Real-Time Energy and IEQ Monitoring of a Compact Living Space

Hongbo LU[1], Emmanuel I. AGHIMIEN[1,2], Xiaosu DING[1],
Ariane REDNOUR[1], Jordan N. Cross[1], Nusrat JUNG[1]

[1]Purdue University, Lyles School of Civil Engineering,
West Lafayette, Indiana, United States
[2]City University of Hong Kong, Department of Architecture Engineering,
Hong Kong, S.A.R. China

* Corresponding Author (email: nusratj@purdue.edu)

ABSTRACT

As the urbanization trend prevails worldwide, more people are moving to major metropolitan areas, causing housing resources to be in urgent demand. Micro-apartments, designed to offer a minimalist lifestyle while also addressing growing housing needs, have become increasingly popular among home seekers. Due to smaller household sizes, tiny homes, occupying less land area, also become more prevalent among families. Meanwhile, individuals primarily spend their time indoors, and with more people adopting work-from-home lifestyles, ensuring a high-quality and comfortable indoor environment becomes crucial for indoor occupants. Many studies have highlighted that the activities of occupants significantly influence indoor environmental quality (IEQ) and energy consumption in buildings. This study performed a comprehensive evaluation of IEQ satisfaction survey and energy usage measurement in the Purdue zEDGE Tiny House as a controlled facility to represent urban and rural compact living spaces. Twenty full-scale experiments were conducted during the winter season. The study first evaluated participants' perception of IEQ factors, with thermal comfort and indoor air quality (IAQ) emerging as top priorities. It then examined energy adaptive behavior to understand maintenance of comfortable indoor conditions, noting primary adaptive strategies included heating, ventilation, and artificial lighting. The study then measured IEQ and energy consumption, evaluating occupants' IEQ satisfaction levels. The average energy use was recorded at 10.3 kWh, with occupants generally satisfied with IEQ in the zEDGE Tiny House. Analysis indicated that indoor heating and electric cooking resulted in significant energy consumption, potentially exposing occupants to high indoor air pollutant levels in a compact living space.

1. INTRODUCTION

Nowadays, majority of human activities are carried out indoors, with studies showing that individuals spend up to 90% of their time within indoor environments (Kelly & Fussell, 2019; Namieśnik et al., 1992) This significant indoor residency underscores the impact of the built environment on daily life, health, and well-being, especially after COVID-19 pandemic, where residential buildings serve as both living and working settings, and people are spending more times carrying out work-from-home activities, which changes the overall indoor environment characteristics drastically since the buildings is occupied for longer times. In this context, residential buildings emerge not only as shelters but also as central to our physical and psychological health (Akbari et al., 2021). The energy consumption of residential buildings further extends their impact to global sustainability challenges, contributing notably to worldwide energy demand (Olu-Ajayi et al., 2022) and greenhouse gas emissions. Consequently, the dual objectives of enhancing occupant comfort and health and reducing environmental impact frame the critical importance of this research. As urbanization intensifies and environmental concerns grow (Huo et al., 2021), the incentive to understand and optimize the interaction between humans, buildings, and the surrounding environment grows significantly.

The evolving trend towards compact residential buildings is driven by growing urban populations, escalating real estate prices, and a broader shift towards sustainability. These compact living spaces, including tiny homes, micro-apartments, and mobile trailer homes, are designed to maximize the utilization of limited urban space and are increasingly popular globally. Tiny homes are particularly prevalent in the U.S. and Australia, offering innovative solutions for affordable and sustainable living. In contrast, micro-apartments are a global phenomenon, with Germany alone projecting a 75% increase in these units over the next decade, reflecting a significant shift towards smaller household sizes. Currently, Germany hosts 340,000 micro-apartments, and this number is expected to rise in response to demographic trends predicting that by 2030, 81% of households will consist of one or two persons.

These compact units typically feature a single-zone configuration that significantly reduces energy and water consumption. However, this design can also pose challenges for maintaining indoor environmental quality (IEQ), as minor pollution sources can have a more pronounced impact due to the reduced space. The study of tiny houses fills critical knowledge gaps concerning IEQ in compact living environments. This focus on tiny homes, along with micro-apartments and mobile trailer homes, emphasizes their role in adapting urban housing solutions to meet the needs of a diverse population, including students, young professionals, and remote workers. This shift towards compact living not only promotes sustainability and affordability but also reflects a strategic response to the evolving urban landscape.

Occupant's adaptive energy behavior covers a range of actions they can undertake to maintain comfort within their living spaces, impacting both electricity consumption and Indoor Environmental Quality (IEQ) (Hong et al., 2016). These behaviors extend beyond the adjustment of HVAC systems to include the use of window blinds for controlling daylight, the operation of electronic devices for entertainment or work, and decisions regarding ventilation and appliance use. Electricity consumption in residential buildings is significantly influenced by occupants' adaptive behaviors. For example, the choice to use fans instead of air conditioning during slightly warm conditions can reduce energy use, while the preference for electric heating over wearing additional clothing in cold weather can increase it (Morgan & De Dear, 2003). Lighting decisions, such as utilizing task lighting instead of whole-room lighting or opting for energy-efficient LEDs with advanced control system over traditional incandescent bulbs, also play a critical role (Chew et al., 2016). Additionally, the timing of appliance use, particularly during off-peak hours, can contribute to energy savings and demand-side management (Ansarin et al., 2020).

Adaptive behaviors also have a significant effect on IEQ. Natural ventilation, can result in introduction of both gas and particle phase pollutants and reduce indoor air quality and can also lead to discomfort during extreme weather conditions. (Ulpiani et al., 2021) Similarly, the use of window coverings such as window blinds can mitigate glare and reduce cooling loads but may also affect visual comfort and might be dependent on occupant preferences (Bennet et al., 2014). The management of indoor noise levels, whether through the selection of building envelope materials or the strategic use of space within the home to segregate noisy activities, further illustrates the impact of adaptive behaviors on IEQ (Khan & Bhattacharjee, 2021). Balancing the impacts of these behaviors requires a comprehensive understanding of their effects on both energy consumption and IEQ. Innovative approaches, such as the integration of smart home technologies and occupant education on sustainable practices, can help optimize these adaptive behaviors. By providing feedback on energy use and environmental conditions, such technologies encourage occupants to make informed decisions that enhance comfort while minimizing energy consumption (Metallidou et al., 2020).]

In essence, there are a wide variety of adaptive energy behaviors carried out by occupants in residential settings, including temperature control, lighting adjustments, ventilation preferences, and appliance use. Each of these behaviors have significant implications for both electricity consumption and IEQ, highlighting the need for a comprehensive approach to optimize these aspects. This study used a mixed-methods approach to explore how adaptive behaviors affect IEQ and energy use in compact living spaces. Surveys captured occupants' perceptions and behaviors related to energy and comfort in these environments, while in-situ real-time measurements provided objective data on energy consumption and environmental conditions. The dual approach allowed us to understand the unique challenges and dynamics of compact living, informing strategies to enhance sustainability and comfort in these settings.

2. METHODOLOGY

2.1 Site Description and Instrumentation Overview

The Purdue zEDGE (zero Energy Design Guidance for Engineers) Tiny House is a compact, single-zone residential structure established on a mobile trailer (Figure 1). Developed and conceptualized by a team from the Lyles School of Civil Engineering at Purdue University, this project was executed, and the house was constructed as per Recreational Vehicle Industry Association (RVIA) standards by Colorado's Mitchcraft Co. in the year 2020. Additionally, it has been certified by the National Organization of Alternative Housing (NOAH).

Presently, the zEDGE Tiny House is located in front of the Architectural Engineering Lab at the Hampton Hall of Civil Engineering (40°25'49.60"N, 86°54'52.00"W), which is situated at Climate Zone 5A (Cool and Humid) according to ANSI/ASHRAE Standard 169-2020. The majority of the windows, including the main entry door, are facing towards the northeast direction (as shown in Figure 2). The zEDGE Tiny House has a total conditioned volume of 60.35 m^3. During the experimental campaign, the occupancy of the zEDGE Tiny House was one adult. The single-zone interior of the zEDGE Tiny House consists of a living area, a kitchen area, a loft, and a bathroom area under the loft. A folding desk and TV set is installed in the living area. A refrigerator (GL35BK Refrigerator, Galanz Americas Limited Company), an electric induction cooktop (KCIG704FBL 24-inch 4-Element Induction Cooktop, Kitchen Aid), a kitchen exhaust, a dishwasher (W11160365D, Whirlpool), and an electric oven (W10758337B, Whirlpool) are installed in the kitchen area. A toilet bowl, a complete shower setup, including a glass divider and a water tap, a washing machine (Whirlpool), an electric water heater (XE28S06SB45U1, Rheem Manufacturing Company), and a bathroom sink with a water tap are installed in the bathroom area.

Figure 1: Purdue zEDGE Tiny House

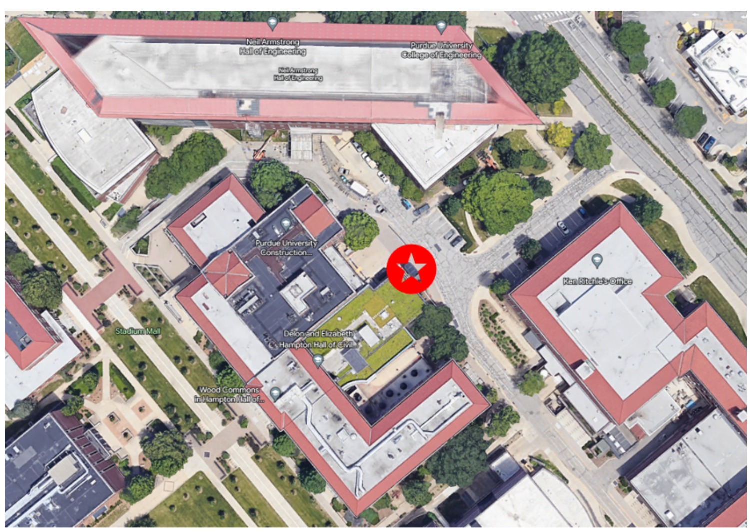

Figure 2: Current location of Purdue zEDGE Tiny House (starred location; map is oriented north up).

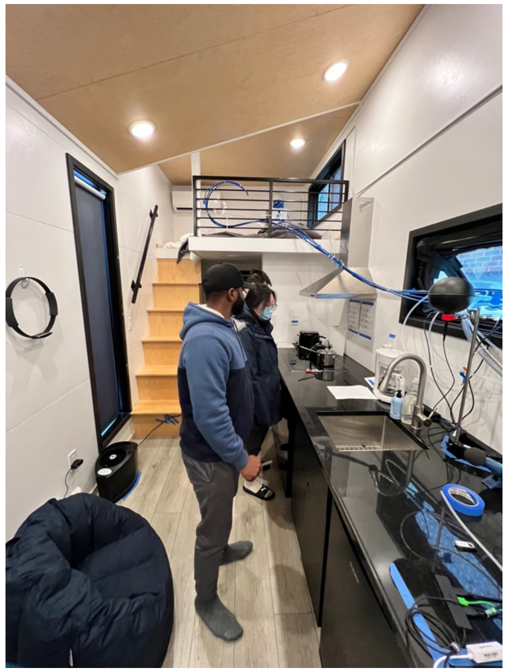

Figure 3: Interior of the Purdue zEDGE Tiny House.

The sensors used for the measurement of IEQ parameters are listed in Table 1. The SiteSage Building Management system (PowerWise Group Inc., USA) is integrated in zEDGE Tiny House to track electricity and water consumption. This system is a gateway-based Internet-of-Things (IoT) device network, and the gateway connects directly to zEDGE Tiny House's breaker panel located on the exterior of building envelope. One of the components is a Sitesage M electricity meter, powered by 120 V from the breaker circuits, for monitoring electricity use of each breaker in real-time across 20 circuits. Additionally, this system includes a connection to another gateway that connects the water meter to monitor water flow, transmitting this data alongside electricity usage. Both sets of data are updated with a time resolution of 1-minute and are sent wirelessly through cloud and stored in the SiteSage Energy Management App, a browser-based platform that provides insights into energy and water use. The data of electricity consumed by individual breakers and water consumption can be downloaded as Excel file for further analysis.

2.2 Experimental Protocol and Data Collection

The measurement campaign was reviewed by the Purdue Institutional Review Board (IRB) and qualified as exempt from IRB review (IRB-2023-197). A total of 20 experiments were conducted among 10 participants recruited via poster and email messages, and the campaign took place during the winter season in West Lafayette, Indiana, U.S. The campaign site was the zEDGE Tiny House. Each experiment took place within a single day during the zEDGE Tiny House operating hours (8AM to 8PM). Before the experiment commences, a 30-minute background period was set for adjusting indoor environmental parameters, including setting up the experimental instrumentation and adjusting indoor temperature and humidity setpoints of the mini split A/C and evaporative humidifier. All properties are recorded in a datasheet during the setup process. Then, upon the participant's arrival in the Architectural Engineering Teaching Lab in the Hampton Hall of Civil Engineering, the researcher will introduce the study site and the experiment and ask the participant if they are comfortable in participating in this study. After an agreement is made between the participant and the researcher, the participant was asked to set up their workstation in the workspace in the zEDGE Tiny House. Then the participant would return to the Architectural Engineering Teaching Lab to complete a pre-experiment survey.

Table 1: Instrumentation Overview

Quantity measured	IEQ variable	Instrument	Measurement range	Location (refer to floor plan)
Outdoor temperature and RH	-	Vaisala probe	-40°C to +80°C 0-100% (RH)	Outdoor
Solar radiation	-	SMP3 Koppen and Zonen Pyranometer	300 to 2800 nm (Spectral range)	Outdoor
Indoor air temperature and RH	Thermal	Vaisala probe	-40°C to +80°C 0-100% (RH)	Main floor
Indoor air temperature and RH	Thermal	Pegasor AQ Indoor	-20 °C to room temperature 0-100% (RH)	Main floor / loft
Mean radiant temperature	Thermal	Testo 0602 0743 Globe Temperature	0 to + 120 °C	Main floor
Indoor illumination	Visual	REED R8100SD Data Logging Light Meter	0 ro 100, 000 Lux	Main floor
Indoor sound level	Acoustic	REED R8070SD-KIT2 Data Logging Sound Meter	0 to 130dB 50dB (dynamic range)	Main floor
CO_2	IAQ	LiCOR (Li-850)	0-20,000 ppm	Main floor / loft
Particle number and surface area concentrations	IAQ	Pegasor AQ Indoor	$<10^1$ to $>10^7$ cm^{-3}	Main floor / loft

Thirty minutes before the start of the experiment, the participant was given two surveys, the in-experiment survey and post-experiment survey, to fill out during and after the experiment. Twenty minutes before the start of the experiment, the indoor environment of the zEDGE Tiny House was adjusted, and the experimental instruments were calibrated by referencing the experimental data sheet. During the experiment, each participant spent a minimum of 1 hour and a maximum of 12 hours carrying out work-from-home activities as they would in their own homes. A qualified researcher was on-site to monitor the instruments, collect the IEQ and energy data, and answer any questions that the participant had. Furthermore, the participant filled out the in-experiment survey related to the IEQ and energy usage patterns, specifically about hourly activities, hourly satisfaction levels of IEQ variables based on a 7-point scale (3-very satisfied, 2-satisfied, 1-slightly satisfied, 0-neutral, -1-slightly dissatisfied, -2-dissatisfied, -3-very dissatisfied), and hourly settings of main appliances, including A/C setpoints, power ventilator setpoints, and humidifier setpoints. At the end of the experiment, the participant informed the researcher about the conclusion of the stay and filled out a post-experiment survey in the Architectural Engineering Teaching Lab, providing an overall IEQ satisfaction assessment and energy activities during the entire period spent in the zEDGE Tiny House. Meanwhile, researchers cleaned up the zEDGE Tiny House, collected data from each experimental instrument, and saved all files on a password-protected hard drive anonymously.

The state in which heat balance across the body and environment is in equilibrium is called Thermal comfort (Guerra-Santin et al., 2016). Generally, The Predicted Mean Vote (PMV) model is an established approach for determining the thermal comfort conditions in an air-conditioned or naturally ventilated building. The PMV equation was developed by Fanger and it has been expanded into the ASHRAE 55-2023 (Silva et al., 2016) seven-point thermal sensation scale or PMV index. The PMV is collected via participants' in-experiment survey responses. The range of the scale is similar to the TSV scale. Also, PMV is calculated using four measurable variables (i.e., air velocity, air temperature, mean radiant temperature and relative humidity) and two (2) expected parameters (clothing and metabolism rate). The PMV equation is presented in Eqn1 as follows:

$$\begin{aligned} PMV = (0.303e^{-0.0336}M + 0.028) \\ \times \{(M - W) - 3.5 \times 10^{-3}[5733 - 6.99(M - W) - pa] - 0.42(M - 58.5) \\ - 1.7 \times 10^{-5} \times M(5867 - pa) - 0.0014M(34 - ta) \\ - 3.96 \times 10^{-8} fcl \times [4(tcl + 273) - 4(tr + 273)] - fcl \times hc(tcl - ta)\} \end{aligned} \quad (1)$$

where *M* and *W* are the metabolic rates and external work (W/m^2), *Pa* is the partial water vapor pressure (Pascal), *ta* and *tr* are the air temperature and mean radiant temperature, respectively (ºC), *tcl* is the surface temperature of clothing, and *hc* is the convective heat transfer coefficient. The calculation procedure for *tcl* and *hc* can be referred to in (Broday et al., 2017). Information on clothing type was asked in the survey and these were prepared in line with the ASHRAE Standard 55-2023. Furthermore, Fanger proposed the Predicted Percentage Dissatisfied (PPD) parameter, and this predicts the percentage of people who feel more than slightly warm or cool (Cheung et al., 2019). Upon developing the PPD, an empirical relationship between PMV and PPD was established as shown in Eqn 2 as follows:

$$PPD = 100 - 95e^{-0.03353 \times PMV^4 - 0.219 \times PMV^2} \quad (2)$$

3. RESULT AND DISCUSSION

3.1 Analysis of IEQ Measurements and Surveys During the Compact Living Space Experiments

Measurements of the PMV, CO2 concentration, sound intensity, indoor illuminance, particle number concentration, and particle surface area concentration are presented in Figure 4 for all 20 compact living space experiments. To assess occupants' comfort level during their stay in the zEDGE Tiny House, the PMV with a 7-point scale utilized was compiled in the experiment hourly log for participants to fill out based on their real-time sensation of all four IEQ parameters. The scale has a range of following points: +3 (very satisfied); +2 (satisfied); +1 (slightly satisfied); 0 (neutral); -1 (slightly dissatisfied); -2 (dissatisfied); -3 (very dissatisfied). At the end of the experiment, participants filled out a post-experiment survey to report their overall satisfaction level based on a TSV scale, which has a similar 7-point system as the PMV scale: +3 (hot); +2 (warm); +1 (slightly warm); 0 (neutral); -1 (slightly cool); -2 (cool); -3 (cold). The top plot presents the box plots of PMV and TSV, where the box color represents the TSV reported by the participants, and the y-axis scale represents the overall PMV range for thermal comfort. Since the experiments were carried out during the winter months, most of the participants reported that they felt either slightly cool or cool, with 16 TSV responses matching the PMV range. In the post-experiment survey, participants evaluated their IAQ satisfaction using a 7-point scale similar to the PMV system. The IAQ satisfaction level was assessed in relation to CO_2 concentrations, as well as the number and surface area concentrations of fine and ultrafine particles in the air.

Regarding CO2 concentrations, ANSI/ASHRAE Standard 62.1-2022 recommends that indoor CO2 concentrations should be less than 1,000 ppm to ensure occupants' comfort and health, and most of the living experiments in zEDGE met this requirement. There was one participant who expressed dissatisfaction, noting an average CO2 concentration of 1,000 ppm, with fluctuations between 750 and 1,300 ppm. However, analysis revealed no clear link between CO2 concentrations and IAQ satisfaction; participants often reported being satisfied with the IAQ even at varying CO2 concentrations. Specifically, participant #17 reported being satisfied across a range of 1,700 to 1,900 ppm.

In addition to CO2, fine and ultrafine particles represent an important indoor air pollutant category. The data suggested a trend: higher particle number concentrations tended to coincide with lower IAQ satisfaction ratings. This observation implies that particle number concentrations may play a more critical role in influencing occupants' perception of air quality than CO2 concentrations. The sound intensity analysis across all 20 experiments showed average levels ranging from 48 to 63 dBA. This is above the typical residential noise levels of 30 to 40 dBA. The data suggests that higher sound levels may lead to discomfort. For instance, participant #14, who was exposed to an average sound intensity of 47.5 dBA, reported being "very satisfied" in their post-experiment survey. In contrast, participant #7, who encountered a higher average sound level of 64 dBA, expressed being "somewhat dissatisfied." This trend highlights a potential correlation between increased sound levels and reduced satisfaction with the indoor environment in tiny homes.

The analysis of indoor illuminance and participant-reported visual satisfaction levels was depicted in an indoor illuminance plot. The data revealed that the maximum measured indoor illuminance level reached 403 lux, while average levels varied from 95 to 379 lux across different spaces. According to standards set by the Chartered Institution of Building Services Engineers (CIBSE) and EN17037-IL, an illuminance level of 300 lux or less is deemed adequate for most residential activities. The findings from our study align with these standards, as most measured illuminance levels were below 300 lux, suggesting that the indoor lighting of zEDGE was generally sufficient for the occupants' needs. Feedback from participants further supported this, indicating overall satisfaction with the lighting conditions within the zEDGE Tiny House. This satisfaction with indoor lighting levels underscores the importance of aligning lighting design with established standards to ensure both functionality and comfort in residential settings.

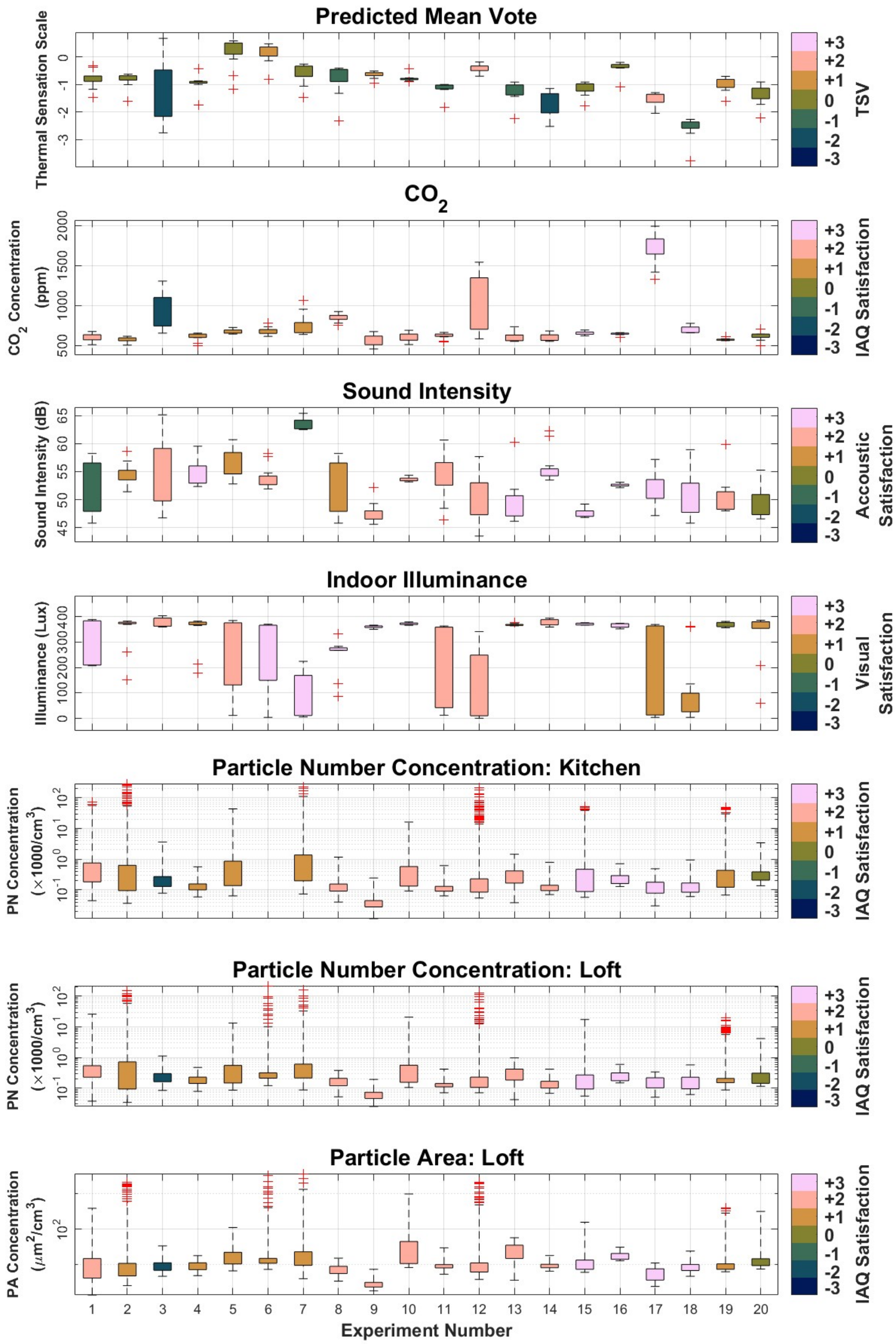

Figure 4: Box plot of IEQ measurement in the Purdue zEDGE Tiny House and corresponding occupant satisfaction levels for all 20 compact living space experiments.

3.2 Analysis of Energy Consumption During the Compact Living Space Experiments

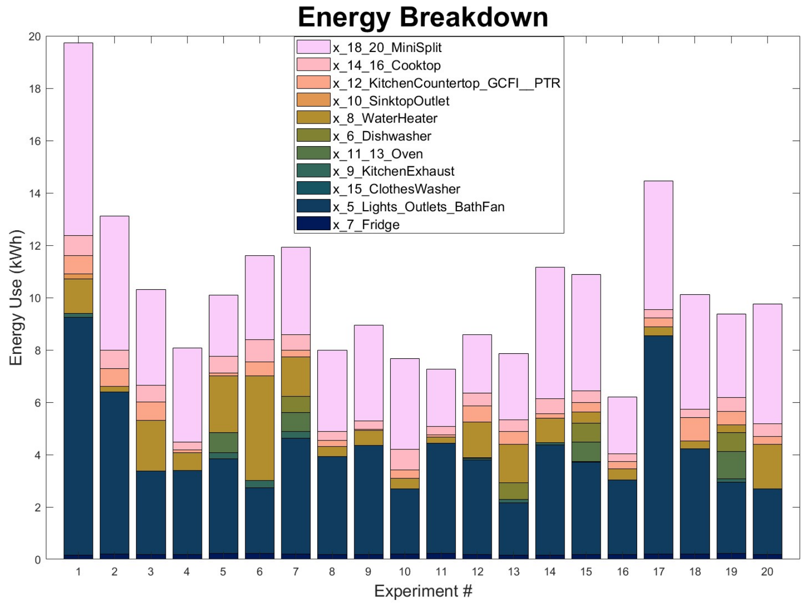

Figure 5: Summary bar plot of energy consumption of all 20 participants.

During the 20 experiments conducted, total energy consumption varied significantly, ranging from 6.19 to 19.72 kWh, and Figure 5 presents the summarized stacked bar plot with electricity consumption of each individual breaker. It was noted that experiments involving fewer cooking activities tended to use less energy. On average, the energy consumption across all experiments was 10.3 kWh. The highest recorded energy use stood out, exceeding the next highest by 6.6 kWh — a margin larger than the lowest energy consumption recorded in any experiment. This is due to extended use of mini-split heating/cooling unit due to colder external conditions to ensure adequate IEQ satisfaction. Further investigation revealed that, in addition to cooking and heating, which are major energy consumers, the experiment with the highest energy usage featured unique adjustments to the power ventilator by the occupant. This adjustment was a significant factor contributing to the increased energy consumption observed.

When comparing the energy usage per square footage to other living spaces of similar size, the tiny house's consumption patterns were found to be relatively efficient. Typical tiny houses and small apartments in similar climates and usage scenarios often exhibit a broad range of energy consumption rates, generally falling between 8 and 25 kWh per day. Given that the average energy consumption for our experiments was 10.3 kWh, the tiny house's performance is on the lower end of this spectrum, suggesting that despite the variations due to individual activities and external conditions, the energy efficiency measures in place were effective. This comparison underscores the potential for optimizing energy use in compact living spaces through targeted interventions in occupant behavior and system controls.

3.3 Correlation Analysis Between Particle Number Concentrations and CO_2 Concentrations

To examine the relationship between the CO2 concentration data measured by the LI-COR device and particle number concentration data gathered using the PIAQ sensor from all 20 compact living space experiments, Figure 6 showcases a correlation plot that juxtaposes these two parameters. Analysis of this plot reveals that there is no evident correlation between CO2 concentrations and particle number concentrations across all experiments. For instance, there are moments when, despite a low particle number concentration, CO2 concentrations surged to a concentration of 2,000 ppm. Conversely, there are instances where CO2 concentrations were within normal ranges, yet the particle number concentration was notably high. This lack of consistent relationship indicates that CO2 concentrations and particle number concentrations vary independently under the conditions of these experiments. For example, in experiment #5, extensive cooking activities generated a significant number of fine and ultrafine particles. However, the CO2 concentrations remained nearly constant during this period as the occupancy remained unchanged.

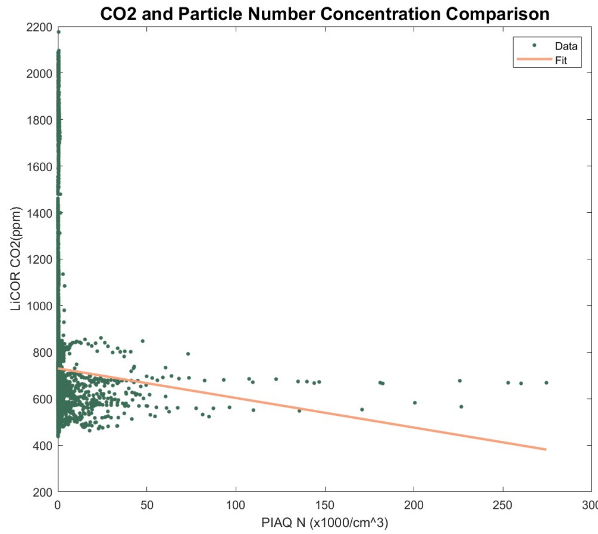

Figure 6: Correlation plot between CO_2 concentrations and particle number concentrations.

3.4 Correlation Analysis Between Occupant Activities and Mini Split Setpoint Temperature

The box plot shown in figure 7 illustrates the relationship between setpoint temperature of a mini-split air conditioner (AC) and various occupant activities, such as eating, working, cooking, resting, showering, cleaning, being out, and baking. Most activities have a median setpoint temperature around 25°C, indicating a general preference for this temperature during these activities. However, cooking, taking shower, and baking showcase lower median setpoint temperatures, around 22°C, suggesting that occupants prefer cooler temperatures while conducting these activities. This data can be useful for optimizing AC settings to enhance comfort and energy efficiency by adjusting temperatures according to the specific activities being performed.

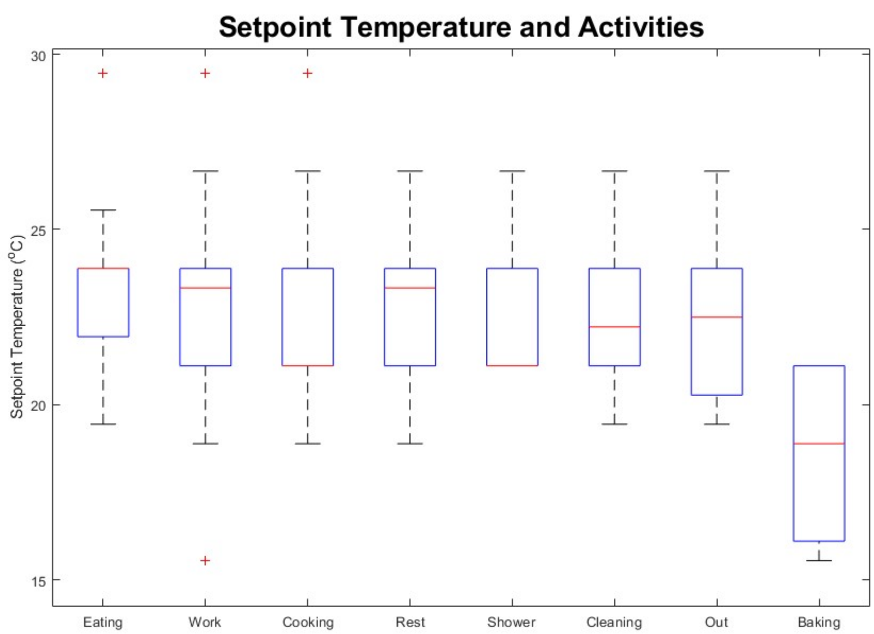

Figure 7: Box plot illustrating the correlation between mini-split AC setpoint temperatures and various occupant activities.

4. CONCLUSION

This investigation into compact living spaces underscores the critical importance of energy monitoring and brings novel insights into the interplay between IEQ, IAQ, and energy usage. The research conducted in the zEDGE Tiny House presents practical implications for the design and operation of HVAC systems in such environments. By meticulously monitoring and analyzing specific IEQ indicators such as temperature, air quality, and relative humidity, the study identifies key design and operational strategies that can significantly enhance the health and well-being of occupants. The findings recommend the adoption of integrated, energy-efficient HVAC systems tailored for small spaces, which include advanced sensor technologies for dynamic environmental control. While these systems may have higher initial costs, the long-term benefits of improved health, comfort, and energy savings justify the investment. Additionally, the study advocates for HVAC systems that incorporate air purification technologies to ensure optimal air quality, crucial in confined living spaces. These insights pave the way for more sustainable and health-conscious design practices in densely populated urban areas and call for a revision of current building codes and standards to accommodate the unique needs of micro apartments and tiny homes, emphasizing the need for further research to refine and expand these recommendations.

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