corresponding spaces in Modern NL and LEED buildings. Figs. 9 and 10 summarize the findings for temperature, relative humidity, formaldehyde, and CO₂ concentrations using boxplots, with green dots representing the means and gold lines indicating the medians. A summary of hygrothermal conditions across spaces is also provided in Appendix C.

The mean levels of PM_{2.5} across both seasons ranged from 2.5 µg/m³ to 10.6 µg/m³, with only Modern NL C exceeding WHO guideline during the heating season. Similarly, formaldehyde levels ranged from

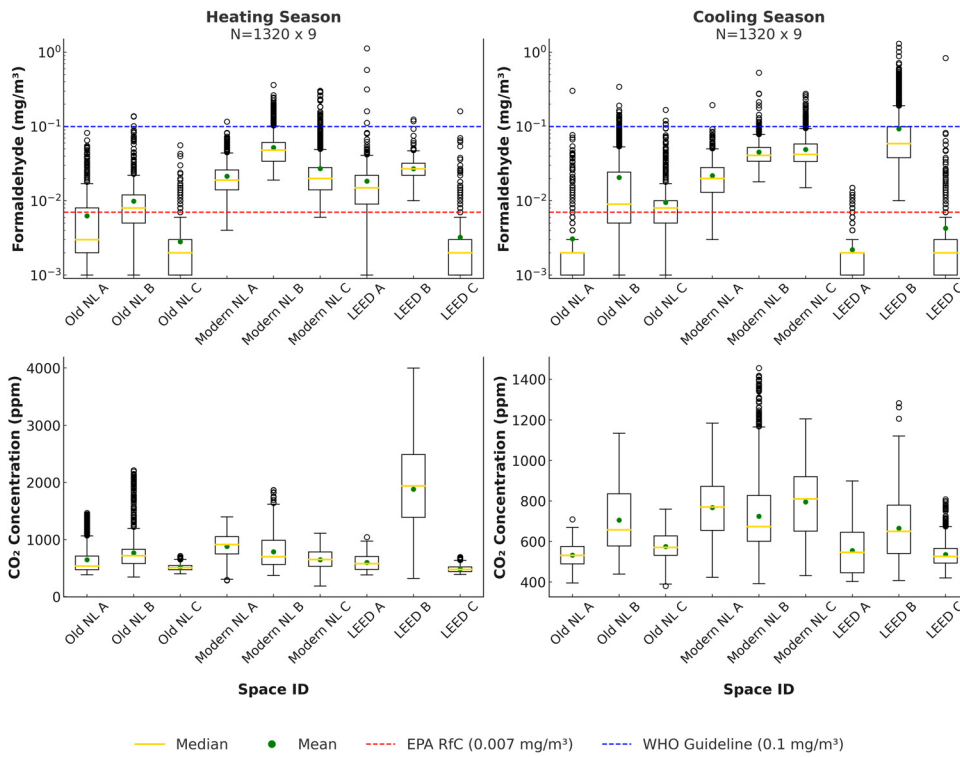


Fig. 9. Summary of air quality measurements across building spaces.

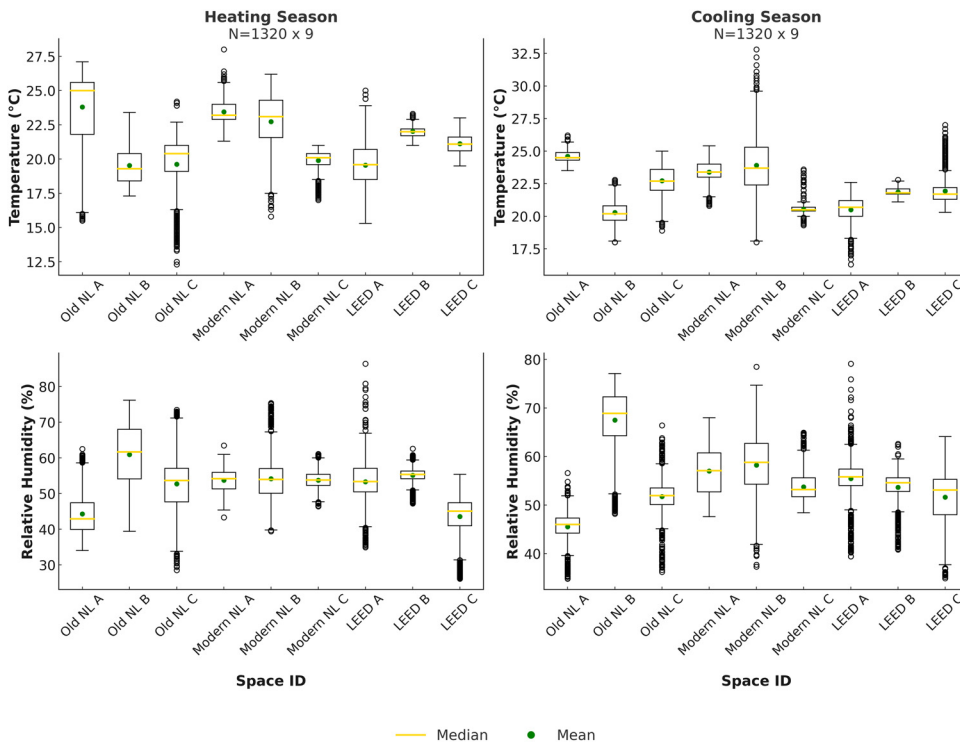


Fig. 10. Summary of hygrothermal conditions across building spaces.

0.002 mg/m³ to 0.093 mg/m³, with Modern NL C showing more frequent exceedances beyond WHO guideline compared to Old NL C and LEED C in both seasons. Dorm rooms frequently surpassed EPA reference concentrations for formaldehyde, highlighting potential indoor air quality issues.

CO₂ concentrations varied across seasons. In the heating season, mean CO₂ levels remained below 1000 ppm in all monitored spaces

except LEED B. However, maximum CO₂ concentrations exceeded 1000 ppm in most spaces except Old NL C and LEED C. During the cooling season, mean levels were below 1000 ppm across all spaces, although frequent exceedances occurred in Old NL B, LEED B, and spaces within Modern NL. Seasonal and daily CO₂ variability is detailed in **Appendix D**. Mann-Whitney U test results revealed statistically significant differences ($p < 0.0001$) in at least one of four periodic comparisons

(e.g., by season and weekday vs. weekend) for all spaces, except Modern NL A and Modern NL C, where no significant differences were observed across any comparisons.

Temperature varied significantly across spaces and seasons. For example, in the heating season, temperatures in Old NL A ranged from 15.5 °C to 27.1 °C, with a mean of 23.8 °C (± 2.6 °C), while in the cooling season, they ranged from 23.5 °C to 26.2 °C, with a mean of 24.6 °C (± 0.4 °C). Similar seasonal variations were observed in other spaces, such as Modern NL A, where temperatures ranged from 21.3 °C to 28.0 °C (mean: 23.4 °C ± 0.8 °C) during the heating season, and 20.8 °C to 25.4 °C (mean: 23.4 °C ± 0.9 °C) during the cooling season. Compared to other building spaces, LEED B exhibited tighter ranges and greater stability in both temperature and humidity, underscoring its controlled environment. Relative humidity also showed substantial cross-seasonal differences. For instance, in Old NL B, relative humidity during the heating season ranged from 39.4 % to 76.2 %, with a mean of 60.9 % (± 8.5 %), compared to 48.2 % to 77.1 % (mean: 67.5 % ± 6.2 %) during the cooling season. Similar patterns were evident in Modern NL B and LEED A, with variations depending on building design and ventilation performance.

The correlations between hygrothermal variables during heating and cooling seasons were mostly weak to moderate. The strongest correlation was observed between CO₂ levels and relative humidity in Old NL A ($r = 0.62$) during the heating season. **Appendix E** illustrates these correlations across monitored spaces. Indoor-outdoor temperature and humidity differences showed strong linear relationships with outdoor conditions, particularly in LEED spaces, Modern NL A, and Modern NL C, with R^2 values ranging from 0.90 to 1.00 (see **Appendix F**). Old NL A exhibited the weakest relationship for temperature ($R^2 = 0.58$) during the heating season, reflecting potential insulation or system inefficiencies. Wilcoxon signed-rank tests confirmed statistically significant cross-seasonal differences in hygrothermal conditions ($p < 0.01$) for most spaces, with exceptions in Old NL A (temperature: $p = 0.76$; relative humidity: $p = 0.30$), Old NL C (relative humidity: $p = 0.33$), Modern NL A (temperature: $p = 0.78$), Modern NL C (relative humidity: $p = 0.90$), LEED A (relative humidity: $p = 0.10$), and LEED B (temperature: $p = 0.12$; relative humidity: $p = 0.04$).

3.1.3. Objective IEQ performance and predicted mean votes

The objective performance of IEQ based on the four key components varied significantly across the monitored building spaces, as illustrated in **Fig. 11**. For Tc, performance ranged from 40.0 % in LEED A to 90.6 % in Old NL A. Other spaces like Modern NL A and Modern NL B performed strongly, achieving 84.4 % and 87.1 %, respectively, while LEED C showed a high Tc performance of 82.2 %, demonstrating substantial variability within LEED spaces.

For Lc, Modern NL A led with 89.6 %, followed by LEED C at 82.7 %, and Old NL A at 82.3 %. Meanwhile, Modern NL C and Old NL B recorded the lowest performances at 59.2 % and 73.1 %, respectively. LEED B and LEED A also showed moderate results at 75.2 % and 79.1 %, respectively. In terms of Ac, LEED C performed exceptionally well with a score of 93.4 %, while Old NL C among Old NL spaces recorded the lowest score of 40.0 %. Modern NL spaces showed mixed results, with Modern NL A achieving 71.2 % but Modern NL B scoring only 29.4 %. LEED A also performed strongly, achieving 89.0 %, whereas LEED B managed 52.8 %.

For IAQ, LEED C achieved the highest score of 88.9 %, closely followed by Old NL C at 85.0 %. In contrast, Modern NL spaces ranged from 59.7 % to 68.1 %, with Modern NL A scoring the lowest. Among LEED spaces, LEED A and LEED B recorded performances of 74.1 % and 56.6 %, respectively.

When aggregated, the objective IEQ (IEQo) performance followed a clear trend across individual spaces (see **Table 5**): LEED C > Modern NL A > Old NL A > Old NL C > LEED A > Modern NL C > Modern NL B > LEED B > Old NL B. At the building level, LEED emerged with the

highest average performance of 73.4 % $\pm$ 12.2 %, followed by Modern NL at 69.1 % $\pm$ 6.2 % and Old NL at 68.0 % $\pm$ 10.9 %.

Seasonal variations in thermal sensation, as indicated by the predicted mean vote (PMV), further highlighted performance differences. During the heating season, Old NL A recorded a PMV value of -0.1 , indicating neutral comfort. Old NL B and Old NL C were slightly cool, with PMV values of -1.2 and -0.76 , respectively. Modern NL spaces performed well, with Modern NL A at PMV = -0.14 (neutral), Modern NL B at PMV = -0.34 (neutral), and Modern NL C at PMV = -0.69 (slightly cool). LEED A and LEED B showed slightly cool sensations at PMV = -1.25 and -0.53 , respectively, while LEED C was neutral at PMV = -0.48 .

In the cooling season, thermal sensations shifted, with most spaces feeling slightly cool to cool. Old NL A had a PMV of -0.64 (slightly cool), Old NL B at -2.13 (cool), and Old NL C at -0.75 (slightly cool). Modern NL spaces ranged from slightly cool to cool, with Modern NL A at -0.99 , Modern NL B at -0.8 , and Modern NL C at -1.42 . LEED spaces followed a similar trend, with LEED A at -2.13 (cool), LEED B at -1.59 (cool), and LEED C at -0.99 (slightly cool).

3.1.4. Subjective-objective IEQ: IEQc and IEQs

The performance of building spaces varied depending on the subjective-objective evaluation model used—IEQc or IEQs. For spaces within the Old NL, Modern NL, and LEED buildings, coefficients were derived from the normalized mean response survey scores (as defined in **Eq. (15)**). **Eqs. (16) to (18)** were then used to compute performance based on IEQc, while **Eqs. (19) to (21)** were applied to calculate IEQs, incorporating the additional EUQ metric.

$$\text{OldNL} : IEQc = 0.224 \cdot IAQ + 0.261 \cdot Tc + 0.235 \cdot Ac + 0.280 \cdot Lc \quad (16)$$

$$\text{ModernNL} : IEQc = 0.248 \cdot IAQ + 0.275 \cdot Tc + 0.223 \cdot Ac + 0.254 \cdot Lc \quad (17)$$

$$\text{LEED} : IEQc = 0.246 \cdot IAQ + 0.256 \cdot Tc + 0.221 \cdot Ac + 0.277 \cdot Lc \quad (18)$$

$$\text{OldNL} : IEQs = 0.175 \cdot IAQ + 0.204 \cdot Tc + 0.184 \cdot Ac + 0.219 \cdot Lc + 0.218 \cdot EUQ \quad (19)$$

$$\text{ModernNL} : IEQs = 0.201 \cdot IAQ + 0.223 \cdot Tc + 0.181 \cdot Ac + 0.206 \cdot Lc + 0.187 \cdot EUQ \quad (20)$$

$$\text{LEED} : IEQs = 0.202 \cdot IAQ + 0.211 \cdot Tc + 0.182 \cdot Ac + 0.228 \cdot Lc + 0.178 \cdot EUQ \quad (21)$$

As shown in **Table 5**, which highlights the elements contributing the least and most to different IEQ performance models for each building space, Old NL A, Modern NL A, and LEED C achieved *Optimal* performance based on the IEQc model, while the remaining spaces were rated as *Acceptable*. Notably, LEED C consistently outperformed other spaces, reflecting the advantage of its green building design. The IEQc trend at the space level was: LEED C > Old NL A = Modern NL A > Old NL C > LEED A > Modern NL B > Modern NL C > LEED B > Old NL B.

When evaluating IEQs, which integrates subjective and energy performance components, only LEED C attained *Optimal* performance, with the other spaces rated as *Acceptable*. The performance trend for IEQs followed a slightly different order: LEED C > Modern NL A > Old NL A > LEED A > Old NL C > LEED B > Modern NL B > Modern NL C > Old NL B.

At the building level, both IEQc and IEQs ratings for Old NL, Modern NL, and LEED buildings were categorized as *Acceptable*. However, LEED buildings demonstrated the highest overall performance, followed by Modern NL and Old NL, emphasizing the potential benefits of green building certifications in optimizing both energy and indoor environmental quality.

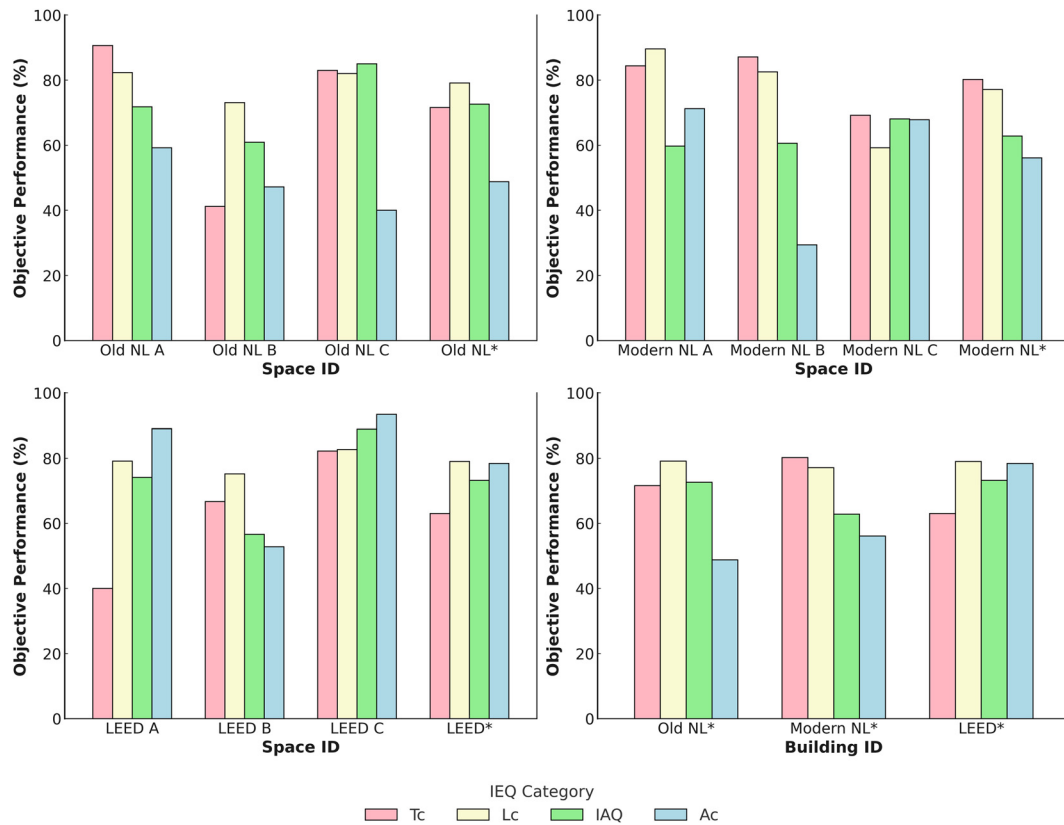


Fig. 11. Objective performance of IEQ factors across residential college buildings. The asterisk (*) denotes averages of monitored spaces within each building.

Table 5

IEQ metrics with highest (HPF) and lowest performing factors (LPF) across building spaces.

Space	IEQo				IEQc				IEQs			
	HPF	LPF	IEQo Score	Explanation	HPF	LPF	IEQc Score	Explanation	HPF	LPF	IEQs Score	Explanation
Old NL A	Tc	Ac	76.0 %	Optimal	Tc	Ac	76.7 %	Optimal	Tc	Ac	70.9 %	Acceptable
Old NL B	IAQ	Tc	55.6 %	Acceptable	Lc	Tc	56.0 %	Acceptable	Lc	Tc	54.7 %	
Old NL C	IAQ	Ac	72.5 %		Lc	Ac	73.0 %		Lc	Ac	68.0 %	
Modern NL A	Lc	IAQ	76.2 %	Optimal	Tc	IAQ	76.7 %	Optimal	Tc	IAQ*	71.6 %	
Modern NL B	Tc	Ac	64.9 %	Acceptable	Tc	Ac	66.5 %	Acceptable	Tc	Ac	63.4 %	
Modern NL C	Tc	Lc	66.1 %		Tc	Lc	66.1 %		Tc	Lc*	63.0 %	
LEED A	Lc	Tc	70.6 %		Lc	Tc	70.1 %		Lc	Tc	70.0 %	
LEED B	Lc	Ac	62.8 %		Lc	Ac	63.5 %		Lc	Ac	64.7 %	
LEED C	Ac	Lc	86.8 %	Optimal	Lc	Ac	86.5 %	Optimal	Lc	Ac*	83.6 %	Optimal

*2nd to EUQ.

3.2. Energy performance

3.2.1. Energy usage and energy use intensity

The total energy consumption was highest in Other NL IV (1868.6–2173.7 MWh), followed by LEED (1640.2–1730.3 MWh), over two consecutive years. In contrast, Other NL I (623.8–676.3 MWh) and Other NL III (641.9–653.0 MWh) exhibited the lowest energy consumption during the same period. Comparisons of the yearly Energy Use Intensity (EUI) for the buildings against national benchmarks—57.9 kBtu/sf and 84.3 kBtu/sf for buildings with similar functions—are presented in Fig. 12, with all buildings performing below the benchmarks. LEED recorded the highest EUI (51.1–53.9 kBtu/sf) in both years, while Other NL I had the lowest EUI (23.4–25.3 kBtu/sf). Yearly EUI increased in the second year for all buildings except Other NL II, where the EUI decreased by 15.3 %.

Carbon emissions intensity trends aligned with EUI patterns, as expected and shown in Fig. 13. LEED recorded emissions intensities of 11.13 lbs of CO₂/sf in the first year and 12.11 lbs of CO₂/sf in the second year. Conversely, Other NL II exhibited lower emissions intensities of 5.09 lbs of CO₂/sf and 5.69 lbs of CO₂/sf across the respective years.

The monthly EUI variation of the buildings, presented individually in Fig. 14, and collectively in Figs. 15 and 16, depicts notable seasonal fluctuations. In the first year, June, followed by July and August, experienced the highest cooling degree days (CDD), while December and January recorded the highest heating degree days (HDD). Similarly, in the second year, August, July, and June had the highest CDD, while January and December had the highest HDD.

The highest median monthly EUI in the first year was in April, compared to the highest median monthly EUI in the second year which was in September and February. In both years, the highest EUI occurred in August for Other NL I and Other NL IV, while the lowest EUI occurred in December. For Old NL and LEED, the highest EUI was observed in March during the first year, shifting to September and June, respectively, in the second year. Modern NL recorded its highest EUI in April during the first year and in September during the second year.

Interestingly, monthly EUI for LEED in the second year exceeded that of the previous year in 66.7 % of the instances. For Old NL, Modern NL, and Other NL I, this figure was 58.3 %, while it was 33.3 % for Other NL II, 50 % for Other NL III, and 75 % for Other NL IV.

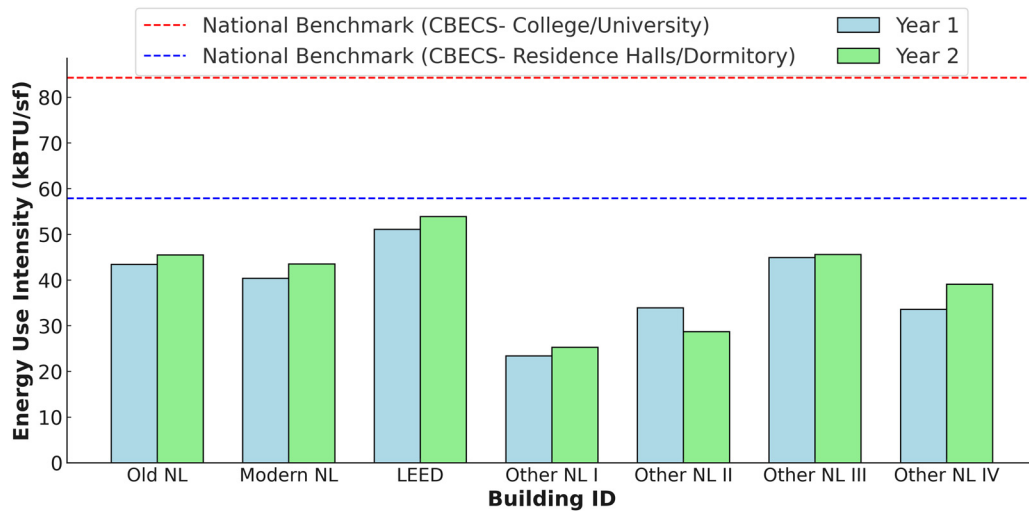


Fig. 12. Annual Energy Use Intensity (EUI) across residential college buildings in comparison to national benchmarks.

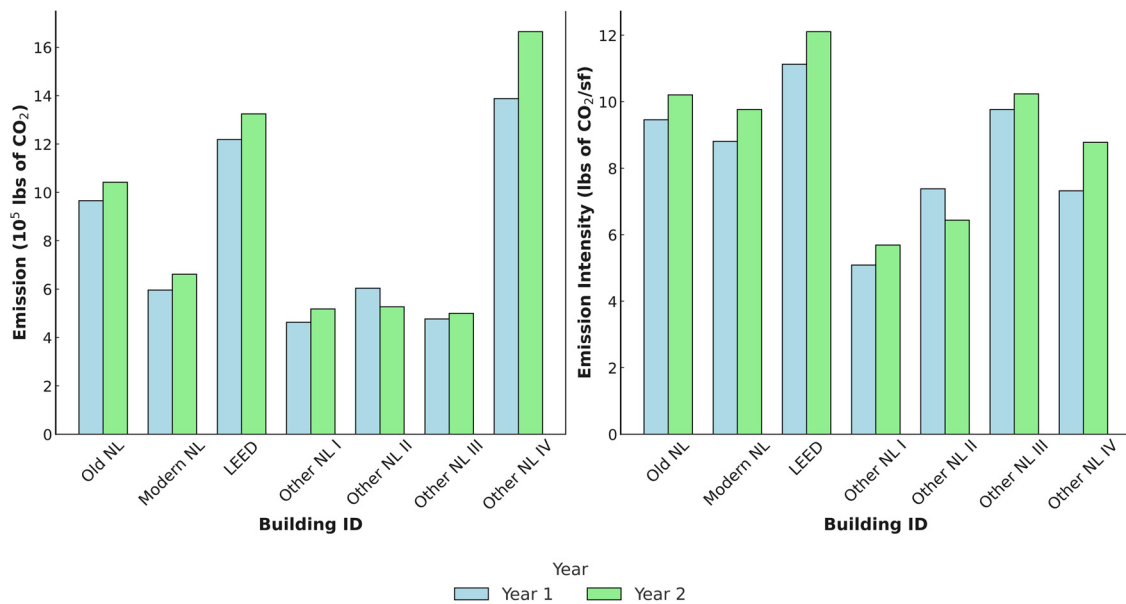


Fig. 13. Carbon emissions and emissions intensity across residential college buildings.

3.2.2. Energy utility quality and satisfaction

The EUQ score for Old NL and Modern NL was 50 %, reflecting a nearly slightly inefficient level. For Other NL III, the score was 30 %, indicating inefficiency, while LEED achieved a score of 70 %, signifying efficiency. Other NL I scored 80 %, indicating a very efficient level, and both Other NL II and Other NL IV scored 100 %, reflecting an extremely efficient level. Based on the EUQ measure, rather than the score resulting from it, the performance trend followed: Other NL II > Other NL IV > Other NL I > LEED > Old NL > Modern NL > Other NL III. Fig. 17 illustrates the performances of these buildings as well as how Old NL, Modern NL, and LEED performed across different metrics.

Housing managers' satisfaction with energy usage and associated costs during comparative seasons revealed significant disparities. Satisfaction with energy usage was highest (>70 %) for Old NL, Modern NL, and LEED, as depicted in Fig. 18. Interestingly, Modern NL recorded satisfaction levels at least 5 % higher than any other building regarding energy costs. However, contrary to expectations, Other NL IV exhibited the lowest satisfaction levels for energy usage and costs across both seasons, with the majority of responses falling at or below the neutral category.

4. Discussion

This section interprets the findings presented in the study, addresses its limitations, and explores broader implications, providing insights into future research and practical applications.

4.1. Interpretation of results

The study revealed significant discomfort caused by noise, particularly in areas where occupants had limited control. Noise sources, such as vents and noisy neighbors, were frequently reported as disruptive to focused student living. To mitigate this, quiet hours or late-night regulations should be enforced, and noise-reducing materials should be incorporated into dorm construction, particularly in livable spaces. Physical measurements supported occupant perceptions of noise issues, although measurements were limited to specific spaces.

Lighting comfort was generally rated high, largely due to the availability of natural light and moderate illuminance levels in dorm rooms, which supported visual comfort. However, in certain spaces, excessive illuminance led to discomfort—such as headaches—highlighting the need

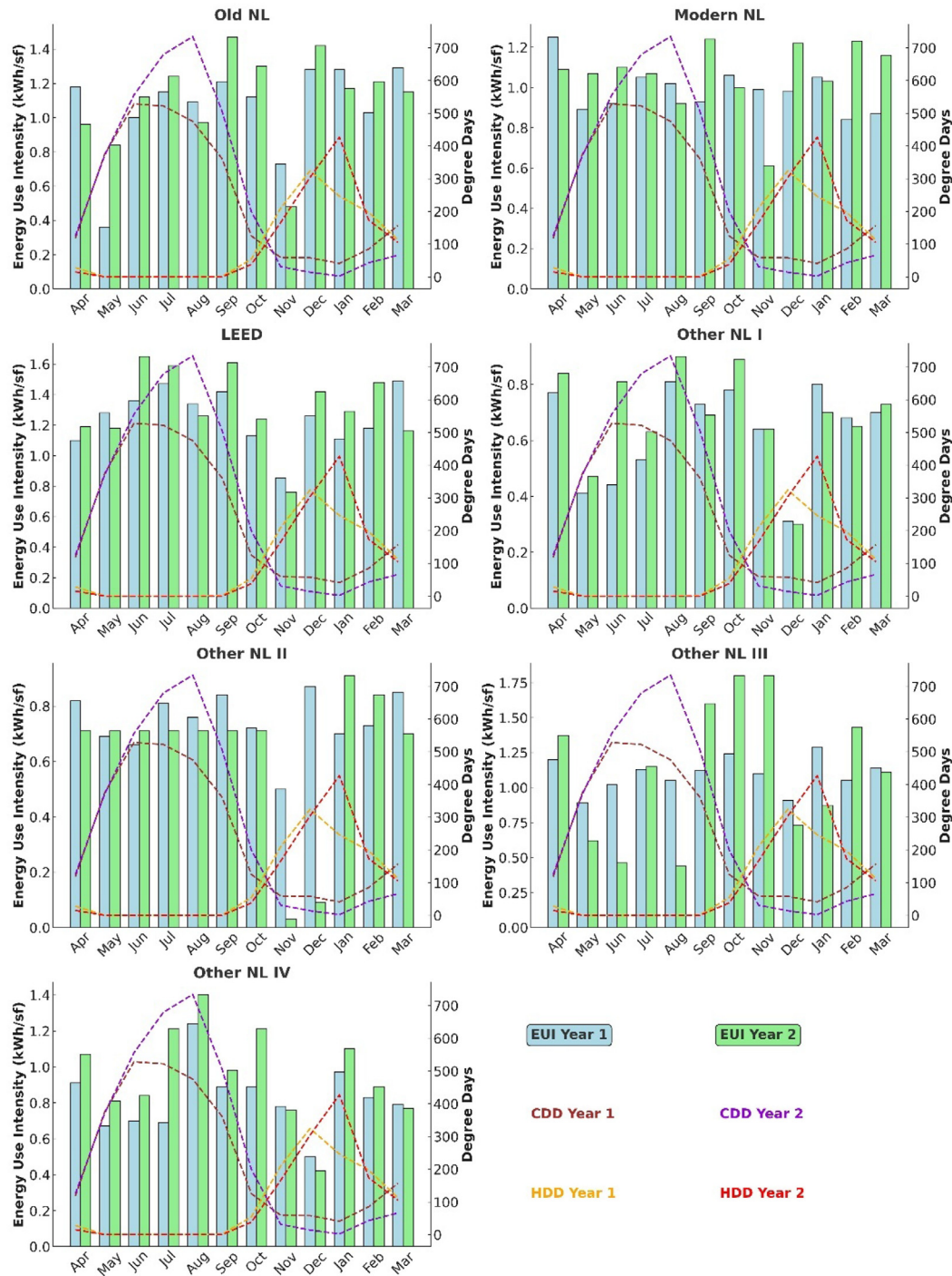


Fig. 14. Monthly EUI trends with heating degree days (HDD) and cooling degree days (CDD) over consecutive years across residential college buildings.

for immediate corrective action. Implementing energy-efficient lighting solutions designed to minimize discomfort can address these issues. Moreover, the combination of high illuminance and poor ventilation may have amplified occupant discomfort, particularly in spaces with elevated CO₂ levels. Periodically high CO₂ levels above 1000 ppm observed in monitored spaces were likely due to overcrowding, vaping and/or infiltration from adjacent rooms [89]. These factors may have contributed to IAQ dissatisfaction. In a related study by Xu et al. [90], the IAQ in 80 % of college dormitories was deemed unacceptable by occupants, even though only 10 % of the dormitories failed to meet the objective assessment criteria for total volatile organic compound (TVOC) concentrations.

Similarly, relatively high formaldehyde concentrations detected in corridor spaces were likely a result of cleaning products used near sensor locations during cleaning periods. While transient odors may be harmless, persistent formaldehyde levels above the EPA Reference Concentration (RfC) in dorm rooms could lead to or exacerbate chronic respiratory conditions such as asthma and bronchitis [91]. Ensuring adequate ventilation in these spaces is critical to dissipate such pollutants and improve IAQ. Potential sources of formaldehyde in dorm rooms include building materials, smoking, cosmetics, and the use of unvented appliances. Addressing these sources through better material selection, ventilation systems, and educational campaigns about the impacts of indoor air pollutants can significantly improve IAQ and occupant health.

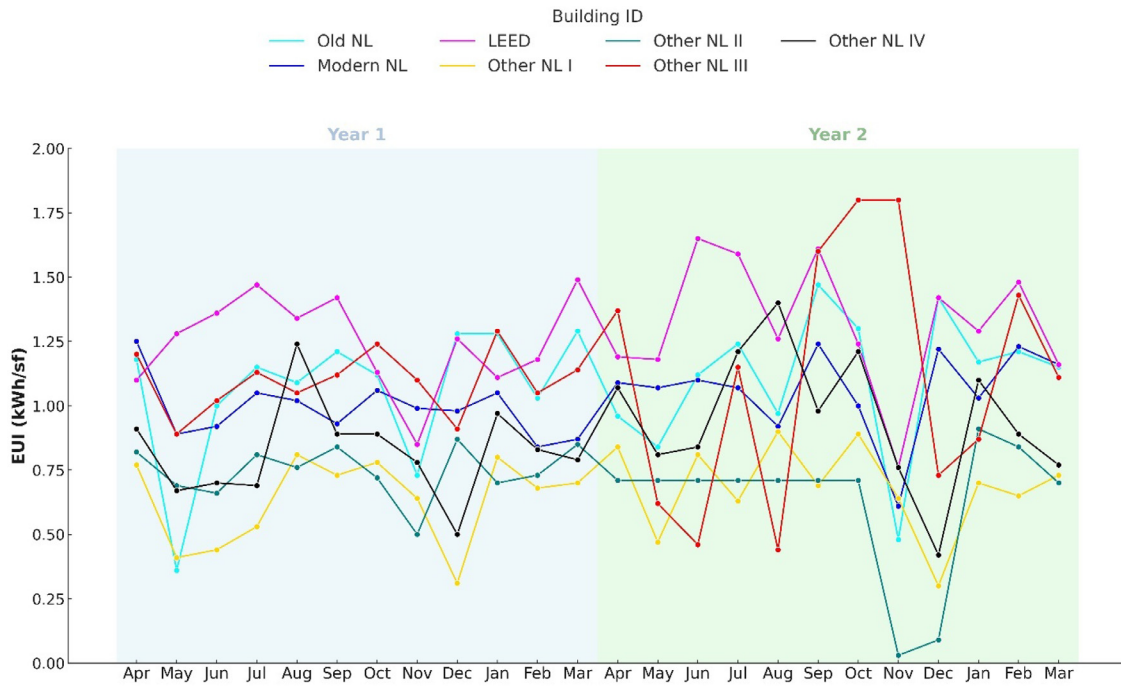


Fig. 15. EUI trends over a 24-month period across residential college buildings.

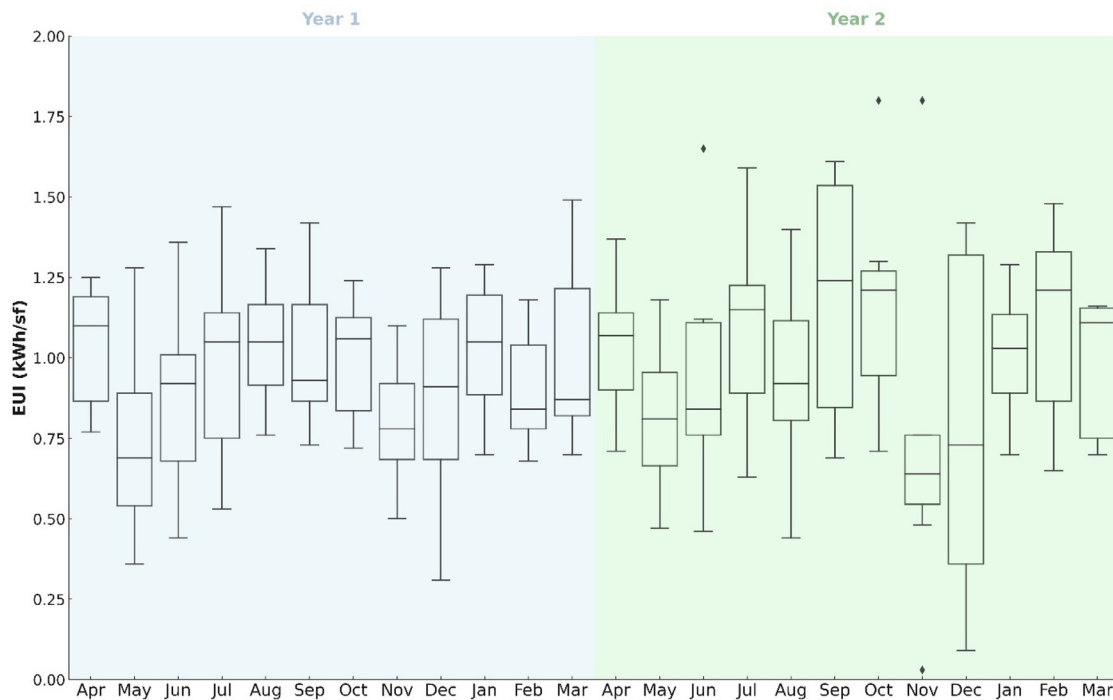


Fig. 16. Monthly EUI distribution in seven residential college buildings.

Thermal comfort results showed mixed outcomes. Although most occupants expressed satisfaction, Old NL had low results, highlighting the need for building upgrades and HVAC replacements. Hygrothermal conditions in monitored spaces frequently fall outside comfort recommendations. While WHO (1987) recommends indoor temperatures of 18–24 °C with no explicit humidity limits, national guidelines suggest ranges of 16–23 °C for heating seasons and 22–28 °C for cooling seasons [92]. Temperatures below 16 °C during heating seasons, combined with relative humidity exceeding 65 %, heighten the risk of respiratory issues, including allergies [73,93,94]. Based on psychrometric output from the

adopted Tc software [70], overcooling was an issue in the cooling season across all dorm rooms, and a setpoint temperature ranging from 24 to 29 °C (or 26 °C, considering the midpoint) is recommended. Besides, Liu et al. [95] recommend 20–23 °C with 20 %–60 % humidity during the cooling season to prevent sick building syndrome. Deviations from these ranges in monitored spaces highlight the need for better thermal management.

The variability in hygrothermal conditions was most pronounced in Old NL, likely attributed to the absence of individual thermal controls. According to the university housing manual, the building's heating and

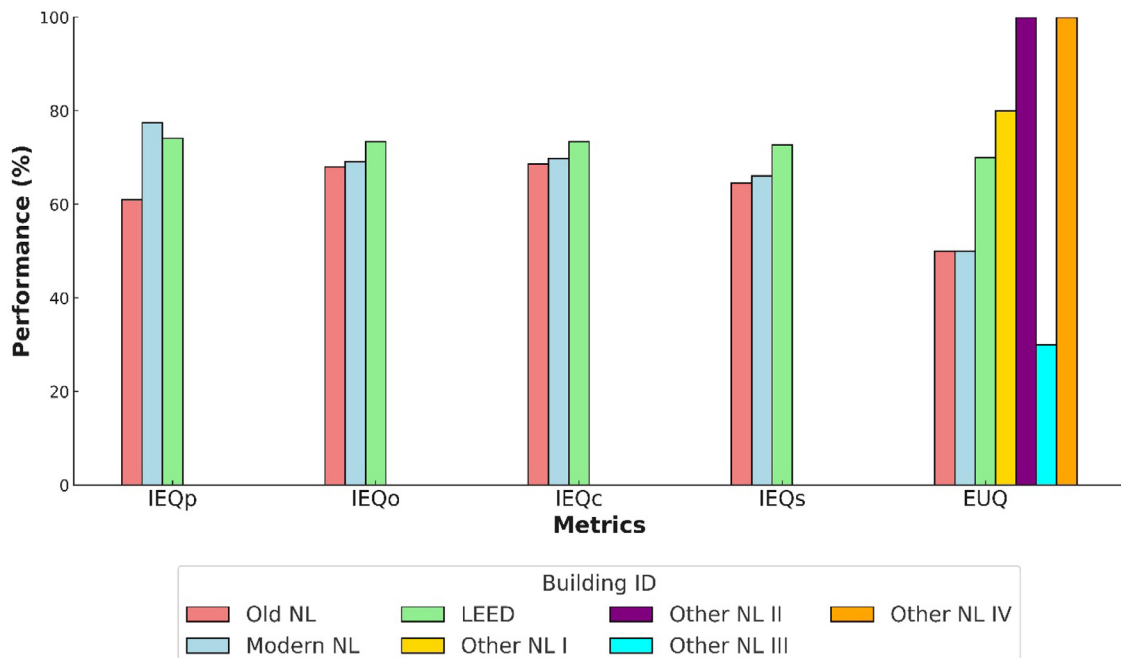


Fig. 17. Multi-metric building performance trends.

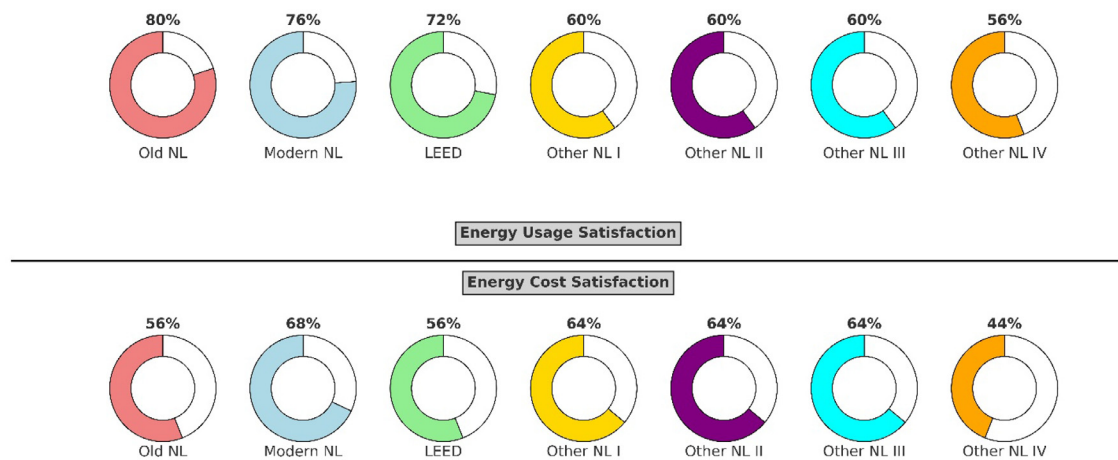


Fig. 18. Energy usage and cost satisfaction scores across residential college buildings.

cooling systems operate using a heated and chilled water mechanism, with adjustments determined by housing managers based on weather patterns. This centralized system may have contributed to occupant discomfort due to its limited responsiveness to individual needs. In contrast, deviations observed in Modern NL and LEED, where individual thermostats are available, highlight a different issue. These deviations suggest a need for occupant education on balancing thermal comfort with energy efficiency. Furthermore, reports from LEED occupants on limited control over room temperatures, particularly at night, may indicate thermostat malfunctions or imposed restrictions on their usage. Maintaining comfort-oriented hygrothermal conditions is crucial, as persistent deviations can contribute to sick building syndrome and negatively impact academic performance.

High humidity levels (>60 %) periodically observed in the dorm rooms risk mold growth and pest infestations such as cockroaches, ants, and termites [94,96]. Ensuring HVAC systems operate effectively or coupling them with dehumidifiers is necessary to address this issue. These high humidity conditions likely strained HVAC systems, impacting their efficiency and contributing to the EUQ performance observed in LEED, Old NL, and Modern NL. Despite LEED outperforming the other two

buildings, its suboptimal energy performance ranking among the seven RCBs may reflect its low credit score (23 %) in the Energy and Atmosphere category of its certification. While all RCBs performed better than national benchmarks, the focus of energy performance should shift toward continuous improvement rather than merely meeting baseline standards.

As HVAC systems often account for the majority of energy consumption [17], facility managers and occupants must prioritize maintaining comfort within efficiency guidelines. Routine inspections of vents for potential clogging are also essential to ensure optimal airflow and system efficiency.

4.1.1. Energy performance insights

The positions of LEED in terms of EUI and EUQ varied in relation to other buildings compared, demonstrating the uniqueness of both metrics for efficiency evaluation. In both cases, the energy performance of LEED was not the highest. This finding aligns with the recent study by Vosoughkhosravi et al. [48], which reported that a LEED-certified RCB in a similar climate performed worse than its non-certified counterparts. However, it contrasts with the results of Tilton and El Asmar [97], who

found that LEED-certified student housing achieved lower EUI values compared to non-certified counterparts.

Meanwhile, the energy satisfaction results in the present study revealed a notable discrepancy, indicating that housing managers prioritized energy consumption and economic considerations over efficiency. This suggests a possible misunderstanding of the factors driving energy performance. For instance, the high total annual energy consumption observed in Other NL IV can be attributed to its larger gross square footage and higher operational capacity compared to other RCBs. Failure to account for these differences may lead to misguided operational decisions or biased interventions.

Facility managers must clearly differentiate between total energy consumption and EUI to make informed decisions. Misinterpretations can not only misguide energy management strategies but also skew the weighting factors used in the introduced IEQs evaluation model, potentially compromising the accuracy of building performance assessments.

4.1.2. IEQ metrics and thermal sensation

Comparative IEQ metrics provided critical insights into individual IEQ factors, with acoustic conditions emerging as the most underperforming factor across all monitored spaces, necessitating targeted interventions. This observation applies to all dorm rooms, as evidenced by the generally low satisfaction levels reported by occupants in the RCBs. Despite this, satisfaction surveys revealed that occupants generally expressed high overall satisfaction with their experiences in RCBs. However, in Old NL, a significant correlation was identified between the duration of occupants' stays and their satisfaction, suggesting that longer stays positively influence overall perceptions and experiences. The subjective IEQ performance of the LEED-certified building in this study aligns with findings from previous research, where LEED buildings have consistently outperformed non-certified ones and exceeded the CBE benchmark, which is based on more than 50,000 completed surveys [48,98].

The mismatch in average TSV versus PMV for the compared RCBs reflects inherent limitations in the PMV model, such as assumptions of fixed clothing insulation levels, uniform metabolic rates, and homogeneous occupant behavior, which may not accurately represent real-world conditions [99,100]. Additionally, the assumption that operational activities across all monitored and unmonitored spaces within each RCB are consistent—particularly across seasons—may introduce further discrepancies. However, the PMV was found to be accurately predictive of TSV by 66.0 % to 93.5 % across examined RCBs (see **Appendix G** for general results and procedure for calculating the accuracy of PMV relative to TSV).

4.2. Limitations of the study

This study has several limitations that should be acknowledged to contextualize the findings. Air velocity was assumed across all monitored spaces and seasons due to resource constraints, limiting the ability to evaluate airflow variability comprehensively. Airflow, which plays a critical role in occupant comfort and IAQ, was not directly investigated. Additionally, the sample sizes for occupant satisfaction surveys were relatively small and varied across buildings, potentially affecting the generalizability of subjective IEQ results. Moreover, the merging of survey responses for Other NL I and II hindered the ability to evaluate each building's individual IEQ performance, despite the availability of unique energy data for each.

Physical measurements of environmental conditions were only conducted in select monitored spaces within the investigated buildings, and no such measurements were performed in other RCBs where occupant satisfaction responses were collected. Additionally, hygrothermal and IAQ measurements did not cover months with the highest cooling degree days, which may have limited insights into seasonal extremes. Similarly, hygrothermal conditions were not analyzed for daytime versus

nighttime variations, which could reveal critical patterns of occupant discomfort.

Noise and lighting were not continuously monitored due to their transient nature and presumed consistency in certain spaces, such as dorm rooms. The study instead focused on identifying potential HVAC noise sources. However, this approach may have overlooked fluctuations in noise levels and their impacts on occupants.

4.3. Implications for future research and practice

The findings from this study highlight several directions for future research and practical applications. Future studies should prioritize continuous and real-time monitoring of environmental parameters, including airflow and noise, to capture transient variations and provide a more accurate assessment of occupant experiences. Longitudinal studies that incorporate advanced machine learning techniques, such as long short-term memory approaches, could offer predictive models for how external environmental factors directly impact indoor conditions across building spaces.

Expanding sample sizes and ensuring consistency across surveyed buildings is critical for improving the robustness of findings related to occupant satisfaction. Investigations should also include hygrothermal and IAQ measurements during peak cooling and heating months, as well as comparisons between daytime and nighttime conditions, to identify temporal variations in occupant comfort and system performance.

Practically, facility managers must implement strategies to optimize hygrothermal conditions, particularly in older buildings like Old NL, where inconsistent performance was noted. Regular inspections and maintenance of HVAC systems, coupled with the use of dehumidifiers in high-humidity spaces, can mitigate issues such as mold growth and pest infestations. Noise mitigation strategies, such as using noise-dampening materials and addressing loud HVAC systems, should also be prioritized, especially in dormitory settings where focus and rest are essential.

The introduction of individual thermal controls, paired with occupant education on balancing comfort and energy efficiency, could help mitigate deviations from recommended hygrothermal conditions in buildings like LEED and Modern NL. Facility managers should also account for operational demands, such as gross square footage and usage patterns, when interpreting energy metrics like annual energy consumption, EUI and EUQ. The EUQ metric, in particular, provides insight into a building's potential climate resilience and offers an enhanced approach for facility managers to critically evaluate energy performance as a preliminary step before conducting a full energy audit. Furthermore, EUQ has the potential to be applied in studies across different climatic zones, especially when grounded in a robust understanding of historical energy consumption patterns and future climate projections. Lastly, institutionalizing multi-metric building performance evaluations can strengthen decision-making, enhance occupant well-being, and support sustainability objectives in residential college buildings.

5. Conclusions

This study investigated the IEQ and energy performance of residential college buildings, one of which was LEED Silver-certified, at a Louisiana university, highlighting variations in occupant satisfaction, hygrothermal conditions, air quality, and energy metrics across buildings and seasons. The findings revealed critical underperformance in acoustic conditions and challenges with high humidity levels, which can pose risks to occupant comfort and health. Although the LEED-certified building generally demonstrated superior performance in IEQ metrics, its energy performance ranking suggests that certification alone does not guarantee optimal operational outcomes.

The integration of subjective and objective IEQ assessments with energy performance metrics proved critical in offering a more comprehensive evaluation of building quality and sustainability. This multidimensional approach allows for data-driven recommendations to improve oc-

cupant comfort, energy optimization, and the overall sustainability of student housing facilities.

Future research should broaden the scope to include a wider range of building typologies, climate periods and zones, and occupant usage patterns, to enhance the generalizability and robustness of findings. Subsequent investigations will also pursue a more in-depth analysis of the relationship between subjective IEQ factors and energy consumption, particularly comparing pre-millennium and post-millennium residential college buildings. To further advance sustainability assessment models, future work will explore a shift from summation-based to product-based integration of IEQ and EUQ metrics, aiming to provide a more synergistic and holistic representation of building performance.

Ethical statement

Ethical approval for the involvement of human subjects in this study was granted by Louisiana State University Institutional Review Board, Reference number IRBAM-23-0856, on the 30th of August 2023, with no expiration date.

Declaration of competing 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.

CRediT authorship contribution statement

Oluwafemi Awolesi: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at [doi:10.1016/j.enbenv.2025.05.006](https://doi.org/10.1016/j.enbenv.2025.05.006).

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