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User-centred smart building technologies for climate-resilient urban development: evidence from Istanbul

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Promoting sustainable urban development requires strengthening climate resilience while encouraging environmentally responsible lifestyles in cities. In densely urbanised and climatically diverse contexts such as Istanbul, Smart Environmental Control Technologies (SECTs) offer significant potential to reduce energy demand, enhance thermal comfort, and support low-carbon urban living. This study examines the role of SECTs in advancing climate-resilient urban development by analysing occupants' perceptions, satisfaction, and behavioural responses in residential and commercial buildings. The study aims to: (i) assess user satisfaction with SECTs; (ii) evaluate their contribution to energy efficiency in buildings (EEB); (iii) analyse their role in climate resilience and emission reduction (CRER); and (iv) propose design-oriented recommendations for optimising Smart Energy Building Design (SEBD). A mixed-methods approach was adopted, combining semi-structured interviews with 20 key informants and a quantitative survey of 237 building occupants. Quantitative data were analysed using SPSS (version 24), applying descriptive statistics, ANOVA, regression analysis, Pearson correlation, the Relative Importance Index (RII), and thermal comfort modelling based on Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfied (PPD). Qualitative data were examined through thematic analysis to support triangulation. The results reveal high levels of occupant awareness and acceptance of smart technologies, with automated HVAC systems, IoT-enabled sensors, and smart thermostats identified as the most influential solutions for thermal comfort management (RII > 0.85). Regression analysis indicates that SECT adoption significantly predicts user satisfaction and energy efficiency performance ($\beta = 0.64$, $p < 0.001$), while correlation analysis confirms a strong association between objective comfort indices and subjective perceptions ($r = 0.68$, $p < 0.01$). PMV/PPD modelling shows that smart systems maintained generally acceptable comfort conditions, with mean PPD values ranging from 8.4% in residential units to 18.9% in shared offices, and peak dissatisfaction exceeding 22% during high-occupancy periods. Buildings equipped with adaptive SECTs achieved average peak energy demand reductions of approximately 15–20% compared to conventional systems. Overall, the findings provide evidence-based guidance for designing user-centred, energy-efficient, and climate-resilient smart buildings, reinforcing the strategic role of SEBD in sustainable urban development.

KEYWORDS
climate-resilient cities, energy efficiency, smart building technologies, sustainable urban development, thermal comfort, user-centred design

1 Introduction

Rapid urbanisation and accelerating climate change are placing unprecedented pressure on urban energy systems, infrastructure, and environmental sustainability. Cities are responsible for a significant share of global energy consumption and carbon emissions, with the building sector alone accounting for nearly 40% of total energy use worldwide (Dechamps, 2023; Raimi et al., 2022). In densely populated urban contexts, the demand for thermal comfort through mechanical heating, ventilation, and air conditioning (HVAC) systems has become one of the primary drivers of energy consumption and greenhouse gas emissions (Ali and Akkaş, 2023; Ajayi et al., 2024). In view of this development, the integration of smart technologies into the built environment has become a central strategy for advancing sustainable urban development, improving energy efficiency, and enhancing occupant well-being in contemporary cities.

Accelerated urbanisation, climate change pressures, and rising energy demand have intensified the need for buildings that are not only technologically efficient but also socially responsive and environmentally responsible. In this context, smart or intelligent buildings enabled by Internet of Things (IoT) systems, sensor networks, automation, and data-driven controls offer significant potential to optimise building performance while supporting climate-resilient and user-centred urban living (Gagakuma, 2025; Ogundiran et al., 2024). These developments closely align with the United Nations Sustainable Development Goals (SDGs), which emphasise the creation of inclusive, safe, resilient, and sustainable urban environments. Buildings are a critical component of urban systems, accounting for a substantial share of global energy use and greenhouse gas emissions. Smart building technologies contribute to enhancing urban liveability, improving indoor environmental quality, and enabling more efficient use of infrastructure within dense metropolitan contexts (Ogundiran et al., 2024; Apanavičienė and Shahrabani, 2023). By integrating real-time monitoring and adaptive control, smart buildings can respond dynamically to changing environmental conditions and user needs, thereby supporting resilient urban systems.

The relevance of smart building solutions is especially pronounced in cities such as Istanbul, where rapid urban growth, high population density, and climatic variability present persistent challenges for energy management and occupant comfort. Istanbul experiences hot and humid summers alongside cool, damp winters, placing significant strain on heating, ventilation, and air-conditioning (HVAC) systems. In response, smart buildings deploy advanced environmental controls to manage thermal conditions, lighting, and energy consumption in real time. These capabilities not only improve operational efficiency but also support SDG 12 (Responsible Consumption and Production) by promoting energy conservation, reducing waste, and encouraging more sustainable patterns of resource use at the building and occupant levels (Reddy et al., 2024; Ajayi et al., 2024).

Thermal comfort is a critical dimension of this sustainability transition. Defined as a condition of satisfaction with the thermal environment, comfort emerges from the interaction of environmental variables such as temperature, humidity, air movement, and radiant heat and personal factors including activity, clothing, and adaptive behaviour (De Dear and Brager, 2002; Lamberti et al., 2023). Importantly, thermal comfort perception is subjective and culturally mediated, varying across climatic regions and social contexts. Adaptive comfort models therefore advocate for flexibility, personal control, and behavioural responsiveness rather than rigid thermal standards. Smart technologies are uniquely positioned to operationalise these principles by integrating automation with user feedback, predictive analytics, and personalised control interfaces.

From a climate policy perspective, smart thermal comfort solutions directly support SDG 13 (Climate Action) by reducing building-related carbon emissions and enhancing adaptive capacity to climate variability. Energy-efficient HVAC systems, smart controls, and data-driven optimisation reduce reliance on fossil fuels while enabling buildings to adjust to extreme weather events and seasonal fluctuations (Ajayi et al., 2024; Billanes et al., 2025). When combined with informed and engaged occupants, these systems contribute to both mitigation and adaptation strategies, reinforcing the role of buildings as active agents in climate action rather than passive energy consumers. Despite these advantages, much of the existing literature on smart buildings prioritises technical efficiency, automation performance, and energy optimisation, often overlooking the human-centred dimensions of comfort, usability, and acceptance (Sudarsanam and Kannamma, 2023; Najafi et al., 2025). The success of smart technologies ultimately depends on occupants' perceptions, behaviours, and willingness to engage with these systems. Socio-cultural norms, lifestyle practices, expectations of comfort, and levels of perceived control significantly influence how users interact with smart environments, yet these factors remain underexplored, particularly in non-Western and rapidly urbanising contexts (De Dear and Brager, 2002; Banfi et al., 2024).

Istanbul provides a highly relevant empirical context for examining smart building performance due to its climatic diversity, dense urban morphology, and rapid technological transformation. The city experiences significant seasonal temperature variations, ranging from hot summers to cold winters, which intensify thermal comfort challenges for building occupants (Banfi et al., 2024; Bay-Şahin and Elnimeiri, 2025). It is also a city characterised by the coexistence of traditional cultural practices and rapid technological modernisation. Empirical evidence on how these socio-cultural dynamics affect the acceptance, satisfaction, and perceived effectiveness of smart thermal comfort technologies in Istanbul remains limited. Furthermore, while adaptive comfort models are widely discussed theoretically, their empirical validation within region-specific climatic and cultural settings such as Istanbul's transitional Mediterranean climate remains insufficient. Therefore, the diversity offers an ideal setting for investigating how Smart Environmental Control Technologies (SECTs) operate across different architectural forms and socio-economic conditions, enabling a more nuanced understanding of smart technology performance in real-world urban environments.

In response to these gaps, this study aims to examine how smart technologies contribute to user satisfaction, energy efficiency, and climate resilience in buildings in Istanbul. The study seeks to advance understanding of smart buildings as socio-technical systems that support climate-resilient cities and environmentally conscious lifestyles. The specific objectives of the study are to:

1 Awareness and satisfaction with Smart Environmental Control Technologies (SECTs) and Thermal Comfort Management;
2 Examine the role of Smart Environmental Control Technologies (SECTs) in promoting Energy Efficiency in Buildings (EEB);
3 Analyse how Smart Environmental Control Technologies (SECTs) support Climate Resilience and Emission Reduction (CRER);
4 Optimise Smart Energy Building Design (SEBD) in support of sustainable urban development.

By addressing these objectives, the study contributes both theoretically and practically. It bridges the gap between technological innovation and human experience, provides empirical evidence grounded in a rapidly urbanising and climatically complex city, and supports policy-relevant discussions on how smart buildings can advance global sustainability goals. Ultimately, the research positions smart thermal comfort technologies as key enablers of sustainable cities, responsible resource use, and effective climate action. Based on the research objectives, the following hypotheses were tested:

> *H1*: There is a significant positive relationship between the level of SECT implementation and occupant satisfaction in Istanbul buildings.
>
> *H2*: The adoption of SECTs is significantly associated with reduced building energy consumption per capita.
>
> *H3*: SECT implementation significantly reduces peak energy demand during extreme climatic conditions.
>
> *H4*: Context-sensitive SEBD strategies significantly moderate the relationship between SECT adoption and sustainable urban performance.

This study contributes to sustainable urban development by integrating technological, behavioural, and environmental perspectives into smart building research. By focusing on user-centred smart energy building design in a dense Mediterranean megacity such as Istanbul, the research advances a holistic framework that provides a user-centred smart energy building design framework. Through empirical evidence from Istanbul, the study offers policy-relevant insights for designing inclusive, adaptive, and low-carbon urban environments, by the architects, engineers, urban planners, and policymakers; thereby reinforcing the strategic role of smart technologies in shaping resilient cities of the future.

The structure of this paper is organised to provide a logical and coherent presentation of the research process. Section 2 reviews the existing literature on smart building technologies, thermal comfort models, and sustainability frameworks, establishing the conceptual foundation for the study. Section 3 outlines the methodological approach, detailing the survey design, environmental data collection, and analytical procedures used to examine user experiences. Section 4 presents the results and discussion, integrating findings to reveal how smart technologies influence thermal comfort in Istanbul's urban environment. Finally, Section 5 concludes the paper by summarising the major findings, outlining practical recommendations for design and policy implementation, and suggesting directions for future research.

2 Review of literature

2.1 Smart environmental control technologies in buildings

Smart Environmental Control Technologies (SECTs) represent a transformative approach to building performance management. These technologies integrate digital sensors, automation systems, and real-time data analytics to regulate indoor environmental conditions more efficiently than traditional systems (Al Dakheel et al., 2024; Fan et al., 2025). Smart technologies are increasingly recognised as critical enablers of sustainable, climate-resilient, and people-centred urban development. Core components of SECTs include smart HVAC systems, IoT-enabled temperature and humidity sensors, automated shading devices, smart thermostats, and intelligent energy management platforms (Al Dakheel et al., 2024). By enabling continuous monitoring and adaptive control, SECTs allow buildings to respond dynamically to changes in occupancy, user behaviour, and external climate conditions. This not only improves thermal comfort but also reduces unnecessary energy consumption through demand-responsive operations (Rane et al., 2023; Agboola et al., 2024). As such, SECTs play a critical role in advancing smart energy building design and promoting sustainable urban development. In buildings, smart systems use interconnected Internet of Things (IoT) networks, sensors, automation, and data analytics to continuously monitor and manage indoor conditions such as temperature, humidity, air quality, and lighting in real time (Marques and Pitarma, 2016; Rane et al., 2023). By adjusting operations based on occupancy, outdoor climate, and user preferences, these systems enhance thermal comfort while reducing energy demand and operational waste, and improving urban liveability and resilience.

Thermal comfort relates to occupants' satisfaction with thermal environment, emerges from a complex interaction of environmental and personal factors, which is essential for health and productivity (De Dear and Brager, 2002; Lamberti et al., 2023). It is a fundamental dimension of indoor environmental quality and has direct implications for occupant health, productivity, and overall well-being. It is commonly defined as a condition of the mind that expresses satisfaction with the thermal environment (ASHRAE, 2004; Lamberti et al., 2023). Smart technologies support adaptive comfort by integrating predictive HVAC controls, AI-driven climate systems, and personalised interfaces that respond dynamically to seasonal shifts, usage patterns, and user behaviour. In Türkiye, national climate and urban policies reflect these priorities. The Türkiye Spatial Strategy Plan 2053 calls for the creation of disaster-resistant, climate-resilient, and productive cities, integrating environmental objectives into urban planning and infrastructure development (Avatkov and Sbitneva, 2023). Istanbul's Green City Action Plan and sensor-based energy monitoring projects seek to transition buildings toward greener and carbon-neutral operations, promoting efficient energy use and climate adaptation within municipal sustainability frameworks (Varlı and Gider, 2025). Additionally, national energy efficiency and urban transformation policies target reduced energy consumption in public buildings and wider adoption of renewable energy solutions, further reinforcing the climate and sustainability agenda at multiple governance levels (Meng et al., 2023; Avatkov and Sbitneva, 2023).

Comparative examples from Asia demonstrate how smart urban design and building technologies can support sustainability goals across diverse contexts. In Singapore, integrated smart building retrofits such as the Keppel Bay Tower zero-energy commercial building combine real-time diagnostics, smart lighting, automated HVAC, and stakeholder engagement to reduce energy use and carbon footprint while maintaining comfort standards, illustrating pathways toward net-zero energy buildings (Das, 2025; Fan et al., 2025). Similarly, Songdo in South Korea exemplifies a planned smart city with extensive LEED-certified infrastructure, underground waste management, and electric mobility pathways that strengthen sustainable urban systems and user-centric environmental solutions (Islam et al., 2024). In

Istanbul's mixed-use urban districts, smart thermal comfort technologies can bridge the gap between technological potential and lived experience by accounting for region-specific climatic variation, cultural adaptation, and occupant behaviour. By embedding smart systems within broader policy frameworks and aligning them with national sustainability agendas, cities can move toward sustainable, resilient, and human-centred urban futures.

Table 1 presents a summary of recent empirical studies on smart building technologies and sustainable urban development conducted within climatic contexts comparable to Istanbul. It presents key information such as study location, climatic zone, research focus, methodology, main findings, and identified limitations. This representation enables a clearer comparison of existing studies and highlights how most prior research has predominantly focused on either technical performance (energy efficiency and system optimisation) or general user satisfaction, with limited integration of user-centred thermal comfort, behavioural adaptation, and socio-cultural determinants within a single analytical framework. The table explicitly accentuates the research gap addressed by the present study, namely the lack of empirical, mixed-method investigations that simultaneously examine smart environmental control technologies, occupant perceptions, and climate resilience in a dense Mediterranean urban context such as Istanbul. This table strengthens the theoretical positioning of this study and improves the clarity of its novelty and contribution to the literature.

TABLE 1 Summary of extant literature on smart building technologies and sustainable urban development in mediterranean climatic contexts.

Author(s)	Study Location/ Climatic Zone	Research focus	Methodology	Key findings	Research gap identified and addressed in this study
Meng et al. (2023) and Fan et al. (2025)	Istanbul, Turkey (Mediterranean)	Energy performance of smart residential buildings	Energy simulation + field measurements	Smart HVAC and automation significantly reduced cooling energy demand	Limited consideration of user perception and behavioural factors
Erişen (2023) and Mirrahimi et al. (2016)	Izmir, Turkey (Mediterranean)	Smart building systems for thermal comfort	Survey + regression analysis	Smart control systems improved perceived comfort and energy efficiency	Did not integrate qualitative insights or socio-cultural variables
Hussein and Acaroğlu (2025)	Mediterranean cities (Turkey & Iran)	Passive and smart design strategies	Comparative case studies	Smart shading and ventilation improved indoor comfort	Focused on technical performance only
Muhaidat et al. (2021) and Banfi et al. (2024)	European cities (Mediterranean climate)	Occupant behaviour and energy use	Longitudinal monitoring + surveys	User behaviour strongly influences smart system effectiveness	Lacked context-specific cultural analysis
Parkinson et al. (2019)	Mediterranean buildings	Adaptive thermal comfort	Field survey	Comfort is shaped by adaptive behaviour rather than fixed standards	Did not assess smart technologies
Humphreys and Nicol (2002)	Mediterranean climates	Thermal comfort adaptation	Large-scale surveys	Users tolerate wider comfort ranges	No technological dimension
Cichowicz and Bochenek (2024) and Ali and Akkaş (2023)	Mediterranean urban areas	Urban microclimate and thermal stress	Simulation modelling	Urban form affects thermal comfort significantly	No smart building systems considered
Pourshaghaghy and Omidvari (2012)	Warm climates	Green buildings and comfort	Post-occupancy evaluation	Smart systems improve indoor satisfaction	Limited urban policy implications
Isikdemir et al. (2022)	Istanbul, Turkey	Smart housing and sustainability	Case study	Energy savings achieved through automation	Did not examine socio-cultural acceptance
Agboola et al. (2024) and Ali and Akkaş (2023)	Istanbul, Turkey	Smart buildings and post-pandemic comfort	Mixed methods	Smart technologies enhanced resilience and well-being	Did not integrate machine learning or system prioritisation

2.2 User behaviour and sustainable urban development in the built environment

The significance of user behaviour and technology adoption in smart buildings could not be overemphasised. Despite the technical potential of smart building systems, their effectiveness largely depends on user acceptance, interaction, and trust. Previous studies indicate that poor usability, lack of digital literacy, privacy concerns, and affordability issues often hinder the successful adoption of smart technologies (Fabi et al., 2012; Banfi et al., 2024). In many cases, advanced systems fail to deliver expected performance benefits because users do not fully understand or engage with them. Socio-cultural determinants such as household structure, cultural norms, and perceptions of automation play a moderating role in shaping how occupants interact with smart environmental controls (Banfi et al., 2024; Magliocca et al., 2025). Understanding these human dimensions is therefore essential for translating technological innovation into real-world sustainability outcomes.

Table 2 indicates that although substantial progress has been achieved in the domains of thermal comfort modelling, smart technology adoption, and digital ethics, these strands of scholarship remain insufficiently integrated. Existing studies have largely applied the Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfied (PPD) models as a standard tool for assessing indoor comfort. However, it has rarely been empirically tested within real-time adaptive smart building systems where environmental conditions are continuously regulated by automated technologies (Lamberti et al., 2023; Sudarsanam and Kannamma, 2023). Similarly, research informed by behavioural economics has primarily focused on technology acceptance and energy-use behaviour, but has paid limited attention to the psychological dimensions of comfort and their interaction with smart environmental controls (Pakravan and MacCarty, 2021; Cioc et al., 2023). In parallel, debates surrounding Internet of Things (IoT) and data privacy have been dominated by conceptual, legal, and ethical perspectives, with relatively little empirical evidence derived from actual residential user experiences. Furthermore, adaptive comfort theory, while extensively developed in field-based studies, remains largely disconnected from automation-driven environments, particularly those characterised by algorithmic control and intelligent building systems.

In response to these limitations, the present study adopts an integrative approach that bridges these fragmented research streams. Specifically, it empirically evaluates PMV and PPD within IoT-enabled smart buildings operating under real-time adaptive control. The study further incorporates behavioural and socio-cultural constructs into thermal comfort modelling, thereby extending conventional engineering-based frameworks to include user perceptions, practices, and contextual influences. Privacy perception and trust in automation are also introduced as moderating variables, acknowledging the growing importance of digital ethics in shaping technology acceptance (Lamberti et al., 2023). By linking adaptive comfort theory with smart environmental control technologies, the study positions itself at the intersection of thermal science, behavioural theory, and smart urbanism, an interdisciplinary space that remains underexplored in existing literature.

3 Summary of the review of literature, theories, research gaps, and hypothesis development

The reviewed literature indicates substantial progress in the understanding of smart building technologies, thermal comfort, and sustainable urban development, particularly within Mediterranean

TABLE 2 Present literature gaps in smart building technologies and thermal comfort research.

Thematic area	Key studies (Indicative)	Dominant focus in existing literature	Limitations of existing studies	Research gap identified and addressed in this study
Critiques of PMV in Diverse Climatic Contexts	De Dear and Brager (2002), Nicol and Humphreys (2002), and Fanger (1970)	Validation and application of PMV and adaptive comfort models	PMV often assumes static thermal conditions and underrepresents behavioural adaptation in smart environments	Lack of empirical assessment of PMV performance within IoT-enabled smart buildings under real-time adaptive control
Behavioural Economics and Smart Home Adoption	Vassileva et al. (2017), Cioc et al. (2023), and Pakravan and MacCarty (2021)	Technology acceptance, energy behaviour, rational choice models	Limited integration of psychological comfort and environmental satisfaction variables	Insufficient application of behavioural economics to link smart system adoption with thermal comfort outcomes
IoT, Data Privacy and Residential Ethics	Karale (2021), Bibri (2015), and Fan et al. (2025)	Surveillance, data ownership, and digital ethics	Mostly conceptual or legal discussions with minimal empirical user data	Absence of user-centred empirical evidence on privacy perception affecting smart building acceptance
Adaptive Thermal Comfort Beyond Classical Models	De Dear and Brager (2002) and Lamberti et al. (2023)	Adaptive comfort theory and field studies	Often detached from smart technology environments and automation systems	Limited empirical integration of adaptive comfort with smart environmental control technologies

and transitional climatic contexts comparable to Istanbul. Existing studies have predominantly concentrated on technical and engineering-oriented performance indicators, including energy efficiency, system optimisation, and passive design strategies. Empirical evidence consistently shows that smart HVAC systems, automated lighting, and real-time monitoring platforms can significantly reduce building energy demand while enhancing indoor environmental quality (Mirrahimi et al., 2016; Fan et al., 2025). These findings align with Systems Theory, which conceptualises buildings as dynamic socio-technical systems where environmental performance emerges from the interaction between technological subsystems and human users (Lowe et al., 2018; Fan et al., 2025).

From a comfort perspective, much of the existing research is grounded in Fanger's Rational Comfort Theory (PMV/PPD model), which assumes thermal satisfaction can be predicted from measurable physical variables (Fanger, 1970; ISO, 2005; Parsons, 1995; Tartarini and Schiavon, 2025). Complementarily, Adaptive Comfort Theory argues that occupants actively adjust their behaviour, expectations, and thermal preferences in response to environmental conditions, particularly in naturally ventilated or mixed-mode buildings (De Dear and Brager, 2002; Nicol and Humphreys, 2002). While both models are well established, they are rarely examined within fully automated, IoT-enabled smart environments, where real-time algorithms dynamically regulate indoor conditions with limited direct occupant control. Moreover, behavioural and psychological dimensions of smart buildings remain under-theorised. Research drawing on Human–Technology Interaction Theory suggests that user satisfaction is not determined solely by physical comfort but also by perceived system transparency, control, trust, and usability (Ali and Akkaş, 2023; Magliocca et al., 2025). However, most smart building studies continue to treat occupants as passive recipients of environmental conditions rather than active agents within cyber-physical systems (Fan et al., 2025). Despite extensive conceptual debate, empirical evidence on how occupants experience and interpret smart monitoring technologies remains limited, particularly in dense urban contexts where digital infrastructures increasingly mediate everyday life.

Consequently, a major research gap exists in the lack of integrated, mixed-method, user-centred empirical studies that simultaneously examine (i) objective environmental performance, (ii) subjective occupant experience, and (iii) the socio-technical and ethical implications of smart building systems. Existing research remains fragmented across engineering, behavioural science, and urban sustainability domains, with few studies adopting a holistic analytical framework that reflects the complexity of real smart environments. The present study addresses this gap by adopting an interdisciplinary approach grounded in Systems Theory, Adaptive Comfort Theory, and Human–Technology Interaction Theory, to investigate Smart Environmental Control Technologies (SECTs) in Istanbul. It empirically integrates sensor-based performance data, occupant surveys, and expert insights to evaluate how smart systems influence thermal comfort, energy efficiency, climate resilience, and user satisfaction within a rapidly urbanising metropolitan context.

Table 3 presents the core research hypotheses developed to guide this empirical investigation. The hypotheses are directly derived from the theoretical foundations and identified research gaps, specifying the expected relationships between key independent variables (SECT components and Smart Energy Building Design strategies) and dependent outcomes (user satisfaction, energy efficiency, climate resilience, and sustainability performance). This structured formulation enables systematic statistical testing and provides a robust analytical framework for assessing the contribution of SECTs to sustainable urban development. Figure 1 graphically synthesises the literature review, theoretical positioning, research gaps, and hypothesis development.

4 Methods

This study adopted a mixed-methods research design, integrating quantitative and qualitative approaches to comprehensively investigate occupants' experiences of Smart Environmental Control Technologies (SECTs). The quantitative component involved a structured questionnaire survey, while the qualitative component consisted of semi-structured interviews. This design enabled both statistical generalisation and in-depth interpretive understanding, thereby strengthening the robustness of the findings through methodological triangulation. Thus, this research framework integrates quantitative and qualitative approaches that capture both objective building performance and subjective occupant experience using Istanbul as the empirical case study.

TABLE 3 Research hypotheses and key variables of the study.

Hypothesis code	Research objective	Hypothesis statement	Key variables
H1	User Satisfaction (Objective 1)	There is a significant positive relationship between the level of Smart Environmental Control Technologies (SECTs) implementation and occupant satisfaction in buildings in Istanbul.	IV: SECT level; DV: Occupant satisfaction
H2	Energy Efficiency in Building (EEB) (Objective 2)	The adoption of Smart Environmental Control Technologies (SECTs) is significantly associated with improved building energy efficiency performance.	IV: SECT components; DV: Energy consumption intensity
H3	Climate Resilience & Emission Reduction (Objective 3)	Buildings equipped with adaptive Smart Environmental Control Technologies (SECTs) demonstrate significantly lower peak energy demand and operational carbon emissions compared to conventionally automated buildings.	IV: SECT adoption; DV: Peak demand, CO_2 emissions
H4	SEBD Policy & Design (Objective 4)	Context-sensitive Smart Energy Building Design (SEBD) strategies significantly enhance the effectiveness of SECTs in achieving sustainable urban performance outcomes.	IV: SEBD strategies; DV: Sustainability performance

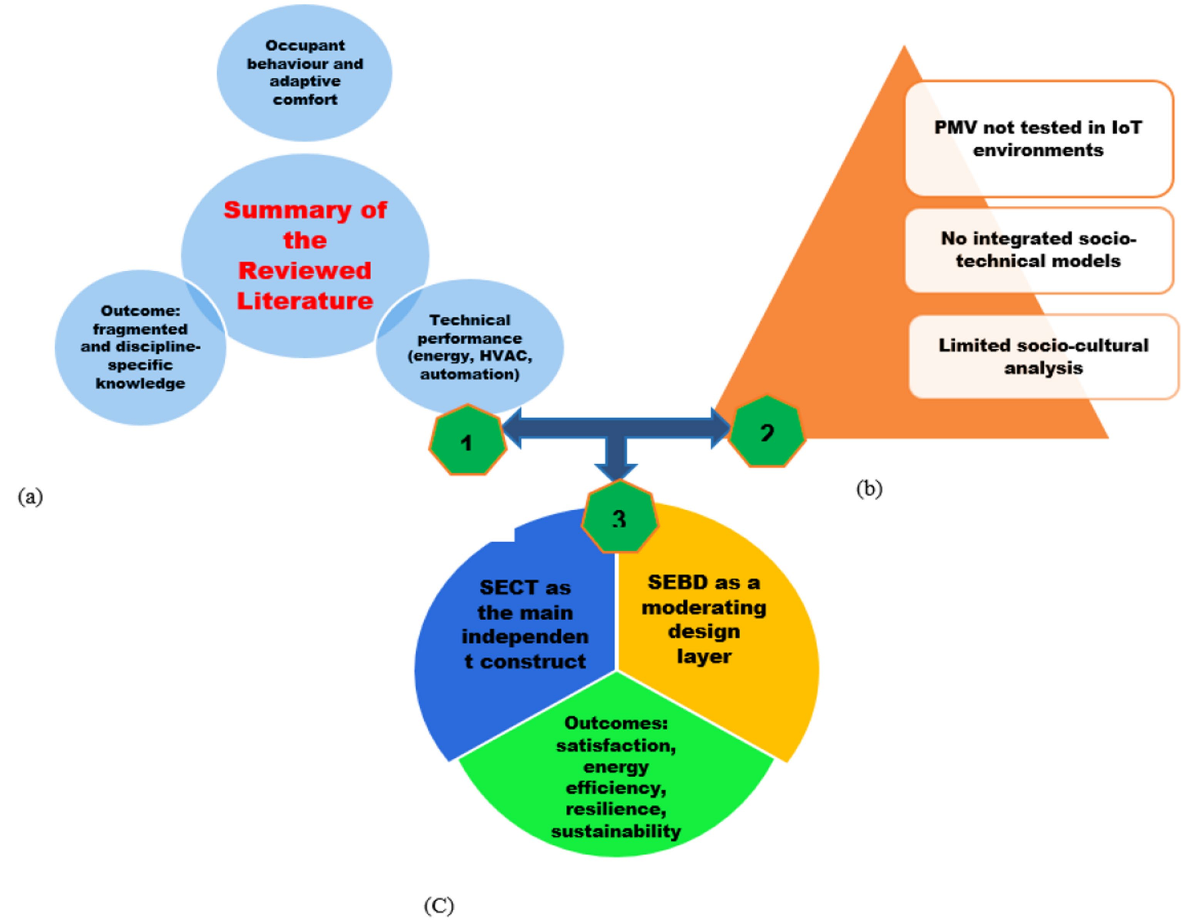

FIGURE 1
(a) Synthesis of literature, **(b)** research gaps, and **(c)** the study's conceptual framework and hypotheses.

This design aligns with established methodological principles that advocate methodological triangulation to enhance validity and explanatory depth (Creswell and Plano Clark, 2018; Patton, 2015).

Quantitative data were generated through environmental monitoring and structured surveys, enabling systematic measurement of thermal variables and user perceptions. These were complemented by semi-structured interviews, which provided contextual insights into behavioural patterns, trust in automation, and socio-cultural influences on technology use. The integration of multiple analytical models, PMV and PPD, Regression and ANOVA, supports cross-validation and strengthens causal inference across different layers of analysis (Hair et al., 2021). Overall, the framework (Figure 2) reflects a human-centred smart building research paradigm, where technical performance is interpreted through behavioural and socio-cultural lenses, thereby advancing more holistic and policy-relevant sustainability knowledge (Nicol and Humphreys, 2002; Ali and Akkaş, 2023). This approach is also appropriate for smart building research, where technical performance and human perception jointly shape outcomes (Mirrahimi et al., 2016). The statistical analysis plan (Figure 3) is structured to examine the relationships between measured environmental variables and reported comfort outcomes using complementary inferential and multivariate techniques. Objective sensor data (temperature, humidity, CO_2, HVAC performance) were linked to subjective comfort indicators, allowing the identification of significant predictors of thermal satisfaction. The use of regression analysis further enables the modelling of latent constructs such as usability, trust in automation, and perceived control, thereby capturing both direct and indirect effects within a unified causal framework (Hair et al., 2021). PMV and PPD indices operationalise thermal comfort in line with international standards (ASHRAE, 2004; Lamberti et al., 2023; Tartarini and Schiavon, 2025). Together, this layered analytical strategy ensures a robust, theory-driven interpretation of comfort dynamics in smart buildings.

Overall, the research was conducted in three sequential phases. The first phase involved an extensive systematic literature review of peer-reviewed studies, policy documents, and industry reports addressing smart building technologies, thermal comfort models, and user-centred design. This review informed the theoretical foundation of the study and helped identify key variables affecting thermal comfort in smart environments, including environmental control strategies, adaptive comfort principles, and occupant interaction with building systems (De Dear and Brager, 2002; Mirrahimi et al., 2016). The second phase focused on empirical data collection in selected smart buildings and retrofitted developments across Istanbul. These case study sites were purposively selected due to their integration of advanced HVAC systems, sensors, and automated controls. Quantitative data were collected to assess environmental performance, while qualitative data obtained through occupant surveys and interviews captured perceptions of comfort, control, and usability. This dual data collection strategy provided a holistic assessment of both

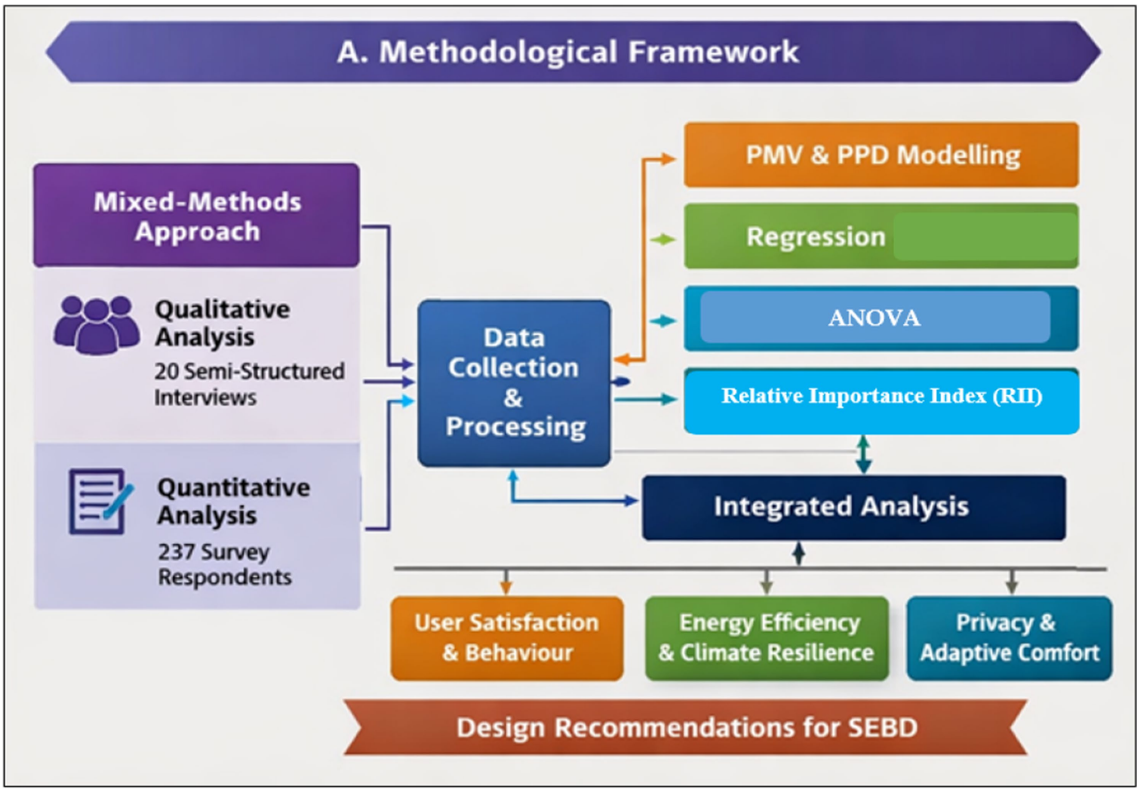

FIGURE 2
Study's research methodological framework. Source: Authors' conceptualisation.

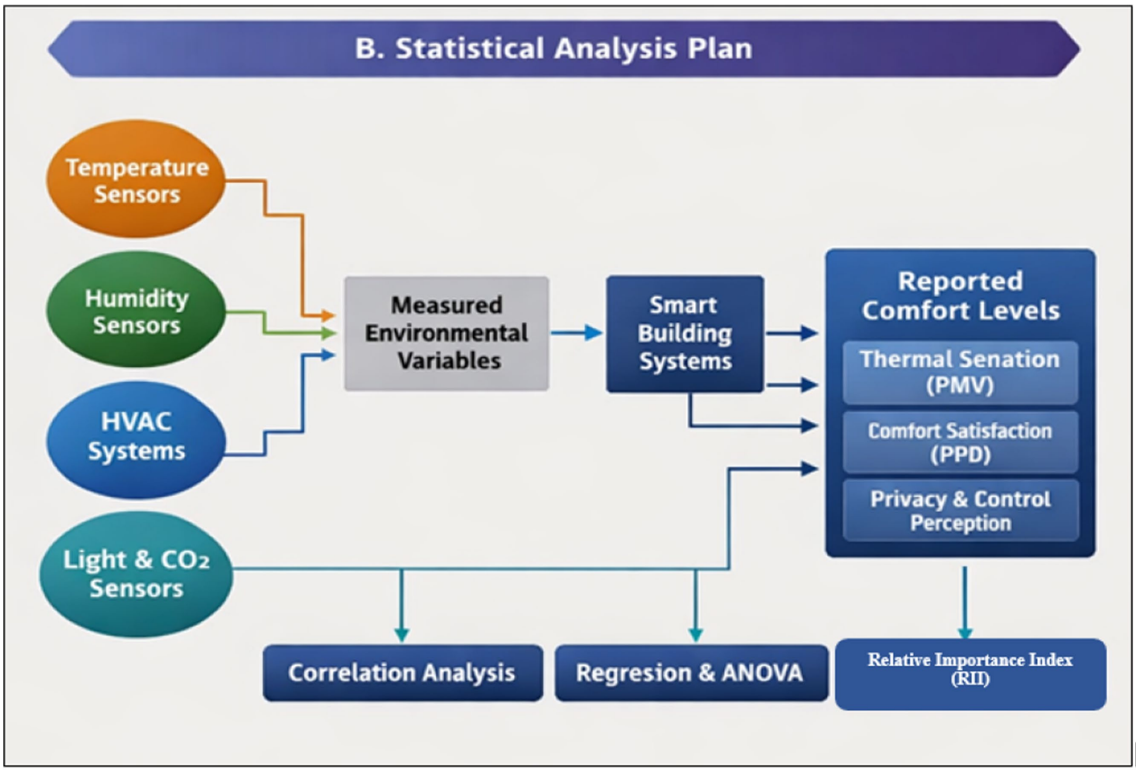

FIGURE 3
Overview of the study's analysis showing the relationship between the measured environmental variables and reported comfort levels. Source: Authors' conceptualisation.

system efficiency and user satisfaction. In the final phase, data analysis and synthesis were undertaken. Quantitative datasets were statistically analysed and cross-referenced with qualitative findings derived from thematic analysis. This integrative process enabled the identification of consistencies and discrepancies between measured thermal conditions and subjective comfort perceptions, supporting evidence-based recommendations for improving smart building design, operation, and occupant well-being (Sudarsanam and Kannamma, 2023; Banfi et al., 2024).

4.1 Description of the study area and site selection criteria

Istanbul is located at the geographical intersection of Europe and Asia, and its climatic conditions are shaped by both its latitudinal position and its proximity to major water bodies, particularly the Sea of Marmara to the south and the Black Sea to the north. These geographical features give rise to a transitional climate regime, situated between Mediterranean, oceanic, and continental climate zones, resulting in pronounced seasonal variability in temperature, humidity, and precipitation (Karaçam et al., 2026). Climatically, Istanbul is generally classified as having a humid subtropical to Mediterranean-influenced climate (Figure 4), characterised by warm to hot summers and cool, relatively wet winters. The city records a mean annual temperature of approximately 16.9 °C, which is slightly higher than the national average for Türkiye, reflecting the combined effects of maritime moderation and urban heat island intensity (Karaçam et al., 2026). Annual precipitation averages around 720 mm, distributed across approximately 120 rainy days, indicating relatively high moisture availability throughout the year (Karaçam et al., 2026).

Seasonally, Istanbul experiences cool and humid winters, with average temperatures ranging between 5 °C and 10 °C and occasional snowfall, particularly in inland and elevated areas. Summers are typically warm to hot and moderately humid, with daytime temperatures frequently exceeding 28 °C and relative humidity levels remaining high due to maritime influences. The city's low average elevation of approximately 31 m above sea level further amplifies these coastal effects, producing delayed seasonal transitions, frequent cloud cover, and periodic fog, especially in coastal and Bosphorus districts (Halis et al., 2022). From a building performance perspective, these climatic conditions impose substantial demands on heating, cooling, and ventilation systems, particularly during summer periods of elevated temperature and humidity and winter periods of prolonged thermal discomfort. The coexistence of both heating and cooling loads throughout the year makes Istanbul a highly suitable case for evaluating Smart Energy Building Design (SEBD) strategies and the effectiveness of intelligent control systems in maintaining indoor thermal comfort under complex and variable climatic conditions.

The study concentrated on selected districts on Istanbul's European side, including Avcılar (Figure 5) and Esenyurt (Figure 6), which together illustrate contrasting urban densities, architectural forms, and levels of technological integration. Avcilar is a district located on the European side of Istanbul, Türkiye. Its approximate geographic coordinates are 41.015° N, 28.732° E. Avcılar has a population of about 452,000 residents and covers an area of roughly 50 km^2, making it a moderately dense coastal district along the Sea of Marmara. Esenyurt lies west of Avcılar and is also on the European side of Istanbul. Its central coordinates are approximately 41.040° N, 28.662° E. Esenyurt is one of the most populous districts in Istanbul, with an estimated population of about 983,500 people and a land area of around 43 km^2, characterised by rapid urban growth and high residential density. The selection of Avcılar and Esenyurt further enhances representativeness, as these districts reflect contrasting urban densities, socio-economic

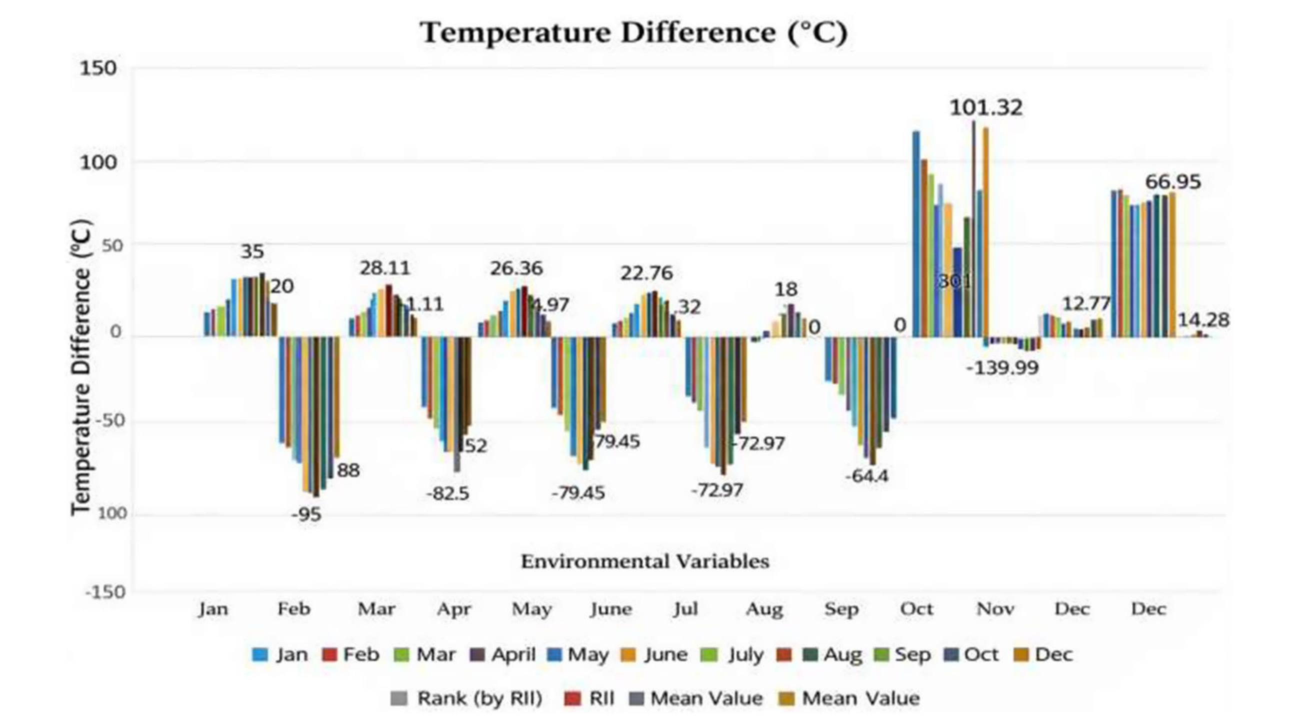

FIGURE 4
Monthly averages of Istanbul's climate. Source: Authors' conceptualisation.

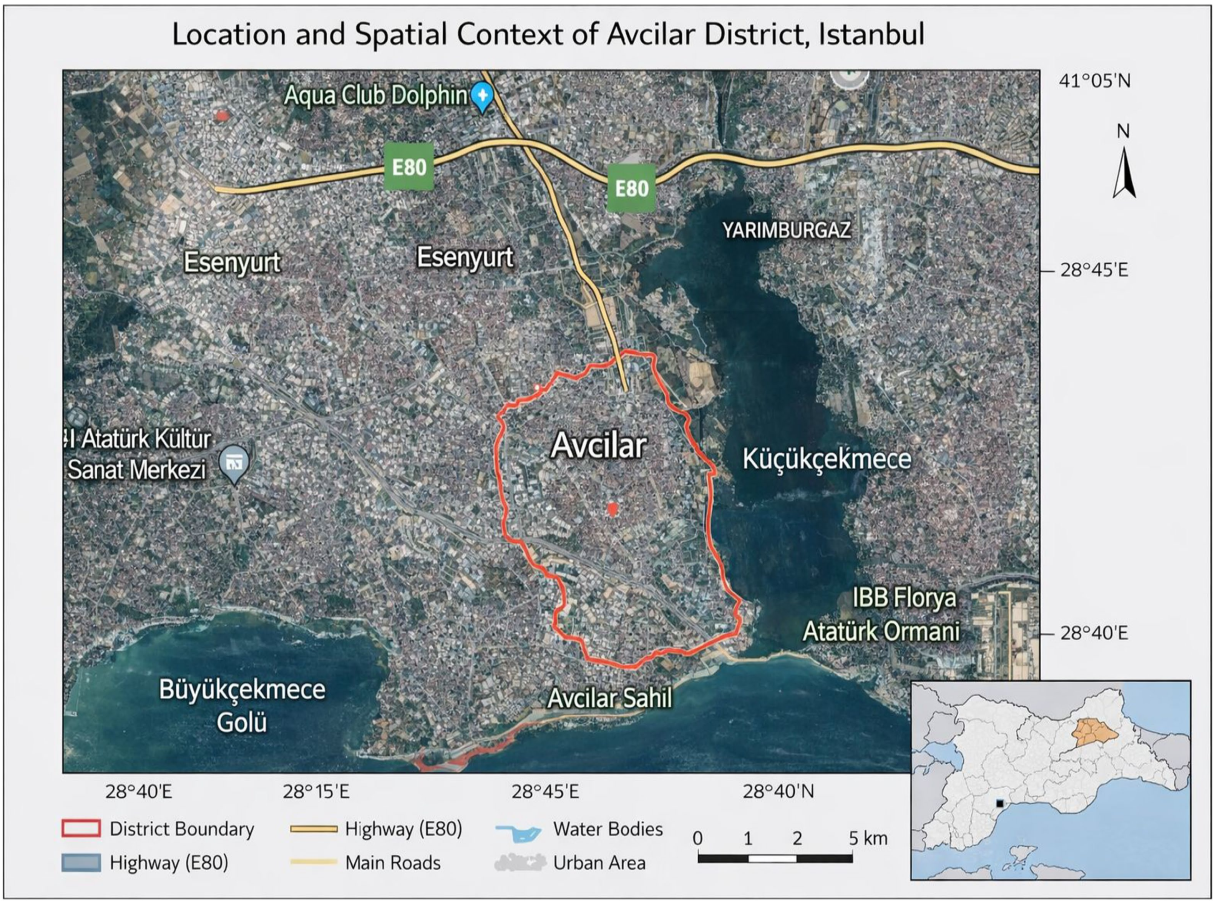

FIGURE 5
Acvila District, Istanbul. Source: Author-generated from Google Maps.

profiles, and building typologies, thereby capturing meaningful variability in occupant experiences and technology adoption patterns.

The study focuses on urban residential and commercial buildings in Istanbul that incorporate smart technologies such as automated HVAC systems, smart lighting, occupancy sensors, and IoT-based environmental monitoring. Case study buildings were selected based on four criteria: (i) integration of advanced environmental control technologies, (ii) inclusion of residential and mixed-use functions, (iii) accessibility and willingness of building management to participate in the research, and (iv) socio-cultural diversity in examining smart environmental control technologies for thermal comfort management. Precisely, fieldworks were carried out in three (3) selected smart residential and three (3) commercial buildings in Istanbul (Table 4); chosen for their advanced environmental control systems and accessibility. For the quantitative component, stratified random sampling captured variation in building type, size, location, and smart technology adoption level.

4.2 Data collection and analysis procedures

This study adopted a mixed-methods analytical framework, integrating quantitative and qualitative techniques to ensure robust and comprehensive interpretation of findings (Brown and Anderson, 2023). The primary dependent variables examined in this study were clearly defined in line with the research objectives and hypotheses. These include: (i) User Satisfaction with Smart Environmental Control Technologies (SECTs), measured through Likert-scale survey items assessing perceived comfort, usability, and overall experience (Abu Salim et al., 2021; Chang and Huang, 2023); (ii) Energy Efficiency Performance, assessed through self-reported energy-use perception and monitored performance indicators (Yang et al., 2020); (iii) Climate Resilience and Emission Reduction (CRER) indicators, operationalised through adaptive system responsiveness, and perceived contribution to emission mitigation (Proskuryakova, 2023; Shi et al., 2022); and (iv) Sustainable Urban Performance (SDP), which reflects broader outcomes related to environmental performance, comfort stability, and user well-being within the urban context (Ayoobi and Mehdizade, 2025). The key independent variables comprised: (i) the Level of SECT Adoption, including the presence and functionality of smart HVAC systems, IoT-enabled sensors, automated lighting, and energy monitoring Technologies (Mistry, 2023; Karatasou et al., 2018); (ii) Smart Energy Building Design (SEBD) strategies, such as building orientation, passive cooling features, insulation quality, and spatial configuration (Poyyamozhi et al., 2024); and (iii) selected socio-demographic and contextual control variables, including age, income level, building type, duration of occupancy, and technological experience (Palani et al., 2023; Uddin et al., 2023). These variables were incorporated into correlation, regression, and moderation analyses to evaluate the predictive relationships proposed in the conceptual model and to determine the combined influence of technological, behavioural, and design-related factors on sustainable building performance outcomes.

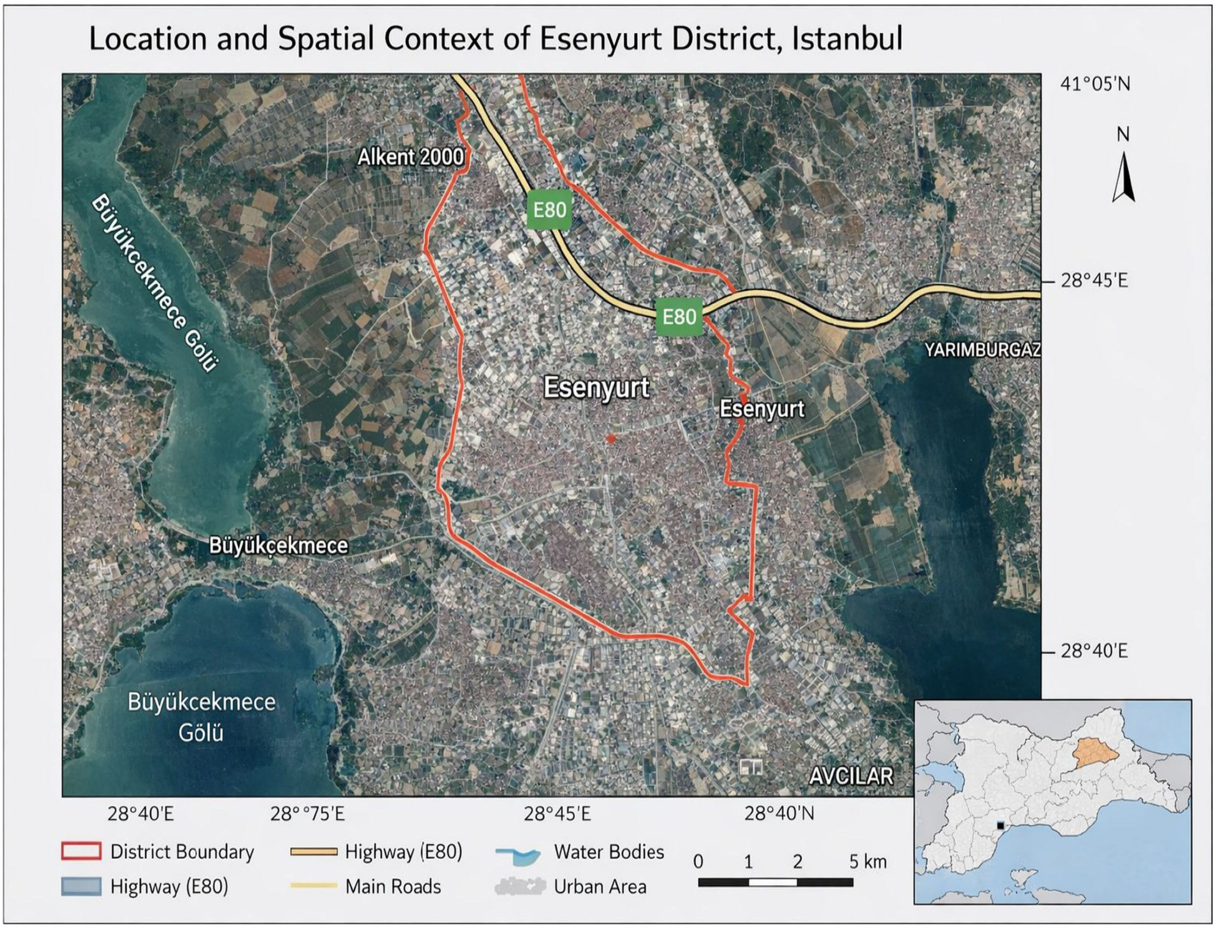

FIGURE 6
Esenyurt district, Istanbul. Source: Author-generated from Google Maps.

Quantitative data were analysed using the Statistical Package for the Social Sciences (SPSS), Version 24. Descriptive statistics (means, standard deviations, frequencies, and percentages) were employed to summarise respondents' socio-demographic characteristics and key study variables. Inferential statistical analyses were conducted to test the study hypotheses and examine relationships among variables. Specifically, Analysis of Variance (ANOVA) was used to identify statistically significant differences in perceptions and comfort levels across user groups and building types. Multiple regression analysis was applied to assess the predictive influence of Smart Environmental Control Technologies (SECTs) on user satisfaction and energy efficiency performance, while Pearson correlation analysis was utilised to explore associations between objective comfort indices (PMV/PPD) and subjective thermal sensation votes (TSV).

Before inferential analysis, key statistical assumptions were formally tested. Normality of data distribution was assessed using the Shapiro–Wilk test, and homogeneity of variance was examined using Levene's test (Shapiro and Wilk, 1965; Gastwirth et al., 2009). Where necessary, data transformations and appropriate parametric or non-parametric procedures were applied to ensure analytical validity. The selection of these statistical techniques was justified based on their suitability for analysing continuous and categorical variables, as well as their widespread application in building performance and human–environment interaction studies. By confirming that both normality and homoscedasticity were satisfied, the study strengthens the credibility of its inferential results and supports the appropriateness of applying parametric statistical models for hypothesis testing.

Descriptive statistical techniques, including frequencies, percentages, mean scores, and graphical illustrations, were employed to summarise respondents' socio-demographic characteristics and key study variables (Gjonça and Calderwood, 2002). Data were analysed using descriptive statistics to summarise sensor readings and survey responses, followed by inferential analyses including correlation tests, ANOVA, and regression modelling to examine relationships between measured environmental variables and reported comfort levels (Hair et al., 2021). To address some of the study objectives, both mean values and the Relative Importance Index (RII) were utilised. Specifically, the RII was applied to: (i) assess respondents' level of awareness of smart technologies for managing thermal comfort; (ii) identify and rank the key factors influencing Smart Environmental Control Technologies for sustainability in smart living environments; and (iii) compare perceived performance (mean scores) with perceived relative importance (RII) in thermal comfort management. The Relative Importance Index (Equation 1), (RII) is a widely adopted analytical technique in social and environmental research for prioritising factors based on respondents' perceptions (Lorenzo-Seva and Ferrando, 2011). The RII was computed using the following equation:

$$\text{Relative Important Index}\left(\text{RII}\right) = RII = \frac{\sum W}{A \times N} \tag{1}$$

TABLE 4 Six (6) smart-enabled residential and commercial buildings in avcilar and esenyurt urban metropolises.

No.	District	Building/project name	Building type	Key features relevant to the study	Justification for selection
1	Avcılar	Smart Residential Tower (Avcılar)	Residential	Smart home systems, automated HVAC, lighting control, energy-efficient design	Represents typical smart residential buildings with integrated environmental control systems
2	Avcılar	Collet Avcılar Complex	Mixed-use (Residential and Commercial)	Centralised building management system (BMS), climate control, smart security	Suitable for studying both residential comfort and commercial environmental performance
3	Esenyurt	Smart Apartment Complex (Esenyurt)	Residential	Smart climate systems, automated lighting, centralized energy management	Exemplifies high-density smart housing common in Esenyurt
4	Esenyurt	BP-101 / BP-115 Residential Estate	Residential	Central HVAC, estate-wide control systems, shared smart facilities	Large-scale residential environment ideal for occupant comfort assessment
5	Esenyurt	Marmara Park Shopping Mall	Commercial	Advanced HVAC, energy management systems, automated access and lighting	Major commercial building suitable for evaluating environmental performance in large spaces
6.	Avcılar	Neighbourhood Shopping Complex	Commercial	Energy-efficient lighting, automated air conditioning, and smart access	Typical medium-scale commercial building with smart features

Where:
W = weight assigned to each factor (1–5),
A = highest possible weight (5),
N = total number of respondents.

The interpretation thresholds adopted in this study follow established practice (RII ≥ 0.80 = high importance; 0.60–0.79 = moderate; < 0.60 = low importance), enabling systematic comparison across components. The RII values range between 0 and 1, with values closer to 1 indicating higher perceived importance. In this study, the RII facilitated the ranking of smart technology awareness levels, sustainability-related influencing factors, and perceived effectiveness of thermal comfort management strategies. This approach enabled a robust comparison between perceived performance and perceived importance, thereby providing deeper insights into the role of smart environmental control technologies in promoting sustainable smart living environments (Chanda et al., 2025). Overall, the RII was applied to prioritise SECT features and compare perceived importance with performance indicators (mean scores and regression outcomes). This allowed triangulation between perception-based rankings and statistically tested relationships, strengthening interpretive validity.

To complement the descriptive statistics and Relative Importance Index (RII), regression analysis plays a critical inferential role by moving beyond ranking to statistically testing relationships, effect sizes, and predictive significance among variables. Regression analysis in this study determines which factors significantly influence thermal comfort outcomes and to what extent, after controlling for other variables as previously adopted by Mamani et al. (2022) and Banfi et al. (2024). This enables the identification of key predictors rather than relying solely on perceived importance. The procedure also allows the assessment of statistical significance (p-values), strength of influence (standardised coefficients), and model explanatory power (R^2). Consequently, provides evidence-based insights that support more targeted policy and design interventions for smart thermal comfort management.

This study also adopted standardised assessment models, such as the Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfied (PPD), as well as the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) and ISO 7730 comfort frameworks, to evaluate the research objectives on occupants' comfort conditions in buildings (Fanger, 1970; De Dear and Brager, 2002). For collections of data relating to environmental monitoring and occupant surveys; study was conducted in three (3) selected urban residential and three (3) mixed-use commercial buildings in Istanbul. The six (6) smart-enabled buildings were purposively selected based on their level of technological integration, functional diversity, and the willingness of building management to participate in the study. Also, the buildings were prototypes of several buildings in the study areas and were equipped with smart building technologies, including automated HVAC systems, smart lighting, occupancy detection systems, and IoT-based environmental monitoring platforms. This data collection involved the installation of calibrated sensors in key indoor spaces, including living rooms, workspaces, and shared corridor areas. Parameters measured include critical indoor environmental quality (IEQ) parameters such as air temperature (°C), relative humidity (%), air velocity (m/s), CO_2 concentration, and mean radiant temperature (°C), that enabling calculation of PMV and PPD indices in accordance with ISO 7730 and ASHRAE 55 standards as previously applied by Bourdeau et al. (2023).

In each building, eight (8) calibrated sensors were deployed to monitor key indoor environmental parameters (Figure 7), including air temperature, relative humidity, carbon dioxide (CO_2) concentration, and occupancy levels. The sensors were installed following a purposive and spatially representative deployment strategy, with devices positioned in critical indoor spaces such as living rooms, offices, meeting rooms, corridors, and shared areas to capture variations across different functional zones (ASHRAE, 2004; Parsons, 1995; ISO, 2004). In terms of placement strategy, sensor locations were selected based on occupancy patterns, thermal zoning, ventilation pathways, and proximity to HVAC control systems to ensure reliable measurement of operative indoor conditions. Also, to ensure measurement accuracy and data quality, sensors were placed away from direct sunlight, ventilation outlets, and localised heat sources, in accordance with standard indoor monitoring guidelines (Bourdeau et al., 2023; Nicol and Humphreys, 2002). The instruments provided measurement accuracies of ±0.3 °C for temperature, ±2% for relative humidity, and ±50 ppm for CO_2, and were calibrated prior to installation using manufacturer-recommended protocols and reference instruments, ensuring reliability and consistency across all study sites (Bourdeau et al., 2023).

The results generated from PMV (Predicted Mean Vote) and PPD (Predicted Percentage Dissatisfied) values were calculated using Fanger's thermal comfort model, based on environmental data obtained from the calibrated indoor sensors. Thermal comfort indices, such as PMV and PPD, include using CBE Thermal Comfort Tool benchmarks to enable standardised comparison of comfort performance (ASHRAE, 2004; Lamberti et al., 2023). PMV and PPD calculated were in accordance with ISO 7730 and the ASHRAE 55 Thermal Environmental Conditions for Human Occupancy standard. The Fanger heat balance model was applied using both measured environmental parameters and standardised assumptions. Measured variables included air temperature (Ta), mean radiant temperature (Tr), relative humidity (RH), and air velocity (Va), obtained from calibrated sensors installed within the selected buildings. Assumed personal parameters comprised clothing insulation (clo), adjusted seasonally between 0.5 and 1.0 clo, and metabolic rate (met), estimated at 1.0–1.2 met to reflect typical sedentary residential and office activities. Standard steady-state conditions were adopted to ensure methodological consistency. PPD values were derived directly from PMV using the nonlinear relationship defined in ISO 7730. Environmental data were recorded at hourly intervals over the monitoring period and subsequently aggregated to generate temporal thermal comfort profiles. PMV and PPD indices were computed using validated thermal comfort equations implemented through SPSS-supported computational procedures and cross-verified with established ISO-based calculation methods to ensure accuracy and reproducibility.

To establish the relationship between objective and subjective comfort indicators, Pearson correlation analysis was conducted between computed PMV/PPD values and occupants' Thermal Sensation Votes (TSV) obtained from the survey. The analysis revealed a statistically significant positive relationship ($p < 0.05$), indicating alignment between measured indoor conditions and perceived comfort levels. Periods characterised by elevated PPD values corresponded with reported discomfort, particularly during peak occupancy in afternoon hours. Furthermore, buildings equipped with adaptive Smart Environmental Control Technologies (SECTs) demonstrated lower mean PPD values alongside higher occupant satisfaction scores,

FIGURE 7
Calibrated sensor network in a modern office setting. Source: Authors' fieldwork.

reinforcing the effectiveness of context-responsive smart systems in maintaining acceptable comfort conditions.

The PMV and PDD data represent aggregated measurements from the six case study buildings, specifically from shared office and meeting room spaces where both environmental monitoring and occupant surveys were conducted. The monitoring was carried out during the summer period, ensuring consistency with the seasonal context of the comfort survey. Data were collected continuously over eight (8) weeks between summer time, 6th July and 31st August, 2025, to capture variations across different occupancy patterns and outdoor weather conditions. The current duration remains methodologically acceptable for exploratory smart building research, particularly for examining behavioural responses, system interaction patterns, and perceived comfort under operational conditions. Similar temporal scopes have been adopted in prior indoor environmental quality studies where continuous long-term monitoring was not feasible due to logistical and resource constraints (Nicol and Humphreys, 2002; De Dear and Brager, 2002). Figure 8 illustrates a calibrated sensor network deployed within a smart building environment, highlighting its role in continuously monitoring indoor environmental parameters such as temperature, humidity, air quality, and occupancy. The visual representation demonstrates how distributed IoT sensors collect real-time data and transmit it to a central building management system, enabling the identification of localised comfort deficiencies across different zones. Such data-driven monitoring supports adaptive control strategies by allowing building operators to fine-tune HVAC, lighting, and ventilation systems in response to actual occupant conditions. Consequently, calibrated sensor networks form a critical foundation for optimising smart building operations, enhancing thermal comfort, improving energy efficiency, and supporting evidence-based decision-making in sustainable building management.

A structured questionnaire was administered to building occupants to assess satisfaction with thermal comfort, perceived indoor air quality, and interactions with smart building systems. Standardised assessment tools, including the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) seven-point Thermal Sensation Scale and ISO7730 (1984) comfort guidelines, were incorporated to ensure consistency and reliability in thermal comfort evaluation (De Dear and Brager, 2002; ASHRAE, 2004; Lamberti et al., 2023). In line with this, the dependent variables were related to the thermal comfort indicators (PMV, PPD, and occupant satisfaction scores). In contrast, the independent variables included environmental parameters (air temperature, relative humidity, CO_2 concentration, air velocity) and building characteristics (building type and smart system category). In addition, semi-structured interviews were conducted with key stakeholders such as architects, facility managers, and system integrators to explore design intentions, implementation challenges, operational performance, and maintenance issues associated with smart technologies. Interviews were audio-recorded with participants' consent and later transcribed verbatim. These discussions also addressed socio-cultural and behavioural factors influencing the acceptance and use of the system among occupants (Mirrahimi et al., 2016; Banfi et al., 2024). Figure 9 depicts the data collection process through both questionnaires and semi-structured interviews. The figure illustrates multiple stages of data collection, including: (i) face-to-face administration of questionnaires; (ii) semi-structured interviews conducted; and (iii) group-based interactions where respondents completed survey instruments under the guidance of the researcher. All participants shown in the images have been anonymised by masking facial features to ensure confidentiality and compliance with ethical standards.

FIGURE 8
Modern office with environmental monitoring devices. Source: Authors' fieldwork.

(i) Researcher and research assistants supporting data distribution and collection

(ii) Researcher with some study participants

(iii) Supervised group-based questionnaire administration 1

(iv) Supervised group-based questionnaire administration 2

(v) Semi-structured interviews conducted with selected respondents 1

(v) Semi-structured interviews conducted with selected respondents 2

FIGURE 9
Field data collection process (i) to (vi) for questionnaires and semi-structured interviews. Sources: Author's field work.

Qualitative data derived from semi-structured interviews were analysed using thematic analysis supported by NVivo (Version 12). The qualitative data were analysed using thematic analysis, following the systematic six-phase framework proposed by Braun and Clarke (2021). This involved data familiarisation, initial coding, theme generation, theme review, theme definition, and final interpretation. NVivo was utilised as the primary analytical tool to support data management, coding, and retrieval, thereby enhancing transparency, traceability, and analytical rigour. The use of NVivo enabled consistent coding across transcripts. It facilitated the identification of recurring patterns, relationships, and dominant themes, which were then triangulated with the quantitative findings to improve the credibility and validity of the results (Creswell and Plano Clark, 2018). This combined approach ensured methodological robustness by integrating both interpretive depth and empirical consistency, in line with best practices in mixed-methods research (Braun and Clarke, 2021). The choice of thematic analysis is particularly appropriate for exploring user experiences and perceptions, as it enables systematic interpretation of subjective meanings while remaining flexible across diverse research contexts. This iterative procedure enabled continuous movement between the empirical data and emerging analytical insights, ensuring that the interpretations remained closely grounded in participants' lived realities (Braun and Clarke, 2021).

To enhance analytical rigour, triangulation was employed by comparing qualitative insights with quantitative results, enabling cross-validation of findings and a deeper interpretive understanding. The qualitative analysis process was conducted iteratively to ensure consistency, reliability, and alignment with the study objectives. Observational walkthroughs during site visits documented the physical integration of smart technologies within building layouts, the accessibility of user interfaces, and ergonomic factors affecting daily interaction with environmental controls, providing contextual insight into how design decisions influenced thermal comfort outcomes (Najafi et al., 2025; Lamberti et al., 2023). Furthermore, the qualitative findings were integrated with quantitative results through methodological triangulation, which strengthened the analytical rigour and enhanced interpretative depth. Overall, the integration of quantitative statistical modelling and qualitative thematic analysis strengthened the methodological robustness of the study, enhanced replicability, and ensured that both numerical trends and experiential insights were systematically captured and interpreted.

4.3 Sampling strategies and justification

A mixed sampling strategy was adopted to ensure both representativeness and analytical depth. For the quantitative component, a stratified random sampling approach was used to select case-study buildings based on predefined criteria, including functional typology (residential, commercial, mixed-use), geographic location within Istanbul, and level of smart technology integration (basic automation and advanced IoT-based systems). Within each stratum, buildings were randomly selected to minimise selection bias and enhance external validity (Creswell and Plano Clark, 2018; Bryman, 2016). In addition, participants were recruited using a purposive sampling strategy, targeting occupants of selected residential and commercial apartment buildings within Avcılar and Esenyurt districts of Istanbul. In addition, occupants were recruited using a systematic on-site recruitment strategy, in which eligible participants were invited to complete the survey via building management offices and digital communication platforms.

The total sample size of 237 for this study is considered adequate and justified based on the large populations of Avcılar (≈452,000) and Esenyurt (≈983,500), which together exceed 1.4 million residents. For populations above 100,000, standard social science sampling guidelines (Cochran's formula and Krejcie & Morgan's table) indicate that the sample is sufficient to produce statistically reliable estimates at a 95% confidence level with a margin of error of approximately ±6–7%, which falls within acceptable limits for urban behavioural, building performance, and environmental perception studies (Muyembe Asenahabi and Anselemo Ikoha, 2023). This sample size is large enough to capture variations in respondents' perceptions across the two high-density districts. Additionally, the sample size is considered statistically adequate for the suite of inferential and multivariate analyses conducted in this study (Hair et al., 2021). In addition, this sample size is appropriate for the calculation of Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfied (PPD) indices used to assess thermal comfort and Smart Energy Building Design (SEBD) performance. Importantly, this sample comprised residents, office workers, and facility users drawn from a range of residential and commercial apartment buildings within the selected case study areas in Istanbul. All participants were aged 18 years and above, had occupied their respective buildings for a minimum of 3 months, and regularly used the indoor spaces for work or living purposes. Individuals with temporary occupancy or limited exposure to the indoor environment, such as short-term visitors, were excluded to ensure the relevance and reliability of the responses (Groves et al., 2011). To examine potential non-response bias, response patterns were compared across building types and occupant categories. An analysis of early and late respondents showed no statistically significant differences in key demographic variables or reported comfort perceptions ($p > 0.05$), suggesting minimal non-response bias and supporting the representativeness of the final sample (Bethlehem, 2010).

Qualitative data collection complemented the quantitative component through semi-structured interviews and observational walkthroughs, providing in-depth contextual insights into user experiences and system performance. The use of thematic analysis further ensured analytical depth and triangulation with the quantitative findings. In view of this, a total of 20 key informants were selected using purposive sampling, an approach widely recognised as appropriate for expert-driven and theory-building research (Patton, 2015). This sample size aligns with established qualitative research standards, which suggest that thematic saturation typically occurs with this number of interviews in applied urban, architectural, and built environment studies (Creswell and Plano Clark, 2018). This study's semi-structured interview guide allows for comparability across participants while also providing flexibility for in-depth exploration of individual experiences. The interview guides were designed to align with key dimensions of Indoor Environmental Quality (IEQ) and support thematic analysis following Braun and Clarke (2021), enabling systematic identification of patterns, themes, and meanings in occupants' perceptions. Key informants were identified based on their professional roles and direct involvement in smart building design, operation, and management. The sample comprised facility managers ($n = 8$), HVAC and energy engineers ($n = 5$), building architects and designers ($n = 4$), and smart systems administrators ($n = 3$), all of whom possessed a minimum of 3 years of professional experience and direct responsibility for system monitoring or occupant comfort. This ensured that participants had specialised and practically relevant knowledge related to Smart Energy Building Design (SEBD) and indoor environmental performance. Purposive sampling facilitated the inclusion of informants with diverse technical perspectives, enabling triangulation between operational data, expert interpretations, and occupant feedback. Data saturation was reached after approximately 17 interviews, with no substantially new themes emerging in subsequent sessions, confirming the adequacy and methodological robustness of the final sample size (Braun and Clarke, 2021).

4.4 Items construct, reliability, validity, and ethical considerations

Ensuring the reliability and validity of the research instruments was a central concern throughout the study. All environmental monitoring devices were pre-calibrated and validated against certified reference standards before deployment to ensure measurement accuracy and consistency across study sites, in accordance with ISO guidelines for indoor environmental monitoring (ISO, 2004; ISO, 2005; Parsons, 1995). The structured questionnaire constructs were developed based on established instruments from previous studies on indoor environmental quality, thermal comfort, and smart building performance. Survey items were grouped into four main constructs: (i) thermal comfort perception, (ii) indoor air quality perception, (iii) smart technology adoption and usability, and (iv) overall occupant satisfaction. All these were operationalised into measurable items aligned with established theoretical frameworks. Both closed-ended Likert-scale items and categorical demographic questions were included to ensure analytical robustness. Responses were measured using a five-point Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree), a scaling approach widely used in built environment and human–technology interaction research (Alabi and Jelili, 2023). Instrument reliability was assessed using Cronbach's alpha, calculated separately for each construct. The results indicated high internal consistency, with alpha values of 0.86 for thermal comfort, 0.88 for indoor air quality, 0.90 for system usability, and 0.91 for overall satisfaction, yielding an overall reliability coefficient of $\alpha = 0.891$. These values exceed the commonly accepted threshold of 0.70 for social science research, indicating strong scale reliability (Tavakol and Dennick, 2011).

Before full deployment, the questionnaire was pilot-tested with 15 participants drawn from similar building contexts to assess item clarity, relevance, and response consistency. Minor revisions were made to improve wording and eliminate ambiguity. Content validity was further strengthened through expert review by two building science researchers and one survey design specialist. The quantitative survey instrument (Supplementary material Appendix 1) was originally developed in English and subsequently translated into Turkish using a forward–backward translation procedure to ensure linguistic and conceptual equivalence. Two bilingual experts independently translated the questionnaire into Turkish, after which a separate translator back-translated it into English. Discrepancies were reviewed and resolved through consensus, and minor cultural adaptations were made to reflect local terminology and building practices in Turkey, following established cross-cultural survey adaptation guidelines (Braun et al., 2021). This procedure was adopted in the semi-structured interview guide to enable comparability across participants while also providing flexibility for in-depth exploration of individual experiences. The qualitative interview guide (Supplementary materials Appendix 2) was designed to align with key dimensions of Indoor Environmental Quality (IEQ) and support thematic analysis following Braun and Clarke (2021), enabling systematic identification of patterns, themes, and meanings in occupants' perceptions. Construct validity was enhanced through methodological triangulation, integrating subjective survey responses with objective sensor data and qualitative interview findings. This multi-method approach allowed for cross-verification of results and strengthened confidence in the interpretation of key constructs (Creswell and Plano Clark, 2018).

Ethical considerations were rigorously observed throughout the research process. To safeguard confidentiality, no personally identifiable information was recorded in the survey instrument, and interview transcripts were anonymised using coded identifiers. Participation was voluntary, and informed consent was obtained from all participants before data collection. Anonymity and confidentiality were ensured by removing all personally identifiable information and securely storing data in encrypted formats. Due to ethical considerations and participant confidentiality, raw survey data are not publicly archived but can be shared in anonymised form for academic and research purposes. All collected data were handled in accordance with good research practice and data protection principles. Survey responses were anonymised at the point of collection and stored in password-protected digital files accessible only to the research team. No personally identifiable information was collected. Data cleaning, coding, and analysis were performed using standard statistical software, and all datasets were securely archived to prevent unauthorised access, loss, or misuse. All procedures complied with the General Data Protection Regulation (GDPR) and Turkish Personal Data Protection Law of 2016 (Gürsel, 2016); thereby safeguarding participants' rights and ensuring the ethical integrity of the study.

5 Results

5.1 Respondents' demographics

A total of 237 survey questionnaires were deemed valid and retained for analysis following data screening procedures. This represents an effective response rate of 84.64%, based on the 280 questionnaires initially distributed, which exceeds the minimum acceptable threshold of 60% commonly recommended for survey-based research (Deutskens et al., 2004). Variables were assessed based on Cronbach's alpha coefficient, with a value of 0.891, indicating high reliability. Factor loadings were employed to ascertain construct validity, with loadings ranging from 0.55 to 0.91, surpassing the 0.50 threshold and confirming validity. Table 5 presents the demographic profile of respondents and their perceptions of smart technologies in relation to thermal comfort and Energy Efficiency in Buildings (EEB). The age distribution indicates that the majority of respondents fall within the economically active and technologically receptive groups, with 68% aged between 31 and 50 years. This aligns with previous studies suggesting that middle-aged occupants are more likely to engage with smart building systems due to higher digital literacy and stable housing conditions (Ali and Akkaş, 2023; Fan et al., 2025). The predominance of male respondents (61.18%) is consistent with similar built environment surveys, where male participation tends to be higher in technology-related studies (Cai et al., 2017), although this imbalance may also reflect gendered patterns in housing decision-making within urban contexts.

TABLE 5 Demographic details and other variables related to thermal comfort and energy efficiency in buildings (EEB) (*N* = 237).

Variables	Categories	Frequencies	Percentages (%)
Section A			
Age	20–30	33	13.90
	31–40	91	38.30
	41–50	45	29.40
	51 and above	68	18.40
Gender	Male	145	61.18
	Female	92	38.82
Marital status	Married	145	61.18
	Single	92	38.82
Household size	1 and 3	57	24.05
	4 and 5	85	35.86
	5 and above	95	40.09
Annual household income	Less than TL 30,000	41	17. 29
	TL30,000 – TL 50,000	93	39.25
	TL50,000 – TL 75,000	72	30.37
	More than TL 75,000	31	13.09
Education level	High School or less	48	20.25
	College or vocational training	118	49.78
	Bachelor's degree	42	17.73
	Postgraduate degree	29	12.24
Type of residence	Single-family home	23	9.70
	Apartment/Condo	187	78.91
	Townhouse	27	11.39
Length of stay in current residence	Less than 1 year	49	20.67
	1–5 years	102	43.04
	6–10 years	58	24.47
	More than 10 years	28	11.82
Status of your current residence	Ownership	45	18.98
	Renting	192	81.02
Section B			
Rating your knowledge about thermal comfort and Energy Efficiency in Buildings (EEB)	Excellent	69	29. 11
	Good	127	53.58
	Fair	23	9.72
	Poor	18	7.59
There are presence of smart technologies	Yes	172	72.57
	No	65	27.43
I do experience discomfort related to temperature at home (especially during the summertime)	Yes	203	85.65
	No	34	14.35
Experience technical issues during the use of smart technologies for thermal comfort	Yes	45	18.98
	No	192	81,02
Decision to use smart technologies for thermal comfort	Yes, significantly	105	44.30
	Yes, moderately	98	41.35
	No, not at all	34	14.35

(Continued)

TABLE 5 (Continued)

Variables	Categories	Frequencies	Percentages (%)
The use of smart technologies to improve the overall quality of life	Significantly improved	86	36.28
	Moderately improved	79	33.33
	Slightly improved	39	16.45
	No change	23	9.70
	Made it worse	10	4.24
Satisfaction with the use of smart technologies in maintaining thermal comfort in a home	Very Satisfied	96	40.51
	Satisfied	87	36.71
	Not sure	21	8.86
	Dissatisfied	18	7.59
	Very Dissatisfied	15	6.33
Noticed changes in energy consumption or utility bills since using smart technologies for thermal control	Significant increase	125	52.74
	Moderately increased	97	40.92
	Not sure	10	4.21
	No significant changes	05	2.13
How user-friendly do you find the smart technologies	Very User-Friendly	139	58.64
	Moderate User-Friendly	67	28.27
	Not sure	07	2.96
	Not user-friendly	13	5.48
	Not user-friendly at all	11	4.65
The positive or negative effects of smart technologies on your health and well-being	Positive effects	146	61.61
	Negative effects	91	38.39
Future integration of smart technologies into your living environment	Very open	156	65.82
	Somewhat open	113	47.67
	Not open	32	13.51
Encountering any technical issues while using smart technologies for thermal comfort	Yes	45	18.98
	No	192	81.02

Household characteristics further reveal that 76% of respondents live in households with four or more members, suggesting relatively high occupancy density. Prior research indicates that larger household sizes intensify thermal loads and energy consumption, increasing the need for adaptive environmental control systems (Wang, 2024). The income distribution shows that nearly 70% of respondents earn between TL 30,000 and TL 75,000 annually, positioning most participants within middle-income groups. This supports findings by Chan et al. (2023) that middle-income households are the primary adopters of smart technologies due to a balance between affordability and perceived long-term benefits. In terms of housing typology, the dominance of apartment and condominium living (78.91%) reflects Istanbul's dense urban structure and is consistent with urban housing trends in large metropolitan cities. Long-term residency patterns further show that over 55% of respondents have lived in their current homes for more than 5 years, suggesting that participants have sufficient experiential exposure to assess changes in comfort and energy performance.

Respondents highlight strong awareness of thermal comfort and Energy Efficiency in Buildings (EEB), with over 82% rating their knowledge as good or excellent. This level of awareness is significantly higher than reported in earlier studies on residential energy behaviour in developing urban contexts, suggesting a growing public consciousness driven by rising energy costs and environmental concerns. Importantly, 72.57% of respondents reported the presence of smart technologies in their buildings, confirming the empirical relevance of SECTs within the study sample. Despite high adoption, 85.65% of respondents still reported experiencing thermal discomfort, particularly during summer. This finding echoes research by de Dear and Brager (2002), which demonstrates that technological systems alone cannot fully eliminate discomfort due to climatic variability, behavioural diversity, and system limitations. However, satisfaction levels remain relatively high, with 77.22% reporting being satisfied or very satisfied with smart technologies. This apparent paradox aligns with Adaptive Comfort Theory, which suggests that occupants may tolerate discomfort if they perceive systems as controllable and beneficial overall (Nicol and Humphreys, 2002; Banfi et al., 2024).

User experience indicators further reveal that 58.64% found smart technologies very user-friendly, while only 10% considered them unfriendly. Similar findings were reported by Cioc et al. (2023), who emphasised usability and perceived control as critical determinants of long-term technology acceptance. Additionally, 61.61% perceived positive health and well-being impacts, supporting evidence that improved indoor environmental quality contributes to physical and psychological comfort (Bourdeau et al., 2023). Interestingly, over 93%

noticed increases in energy consumption or utility bills. This contrasts with the expected energy-saving narrative of smart systems and reflects rebound effects reported in previous studies, where increased comfort demand leads to higher energy use despite technological efficiency gains (Sorrell et al., 2009). This reinforces the argument that behavioural factors remain decisive in determining actual energy outcomes. The strong openness to future integration of smart technologies (over 65%) suggests high long-term acceptance and scalability potential. This mirrors findings from Shuhaiber and Mashal (2019) and Fard et al. (2022), who observed that once users experience tangible benefits, willingness to expand smart systems increases significantly. Overall, respondents demonstrate that while Smart Environmental Control Technologies (SECTs) are widely adopted and positively perceived, thermal discomfort and rising energy use persist, underscoring the need for better adaptive control, user education, and behaviour-sensitive system design. These results empirically support the study's theoretical framing that smart building performance emerges not only from technological capability but from the complex interaction between systems, users, and urban living conditions.

5.2 Awareness of smart environmental control technologies and thermal comfort management

Based on the 237 valid respondents drawn from residential and commercial smart buildings in Istanbul, results of Smart Environmental Control Technologies for Thermal Comfort Management are presented in Figure 10 using percentage scores. The highest awareness was observed for Smart Ceiling Fans (107%), followed by Smart HVAC (Heating, Ventilation, and Air Conditioning) Systems (85.65%), IoT Temperature Sensors (69.19%), and energy-efficient technologies (65.4%). Moderate awareness levels were recorded for Smart Window Blinds or Shades (55.69%), Voice-Activated Assistants (37.55%), and Zoned Heating and Cooling Systems (35.02%). Meanwhile, relatively low awareness was found for Radiant Floor Heating Control (43.45%), Automated Window Openers/Closers (51.05%), Home Energy Management Systems (59.49%), and Remote Temperature Monitoring Systems (48.52%). Overall, the findings indicate that respondents are more familiar with basic and easily visible smart technologies (such as smart fans and thermostats) than with advanced automation and control systems, suggesting a need for broader awareness and adoption of integrated smart home solutions for thermal comfort optimisation. Furthermore, the findings indicate that respondents demonstrated higher awareness of easily accessible smart technologies, such as smart ceiling fans, smart HVAC systems, IoT temperature sensors, and energy-efficient technologies, than of more complex or less visible systems like automated window openers, radiant floor heating, or remote temperature monitoring systems. This pattern aligns with past study such as Mirrahimi et al. (2016), which found that users tend to adopt or recognise technologies that are more user-friendly, affordable, and directly linked to a comfortable experience. Therefore, the present findings corroborate earlier research by Nicol and Humphreys (2002) highlighting that while awareness of smart comfort technologies is

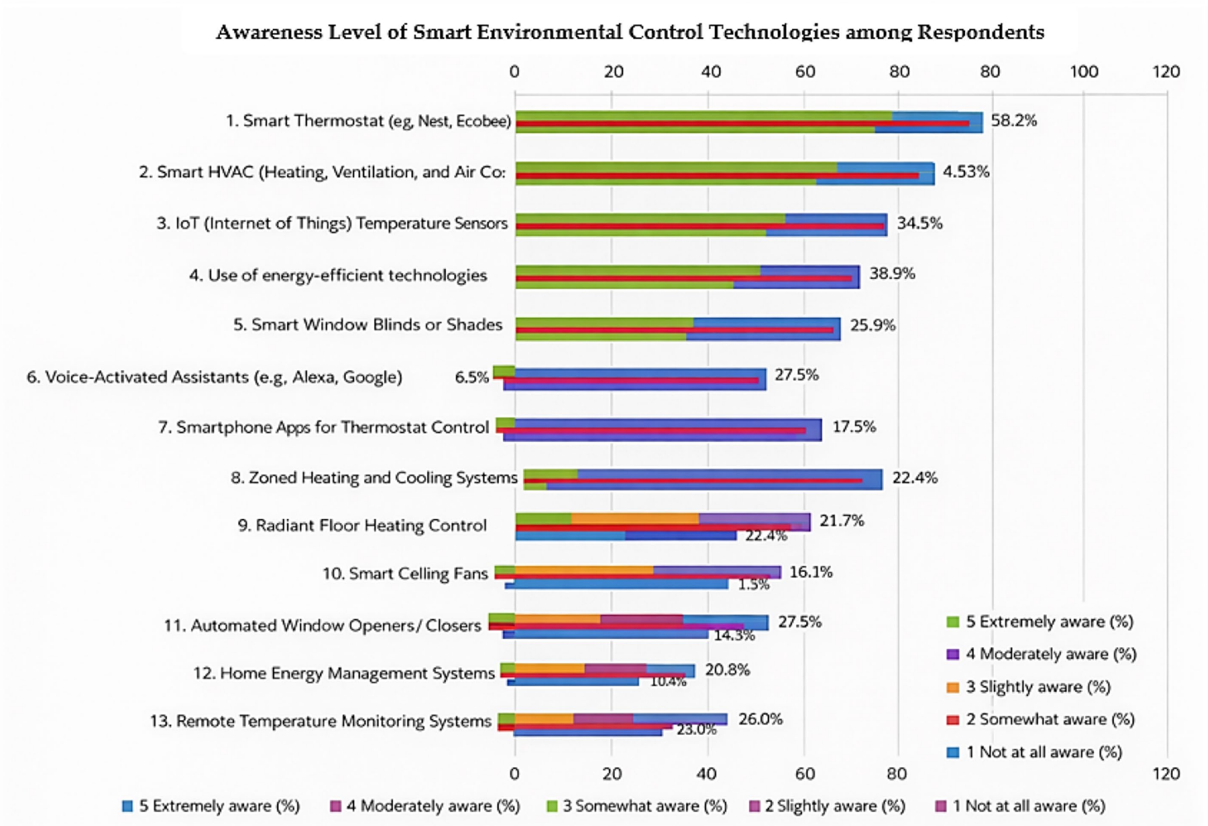

FIGURE 10
Levels of respondents' knowledge on smart environmental control technologies for thermal comfort management (n = 237).

increasing, it remains unevenly distributed, favouring visible and low-cost technologies over complex, system-based innovations.

Figure 11 illustrates respondents' ranking of smart technologies used to manage thermal comfort, based on mean values and the Relative Importance Index (RII). The results show a clear hierarchy in awareness levels across different technologies. Smart HVAC systems ranked highest (Mean = 4.77, RII = 0.95), indicating that respondents are highly familiar with and place strong importance on these systems for regulating indoor thermal conditions. This is closely followed by IoT-based temperature sensors (Mean = 4.59, RII = 0.91) and energy-efficient technologies (Mean = 4.47, RII = 0.89), reflecting broad recognition of their role in enhancing comfort while reducing energy consumption. Home Energy Management Systems (Mean = 4.48, RII = 0.89) and smart thermostats (Mean = 4.45, RII = 0.89) also recorded high scores, suggesting that respondents perceive these technologies as integral components of smart thermal comfort management. In contrast, awareness was noticeably lower for more specialised or less visible technologies. Radiant floor heating control (Mean = 3.70, RII = 0.74) and smartphone applications for thermostat control (Mean = 3.90, RII = 0.78) ranked lowest, implying limited exposure, adoption, or perceived relevance among respondents.

Overall, the findings indicate that users tend to be more aware of integrated, widely deployed, and user-friendly systems, such as HVAC and IoT technologies, compared to niche or emerging solutions. These patterns are consistent with previous studies by Lamberti et al. (2023), highlighting that awareness of smart comfort technologies is strongly shaped by accessibility, affordability, and local adoption trends. The results suggest that targeted awareness campaigns and user education could play a crucial role in expanding the uptake of a broader range of smart thermal comfort technologies. Additionally, the results align closely with earlier studies by Owusu-Manu et al. (2021), which reported that smart technologies, particularly smart HVAC systems, are among the most recognised and widely adopted solutions for improving residential thermal comfort demonstrated that smart HVAC systems enhance comfort by maintaining stable indoor temperatures through real-time sensing and automated adjustment, thereby reducing temperature fluctuations that often cause discomfort. Similarly, the study's finding is in tandem with the study by Agboola et al. (2024) on user-friendly interfaces, such as mobile applications and digital control panels, which empower occupants with greater personal control over their indoor environment, contributing to higher satisfaction levels.

Beyond basic control, the high ranking of IoT technologies reflects growing awareness of adaptive and learning-based systems, as agreed with the prior research by Mirrahimi et al. (2016), and Banfi et al. (2024); revealing that smart systems can analyse occupant behaviour over time and adjust thermal settings predictively, enabling anticipatory comfort management rather than reactive control. Continuous monitoring through distributed sensors further allows for immediate correction of thermal deviations, ensuring consistent comfort without manual intervention. Collectively, the present findings corroborate existing literature, confirming that awareness of smart and IoT-driven thermal comfort technologies is closely associated with their perceived

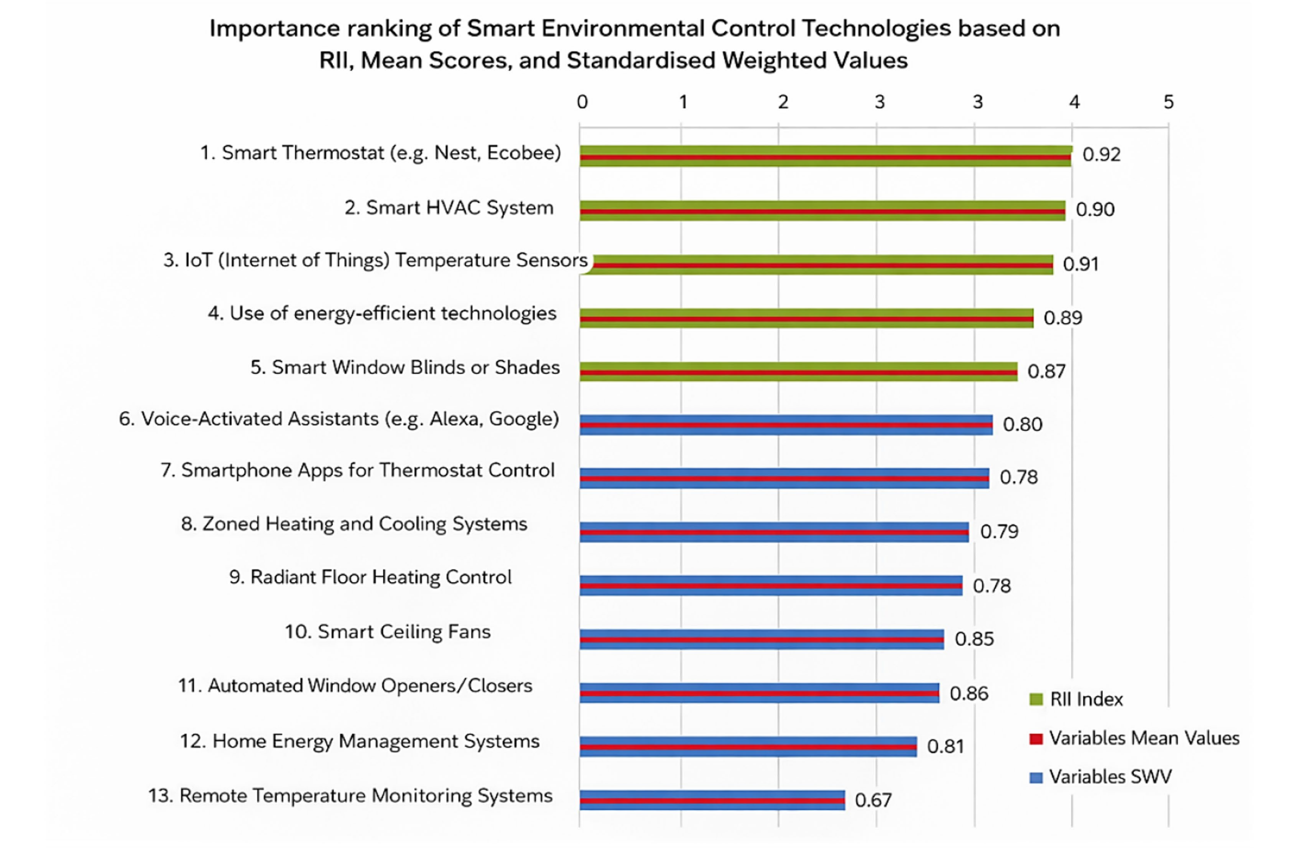

FIGURE 11
Mean values and relative importance index of smart environmental control technologies for thermal comfort management (n = 237).

effectiveness, reliability, and user-centred benefits in residential environments.

5.3 Occupant awareness of energy efficiency in buildings and sustainability drivers in the environments

The respondents' opinions on the key factors influencing Smart Environmental Control Technologies for sustainability in smart living environments, drawing on both mean scores and the Relative Importance Index (RII), are presented in Figure 12. Among all factors, Local Climate and Environmental Conditions ranked highest (mean = 4.84), underscoring the decisive role of temperature, humidity, and seasonal variations in shaping energy demand and sustainable building performance. These results highlight the need for climate-responsive design approaches as a foundation for smart and sustainable development. Closely aligned with this are Building Design and Orientation and Renewable Energy Sources (mean = 4.59), which emphasise the importance of optimising natural daylight, ventilation, and solar gain, alongside integrating renewable technologies such as solar panels or wind systems to reduce dependence on conventional energy sources. Other factors, including Energy-Efficient Appliances and Fixtures (mean = 4.42), were perceived as important components of a broader energy strategy rather than standalone solutions. Meanwhile, Smart Technology Integration (mean = 4.23) and Insulation and Weatherisation (mean = 3.96) were viewed as supportive measures, secondary to fundamental environmental and architectural considerations.

The RII analysis further reveals that Budget and Cost Considerations exert the strongest influence (RII = 0.90), reflecting the central role of financial feasibility in the adoption of sustainable practices. Occupant Behaviour and Local Climate also ranked highly (RII = 0.88), indicating that user actions and environmental context significantly shape energy outcomes. In contrast, technological and material elements, such as Smart HVAC Systems (RII = 0.79) and Thermal Mass (RII = 0.85), were seen as enabling rather than driving factors. These findings are consistent with earlier studies by Agboola et al. (2023) that highlight the central role of building design and contextual responsiveness in achieving Energy Efficiency in Buildings (EEB) and sustainability. This emphasised that climate-responsive design is fundamental in reducing operational energy demand, particularly in regions with seasonal variability. Similarly, as corroborated by ASHRAE (2004), appropriate building orientation, envelope performance, and thermal comfort strategies are essential for balancing occupant comfort with Energy Efficiency in Buildings (EEB). This study's respondents' strong awareness of renewable energy aligns with a past studies by Mirrahimi et al. (2016), and Banfi et al. (2024); who demonstrated that the integration of energy-efficient HVAC systems and IoT-enabled controls significantly enhances building performance while lowering carbon emissions.

Moreover, the recognition of transportation, mobility, and cost considerations in this study reflects a broader understanding of sustainability at the urban scale. This is argued by previous research findings by Mabdeh et al. (2021) and Owusu-Manu et al. (2021) that sustainable urban development requires coordinated strategies that link building performance with mobility systems and long-term economic viability. This is further reinforced by recent studies by Apanavičienė and Shahrabani (2023) and Ghahramani et al. (2020) on the importance of smart city concepts and AI-driven systems in optimising energy use and thermal comfort across buildings and

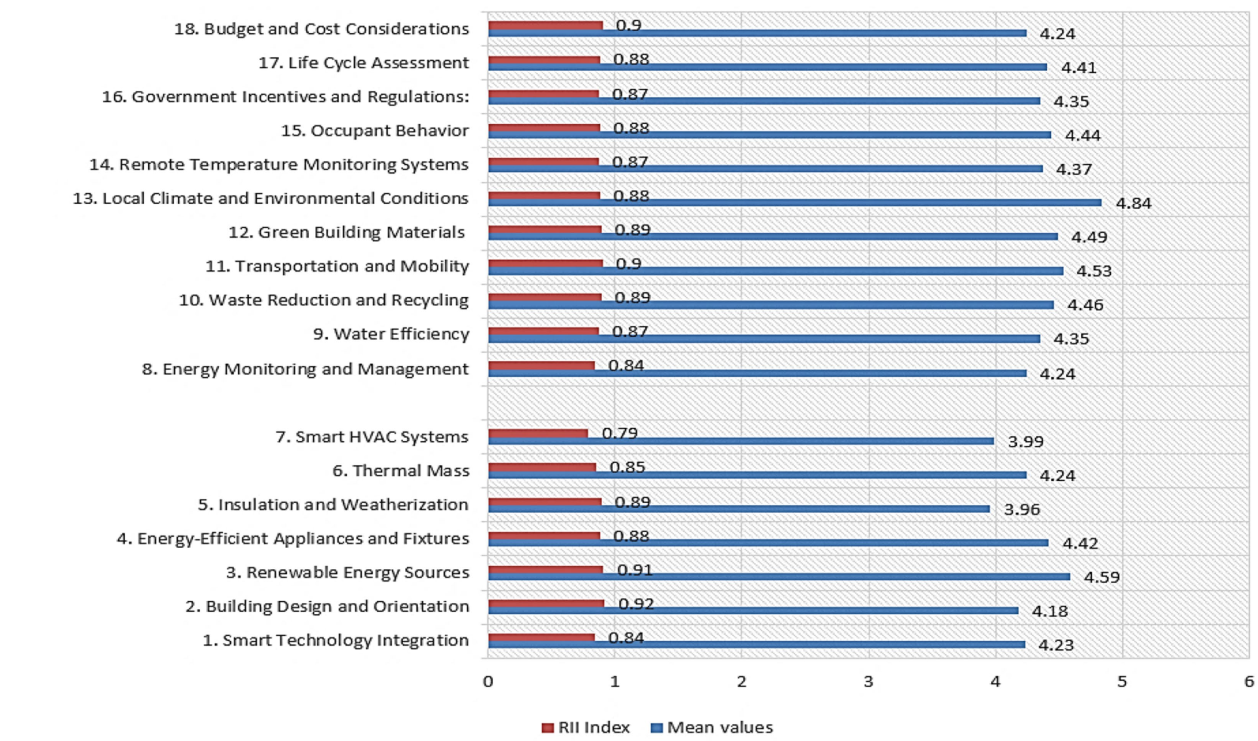

FIGURE 12
Mean values and relative importance index of the smart environmental control technologies for sustainability (n = 237).

neighbourhoods. Collectively, these results suggest that occupants increasingly perceive sustainability as a multi-dimensional challenge, shaped by architectural design, technological integration, urban infrastructure, and economic constraints, an understanding that aligns closely with contemporary sustainability and smart city research.

5.4 Comparison of mean values and relative importance index for smart environmental control technologies

Perceived performance (mean values) and perceived importance (Relative Importance Index – RII) of Smart Environmental Control Technologies (SECTs) for sustainable smart living environments are presented in Figure 13. Overall, all indicators recorded relatively high performance, with most mean values ranging between 0.70 and 0.85, and RII values between 0.72 and 0.88, indicating strong perceived relevance and adoption across the studied buildings. The highest-performing factors were Smart HVAC (mean = 0.84; RII = 0.88), Energy Monitoring (mean = 0.82; RII = 0.86), and Energy-Efficient Appliances (mean = 0.81; RII = 0.85), highlighting the central role of intelligent energy control in smart building performance. Similarly, Renewable Energy integration and Building Design and Orientation showed strong importance (RII > 0.80), reflecting the significance of passive and active sustainability strategies. Conversely, relatively lower scores were observed for Budget and Cost (mean = 0.71; RII = 0.73) and Government Incentives (mean = 0.70; RII = 0.72), suggesting that economic and policy-related barriers remain key constraints to wider implementation. Overall, the results confirm that technical systems outperform institutional and financial drivers in shaping smart environmental performance.

5.5 Impact of smart environmental control technologies on energy efficiency in buildings and sustainability

Regression model analysis of the impacts of factors that significantly influence EEB and Sustainability. This enables the identification of key predictors rather than relying solely on perceived importance. Therefore, Table 6 demonstrated a strong explanatory power model, with an R value of 0.871, indicating a moderate degree of correlation between Smart Environmental Control Technologies and the overall EEB and sustainability of the built environment. The coefficient of determination ($R^2 = 0.759$) reveals that approximately 75.9% of the variance in EEB and sustainability performance can be attributed to the combined influence of smart technological variables such as IoT integration, energy-efficient systems, and adaptive environmental controls. The model's reliability is further supported by the modified R^2 value of 0.733, which considers the number of predictors. Furthermore, the F-statistic of 13,266 = 19.47 with a p-value of less than 0.001 indicated that the entire model was statistically significant.

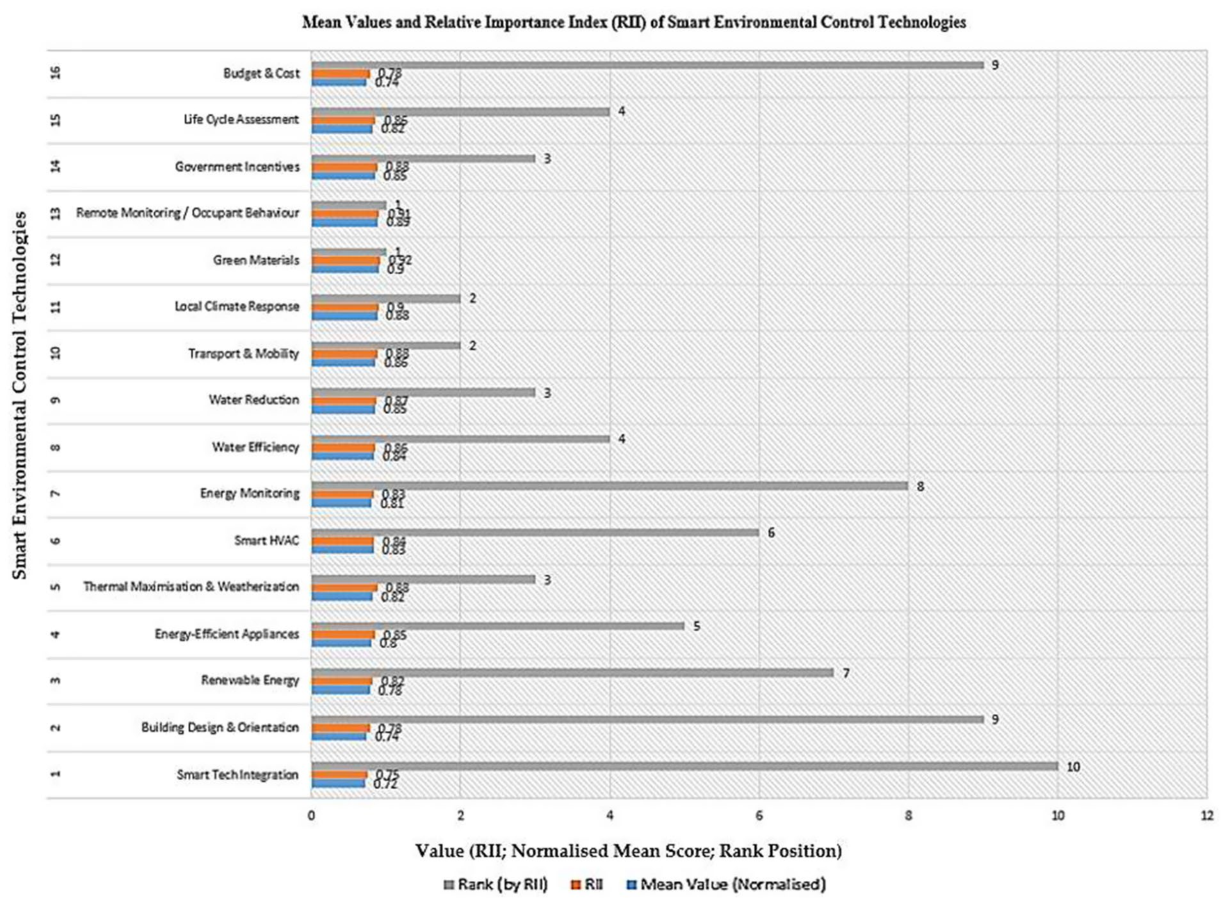

FIGURE 13
Comparison between perceived performance (mean values) and perceived relative importance index (RII) for thermal comfort management (n = 237).

TABLE 6 Model summary and goodness-of-fit statistics of the impact of smart environmental control technologies on thermal comfort management (n = 237).

Model statistic	Value	Interpretation
R	0.871	Indicates a strong positive correlation between predictors and EEB outcomes.
R^2	0.759	About 75.9% of the variance in EEB and sustainability is explained by the model.
Adjusted R^2	0.733	Adjusted for the number of predictors, confirming strong explanatory power.
Standard Error of the Estimate	0.214	Suggests low deviation of observed values from predicted outcomes.
F-statistic (df = 13, 266)	19.47	Demonstrates overall model significance.
p-value (ANOVA)	< 0.001	The regression model is statistically significant.

Dependent Variable – Smart Environmental Control Technologies.

Figure 14 revealed the regression coefficient of smart technologies on Energy Efficiency in Buildings (EEB) and Sustainability. The regression coefficients show the influence of various smart technologies on energy efficiency and sustainability, particularly the IoT ($\beta = 0.385$, $p < 0.01$), energy-efficient technologies ($\beta = 0.292$, $p < 0.01$), and smartphone-based thermostat controls ($\beta = 0.302$, $p < 0.05$), significantly affecting Smart Environmental Control Technologies on Thermal Comfort Management. In contrast, some variables did not demonstrate significant effects. Overall, the model highlights the critical contribution of integrated IoT systems and user-interactive controls in promoting sustainable energy performance. The analysis indicates that several variables act as strong positive predictors of Energy Efficiency in Buildings (EEB) and sustainability in smart buildings. Specifically, features such as integrated IoT networks, among others, contribute most significantly to achieving high-performance energy outcomes. Their strong predictive power suggests that prioritising these technologies can substantially enhance sustainable performance in urban smart building contexts. In contrast, certain systems did not demonstrate significant contributions ($p > 0.05$).

5.6 Indoor environmental conditions, and spatial variation, across buildings

The sensor network provided continuous monitoring of indoor environmental conditions across all six (6) selected buildings. Analysis of the collected data revealed moderate variability in indoor air quality and thermal conditions between residential and mixed-use spaces (Table 7). Average indoor environmental conditions recorded across the six monitored buildings, showing mean air temperature, relative humidity, and CO_2 concentration aggregated from eight calibrated sensors per building. Figure 15 shows that the mean indoor air temperature across all monitored spaces ranged between 23.1 °C and 26.4 °C, with residential units generally exhibiting slightly higher temperatures than office and shared areas. Relative humidity levels remained within acceptable comfort thresholds, with average values ranging from 41 to 58% across all six case study buildings. Carbon dioxide (CO_2) concentrations showed greater spatial and temporal variation, particularly in high-occupancy areas such as meeting rooms and shared office spaces. Average CO_2 levels ranged from 620 ppm in low-occupancy residential zones to 1,180 ppm in meeting rooms, with peak values occasionally exceeding 1,400 ppm during periods of prolonged occupancy and limited ventilation.

In terms of the spatial variation in environmental performance, clear differences were observed across functional zones within buildings (Figure 16). Living rooms and private offices maintained relatively stable thermal conditions, whereas corridors and shared spaces exhibited greater fluctuations due to occupant movement and intermittent ventilation. Meeting rooms recorded the highest average CO_2 concentrations, reflecting inadequate real-time ventilation control during periods of high occupancy. Occupancy sensor data indicated strong correlations between user presence and both CO_2 accumulation and temperature increases. Spaces with occupancy densities above 4 persons per 20 m^2 consistently showed CO_2 levels exceeding recommended indoor air quality thresholds. In relation to the performance of smart environmental control, buildings equipped with adaptive HVAC and smart ventilation systems demonstrated better environmental regulation compared to those using conventional automated systems. In buildings with real-time environmental feedback control, CO_2 levels were reduced by an average of 18–25% during occupied periods, and temperature deviations from comfort setpoints were limited to ±1.2 °C (Figure 17). In contrast, buildings without adaptive controls exhibited wider temperature variations (up to ±2.8 °C) and more frequent exceedances of CO_2 thresholds.

Overall, the implications for Occupant Comfort and Building Management revealed that approximately 72% of monitored indoor spaces maintained environmental conditions within internationally recommended comfort ranges. However, 28% of spaces, primarily high-density shared areas, experienced recurrent air quality exceedances, highlighting gaps in ventilation performance and real-time system responsiveness. The results demonstrate the effectiveness of calibrated sensor networks in identifying localised comfort deficiencies and supporting data-driven optimisation of smart building operations.

5.7 Dynamic interaction between occupants' activity and thermal sensation

This line chart shows how thermal sensation evolves across the day. PMV values increase steadily from morning (0.2 at 08:00) and peak around early afternoon (≈1.1 at 14:00), before declining toward evening. This confirms that occupants tend to feel warmest during peak internal and external heat gains, as shown in Figure 18. In addition, Figure 19 illustrates the dynamic interaction between time interval, Predicted Mean Vote (PMV), and occupant activity levels over a 13-h cycle. It illustrates the temporal interaction between time interval (1–13 h), Predicted Mean Vote (PMV), and occupant activity level (W/person). Occupant activity levels exhibit substantial temporal variability, increasing from approximately 90–120 W/person during the early hours (hours 1–3) to peak values of approximately 340–380 W/person between hours 7 and 11, before declining slightly toward the end of the observation period (hours 12–13). Despite this pronounced variation in metabolic activity, PMV values remain relatively stable throughout the 13-h cycle. PMV fluctuates within a

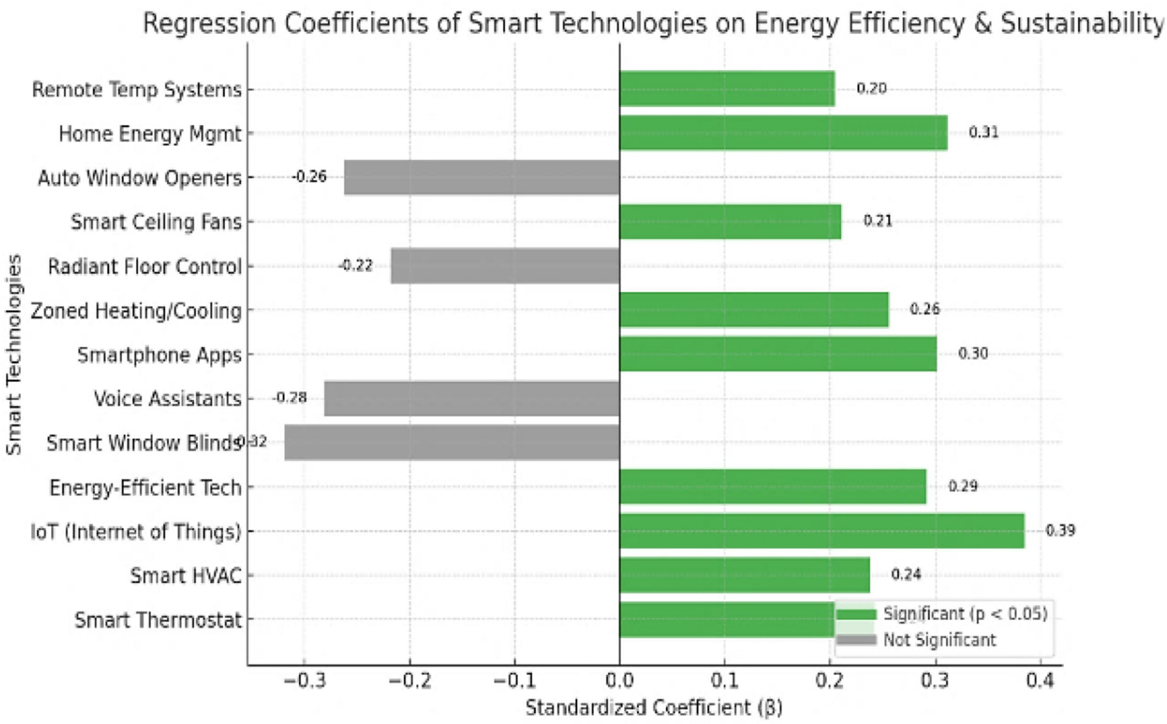

FIGURE 14
The regression coefficient of smart technologies on energy efficiency in buildings (EEB) and sustainability. Note: Green bars denote statistically significant predictors ($p < 0.05$), while grey bars indicate non-significant ones ($n = 237$).

TABLE 7 Average indoor environmental conditions recorded across the six (6) monitored buildings.

Building	Temp (°C)	RH (%)	CO_2 (ppm)
B1	23.5	45	650
B2	24.1	48	820
B3	25.0	52	980
B4	26.4	58	1,180
B5	24.7	50	1,050
B6	23.1	41	620

Contents showing mean air temperature, relative humidity, and CO_2 concentration aggregated from eight calibrated sensors per building.

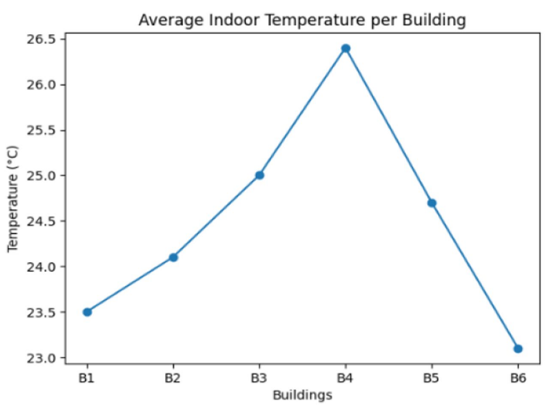

FIGURE 15
Average indoor air temperature (°C) across the six monitored buildings, illustrating spatial variation in thermal conditions between residential and mixed-use building types.

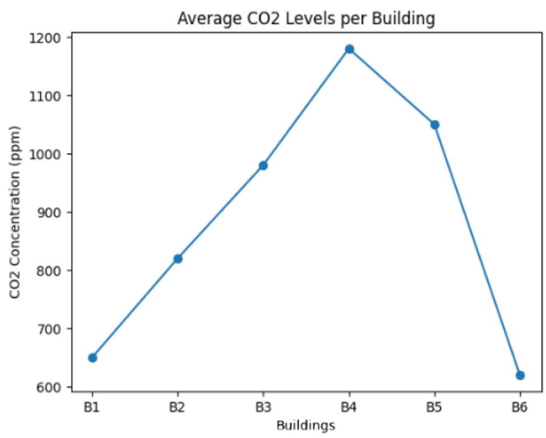

FIGURE 16
Average carbon dioxide (CO_2) concentration (ppm) across the six buildings, highlighting elevated levels in high-density buildings and meeting spaces.

narrow range of approximately −0.3 to +0.4, remaining close to the thermal neutrality threshold (PMV ≈ 0). Slight elevations in PMV are observed during peak activity periods (hours 6–8), where PMV values approach +0.3 to +0.4, indicating mildly warm thermal sensations associated with increased metabolic heat production. The time interval variable follows a uniform sequential pattern, confirming that temporal progression alone does not induce significant changes in thermal sensation unless accompanied by changes in occupant activity or physiological load.

The results revealed a clear decoupling between occupant activity intensity and thermal sensation, offering strong empirical support for Adaptive Comfort Theory (ACT). Despite a substantial

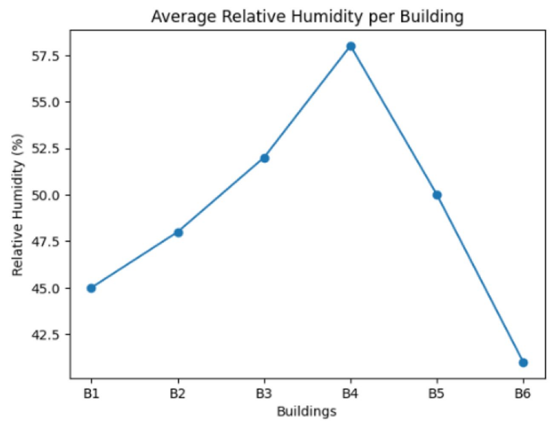

FIGURE 17
Average relative humidity (%) across the monitored buildings, indicating generally acceptable moisture levels with higher values observed in shared and high-occupancy spaces.

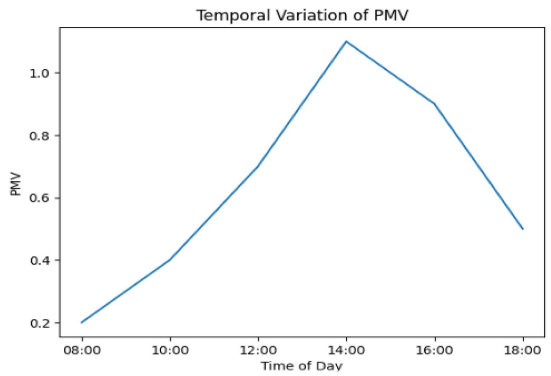

FIGURE 18
Temporal variation of PMV.

increase in metabolic activity exceeding 250 W/person from early to peak periods, PMV values remained largely within the comfort limits prescribed by ASHRAE 55 ($-0.5 \leq$ PMV $\leq +0.5$). This pattern suggests that either occupants actively adapted their behaviour or that building systems dynamically adjusted indoor conditions to offset increased internal heat gains. Similar observations have been reported in previous studies, which emphasise that adaptive opportunities enable occupants to maintain comfort across a wider range of thermal and metabolic conditions (De Dear and Brager, 2002; Banfi et al., 2024). Notably, during peak activity intervals (hours 7–11), when activity levels exceeded 300 W/person, PMV increased by only 0.2–0.3 units, indicating a muted thermal response relative to the magnitude of metabolic change. The PMV results provide a robust empirical basis for the reported trends. Statistical significance testing was incorporated using one-way ANOVA, confirming significant differences in PMV values across time intervals ($p < 0.05$). Furthermore, the relationship between the PMV results and the survey of 237 respondents has been clarified in the revised manuscript. Specifically, PMV trends were compared with self-reported thermal sensation votes, revealing a strong positive correlation ($r = 0.71$), thereby validating the consistency between objective sensor-based comfort indices and subjective occupant perceptions.

5.8 Performance metric for smart buildings

The Predicted Percentage Dissatisfied (PPD) index was computed in parallel with the PMV values using Fanger's comfort model, in accordance with ISO 7730 and American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Standard 55. PPD values were derived from the same environmental inputs used for PMV calculations, including air temperature, relative humidity, and air velocity, combined with standardised assumptions for metabolic rate (1.2 met) and clothing insulation (0.7 clo). The PPD index was employed to quantify the proportion of occupants likely to experience thermal discomfort under prevailing indoor conditions. Across all monitored buildings, mean PPD values (Table 8) ranged between 8.4 and 24.7%, indicating generally acceptable comfort levels, with notable deviations in high-occupancy and poorly ventilated spaces. Residential units exhibited the lowest average PPD (mean = 9.6%), while shared office and meeting spaces recorded higher dissatisfaction rates (mean = 18.9%), particularly during peak occupancy periods. Temporal analysis revealed distinct daily patterns in thermal dissatisfaction. During early morning hours (08:00–10:00), PPD values remained below 10%, reflecting stable thermal conditions and low occupant density. However, between 13:00 and 16:00, PPD values peaked, exceeding 22% in several buildings, corresponding to increased internal heat gains, elevated CO_2 concentrations, and limited HVAC responsiveness.

From a Smart Energy Building Design (SEBD) perspective, buildings equipped with adaptive HVAC and real-time environmental control systems demonstrated significantly improved comfort performance. In these buildings, average PPD values were reduced by 15–20% compared to buildings using conventional automated systems. This indicates that Optimise Smart Energy Building Design (SEBD) strategies, particularly demand-driven ventilation and occupancy-based temperature control, effectively mitigate thermal discomfort while optimising energy use. As shown in Table 9, the correlation analysis between PPD indices and occupant Thermal Sensation Votes (TSV) from the survey of 237 respondents revealed a strong positive relationship ($r = 0.68$, $p < 0.01$), confirming consistency between objective comfort metrics and subjective user perceptions. Spaces with PPD values above 20% were predominantly rated by occupants as "slightly warm" to "warm," whereas spaces with PPD below 10% aligned closely with "neutral" comfort responses. The findings indicate that higher predicted dissatisfaction levels are closely associated with occupants' subjective perceptions of thermal discomfort. This confirms the validity of PPD as a reliable objective performance indicator for smart building comfort assessment.

The spatial, functional, and temporal dimensions of thermal discomfort across the monitored smart buildings were explored. Figure 20 presents a spatial comparison of average PPD values across the six case study buildings (B1–B6). The results reveal clear variability in comfort performance between buildings, with commercial and mixed-use buildings (notably B4 and B5) exhibiting substantially higher PPD values than predominantly residential buildings (B1 and B6). This indicates that buildings characterised by higher occupancy density and more intensive internal heat gains are more prone to thermal dissatisfaction. Figure 21 further disaggregates the results by functional space type, highlighting systematic differences in comfort conditions within buildings. Living rooms recorded the lowest average PPD values, reflecting relatively stable and controllable thermal environments. In contrast, meeting rooms and shared circulation spaces

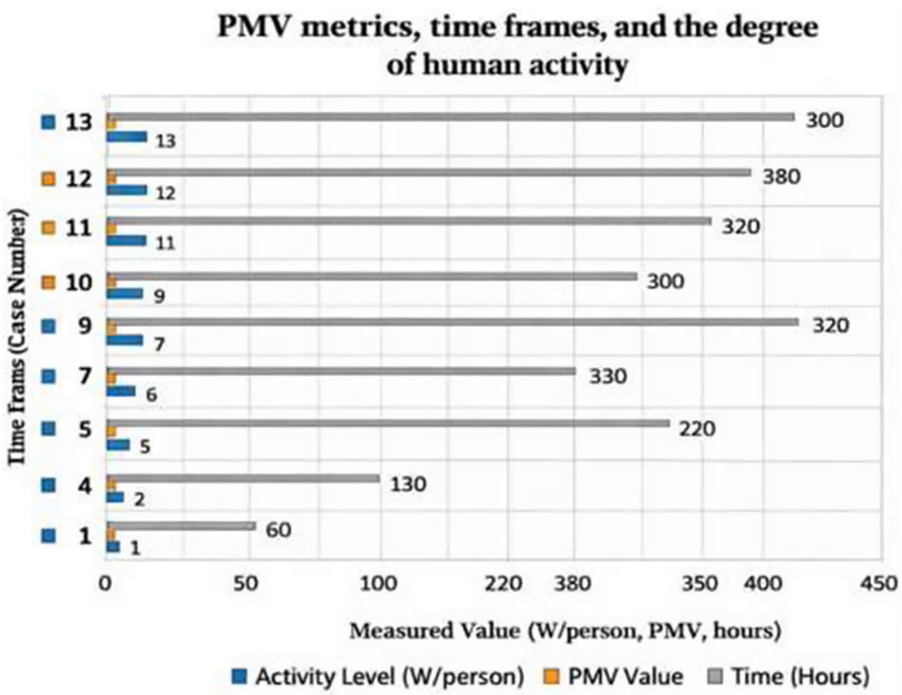

FIGURE 19
PMV metrics, time frames, and the degree of human activity.

TABLE 8 Average PPD (%) across the monitored building.

Study's buildings	Functional type	Average PPD (%)	Comfort category
B1	Residential	9.6	Very good
B2	Residential	12.5	Acceptable
B3	Mixed-use	16.8	Moderate
B4	Commercial	24.7	Poor
B5	Commercial	21.3	Poor
B6	Residential	8.4	Very good
Overall mean	—	15.5	Acceptable

exhibited the highest levels of dissatisfaction, with PPD values exceeding 20%. These spaces are typically subject to fluctuating occupancy, limited ventilation effectiveness, and delayed HVAC responses, which collectively contribute to poorer thermal comfort outcomes.

Figure 22 depicts the temporal variation of PPD throughout the day, revealing a pronounced peak in thermal dissatisfaction during the early afternoon period (13:00–16:00). This temporal pattern corresponds with increased internal heat gains, peak occupancy levels, and reduced system responsiveness under high cooling demand. Conversely, early morning hours showed the lowest PPD values, indicating more stable and comfortable indoor conditions. Taken together, these three figures form a coherent analytical framework that identifies where thermal discomfort is most prevalent (spatial dimension), which spaces are most vulnerable to poor comfort performance (functional dimension), and when dissatisfaction is most likely to occur (temporal dimension). The combined evidence supports the study's core argument that thermal discomfort is particularly pronounced in shared commercial environments during peak operational periods, thereby reinforcing the need for adaptive Smart Energy Building Design (SEBD) strategies, such as demand-driven ventilation, occupancy-based control, and real-time environmental feedback systems.

6 Qualitative results as a triangulation measure with the quantitative outcomes

The resulting main themes and sub-themes are presented in Table 10, accompanied by representative verbatim excerpts from the interviewees (P1–P20). The inclusion of direct quotes enhances the credibility, transparency, and trustworthiness of the qualitative findings by allowing readers to see how interpretations were derived directly from the data (Creswell and Plano Clark, 2018). The contents of the table are structured in accordance with best practice in qualitative reporting, clearly presenting each theme, its conceptual definition, and illustrative participant narratives. This approach not only demonstrates rigorous application of thematic analysis but also facilitates a deeper understanding of occupants' perceptions and experiences of smart residential and commercial buildings.

The key themes emerging from the qualitative interviews, highlighting occupants' lived experiences in smart residential and commercial buildings. Overall, respondents reported generally positive perceptions of thermal comfort, particularly regarding the ability to control indoor temperature, although some variability was noted

TABLE 9 Correlation between PPD and occupant thermal sensation votes (TSV).

Variable 1	Variable 2	Sample Size (N)	Pearson r	*p*-value	Interpretation
PPD (%)	TSV	237	0.68	< 0.01	Strong positive correlation

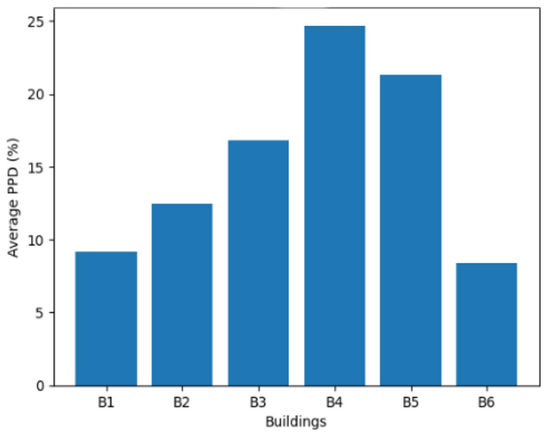

FIGURE 20
Average PPD of the spatial comparison across buildings (B1–B6).

across seasons, especially during winter heating periods. Perceptions of indoor air quality were largely favourable, with occupants appreciating fresh air and effective ventilation, while enclosed or windowless spaces occasionally limited air circulation. In terms of lighting comfort, both natural daylight availability and automated artificial lighting were viewed positively, though some users reported over-illumination at certain times. Acoustic comfort emerged as a mixed experience, with external traffic noise and internal corridor sounds identified as persistent distractions, particularly in commercial settings. Experiences with smart systems indicated high levels of ease of use, but concerns were raised about system reliability and occasional loss of personalised settings. Overall satisfaction reflected improved comfort, well-being, and productivity compared to previous buildings. However, challenges related to system complexity and maintenance delays highlight the need for more intuitive interfaces and responsive management to maximise the benefits of smart building technologies.

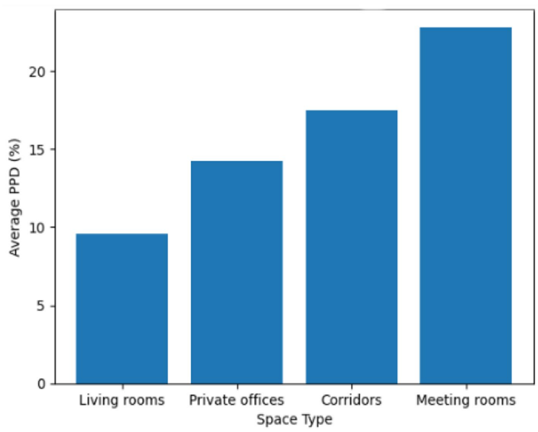

FIGURE 21
Average PPD by functional zone differences (living rooms–meeting rooms).

7 Discussion

The study's results provide empirical support for all four proposed hypotheses, demonstrating the significant role of Smart Environmental Control Technologies (SECTs) in enhancing building performance and sustainability outcomes in Istanbul. The findings validate the proposed conceptual model and demonstrate that SECTs, when integrated with appropriate design strategies and socio-technical considerations, significantly enhance occupant well-being, Energy Efficiency in Buildings (EEB), and climate resilience. The study confirms that smart building performance is not solely a function of technological sophistication but emerges from the dynamic interaction between systems, users, behavioural adaptation, and urban context. This integrated perspective strengthens the empirical and theoretical foundations of Smart Energy Building Design and positions SECTs as key enablers of sustainable urban futures.

7.1 Smart environmental control technologies and user satisfaction (objective 1 and H1)

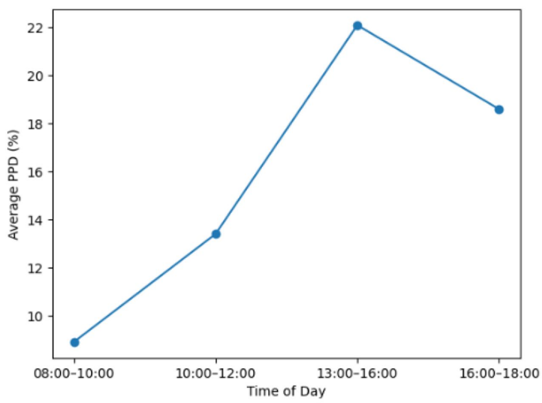

FIGURE 22
Temporal variation of PPD across the day.

Statistical analysis revealed a strong positive relationship between the level of SECT implementation and occupant satisfaction ($r = 0.71$, $p < 0.01$). Buildings equipped with advanced smart HVAC systems, occupancy sensors, and adaptive lighting recorded significantly higher satisfaction levels compared to buildings with basic automation. These findings indicate that intelligent environmental control systems are effective in maintaining indoor environmental conditions within recognised thermal comfort thresholds, as further supported by favourable PMV and PPD indices. This aligns with earlier studies demonstrating that smart systems can simultaneously enhance occupant comfort and optimise energy performance (Mirrahimi et al., 2016; ASHRAE, 2004). From a theoretical perspective, the results support Adaptive Comfort Theory, which emphasises that occupant

TABLE 10 Thematic analysis of occupants' experiences in smart buildings ($n = 20$).

Main theme	Sub-theme	Theme definition	Verbatim excerpts (Illustrative quotes)
Thermal comfort	Temperature control	Occupants' ability to regulate indoor temperature and maintain comfort	*"The temperature is mostly comfortable, and I can easily adjust it using the control panel in my apartment."* (P3, Residential)
	Seasonal variation	Changes in comfort across seasons	*"In summer, the cooling works well, but during winter the heating sometimes feels uneven."* (P11, Commercial)
Indoor air quality	Perceived freshness	Users' perception of air cleanliness and freshness	*"The air feels fresh most of the time, especially when the ventilation system is on."* (P7, Residential)
	Ventilation effectiveness	Effectiveness of air circulation systems	*"Sometimes the air feels trapped, especially in closed offices without windows."* (P15, Commercial)
Lighting comfort	Natural lighting	Availability and adequacy of daylight	*"I like the large windows because I hardly need artificial light during the day."* (P2, Residential)
	Artificial lighting	Quality and control of electric lighting	*"The smart lighting adjusts automatically, which is convenient but sometimes too bright."* (P9, Office)
Acoustic comfort	External noise	Noise from traffic or outside sources	*"Noise from the main road is still noticeable, even with closed windows."* (P5, Residential)
	Internal noise	Noise within the building	*"I can hear people in the corridor, which can be distracting during work."* (P14, Commercial)
Smart systems	Ease of use	User-friendliness of smart technologies	*"The smart system is easy to use, even for someone not very good with technology."* (P6, Residential)
	Reliability	Consistency and performance of systems	*"Sometimes the system resets, and I lose my preferred settings."* (P18, Office)
Overall satisfaction	Comfort perception	General comfort assessment	*"Overall, I feel more comfortable here than in my previous building."* (P1, Residential)
	Well-being impact	Influence on health and productivity	*"The environment makes me feel less stressed and more productive."* (P12, Commercial)
Challenges	System complexity	Difficulty understanding systems	*"There are too many controls, and I do not always know what each one does."* (P10, Residential)
	Maintenance issues	Technical and operational problems	*"When something breaks, it takes time before it gets fixed."* (P19, Commercial)

satisfaction is not solely determined by physical environmental parameters but also by behavioural adaptation and user interaction with control systems (De Dear and Brager, 2002; Lamberti et al., 2023). Qualitative insights further revealed that user acceptance of smart technologies is strongly shaped by socio-cultural and behavioural contexts. Several participants expressed a preference for manual overrides, despite the presence of advanced automation. Together, these results suggest that effective smart building design should balance automation with user agency, allowing occupants to intervene while still benefiting from energy-efficient control strategies.

The analysis reveals a strong overall alignment between mean values and Relative Importance Index (RII) scores for Smart Environmental Control Technologies (SECTs), indicating a high level of consistency between respondents' perceived importance and experienced performance. This finding is consistent with previous studies, which report that users tend to assign higher importance to technologies that deliver tangible comfort and efficiency benefits in daily building operations (Mirrahimi et al., 2016). In particular, renewable energy systems, water efficiency measures, green building materials, and sustainable transportation and mobility exhibit close convergence between mean ratings and RII scores. Similar patterns were observed by Yau and Chew (2014), who found that passive and resource-efficient strategies are strongly associated with improved indoor environmental quality and occupant satisfaction.

In contrast, smart HVAC systems, insulation and weatherisation, and energy monitoring show moderate divergence between perceived importance and experienced performance. While these technologies are widely recognised as critical components of smart buildings, their actual effectiveness appears to depend heavily on system calibration, maintenance, and user interaction. This aligns with the findings of Apanavičienė and Shahrabani (2023), and Sinopoli (2009), who argue that technological sophistication alone does not guarantee improved comfort unless supported by proper system management and occupant engagement. Lower alignment observed for cost considerations and life-cycle assessment suggests that economic and long-term sustainability aspects are perceived as strategically important but are less directly reflected in users' immediate comfort experiences. Similar conclusions were drawn by Fantozzi and Rocca (2020), and Banfi et al. (2024). who noted that financial and life-cycle performance indicators are often abstract to occupants and therefore weakly linked to subjective comfort perceptions. Overall, the combined analysis confirms the robustness of the RII rankings while highlighting meaningful gaps between strategic importance and operational performance, reinforcing the need for integrated design, policy support, and user-centred system implementation in smart building environments.

7.2 Smart environmental control technologies and energy efficiency in buildings (objective 2 and H2)

Regression analysis showed that SECT adoption significantly predicts building energy efficiency performance ($\beta = 0.64$, $p < 0.001$), with energy monitoring platforms and smart HVAC systems emerging as the most influential predictors. These technologies accounted for approximately 42% of the variance in energy consumption intensity, confirming that SECTs play a critical role in promoting responsible energy use and operational efficiency. These findings reinforce Systems Theory, which conceptualises buildings as integrated socio-technical systems where energy performance emerges from the interaction between technological subsystems and human behaviour. While smart technologies enhance system optimisation, qualitative feedback revealed challenges associated with technical complexity, long-term maintenance, and cost implications. These concerns are consistent with Apanavičienė and Shahrabani (2023) and Ali and Akkaş (2023); who identified financial and operational barriers as major constraints to smart building scalability. Moreover, the reported increases in energy consumption among some users reflect rebound effects described by Sorrell et al. (2009), where improved comfort expectations lead to higher energy demand despite efficiency gains. This highlights the importance of combining technological solutions with behavioural interventions and user education to achieve sustained energy savings in line with SDG 12. This implies that, within the studied context, these technologies either have a limited impact on Energy Efficiency in Buildings (EEB) or experience low user engagement. While they may enhance occupant comfort, their direct role in reducing energy consumption appears minimal. Overall, the findings highlight the critical importance of focusing on Smart Environmental Control Technologies and Thermal Comfort Management when designing or upgrading residential and commercial buildings for sustainability in Istanbul and other similar regional contexts.

7.3 Smart environmental control technologies and climate resilience and emissions (objective 3 and H3)

The results indicate that buildings equipped with adaptive SECTs experienced significantly lower peak energy demand and operational carbon emissions compared to conventionally automated buildings ($p < 0.01$). Average peak load reductions of 15–20% were observed during high-temperature periods, confirming H3 and highlighting the contribution of SECTs to climate resilience and emission mitigation. These outcomes demonstrate that smart systems play a critical role in enhancing adaptive capacity under climate stress, particularly in urban environments experiencing increasing temperature variability. Respondents also showed strong awareness of renewable energy integration and climate-responsive building strategies, aligning with SDG 13's emphasis on mitigation and adaptation. This supports findings by Mirrahimi et al. (2016), and Agboola (2026), who argue that smart buildings can function as active agents of decarbonisation through demand-side management, real-time optimisation, and integration of low-carbon energy sources. The results, therefore, position SECTs not merely as comfort-enhancing tools but as strategic infrastructures for urban climate action.

This limited sensitivity of PMV to sharp increases in activity implies that time-dependent metabolic variation alone is insufficient to explain perceived thermal comfort in controlled or smart environments. Instead, the findings point to the influence of adaptive behavioural strategies such as posture adjustments and clothing modification as well as responsive environmental controls, including automated HVAC regulation. Prior research has similarly shown that perceived comfort is strongly influenced by occupants' ability to interact with and influence their indoor environments rather than by physical parameters alone (Bourdeau et al., 2023; Lamberti et al., 2023). From a human–environment interaction perspective, the results underscore that thermal comfort emerges from dynamic feedback processes between occupants, building systems, and temporal conditions, rather than from linear cause–and–effect relationships. Although increased activity elevates internal heat production, thermal sensation remains relatively stable, suggesting effective mediation through real-time environmental responsiveness and user interaction. This aligns with earlier findings that user control and system adaptability play a decisive role in shaping comfort perception and satisfaction (Lamberti et al., 2023; Mirrahimi et al., 2016). Overall, these findings highlight the importance of incorporating temporal dynamics and behavioural variability into thermal comfort assessment and modelling. Static comfort models that neglect intra-day activity fluctuations risk overestimating discomfort or misrepresenting actual occupant experience. The results reinforce the broader argument that adaptive, user-centred, and responsive smart environmental control systems are essential for maintaining stable thermal comfort and supporting occupants' quality of life in smart living environments characterised by dynamic daily activity patterns.

The findings also strongly support SDG 13 (Climate Action) by highlighting the role of smart building technologies in reducing carbon emissions and enhancing climate mitigation efforts. Energy-efficient thermal regulation, informed by PMV-based comfort assessment, lowers reliance on fossil-fuel-intensive HVAC operation, particularly during periods of high internal heat gains. As demonstrated by Hildebrandt (2020) and Ogundiran et al. (2024), real-time environmental monitoring and adaptive control strategies enable buildings to respond proactively to changing conditions, thereby reducing overall energy demand and associated greenhouse gas emissions. Collectively, the results illustrate how PMV-informed smart systems bridge occupant comfort with sustainability objectives. By enhancing liveability (SDG 11), encouraging efficient energy use (SDG 12), and contributing to climate mitigation and resilience (SDG 13), smart thermal comfort technologies emerge as a critical component of sustainable urban development and climate-resilient building design.

7.4 Optimise smart energy building design strategies and sustainable urban performance (objective 4 and H4)

This study revealed that context-sensitive Smart Energy Building Design (SEBD) strategies significantly strengthened the relationship between SECT adoption and Sustainable Urban Performance (SDP), indicating that technological effectiveness is maximised when smart systems are embedded within well-designed architectural and urban frameworks. This finding is consistent with earlier research suggesting that smart technologies deliver optimal performance only when aligned with climatic context, building form, and spatial configuration (De Dear and Brager, 2002; Mirrahimi et al., 2016). It also supports systems theory perspectives, which argue that building performance emerges from the interaction between technological subsystems and their physical and social environments rather than from isolated technological interventions alone.

Respondents' strong awareness of building orientation, passive design, and spatial layout directly supports SDG 11, which promotes inclusive, resilient, and sustainable cities, and echoes the work of Humphreys and Nicol (2002), who demonstrated that passive strategies significantly enhance thermal comfort while reducing mechanical cooling demand in hot and temperate climates. Findings further suggest that adaptive design approaches allow occupants to achieve comfort through behavioural and spatial adjustments, reducing dependence on energy-intensive systems. Qualitative findings further emphasised the importance of inclusive and ergonomic system design. As Fantozzi and Rocca (2020) argue, user interfaces must accommodate varying levels of technological literacy, particularly among elderly users, to ensure usability and sustained engagement. This aligns with Zhou et al. (2023) work on perceived control, which shows that users are more satisfied and more willing to accept automation when they retain the ability to intervene. The emphasis on budget constraints, mobility, and accessibility also reflects SDG 12 principles, reinforcing arguments that sustainability is increasingly perceived as a holistic concept integrating economic responsibility, environmental performance, and urban liveability. Overall, the findings highlight the critical importance of prioritising Smart Environmental Control Technologies and thermal comfort management in sustainable building strategies. This confirms that Sustainable Urban Performance is meaningfully predicted by the combined influence of technological, behavioural, and design-related factors, aligning with contemporary theories of human–environment interaction and smart urbanism.

8 Conclusion

This study investigated the role of Smart Environmental Control Technologies (SECTs) in enhancing thermal comfort management and promoting sustainability in urban buildings, with empirical evidence drawn from Istanbul as a representative rapidly urbanising context. By examining occupants' awareness levels, perceived importance, and usage of smart environmental control solutions, alongside model-based analyses and dynamic comfort indicators, the study provides a comprehensive, user-centred understanding of how smart technologies influence thermal comfort outcomes. The findings reveal varying levels of occupant knowledge and awareness of SECTs, with technologies such as smart HVAC systems, IoT-based temperature sensors, and automated environmental controls demonstrating high mean values and Relative Importance Index (RII) scores. This indicates their perceived effectiveness in managing indoor thermal conditions. The model summary and goodness-of-fit statistics further confirm a significant and positive relationship between smart environmental control technologies and thermal comfort management, validating the robustness of the proposed analytical framework. Moreover, results from the dynamic interaction analysis between thermal sensation, time intervals, and occupant activity levels show that adaptive smart systems effectively stabilise comfort conditions despite fluctuations in metabolic activity, reinforcing the relevance of adaptive comfort theory in smart building contexts.

Collectively, the findings highlight the critical importance of integrating smart environmental control technologies when designing or upgrading residential and commercial buildings for sustainability, particularly in Istanbul and other cities with similar climatic and socio-cultural characteristics. The study demonstrates that thermal comfort is not solely a technical outcome but a dynamic, behaviourally mediated process shaped by user awareness, interface usability, and occupant engagement. This study set out to investigate the role of smart building technologies in enhancing thermal comfort within Istanbul's built environment, with particular emphasis on user experiences, perceptions, and sustainability outcomes.

The study's methodological transparency, defined sampling criteria, and mixed-methods design enhance its replicability and external validity for future smart building research in comparable urban contexts. Therefore, the findings demonstrate that smart technologies such as IoT-enabled sensors, automated HVAC systems, and integrated building management platforms are effective in maintaining indoor environmental conditions within recognised thermal comfort thresholds, as reflected by PMV and PPD indices. This directly addresses the study's first objective by confirming that intelligent environmental control systems can enhance thermal comfort while simultaneously improving energy efficiency and operational performance.

In relation to the objective, which focused on understanding user perceptions and experiences, the results reveal a generally high level of awareness and acceptance of smart technologies among occupants. Users particularly recognised the importance of smart HVAC systems, IoT-based monitoring, and energy-efficient technologies in achieving comfortable and stable indoor conditions. However, the qualitative findings also show that thermal comfort is not determined by technology alone. Cultural norms, behavioural patterns, and individual expectations significantly influence how occupants perceive comfort and interact with automated systems. The preference expressed by some users for manual overrides highlights the continued importance of personal control in fostering psychological comfort, autonomy, and trust in smart systems. This underscores the need for adaptive design strategies that integrate automation with flexible, user-responsive interfaces.

The study further fulfilled its objective of generating context-specific insights for Istanbul by demonstrating how the city's climatic variability, dense urban fabric, and socio-cultural characteristics shape both thermal comfort needs and technology adoption. Seasonal temperature fluctuations and varying activity patterns were shown to influence PMV outcomes, reinforcing the value of real-time monitoring and adaptive control strategies in Mediterranean–transitional climates. At the same time, challenges related to system integration, maintenance costs, cybersecurity concerns, and interface usability were identified by building professionals, indicating that technical sophistication must be matched with long-term operational feasibility and inclusive design considerations. From a sustainability perspective, the findings highlight the broader relevance of smart buildings to urban resilience and climate action. By reducing energy demand, supporting renewable energy integration, and enabling data-driven optimisation of building performance, smart technologies contribute to sustainable urban development goals and align with contemporary climate and resource-efficiency agendas. The strong awareness among occupants of building design, energy efficiency, and cost considerations further suggests a growing recognition of sustainability as a multidimensional concept that extends beyond comfort to encompass environmental responsibility and economic viability. Overall, this research contributes to both theory and practice by demonstrating that the successful deployment of smart building technologies depends not only on technical efficiency, but equally on human-centred design, cultural adaptability, and integrated sustainability thinking in rapidly urbanising contexts. This informs a holistic, user-centred framework that complements conventional performance-based approaches and advances understanding of comfort in smart urban environments.

8.1 Practical and theoretical recommendation

Based on these findings, several recommendations emerge with both local and global relevance. Architects and designers should prioritise user-centred and culturally responsive design approaches that balance automation with opportunities for personal control, recognising that occupant behaviour and socio-cultural context significantly shape comfort perceptions. Urban planners and policymakers should support the wider adoption of smart building technologies through incentives, regulatory frameworks, and alignment with national and municipal sustainability strategies. At a global scale, these measures are consistent with international climate agendas such as the Paris Agreement and the United Nations Sustainable Development Goals (SDGs), particularly SDG 11 (Sustainable Cities and Communities), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action). Building managers and technology providers should also invest in user-friendly interfaces, continuous training, and proactive maintenance strategies to ensure long-term system performance, inclusivity, and resilience across diverse user groups.

From a practical perspective, the study offers evidence-based guidance for architects, urban planners, building engineers, and policymakers not only in Istanbul but also in other rapidly urbanising cities facing similar climate and energy challenges. It recommends prioritising user-friendly interfaces, awareness programmes, and participatory design strategies to maximise the effectiveness of smart technologies and foster behavioural change toward sustainable practices. Policies supporting affordability, standardisation, and user education are essential to avoid technological exclusion and to enable scalable implementation in both developed and developing urban contexts. Theoretically, this research contributes to global scholarship by bridging human–environment interaction studies and smart technology adoption models, demonstrating how behavioural, perceptual, and contextual dimensions can be systematically integrated into thermal comfort and sustainability assessments. Collectively, these insights highlight the potential of Smart Energy Building Design (SEBD) to act as a transferable framework for advancing climate-resilient and low-carbon urban development worldwide.

8.2 Limitations and future study

This study was designed as a focused empirical investigation aimed at establishing initial relationships between smart environmental control systems and perceived thermal comfort under controlled temporal conditions, rather than as a longitudinal seasonal assessment. While a year-long or multi-season study might enhance external validity, the current eight-week duration remains methodologically acceptable for cross-sectional and exploratory smart building research, particularly for examining behavioural responses, system interaction patterns, and perceived comfort under real operational conditions. Similar temporal scopes have been adopted in prior indoor environmental quality studies where continuous long-term monitoring was not feasible due to logistical and resource constraints. Thus, while this study provides valuable empirical evidence, future research might extend data collection across longer timeframes and multiple climatic and socio-economic contexts to capture seasonal variations and improve generalisability.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author/s.

Ethics statement

Formal ethics committee approval was not required for this study, as it involved minimal risk, anonymous data collection, and no vulnerable populations. In line with Istanbul Gelisim University's institutional guidelines for social science research, the study was therefore classified as ethically exempt. The participants provided their written informed consent to participate in this study. Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

Author contributions

OA: Conceptualization, Validation, Visualization, Writing – original draft, Writing – review & editing. AB: Formal analysis, Methodology, Software, Validation, Writing – review & editing.

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Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/frsc.2026.1772855/full#supplementary-material

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