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Comparative Assessment of Climate-Responsive Design and Occupant Behaviour Across Türkiye's Building Typologies for Enhanced Utilisation and Performance

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Abstract

This study evaluates and compares the sustainability performance of selected historic, commercial, and institutional buildings in Istanbul to identify effective climate-responsive and energy-efficient design strategies. The objectives are to assess performance using LEED-based criteria, examine variations across building typologies, and outline implications for future sustainable design. Using an evaluation matrix, responses from 175 experts were analysed across key LEED categories for seven case study buildings. The comparative assessment reveals notable variations in sustainability performance across the seven evaluated buildings. ERKE Green Academy consistently achieved the highest mean scores (≈4.40–4.60), particularly in Sustainable Sites, Water Efficiency, Energy and Atmosphere, and Indoor Environmental Quality. This strong performance reflects its integration of advanced green technologies, optimised daylighting strategies, biophilic elements, and smart system controls. Modern commercial towers, such as the Allianz Tower and Sapphire Tower, recorded strong mean scores (≈4.20–4.50) across categories related to Integrative Design, Energy Efficiency, and Materials and Resources. Their performance is largely driven by intelligent façade systems, double-skin envelopes, automated shading, and high-performance mechanical systems that enhance operational efficiency. In contrast, heritage buildings including Hagia Sophia and Sultan Ahmed Mosque demonstrated moderate yet stable performance levels (≈4.00–4.40). Their strengths were most evident in Indoor Environmental Quality, where passive systems such as thermal mass, natural ventilation, and inherent spatial configurations contribute significantly to occupant comfort. Overall, the findings underscore the complementary value of combining traditional passive strategies with modern smart technologies to achieve resilient, low-energy, and user-responsive architecture. This study is novel as it uniquely demonstrates how traditional passive design strategies and modern smart technologies can be integrated to enhance climate-responsive and energy-efficient performance across diverse building typologies. The study recommends enhanced indoor air quality strategies, occupant education on system use, and stronger policy alignment with LEED standards.

Keywords: climate-responsive design; thermal comfort; occupant behavior; energy efficiency; sustainable architecture

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1. Introduction

The growing global emphasis on environmental sustainability and energy efficiency has intensified the demand for innovative solutions in the building sector [1,2]. The

necessity for sustainable building design that balances energy efficiency with human comfort has grown crucial as the urban population increases, resource scarcity intensifies, and climate change puts increasing strain on cities. Istanbul's location at the meeting point of Europe and Asia produces microclimatic fluctuations that have a substantial impact on thermal comfort and energy consumption [2,3]. These factors provide unique challenges for architects and urban planners tasked with designing energy-efficient buildings that enhance occupant well-being. The city's current building foundation is made more challenging by the wide variety of architectural styles, construction eras, and systems. However, this complexity also presents important opportunities to advance context-sensitive sustainable design strategies that might serve as models for other rapidly urbanising regions. In determining building energy performance and indoor thermal comfort, recent research emphasises the combined significance of architectural design and occupant behaviour [3,4]. Architectural decisions, including material selection, building orientation, façade design, and integration of passive cooling strategies, profoundly shape energy consumption and thermal regulation. At the same time, occupant behaviours such as adaptive comfort strategies, patterns of mechanical system use, and personal comfort adjustments directly influence operational energy performance [5]. These strategies may involve actions like adjusting ventilation rates or modifying airflow through systems such as variable air volume (VAV) terminals that dynamically adapt their geometry to meet comfort needs. Understanding how such behavioural responses interact with building design features is therefore essential for developing effective and sustainable building performance strategies.

Furthermore, there are currently trends toward high-rise and glass-dominated buildings, which have frequently led to an increased reliance on active HVAC systems. This has resulted in a decrease in Indoor Environmental Quality (IEQ) and an increase in operational energy demand [3,5]. As a result, many contemporary buildings in Istanbul have issues, including overheating, thermal discomfort, and poor air quality despite their contemporary appearance or technological infrastructure. It is becoming increasingly clear that achieving holistic building efficiency requires integrating occupant behaviour with climate-responsive architectural design to address this mismatch.

Climate-sensitive architecture design is defined as the approach in which buildings' form, orientation, envelope system, and materials are selected according to local climate conditions for the dual goals of reducing energy consumption and enhancing occupant thermal comfort [4,6]. Furthermore, how occupants engage with buildings, for example, how they use and control blinds, windows, thermostats, or activate natural ventilation, can be of critical importance in determining actual energy performance [7]. For places like Istanbul, which have a transitional Mediterranean climate with hot, muggy summers and cold, rainy winters, this strategy is especially important [8].

The purpose of this study is to examine how occupant behaviour and climate-responsive architectural design interact to maximise thermal comfort and energy efficiency in Istanbul's built environment. Recent research highlights the significant impact of occupant behaviour on indoor air quality (IAQ), energy consumption, and overall building performance. Studies show that window-opening patterns, manual and automated ventilation control, and personal comfort adjustments significantly shape indoor environmental conditions and energy demand [9]. Advancements in sensing technologies and behavioural modelling have further expanded this understanding, particularly through real-time data collection and intelligent algorithms that predict and respond to occupant-driven variations in IAQ. Contemporary approaches increasingly incorporate behaviour-responsive systems, such as dynamic sensor networks and machine-learning tools capable of identifying, modelling, and optimising IAQ-related occupant actions [10]. These emerging methods highlight a shift toward user-responsive building management, where effective

IAQ optimisation depends not only on mechanical system efficiency but also on accurately capturing human–environment interactions [11]. Situating the current study within this evolving research landscape strengthens the link between climate-responsive design, occupant decision-making, and sustainability performance across diverse building typologies. Thus, this study's comparative sustainability assessment of three distinct building typologies—historic, commercial, and institutional—in Istanbul, which have not been jointly evaluated in previous studies using a unified LEED-based framework, makes a significant contribution to the literature by providing an integrated performance perspective that highlights typology-specific strengths, weaknesses, and priority intervention areas for sustainable building improvement.

The research investigates how design strategies and user behaviour interact to improve building performance through an empirical evaluation of seven case study buildings, ranging from modern green-certified facilities like ERKE Green Academy and Trump Towers to historic sites like Hagia Sophia and the Sedefkar Mehmed Agha Mosque. In order to find best practices and guide future climate-adaptive design strategies, the analysis uses a range of sustainability criteria, such as structural planning, thermal comfort, material and energy efficiency, interior environmental quality (IEQ), smart systems integration, and social innovation.

Findings reveal that buildings employing passive solar design strategies, green roofs, and high-performance glazing systems report significantly lower mechanical energy dependency. Simultaneously, user-oriented features such as thermal zoning, biophilic design, and smart sensor integration were linked to higher levels of user satisfaction and behavioural energy savings. Remarkably, the successful conversion of historic buildings to contemporary sustainability standards suggests that it is possible to modify old buildings to meet modern green requirements. This study highlights Istanbul's need for a more integrated design strategy that anticipates occupant interaction patterns, in addition to adapting to the city's climate. The ramifications encompass design education, green certification schemes (such as LEED and WELL), and building regulations. To enable evidence-based adaptation across Istanbul's different building typologies, future research is advised to incorporate post-occupancy assessments, climate simulation modelling, and real-time user monitoring.

2. Review of the Literature

2.1. Thermal Comfort and Climate-Responsive Architectural Design Strategies

The feeling of comfort in a particular thermal environment has been described as a condition of mind which expresses satisfaction with the thermal environment [12–14]. Thermal comfort is crucial for the occupants of the building, their well-being, and the overall performance of the building. A lot of research has been conducted on thermal comfort factors such as air temperature, humidity, air movement, radiant temperature, clothing, and metabolic rate. Adaptive comfort models suggest that occupants can adjust their behaviour, such as changing clothing, opening windows, or modifying thermostat settings, to maintain comfort under varying conditions. These behavioural adaptations are especially relevant in urban environments with fluctuating microclimates, such as Istanbul. One foundational aspect of climate-responsive design is orientation and building form. Proper orientation ensures that buildings capitalise on solar gains during winter while minimising overheating during summer. For instance, south-facing facades can harness winter solar energy, while external shading mechanisms like overhangs and fins can reduce solar heat gain during the warmer months [7,12]. Compact forms also reduce external surface exposure, thereby limiting thermal exchange with the environment. In transitional climates, achieving energy efficiency requires a careful blend of passive solar heating and cooling strategies. Techniques such as night flushing, cross-ventilation, and evaporative

cooling are highly effective for summer comfort, while direct solar gain through south-facing glazing, indirect gain systems [14], and sunspaces contribute significantly to passive winter heating [4]. These approaches reduce dependence on mechanical systems and help lower overall energy demand. Natural ventilation is particularly valuable in Istanbul's mid-season periods, where cross and stack ventilation can effectively remove internal heat and humidity, improving comfort while minimising HVAC use [15].

Shading devices ranging from architectural elements like overhangs, louvres, and fins to vegetative shading play a vital role in managing solar gain. Deciduous trees offer a dynamic seasonal response by blocking excessive summer sun while allowing winter solar penetration [14,15]. Thermal mass further stabilises indoor temperatures, with materials such as stone or concrete absorbing heat during the day and releasing it at night. Combined with high-performance insulation, these measures significantly reduce heating and cooling loads [16]. Green roofs and walls provide added insulation, support biodiversity, and mitigate urban heat island effects, which are essential in dense cities like Istanbul [12,17]. Material selection also influences energy performance; using locally sourced, low-embodied-energy materials and high-reflectivity surfaces helps reduce emissions and summer heat gain [3,12]. Collectively, the strategies illustrated in Figure 1 offer a comprehensive framework for a climate-responsive, energy-efficient design suited to Istanbul's environmental and cultural context.

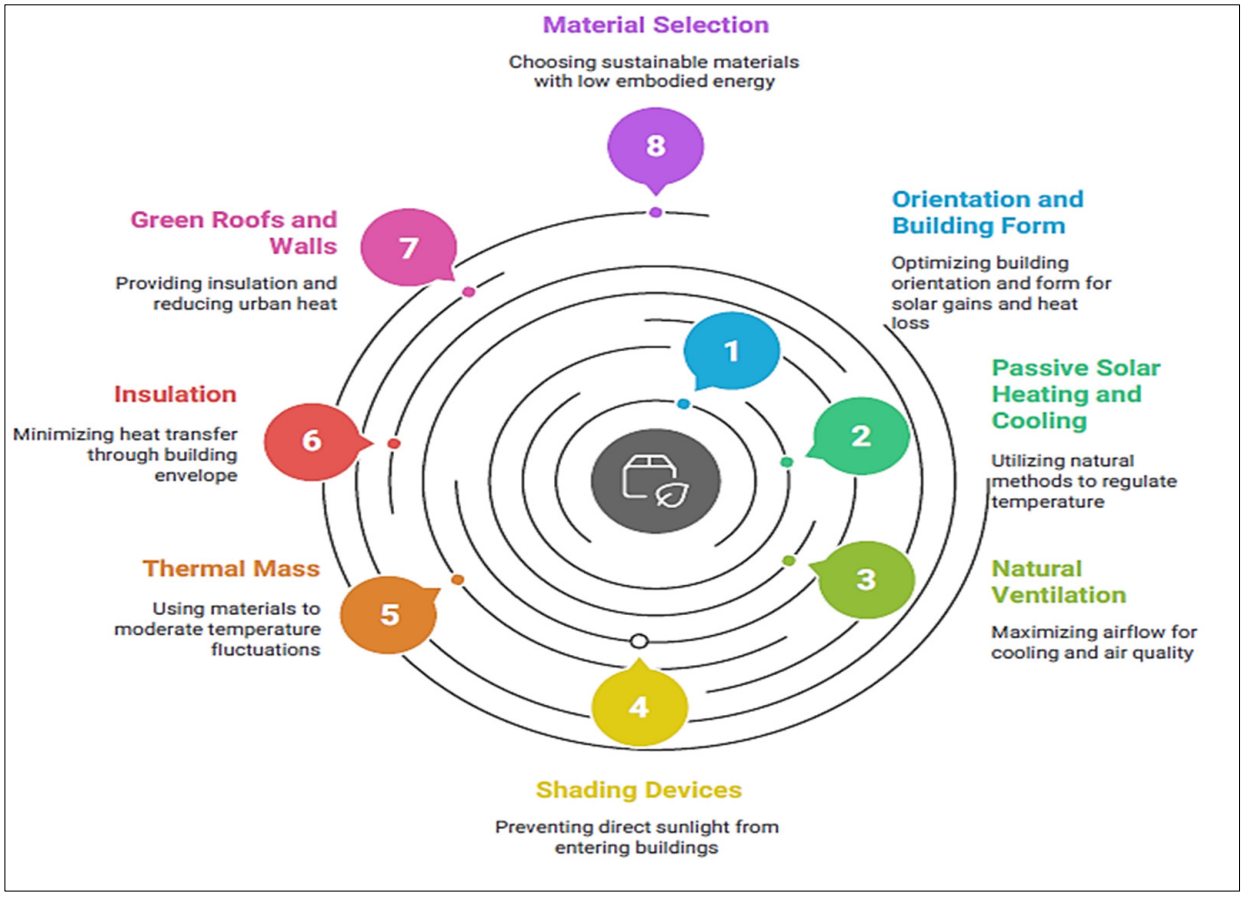


Figure 1. Climate-responsive design strategies. Source: author's conceptualisation.

2.2. Energy Efficiency, Occupant Behaviour, and Its Impact on Energy Consumption

About 40% of the world's energy consumption and 30% of greenhouse gas emissions are attributable to the built environment [15,16]. A building's energy consumption is directly impacted by architectural design choices such as building orientation, envelope

features, glazing ratios, shading, and insulation [3,18]. Reliance on mechanical systems can be greatly decreased by incorporating passive design techniques such as solar control, thermal mass, and natural ventilation [3]. These techniques are especially helpful for preserving comfort while consuming the least amount of energy in Istanbul's environment, which is characterised by scorching summers and frigid winters.

Occupant behaviour, on the other hand, is increasingly recognised as a critical determinant in the actual energy performance of buildings, often diverging significantly from predicted models based solely on design assumptions [18,19]. Behavioural factors, including thermostat settings, window operation, appliance usage, and adaptive comfort strategies, can cause significant variability in energy use even among similar buildings [20]. Cultural norms and expectations of comfort also influence behaviours, highlighting the importance of context-specific studies. In Istanbul, where cultural practices and socioeconomic diversity shape daily life, understanding occupant behaviour is essential for designing effective energy-efficient buildings. While architectural and technological systems lay the foundation for energy efficiency, it is ultimately the choices and habits of occupants that dictate real-world outcomes.

Window operation remains one of the most direct ways occupants influence indoor environmental conditions. Decisions about opening or closing windows significantly affect air quality, indoor temperature, and natural ventilation. Studies show that perceived thermal comfort, air freshness, outdoor noise, and even social norms can shape window-use patterns [20]. In climates such as Istanbul's, strategic night-time ventilation can reduce reliance on mechanical systems. Thermostat settings are another major determinant of heating and cooling loads. Occupants' temperature preferences vary widely due to factors such as age, gender, clothing, metabolic rate, and cultural expectations [20]. Mismanaged thermostat adjustments or disagreements among users can result in unnecessary energy consumption, highlighting the importance of smart, adaptive controls that learn from occupant behaviour over time.

Lighting behaviour also contributes significantly to a building's energy footprint. Research indicates that people often leave lights on in unoccupied rooms or select illumination levels higher than needed, particularly in office and institutional environments [21]. Such habits increase energy use and reduce system lifespan, suggesting that behavioural prompts or automated lighting controls could be beneficial. Appliance usage further compounds overall energy demand, especially in residential and mixed-use buildings, where diverse devices—from entertainment systems to kitchen equipment—intensify consumption patterns [22]. Similarly, shading devices, despite their potential to reduce glare and solar heat gain, are often underutilised due to a lack of awareness or misuse [18]. Overall, variations in occupant behaviour pose challenges for achieving consistent energy performance but also present opportunities for improvement through education, feedback systems, and user-centric design. Buildings that incorporate operable features, intuitive interfaces, and real-time feedback are more likely to meet energy efficiency targets. As illustrated in Figure 2, integrating climate-responsive strategies with user behaviour through BAS, POE, and personalised comfort systems is essential for optimising energy efficiency and thermal comfort.

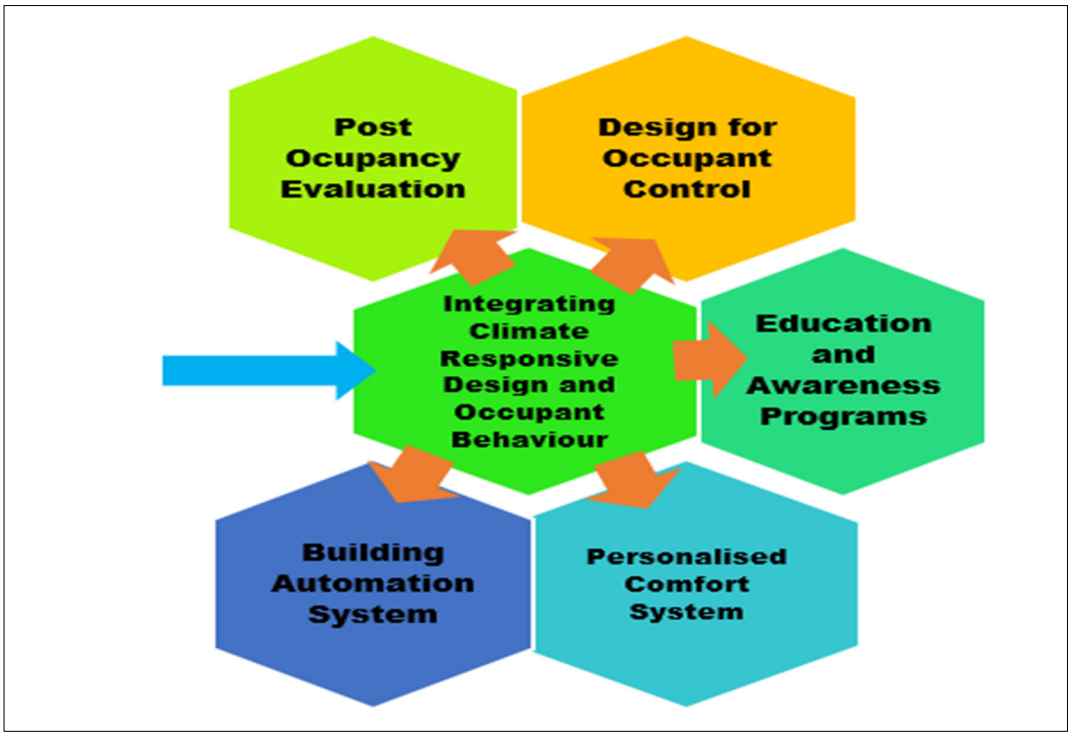


Figure 2. Strategies for integrating climate-responsive design and occupant behaviour. Source: author's conceptualisation.

2.3. Theoretical Framework on Assessment of Climate-Responsive Design, Occupant-Driven IEQ and Energy Performance

Assessment of climate-responsive design is grounded in bioclimatic and adaptive design theories, which emphasise aligning buildings with local climatic conditions to optimise comfort, energy efficiency, and environmental performance [23]. Bioclimatic theory advocates the use of passive strategies such as natural ventilation, daylighting, shading, and thermal mass to harness or mitigate climatic forces. Adaptive design theory complements this by recognising that occupant behaviour, seasonal variations, and local cultural practices influence the effectiveness of climate-responsive strategies. Additionally, a substantial body of literature has demonstrated that the interaction between building occupants and their indoor environments plays a decisive role in shaping both Indoor Environmental Quality (IEQ) and overall energy performance. Previous studies in environmental psychology and building science show that occupants continuously modify their surroundings through window operation, thermostat use, lighting behaviour, and equipment utilisation, often exerting greater influence on energy outcomes than the building systems themselves [24,25]. These behavioural dynamics are well explained by the Theory of Planned Behaviour (TPB), which argues that behavioural intentions are driven by attitudes toward the behaviour, subjective norms, and perceived behavioural control [26]. TPB has been widely applied in the built environment sector to understand energy-saving behaviours and comfort-driven actions.

Within the field of thermal comfort research, adaptive thermal comfort theory has served as a foundational framework [23], which contends that occupants respond to environmental fluctuations using behavioural, physiological, and psychological adjustments. Empirical studies have confirmed that adaptive actions such as adjusting clothing levels, opening windows, and operating shading devices significantly affect perceived comfort and actual building energy use [15]. This theoretical foundation underscores the notion

that comfort is not solely delivered by mechanical systems but co-produced through occupant adaptation.

Parallel advancements in building technologies, including smart controls, high-performance HVAC systems, and renewable energy solutions, have been shown to enhance building performance when effectively integrated with user behaviour. For example, studies examining building-integrated photovoltaics (BIPVs) demonstrate substantial benefits for reducing grid dependency and enabling near-zero energy performance; however, these benefits often depend on occupants' operational behaviour, awareness, and interaction with energy systems. Research within socio-technical systems theory supports this view, arguing that technological performance is shaped by the interdependence of technology, user practices, and institutional context. Taken together, these prior studies converge on a consistent conclusion: technical solutions alone cannot deliver optimal IEQ and energy performance without being aligned with real-world occupant behaviours. The combined insights from TPB, adaptive comfort theory, and socio-technical systems theory, therefore, provide a robust foundation for the methodological choices and interpretive lens adopted in the present study.

3. Materials and Methods

This study employs a mixed-methods research design that integrates qualitative and quantitative approaches to examine the complex relationships among architectural design strategies, occupant behaviour, and energy efficiency in Istanbul's diverse urban environment. This combined methodology is particularly suitable for capturing both the measurable outcomes of design interventions and the subjective experiences of building users [27]. The research framework comprises three interconnected components: (i) field surveys, (ii) detailed case studies, and (iii) statistical data analysis. Assessing climate-responsive design in Istanbul requires close professional collaboration among architects, engineers, environmental scientists, and policy experts to ensure a holistic and context-sensitive evaluation. Architects and architectural designers assess the integration of passive design principles and overall building performance [13], while mechanical engineers evaluate HVAC efficiency and energy management systems [28]. Environmental and sustainability consultants review LEED compliance and environmental impacts, and urban climatic scientists analyse how building form interacts with microclimate and thermal comfort [20]. Energy efficiency analysts verify energy-use patterns and passive system performance, whereas occupant behaviour researchers explore user comfort perception and behavioural contributions to energy savings. For heritage sites such as Hagia Sophia, conservation specialists ensure that sustainability interventions respect historical integrity [29]. Policy analysts and urban planners then interpret the findings within broader urban sustainability frameworks relevant to Istanbul [30].

The Environmental Impact Scorecard is used as a comprehensive tool for reporting sustainability performance across key indicators, including resource efficiency, waste reduction, and material use, thereby supporting alignment with LEED and WELL standards [31]. By integrating user-perception data with building performance metrics and a multi-layered case study approach, the study provides an in-depth evaluation of climate-responsive strategies in transitional climates. This methodological rigour strengthens the study's contribution to guiding future sustainable building design. The conceptual framework (Figure 3) illustrates the connections among architectural design, occupant behaviour, energy performance, and thermal comfort.

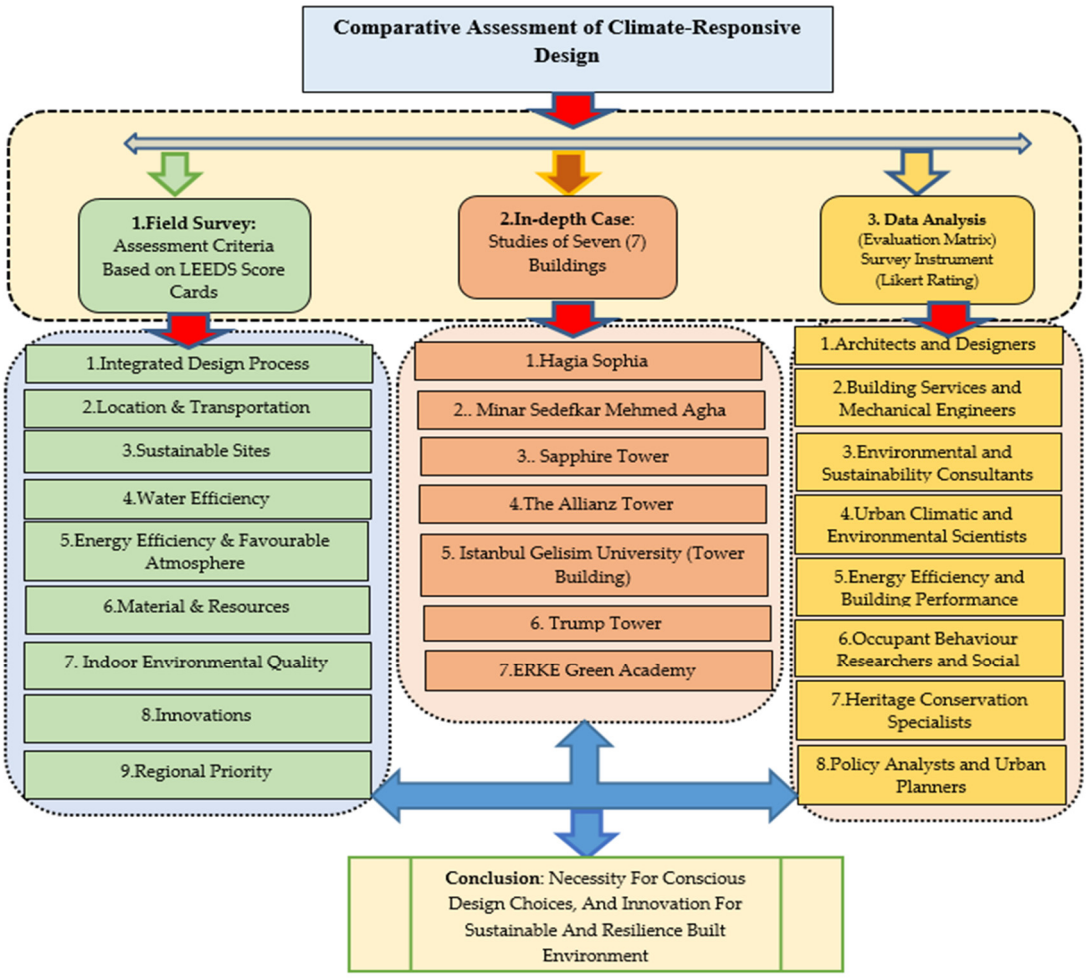


Figure 3. Study's conceptual framework. Source: author's conceptualisation.

3.1. The Urban Context of Istanbul

Given its diversified terrain, intricate urban structure, and changeable climate, Istanbul, one of the largest and most complex metropolitan settings in the world, offers a singular case study in this regard. With hot, muggy summers and chilly, rainy winters, Istanbul's transitional Mediterranean climate is a defining feature of this transcontinental city that connects Europe and Asia [8]. Achieving indoor thermal comfort and reducing energy usage are two major design challenges posed by this particular climatic setting. To alleviate seasonal discomfort, traditional structures in the area have historically depended significantly on passive architectural techniques such as natural ventilation systems, courtyard layouts, thick thermal mass walls, and strategic orientation. High-density developments have proliferated as a result of rapid urbanisation, but many of them lack integrated design techniques for comfort and energy efficiency. A comprehensive strategy that takes into account both technological advancements and human aspects is needed to address these issues. Turkey has become a pioneer in environmentally friendly building and sustainable architecture. Turkey has been named ninth in the United States Green Building Council's (USGBC) annual Top 10 Countries for LEED (Leadership in Energy and Environmental Design), demonstrating a significant commitment to lowering carbon emissions and improving energy efficiency. Since 42% of Turkey's net electricity usage comes from the building industry alone, sustainable design and construction are crucial to improving the nation's environmental quality and lowering its carbon footprint [20]. Turkey's dedication to environmentally friendly building practices and sustainable architecture is demonstrated by its ninth-place ranking in the annual Top 10 Countries for LEED. Turkey's green building

boom shows the country's potential for long-term economic and environmental progress and is a reaction to the country's growing energy needs.

3.2. Measurement of Variables

The Integrative Process promotes a holistic and sustainable approach to planning and design within the LEED framework, prioritising flexibility, durability, cost-effectiveness, and occupant well-being [31,32]. It supports efficient spatial layouts, adaptable building systems, and waste-minimising strategies that enhance long-term environmental and operational performance. Incorporating case study protocols aligned with LEED assessments further strengthens the rigour and reliability of sustainability evaluations [33]. Within this framework, the Location and Transportation criterion focuses on strategic site selection guided by LEED for Neighbourhood Development, emphasising equitable access, public transit connectivity, and reduced vehicle emissions [31,32]. Projects embedded in dense, mixed-use areas foster sustainable urbanism, improve mobility, and support inclusive community development [33]. The Sustainable Sites component integrates ecological restoration, pollution control, and the creation of green open spaces to improve environmental quality [9]. Effective rainwater management and heat island reduction are especially critical in Istanbul, where dense urban conditions require resilient microclimatic solutions. Water Efficiency measures enhance conservation through advanced metering, low-flow fixtures, and drought-tolerant landscaping, ensuring long-term sustainability and alignment with global certification standards [31,33].

Energy and Atmosphere performance is strengthened through systematic commissioning, renewable energy integration, and smart energy management systems. The use of eco-friendly refrigerants, efficient HVAC technologies, and post-occupancy evaluations ensures that design intentions translate into real performance outcomes [31,32]. The Materials and Resources category emphasises recycled, regional, and environmentally transparent products, alongside construction-waste diversion practices that reduce embodied impacts. Indoor Environmental Quality enhances health and comfort through robust ventilation, low-emission materials, and optimised thermal and daylight conditions—priorities given Istanbul's climatic demands [34,35]. Innovation credits recognise advanced technologies, biophilic design, and sustainability education initiatives, particularly when guided by LEED-accredited professionals [31,32]. Finally, Regional Priority credits address Istanbul's environmental and socio-cultural challenges, including heat island mitigation, seismic resilience, water conservation, and heritage protection, ensuring sustainability strategies remain culturally and contextually grounded [33,35].

3.3. Field Survey

To thoroughly investigate the impact of professional perceptions, behavioural adjustments, and architectural solutions on thermal comfort and sustainability in Istanbul, this study employed a mixed-methods approach that combined in-depth case studies with structured field surveys. To ensure adequate representativeness, the survey component used a stratified random sampling strategy across a variety of building typologies, residential, institutional, and commercial contexts [36]. Experts' opinions were recorded using a Likert-scale questionnaire. Both online and in-person surveys were used for data collection, as presented in Supplementary Material S1, for a more in-depth contextual understanding [27]. Also, detailed demographics of the respondents and the participants' consent to participate in the survey are presented in Supplementary Material S2.

Seven architecturally significant structures, including the Hagia Sophia, Sultan Ahmed Mosque, Sapphire Tower, Allianz Tower, Istanbul Gelişim University, Trump Towers, and ERKE Green Academy, were chosen for in-depth case analysis to supplement survey

data. The case study methodology and an integrated case study protocol that included LEED-based performance assessments that served as the selection criteria in this study are presented in Supplementary Material S3. A critical assessment of the trade-offs between sustainability innovation and historic protection was made possible by the triangulation of surveys and site observations [18]. This integrated approach is an in-depth comprehension of user interactions, environmental performance, and climate-responsive design methods for Istanbul's urban fabric.

Occupant behaviour plays a pivotal role in shaping Indoor Environmental Quality (IEQ) and overall building sustainability [37]. While advanced building technologies and high-performance design strategies aim to optimise energy efficiency, thermal comfort, and air quality, their effectiveness largely depends on how occupants interact with the built environment. Understanding behavioural patterns such as window operation, lighting usage, thermostat adjustments, and spatial occupancy is therefore essential for assessing actual building performance and identifying opportunities for design optimisation [25]. This study employed structured survey questionnaires to investigate how occupant behaviours influence IEQ and energy performance (Supplementary Material S14). These were systematically conducted across selected building zones to record respondents' actions such as window opening, daylight utilisation, occupancy duration, and the use of personal heaters or fans, behaviours widely acknowledged as key determinants of building performance [15,19]. These observations offered real-time insight into occupant interaction with the indoor environment under routine conditions.

3.4. Data Analysis

In order to find trends and produce insightful information about climate-responsive design and occupant behaviour in Istanbul's built environment, data from comprehensive case studies and structured surveys were methodically combined in this study. One important methodological tool used is the evaluation matrix, which systematically evaluates the effectiveness of integrative design strategies using Likert-scale evaluations performed by experts: 1 = Strongly Disagree/Very Poor; 2 = Disagree/Poor; 3 = Fair/Neutral; 4 = Agree/Good; 5 = Strongly Agree/Excellent. By analysing the mean scores and standard deviations of survey responses across multiple case study buildings, performance trends were identified across nine (9) integrative design indicators, such as (i) Integrative Process, (ii) Location and Transportation, (iii) Sustainable Sites, (iv) Water Efficiency, (v) Energy Efficiency and Atmosphere, (vi) Materials and Resources, (vii) Indoor Environmental Quality, (viii) Innovation, and (ix) Regional Priority. This approach enabled the identification of performance criteria and those areas requiring improvement in sustainability or user-centred strategies.

Statistical analysis, through mean values and standard deviations, is effective for categorising buildings into performance clusters, enabling clearer comparisons and revealing the factors that most strongly influence building performance and user satisfaction [24]. This approach aligns with established sustainability assessment frameworks that rely on statistical profiling to support design decision-making [3,12]. A stratified random sampling technique was applied to select residential, commercial, and institutional buildings across Istanbul. Selection criteria included historical and architectural significance, accessibility for fieldwork, and availability of operational data [27]. These buildings reflect the city's diverse urban fabric, shaped by multiple cultural and architectural layers [38]. The synthesised findings aim to generate strategic recommendations for enhancing energy efficiency and thermal comfort through integrated climate-responsive design [18]. Ethical standards guided all stages of the research. Informed consent was obtained from participants, data were anonymised, and secure data-handling protocols were implemented to meet established regulations. A comparative benchmarking tool (Supplementary Table S4)

was employed to identify the highest and lowest scoring criteria in each category, quantifying performance differences across the seven case studies. This comparative analysis provides deeper insight into how design strategies translate into measurable environmental outcomes, enabling the identification of best practices and performance gaps for future policy and architectural improvements [3,12].

Regarding real-time insight into occupant interaction with the indoor environment under routine conditions, self-reported information on comfort preferences, ventilation habits, lighting choices, and perceived environmental quality was analysed. This method aligns with established frameworks for capturing human factors in building performance research [25,37] and helps clarify the motivations behind occupant actions, enabling comparisons between reported behaviours. Thus, correlation analysis was applied to examine relationships between documented behaviours and the corresponding IEQ or energy trends. These methods allowed the identification of behavioural patterns consistent with recent findings [34,35].

A composite equation was developed to calculate the mean scores and standard deviations for the buildings' criteria. For instance, the mean scores and standard deviation for the nine (9) Integrative Design Performance Scores (IDPSs) were based on these equations:

S_{ij} = score of building i for criterion j (mean value from the table)

w_j = weight assigned to each criterion j (if all criteria are equally important, set $w_j = \frac{1}{9}$)

$IDPS_i$ = Integrative Design Performance Score for building i

Then,

$$IDPS_i = \sum_{j=1}^{9} (w_j . S_{ij}) \quad (1)$$

Equal weighting:

$$IDPS_i = \frac{1}{8} (S_{i1} + S_{i2} + S_{i3} + S_{i4} + S_{i5} + S_{i6} + S_{i7} + S_{i8} + S_{i9}) \quad (2)$$

Criterion Labels (j = 1 to 9):

i. Integrated Process Performance
ii. Location and Transfer
iii. Sustainable Sites
iv. Water Efficiency
v. Energy Efficiency and Favourable Environment
vi. Materials and Resources
vii. Indoor Environmental Quality
viii. Innovations
ix. Regional Priority

For example, the calculation for Hagia Sophia is as follows:
Using the mean values,

$$IDPS_{H\,S} = \frac{1}{8} (4.30 + 4.59 + 4.12 + 4.05 + 4.48 + 4.02 + 4.67 + 4.15 + 4.03) = \frac{1}{9} (34.38) = 4.297I$$

So, the overall score for Hagia Sophia is approximately 4.30.

For the standard deviations, the calculation was based on a weighted score adjusted for consistency using the following:

$$IDPS_i = \frac{\sum_{j=1}^{9}\left(\frac{S_{ij}}{\sigma_{ij}}\right)}{\sum_{j=1}^{9}\left(\frac{1}{\sigma_{ij}}\right)} \quad (3)$$

where σ_{ij} is the standard deviation of score S_{ij}.

Thus, the standard deviation for Structure Planning in Hagia Sophia is 0.39. Overall, the mean ± standard deviation format is 4.30 ± 0.39. These methods and procedures were used to generate subsequent results for the other variables. However, these criteria have been reorganised into four logical categories: (i) Process and Context, (ii) Sustainable Resource Management, (iii) Energy and Environmental Performance, and (iv) Innovation and Regional Relevance. Each group combines related criteria while keeping the associated results and discussions. The Grouping of IDPS Criteria includes the following:

i. Process and Context
   a. Integrated Design Process (j = 1);
   b. Location and Transfer (j = 2).

ii. Sustainable Resource Management
   a. Sustainable Sites (j = 3);
   b. Water Efficiency (j = 4).

iii. Energy and Environmental Performance
   a. Building Energy Efficiency and Favourable Environment (j = 5);
   b. Materials and Resources (j = 6);
   c. Indoor Environmental Quality (j = 7).

iv. Innovation and Regional Relevance
   a. Innovations (j = 8);
   b. Regional Priority (j = 9).

4. Results

4.1. Demographic Results

The demographic characteristics of the study participants (n = 175) demonstrate notable diversity in gender, age, education, and professional background. This was achieved through a purposive sampling technique to ensure that only qualified and expert participants were included in the study. As illustrated in Figure 4, males comprised 60.6% (n = 106) of the sample, while females represented 39.4% (n = 69). The age distribution shows that the largest group was 36–45 years old (27.4%), followed by 26–35 years (25.7%) and 46–55 years (18.9%), indicating a predominance of middle-aged professionals actively engaged in the construction and design sectors. Younger (18–25 years) and older participants (56+) accounted for 13.1% and 14.9%, respectively, ensuring perspectives from both emerging and senior experts [24]. While male dominance reflects traditional industry trends, the substantial participation of females underscores the increasing gender diversity in sustainability-related fields. Education and professional experience (Figure 5) reveal a highly skilled cohort, with 61.7% holding professional certificates, 29.7% postgraduate degrees, and 8.6% undergraduate degrees. Professionally, architects formed the largest group (16.0%), followed by mechanical engineers (14.3%), energy efficiency analysts (13.1%), and environmental and sustainability consultants (13.7%), alongside urban climatic scientists, policy analysts, social scientists, and heritage specialists (Figure 6). Nearly half (49.1%) had over six years' experience, supporting responses grounded in practical expertise.

Awareness of sustainability and LEED principles was high, with 49.1% reporting strong knowledge, 38.9% moderate, and 12.0% limited awareness (Figure 7). This diverse, experienced sample provides a robust foundation for assessing climate-responsive architecture and guiding evidence-based sustainable design practices.

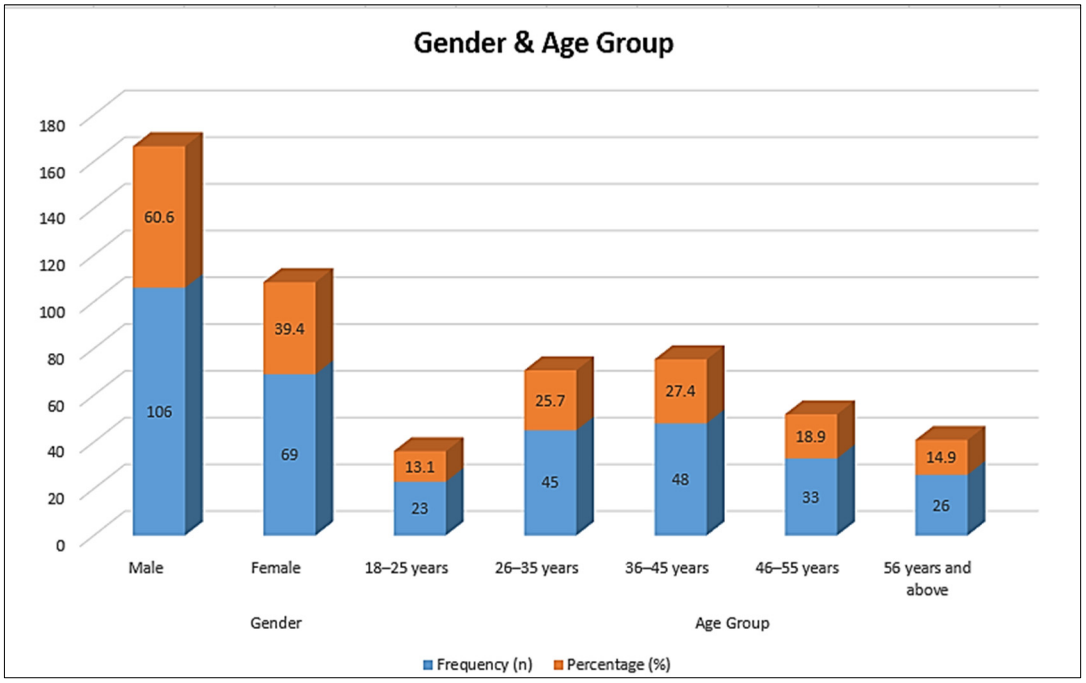


Figure 4. Respondents' gender and age group.

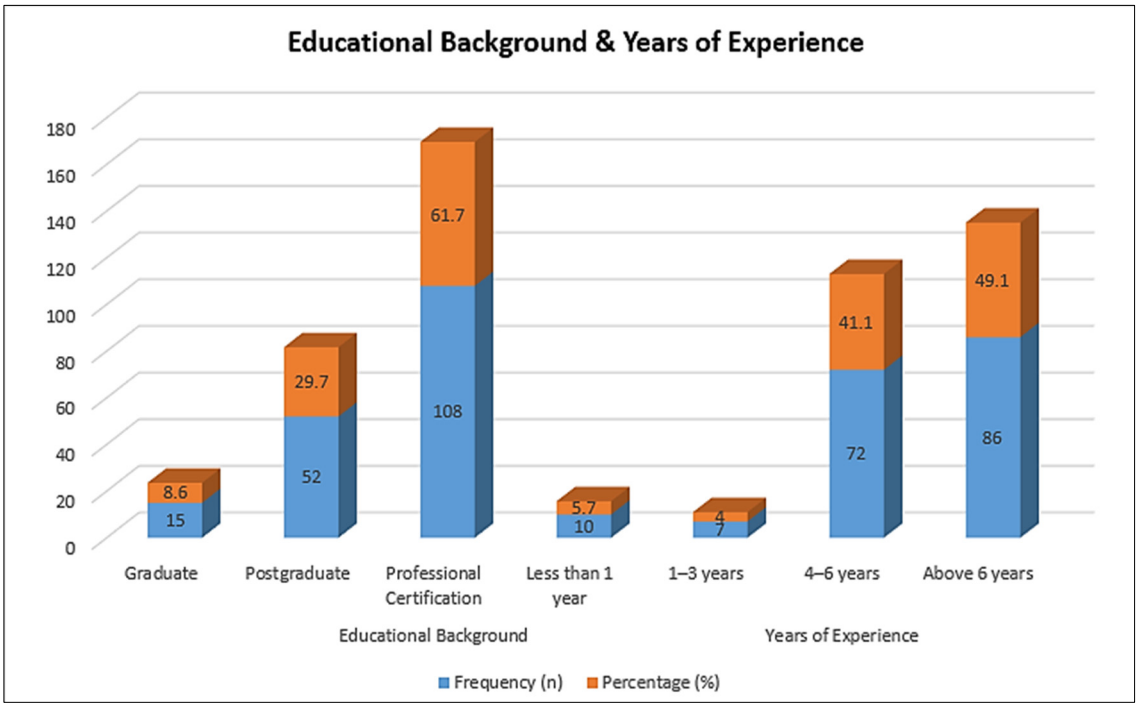


Figure 5. Respondents' educational background and years of experience.

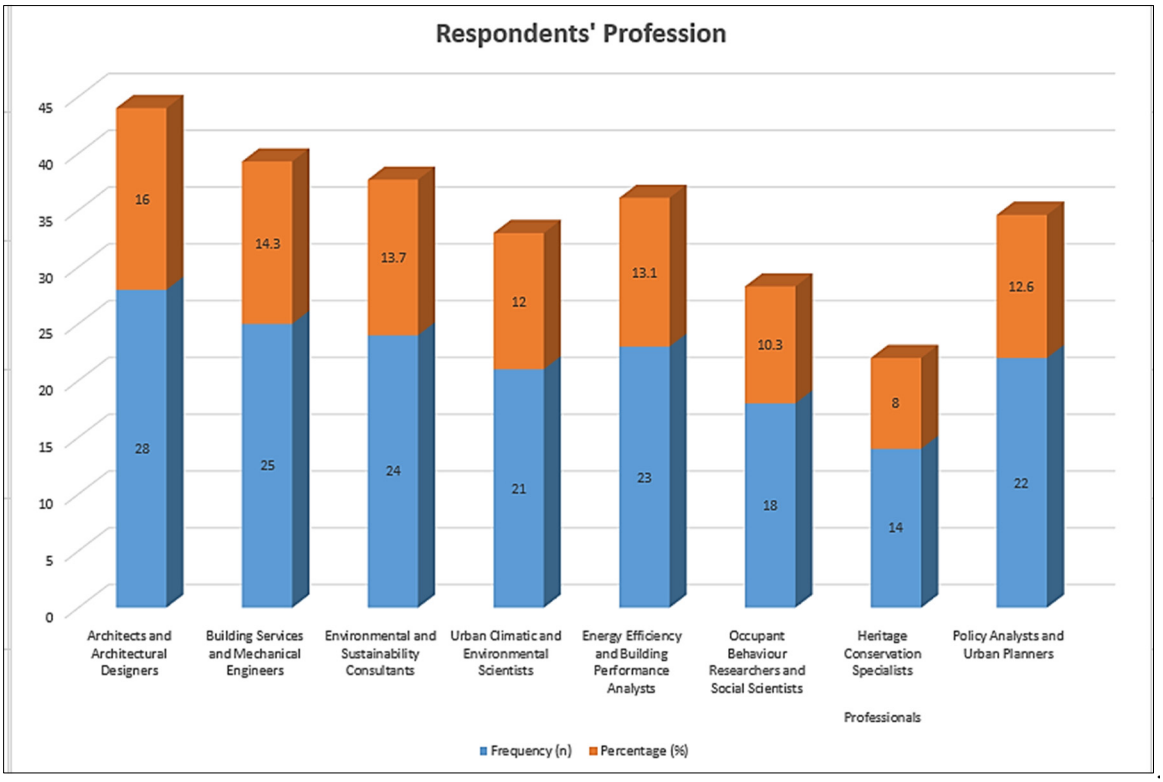


Figure 6. Respondents' profession.

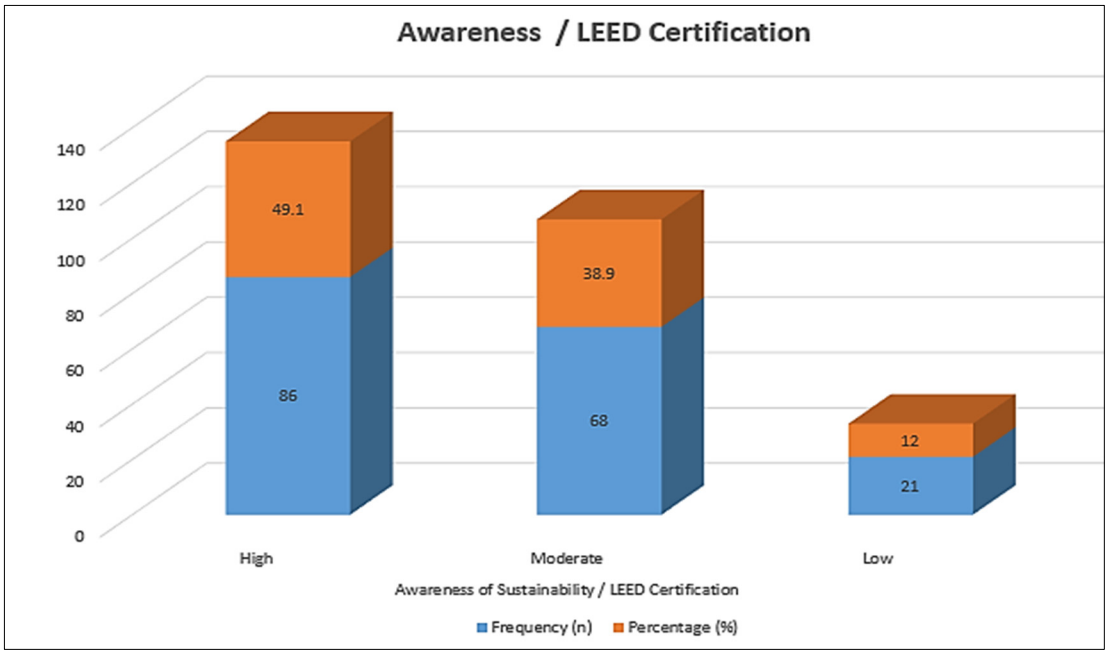


Figure 7. Respondents' level of awareness of LEED certification.

4.2. Instrument Reliability and Validity

The statistical validation of the sustainability assessment instrument demonstrates a high level of reliability and construct validity. As presented in Table 1, all eight sustainability categories recorded Cronbach's Alpha values above 0.87, with the overall scale reaching $\alpha = 0.936$, indicating excellent internal consistency across the 59 items. Categories such as Integrative Design ($\alpha = 0.921$), Energy and Atmosphere ($\alpha = 0.936$), and Indoor Environmental Quality ($\alpha = 0.918$) performed particularly well, confirming that

the items within each construct reliably measure the targeted sustainability dimensions. Sampling adequacy tests further support the suitability of the dataset for factor extraction. The Kaiser–Meyer–Olkin (KMO) value of 0.907 and the statistically significant Bartlett's Test of Sphericity (χ^2 = 6824.53, $p < 0.001$) (Table 2) indicate that the correlation matrix is appropriate for Exploratory Factor Analysis (EFA). These values reflect strong inter-item correlations and justify the use of multivariate reduction techniques.

Table 1. Reliability analysis (Cronbach's Alpha).

Construct/Category	Number of Items	Cronbach's Alpha (α)	Interpretation
Integrative Design	8	0.921	Excellent
Location and Transportation	8	0.907	Excellent
Sustainable Sites	7	0.894	Good
Water Efficiency	5	0.882	Good
Energy and Atmosphere	10	0.936	Excellent
Materials and Resources	6	0.905	Excellent
Indoor Environmental Quality (IEQ)	11	0.918	Excellent
Innovation and Regional Priority	4	0.873	Good
Overall Scale	59	0.936	Excellent

Internal consistency of the sustainability assessment instrument (n = 175).

Table 2. Kaiser–Meyer–Olkin (KMO) and Bartlett's Test of Sphericity.

Statistical Test	Value	Interpretation
Kaiser–Meyer–Olkin (KMO) Measure	0.907	Meritorious sampling adequacy
Bartlett's Test of Sphericity	$\chi^2(1711) = 6824.53$	Significant ($p < 0.001$)
Significance Level (p-value)	<0.001	Correlation matrix suitable for EFA

Assessment of sampling adequacy and suitability for factor analysis.

The EFA results (Table 3) identified eight distinct latent factors corresponding to the conceptual LEED-based categories. These factors collectively explain 73.84% of the total variance, demonstrating a strong underlying structure and confirming that sustainability performance in buildings is multidimensional. Factor 1 (IEQ and Thermal Comfort) and Factor 2 (Energy and Atmosphere) accounted for the largest proportion of explained variance, emphasising their centrality in determining overall building sustainability performance. Subsequent factors such as Sustainable Sites, Materials and Resources, and Water Efficiency also emerged as coherent constructs, aligning with theoretical expectations within the green building literature. Robustness checks (Table 4) further validate the strength of the measurement model. Variance Inflation Factors (VIFs) ranged from 1.22 to 3.84, indicating an absence of multicollinearity among items. The split-half reliability coefficient (0.902) confirms high consistency across measurement halves, while the Shapiro–Wilk results suggest approximate normality suitable for parametric interpretation. Anti-image correlations (0.72–0.91) and the acceptable determinant of the R-matrix (0.000276) demonstrate that the dataset meets key assumptions for factor analysis. Overall, the combined reliability, validity, and robustness results confirm that the instrument provides a statistically sound basis for evaluating sustainability performance across the seven case study buildings. This strengthens the credibility of subsequent comparative analyses and supports the use of

LEED-based criteria as an appropriate framework for assessing climate-responsive design and operational performance in Istanbul's diverse building typologies.

Table 3. Exploratory Factor Analysis (EFA) summary.

Factor	Eigenvalue	% of Variance Explained	Cumulative Variance (%)
Factor 1—IEQ and Thermal Comfort	12.84	21.76%	21.76%
Factor 2—Energy and Atmosphere	9.62	16.32%	38.08%
Factor 3—Sustainable Sites	6.24	10.58%	48.66%
Factor 4—Materials and Resources	4.92	8.35%	57.01%
Factor 5—Water Efficiency	3.41	5.79%	62.80%
Factor 6—Integrative Design	2.76	4.66%	67.46%
Factor 7—Location and Transportation	2.14	3.64%	71.10%
Factor 8—Innovation and Regional Priority	1.62	2.74%	73.84%

(i) Extraction method: principal component analysis; (ii) rotation method: Varimax with Kaiser normalisation.

Table 4. Robustness checks and multicollinearity diagnostics.

Test Type	Indicator	Value/Range	Interpretation
Multicollinearity	Variance Inflation Factor (VIF)	1.22–3.84	No multicollinearity detected
Reliability Stability	Split-Half Reliability (Guttman)	0.902	Strong internal stability
Sampling Normality	Shapiro–Wilk Test	$p > 0.05$ for the majority of items	Approximately normal distribution
Item Adequacy	Anti-Image Correlations	0.72–0.91	Items suitable for factor extraction
Data Suitability	Determinant of R-matrix	0.000276	Acceptable for factor analysis

4.3. Qualitative Results of the Case Study Buildings

A qualitative analysis was conducted on seven architecturally and environmentally significant case study buildings in Istanbul through a completed expert survey. The results are summarised in Table 5, which groups each feedback into four analytical categories, namely Key Findings, Occupant-Centric Features, Climate Responsiveness, and Design Strategy. This includes the selected range of building types, such as commercial and educational buildings like Sapphire Tower and IGU Tower, to historic religious landmarks like Hagia Sophia. Results include traditional architecture, such as the Sedefkar Mehmed Agha Mosque, and ERKE Green Academy. The results present a comparative, cross-temporal examination that demonstrates how design philosophies, cultural history, and technical innovation come together to affect the environmental performance and occupant comfort of Istanbul's buildings.

Table 5. Results of the seven (7) reviewed case studies related to the climate-responsive and occupant-centric design strategies.

Case Study Buildings	Design Strategy	Climate Responsiveness	Occupant-Centric Features	Findings	Picture
1. Hagia Sophia	• Adaptive reuse efforts reflect climate-conscious strategies despite Hagia Sophia's historical limitations. • High-performance glazing helps maintain interior temperature without compromising historical aesthetics. • Thick masonry and dome structure act as a passive solar design, buffering temperature changes. • Vaulted roof's layered insulation minimises heat gain and loss, mimicking a green roof. • Natural ventilation is enhanced by the building's spatial configuration and window placements. • Orientation and thermal mass contribute to reduced reliance on mechanical heating and cooling systems.	• East–west orientation enhances natural daylight penetration throughout the year. • Deep-set windows and stone cladding reduce summer solar heat gain. • Buttressed walls provide thermal mass for temperature moderation. • Elevated openings enable effective cross-ventilation. • Passive cooling reduces reliance on mechanical ventilation systems.	• Internal volumes like galleries and naves balance different thermal and occupancy needs. • Transitional zones (e.g., narthex, courtyards) serve as climatic buffers. • Layered spatial design helps regulate indoor temperature indirectly. • Daylight modulation enhances visual comfort across varied spaces. • Thermal zoning reduces overall energy dependency. • Spatial hierarchy supports adaptive occupant comfort strategies.	• Traditional features reduce need for mechanical heating and cooling. • Thermal mass buffers internal temperature fluctuations efficiently. • Selective glazing improves energy efficiency without altering heritage aesthetics. • Natural ventilation supports passive cooling and air exchange. • Reduced mechanical dependence lowers environmental impact. • Enhances conservation of UNESCO heritage status through sustainable means.	Figure 8
2. Sultan Ahmed Mosque	• Passive solar design is used to optimise natural heating and cooling. • Courtyard-centred layout enhances daylighting and cross-ventilation. • High-performance glazing reduces heat transfer while preserving daylight and views. • Green roof segments contribute to insulation and stormwater control. • Insulated domes strengthen the thermal envelope without altering historic features. • Design balances energy efficiency with conservation of architectural heritage.	• Strategic building orientation reduces direct sun exposure during peak summer months. • Wide overhangs and deep-set windows provide effective facade shading. • Shading elements minimise solar heat gain and support passive cooling. • Open arches and corridors create natural ventilation pathways. • Clerestory windows enable warm air to escape, enhancing airflow. • Design utilises Istanbul's coastal breezes for improved indoor comfort.	• Mixed-use spaces accommodate religious, cultural, and educational functions efficiently. • Interior thermal zoning responds to changing occupancy and usage patterns. • Semi-open arcades support passive airflow and seasonal adaptability. • Porticos enhance indoor–outdoor connection for thermal comfort. • Layout promotes flexible space usage across different climate conditions. • Transitional zones buffer interior spaces against external temperature shifts.	• Passive design strategies reduce mechanical cooling requirements significantly. • Traditional thermal massing helps maintain stable indoor temperatures. • Energy efficiency is achieved without reliance on active systems. • Occupants enjoy improved thermal comfort year-round. • Sustainability targets are met without altering cultural integrity. • Design balances heritage conservation with modern environmental performance.	Figure 9
3. Sapphire Tower	• High-performance glazing and automated shading control solar heat gain and maximise daylight use. • The double-skin façade acts as a thermal buffer, reducing interior temperature fluctuations. • Green terraces at multiple levels support stormwater management and urban thermal regulation. • Passive solar strategies inform glazing and window orientation for seasonal energy balance.	• East–west orientation reduces direct solar exposure and associated thermal gain. • Automated louvre systems adjust to solar angles, lowering glare and cooling demand. • Double-skin façade includes a buffer zone for natural ventilation and thermal regulation. • Passive cooling is enhanced, reducing dependence on mechanical systems in summer.	• Mixed-use facility integrating residential, commercial, and leisure zones. • Adaptive thermal zoning tailored to occupancy patterns and floor functions. • Sky gardens and terraces offering semi-outdoor spaces with views, natural ventilation, and daylight. • Design supports occupants' physical and mental well-being. • Building management systems enable personalised climate control within interior spaces.	• Significant energy reductions achieved through passive design strategies, smart technologies, and adaptive zoning. • High-performance envelope and dynamic façade systems enhance thermal comfort. • Reduced reliance on HVAC systems through optimised building design. • Demonstrates a sustainable high-rise model in Istanbul. • Balances energy performance, architectural aesthetics, and user-centred design values.	Figure 10

Table 5. *Cont.*

Case Study Buildings	Design Strategy	Climate Responsiveness	Occupant-Centric Features	Findings	Picture
4. The Allianz Tower	• High-performance double-skin façade with automated external shading. • Solar control glazing and passive solar orientation reduce thermal gains and optimise daylight. • Rooftop features reflective materials and vegetation to combat urban heat island effect. • Partial green infrastructure supports rainwater collection. • Modular floor plans allow for future adaptability and efficient space zoning.	• Strategically oriented to optimise north–south solar exposure. • Minimises direct sunlight on highly exposed façades. • Double façade with ventilated cavity functions as a thermal buffer. • Reduces solar heat gain in summer and retains warmth in winter. • Automated external blinds respond to sun position and temperature. • Lowers peak cooling loads and improves indoor thermal comfort.	• Zoned HVAC systems enable personalised thermal comfort. • Smart building automation and environmental sensors optimise indoor conditions. • Green terraces and communal spaces promote rest, collaboration, and indoor–outdoor connectivity. • Ample daylight and views enhance user experience. • Flexible interior layouts accommodate diverse team sizes and workstyles. • Biophilic design elements support mental well-being and occupant satisfaction	• Sophisticated building envelope and adaptive systems reduce energy consumption. • Achieves up to 30% lower energy use compared to conventional high-rise towers. • Enhanced thermal comfort reported by occupants. • Integrates cutting-edge design with sustainability principles. • Serves as a pioneering model for future commercial developments in Istanbul's urban skyline.	Figure 11
5. Istanbul Gelisim University (Tower Building)	• High-performance glazing with solar control optimises daylight and reduces heat gain • Passive solar design with strategic window placement and insulation enhances energy efficiency. • Rooftop vegetation and permeable materials support microclimate regulation and stormwater retention. • Site limitations prevent a full green roof system, but sustainable elements are integrated where possible. • Modular design allows flexible spatial reconfiguration, especially suited for evolving educational needs.	• Building orientation and façade design regulate solar exposure • South-facing windows feature brise-soleil and overhangs for seasonal solar control • Limits heat gain in summer and allows passive heating in winter. • Reduces internal cooling demand during hot months. • Natural ventilation strategies enhance thermal comfort and energy efficiency.	• Flexible design accommodates academic and administrative functions • Includes multi-functional indoor–outdoor learning terraces and breakout spaces • Adaptable classrooms support diverse group sizes and teaching methods • Zoned HVAC systems ensure personalised thermal comfort • Daylight-responsive lighting enhances energy efficiency and user experience. • Large windows offer views and natural light, supporting cognitive health and user satisfaction.	• Responsive building envelope and internal zoning reduce cooling energy loads. • Increased natural light use lowers reliance on daytime artificial lighting. • Occupant feedback indicates improved comfort and reduced fatigue. • Spatial flexibility supports varied educational activities and needs. • Emphasises the importance of climate-responsive and user-centred educational design.	Figure 12
6. Trump Tower	• High-performance glazing with low-emissivity coatings reduces solar heat gain and enhances daylight penetration. • Passive solar design includes deep-set windows, reflective façades, and seasonally responsive apertures. • Traditional green roofs are limited due to tower height constraints. • Green terraces and landscaped podiums act as thermal buffers and recreational areas. • Contribute to microclimate regulation and user comfort.	• Strategically oriented façades feature vertical shading fins for solar regulation. • Double-skin envelope systems enhance thermal insulation and energy efficiency. • Design minimises heat gain in summer and maximises solar access in winter. • Automated blinds adjust based on sun position and temperature. • Responsive HVAC zoning adapts to seasonal and daily climatic changes. • Reduces reliance on mechanical heating and cooling systems.	• Mixed-use development combining residential, commercial, and retail functions. • Thermal zoning tailored to different space types ensures personalised comfort. • Interiors maximise access to daylight, fresh air, and city views. • High indoor air quality and acoustic optimisation support health and productivity. • Accessible terraces and atria enhance indoor–outdoor connectivity for all users.	• High-performance façade and selective natural ventilation reduce mechanical cooling needs. • Intelligent thermal zoning optimises energy efficiency across different areas. • Measurable reductions in HVAC and lighting energy consumption. • Occupants report enhanced comfort, daylight quality, and indoor satisfaction. • Demonstrates the integration of luxury, functionality, and sustainability through climate-adaptive design.	Figure 13

Table 5. *Cont.*

Case Study Buildings	Design Strategy	Climate Responsiveness	Occupant-Centric Features	Findings	Picture
7. ERKE Green Academy	• Comprehensive green roof system provides insulation, stormwater management, and biodiversity support. • Passive solar design guides building orientation and massing for seasonal energy efficiency. • Maximises solar gain in winter and reduces heat infiltration in summer. • High-performance triple-glazed windows with solar control coatings minimise thermal transfer and glare. • Enhances both visual and thermal comfort for occupants.	• Horizontal and vertical shading devices minimise direct solar radiation, especially on west-facing façades. • Operable windows and wind corridors support natural ventilation aligned with prevailing breezes. • Energy simulation tools used to model and optimise the building envelope. • Year-round thermal performance reduces reliance on HVAC systems. • Design responds effectively to Istanbul's temperate climate conditions.	• Flexible thermal zones allow customised comfort settings for classrooms, offices, and labs. • Emphasis on indoor–outdoor connectivity through green terraces and courtyards. • Design encourages interaction with nature to enhance user experience. • Integrated air quality sensors ensure a healthy indoor environment. • Daylight-responsive lighting supports energy efficiency and visual comfort. • Acoustic panels improve sound quality, boosting cognitive performance and well-being.	• Significant energy reduction achieved, particularly in cooling loads. • Passive design strategies and user-responsive systems drive efficiency. • Improved indoor air quality and daylighting conditions over conventional facilities. • Enhanced occupant satisfaction reported through post-occupancy studies. • Validates ERKE Green Academy as a benchmark for climate-conscious, human-centred educational design.	Figure 14



Figure 8. Hagia Sophia. Source: [39].



Figure 9. Sultan Ahmed Mosque. Source: [40].



Figure 10. Sapphire Tower. Source: [41].



Figure 11. The Allianz Tower. Source: [42].



Figure 12. Istanbul Gelisim University. Source: [43].



Figure 13. Trump Tower. Source: [44].



Figure 14. ERKE Green Academy Source: [45].

4.4. Results of the Integrative Design Performance Scores (IDPSs)

The results presented in this section are derived directly from the methodological procedures outlined earlier. Data from the case studies and structured surveys were integrated and analysed using the evaluation matrix, which enabled experts to score the nine Integrative Design Performance (IDP) criteria on a Likert scale. These scores provided the quantitative basis for calculating mean values, standard deviations, and the composite Integrative Design Performance Scores (IDPSs) for each building. The resulting statistical patterns such as variations in performance levels and the clustering of higher- and lower-performing buildings emerged from this computation. Comparative benchmarking further identified the strongest and weakest criteria across the case studies, enabling a cross-case understanding of best practices and performance gaps. Occupant-related findings were

generated from structured observations and survey responses on comfort preferences, ventilation practices, lighting behaviour, and perceived Indoor Environmental Quality. Correlation analysis was then used to reveal relationships between these behavioural patterns and corresponding IEQ and energy trends.

4.4.1. Results of the Integrated Performances (A) and Location and Transportation (B)

Figure 15 and Supplementary Material S5 summarise the results of the Integrative Design Performance Criteria (A) for seven notable buildings in Istanbul. Mean scores (± standard deviation) across eight integrative design criteria highlight the strengths and weaknesses of these buildings in sustainable and adaptive design. Indoor Environmental Quality and health emerged as key priorities, with Hagia Sophia achieving the highest score (mean = 4.67), followed by Istanbul Gelişim University (4.62) and Trump Towers (4.61). These results indicate that both historic and contemporary buildings can maintain high standards in occupant comfort, air quality, and overall well-being. Flexible Design scored highest for Sapphire Tower (4.77) and Allianz Tower (4.78), reflecting their adaptability to future functional and technological changes. Material sustainability was notable for Sultan Ahmed Mosque (4.49) and Allianz Tower (4.75), demonstrating responsible material selection alongside innovation and preservation. Trump Towers (4.58) and Istanbul Gelişim University (4.62) excelled in cost-effectiveness, while Trump Towers (4.71) and ERKE Green Academy (4.73) achieved high performance through efficient energy and resource use. Waste reduction remained a challenge, with Sapphire Tower (4.02) and Hagia Sophia (4.03) scoring lowest, whereas Allianz Tower (4.66) and Trump Towers (4.62) maintained strong low-environmental-impact performance, emphasising sustainable stewardship.

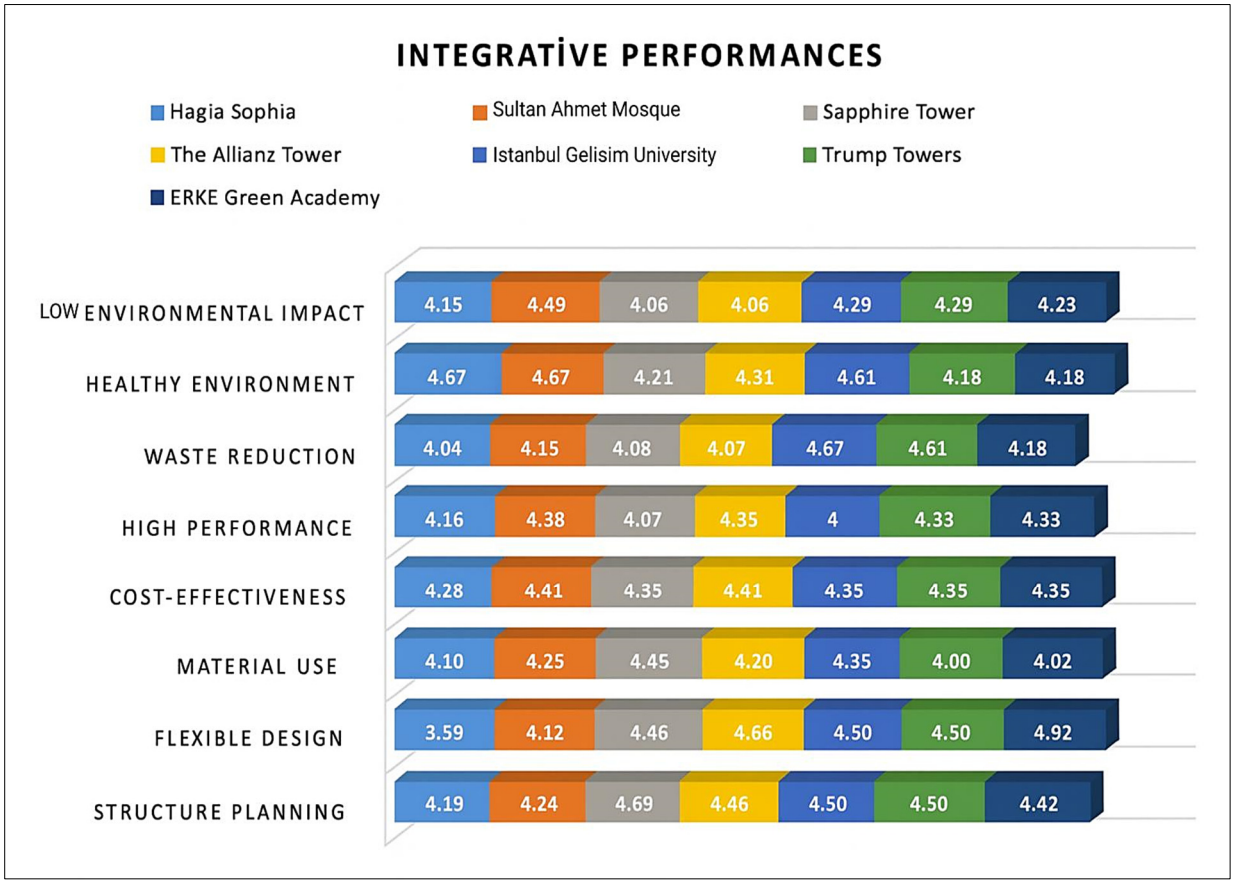


Figure 15. Mean chart for integrated performances (A).

In addition, the eight LEED-based Location and Transportation criteria were applied to assess seven notable buildings in Istanbul, as presented in Supplementary Material S6 and Figure 16. These criteria evaluate each building's alignment with sustainable urban development, focusing on accessibility, transit infrastructure, and integration within the neighbourhood. Scores, expressed as mean ± standard deviation, reflect overall performance in promoting sustainable land use and mobility. LEED Neighbourhood Location scores exceeded 4.0 for all buildings, indicating strong integration with sustainable urban planning. ERKE Green Academy ranked highest (mean = 4.50), followed closely by Hagia Sophia (mean = 4.45) and Sultan Ahmed Mosque (mean = 4.38), reflecting well-chosen urban locations that enhance accessibility and connectivity. Scores from 4.05 to 4.40 suggested moderate attention to land protection, with Trump Towers scoring lowest (mean = 4.05), highlighting potential improvements in ecological impact mitigation. In the High-Priority Site and Equitable Development category, ERKE Green Academy (4.45) and Hagia Sophia (4.40) performed best, underscoring socially conscious site selection. Transit access was strong, particularly for Allianz Tower (4.38) and ERKE Green Academy (4.42). Sustainable transportation measures—reduced parking footprint, bicycle facilities, and EV infrastructure—varied, with EV support remaining lowest (means 4.00–4.40), indicating the need for expanded infrastructure.

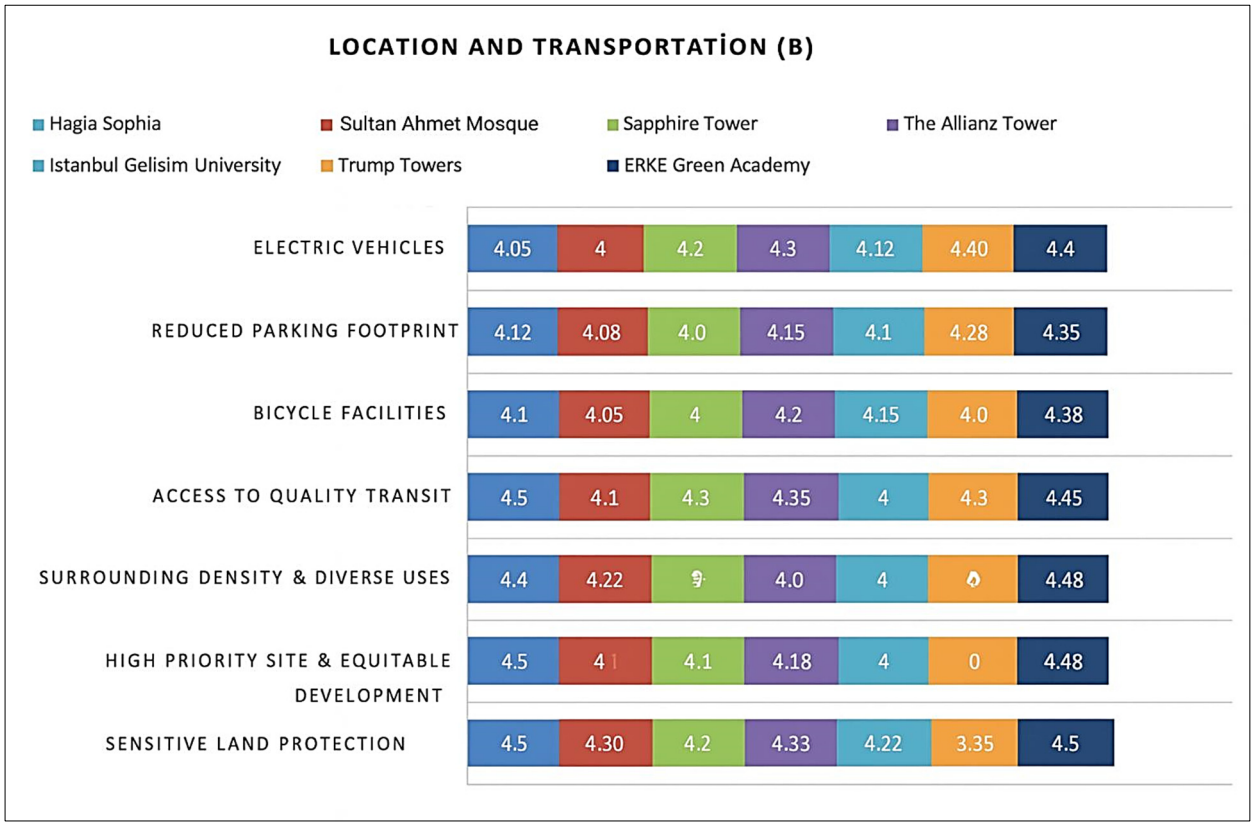


Figure 16. Mean chart for Location and Transportation (B).

4.4.2. Results of the Sustainable Sites Criteria (C) and Water Efficiency Criteria (D)

The evaluation of seven Istanbul buildings using Sustainable Site criteria, summarised in Supplementary Material S7 and Figure 17, examined environmental stewardship before and after construction. Indicators included habitat preservation, open space provision, rainwater management, heat island reduction, light pollution reduction, construction pollution prevention, and site assessment. ERKE Green Academy consistently led across all categories, excelling in heat island reduction (mean = 4.47), rainwater management (4.48), and

open spaces (4.50), demonstrating a comprehensive commitment to ecological design and sustainable site planning. Heritage sites such as Hagia Sophia and Sultan Ahmed Mosque also performed strongly in habitat protection (mean scores = 4.42 and 4.30), indicating that historical structures can support environmental preservation while maintaining cultural value. Modern academic and commercial buildings, including Istanbul Gelişim University, showed solid performance, particularly in rainwater management (mean = 4.38). Trump Towers had the lowest overall score, notably in habitat restoration (4.08) and site assessment (4.10). Light pollution reduction remained a persistent challenge across all buildings (mean = 4.18–4.44), highlighting the need for improved night-time lighting strategies.

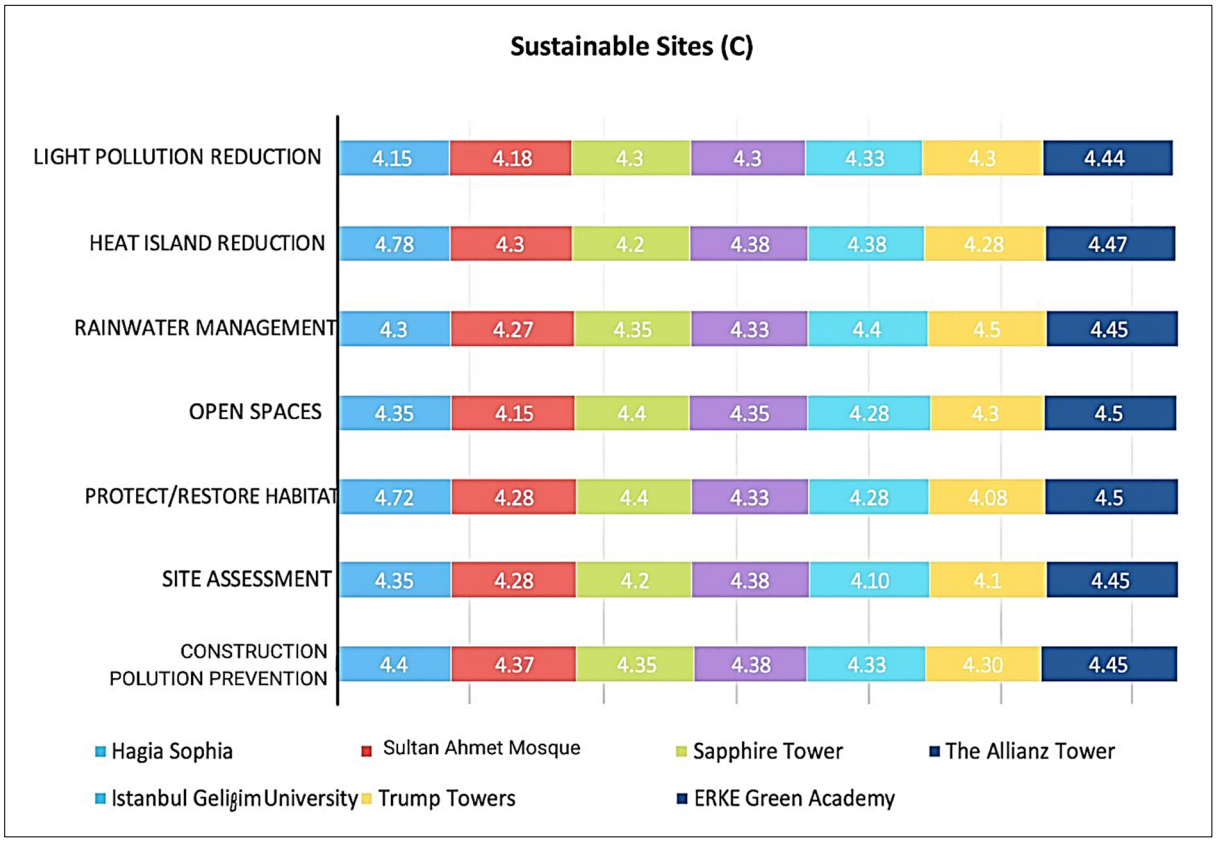


Figure 17. Mean chart for Sustainable Sites (C).

The assessment of seven well-known Istanbul structures using five fundamental Water Efficiency criteria is summarised in Supplementary Material S8 and Figure 18. For Water Efficiency, ERKE Green Academy excels in every category, with notable strengths in facility-level water metering (mean score: 4.50) and indoor water use reduction (mean score: 4.48). The facility received the highest overall mean scores, demonstrating a thorough and proactive commitment to sustainable water management. When it comes to the performance of the buildings, both Istanbul Gelişim University and Allianz Tower were certainly the winners. The indoor Water Efficiency ratings showed that the buildings were good performers, as they ranged between the averages of 4.35 and 4.40, indicating that water-saving measures were effectively incorporated into daily operations. The ancient buildings of Hagia Sophia and Sultan Ahmed Mosque have also been examples of structures that have successfully met the sustainability requirement and have been outstanding in reducing water consumption both indoors and outdoors (mean scores = 4.28–4.40). This illustrates how historic structures can be equipped with efficient water management systems without sacrificing their cultural significance. Trump Towers and Sapphire Tower, on the other hand, exhibited relative weakness, particularly in the areas of water process optimisation

(mean = 4.10) and general water metering, and they were still scoring above the average. Reductions in indoor water usage received very high scores (mean score = 4.18–4.48) across all buildings, highlighting the necessity of user-centred actions in achieving eco-friendly water use.

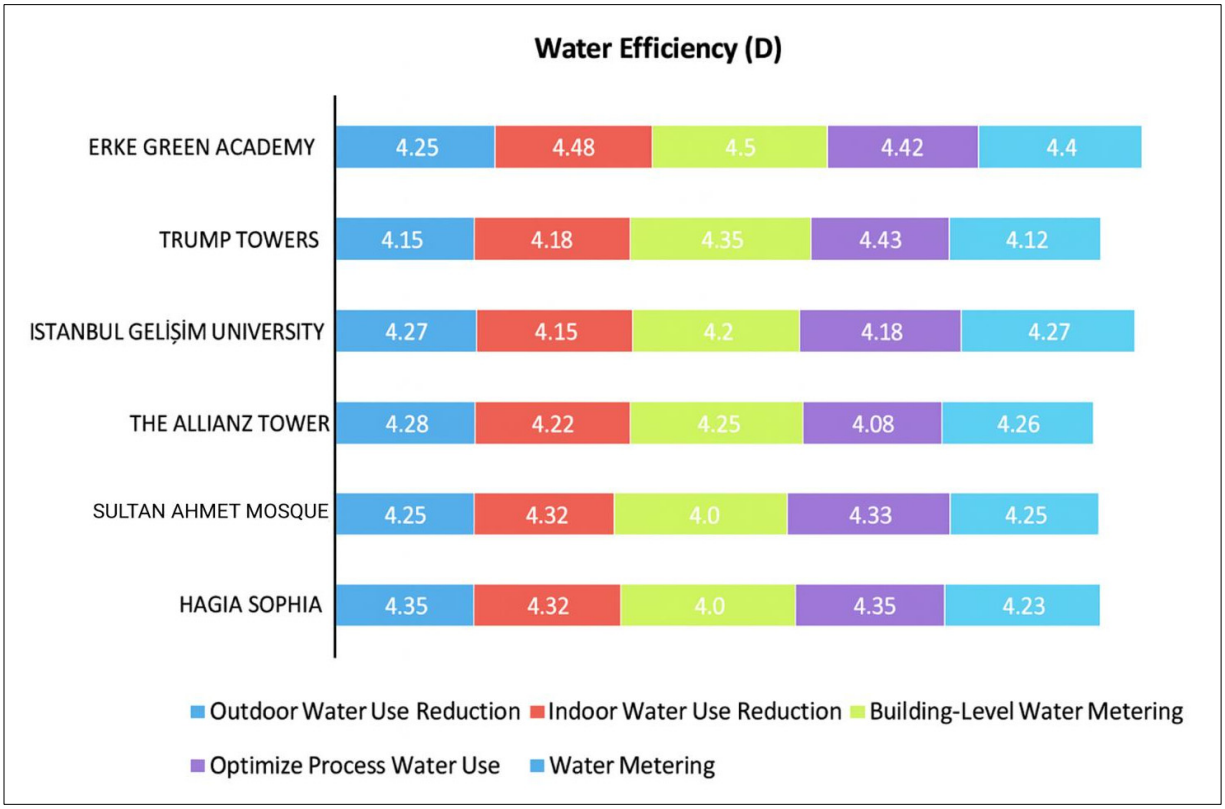


Figure 18. Mean chart for Water Efficiency (D).

4.4.3. Energy Efficiency and Favourable Atmosphere (E) and Materials and Resources Sustainability Indicators (F)

The evaluation is conducted with the theme of Energy Efficiency and Favourable Atmosphere and uses ten indicators. The evaluation is presented in Supplementary Material S9 and Figure 19. These results indicate the effectiveness of sustainable energy strategies and their implementation. Higher mean scores indicate better implementation. ERKE Green Academy surpasses the rest by a significant margin and clearly sets an example with energy management for the rest. The building has the top scores for Building-Level Energy Metering (mean score = 4.52), Minimum Energy Performance (mean score = 4.50), and Fundamental Refrigerant Management (mean score = 4.48), clearly showing its superior performance on sustainable building practices and energy efficiency. This proposition implies that, for atmospheric sustainability, both modern and historical buildings can utilise energy management techniques which are efficient. Sultan Ahmed Mosque and Istanbul Gelişim University rated well above the average in every aspect, especially in Building-Level Energy Metering (mean score = 4.35) and Minimum Energy Performance (mean scores = 4.33–4.35). Their report asserts that the regular implementation of energy-efficient solutions guarantees the environmental performance that is reliable. In contrast, Sapphire Tower and Trump Towers, with their lower scores in crucial areas such as Grid Harmonisation (mean scores = 4.10 and 4.00) and Enhanced Refrigerant Management (mean scores = 4.15 and 4.02), could not keep up with the other structures. Grid Harmonisation was in the position of having the lowest mean scores (mean scores = 4.00–4.35) across all buildings, thus re-

vealing a possible development area with respect to the synchronisation of building energy systems with larger energy networks for the sake of increasing overall sustainability.

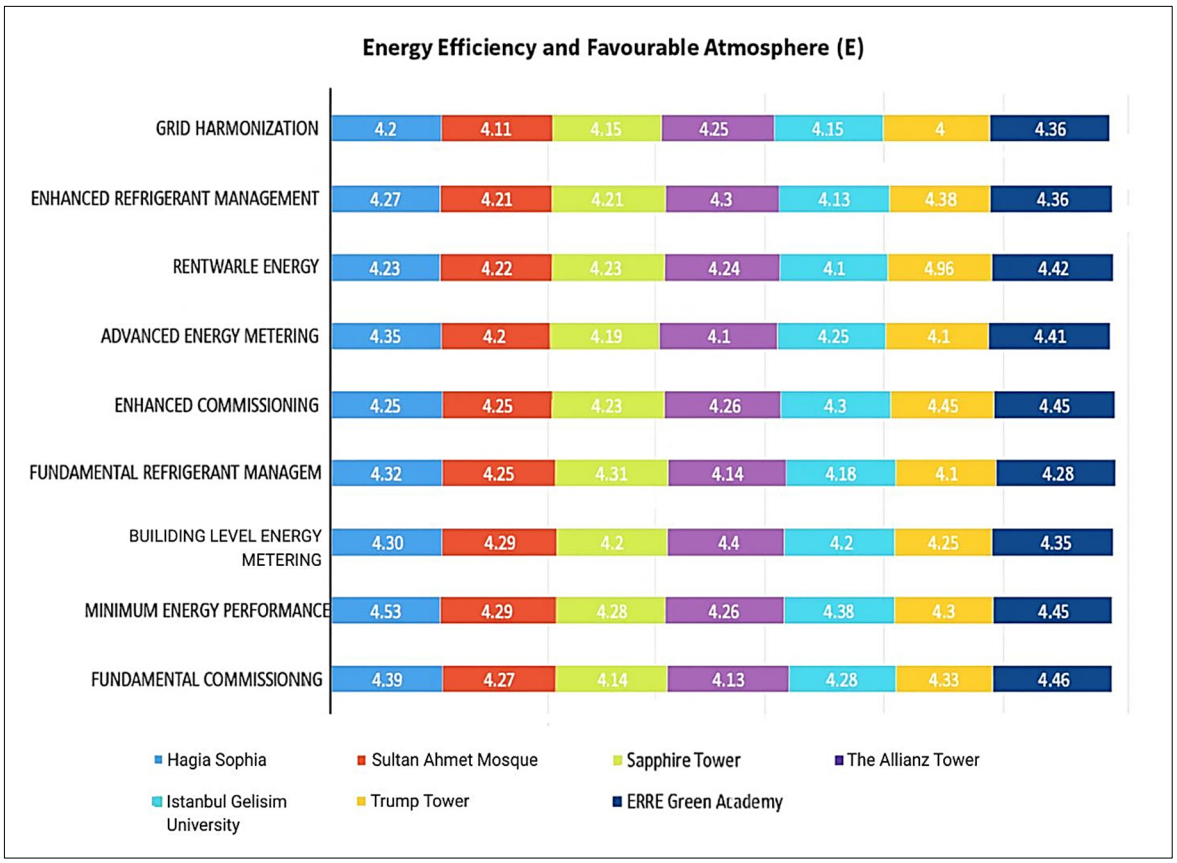


Figure 19. Mean chart for the Energy Efficiency and Favourable Atmosphere (E) for the case study buildings.

Figure 20 and Supplementary Material S10 show the evaluation of Materials and Resources indicators of the seven notable buildings in Istanbul. The spread of assessment among building types shows ERKE Green Academy clearly took the lead in the evaluation of resource sustainability. The academy demonstrated best practices in materials management as an institution by achieving the highest scores in all the indicators. Its strengths were the comprehensive use of Environmental Product Declarations (EPDs) (mean score = 4.42), strong focus on life-cycle impact reduction (mean score = 4.48), and transparency in material ingredients (mean score = 4.38), which were all cited as best practices by the other evaluators. This shows the commitment to sustainable material selection and environmental responsibility. Hagia Sophia and Allianz Tower demonstrated consistently strong performance, with scores never falling below 4.25. Allianz Tower excelled in Storage and Collection of Recyclables (4.40) and EPD implementation (4.35), reflecting operational focus on circular material flows. Hagia Sophia achieved notable life-cycle impact reduction (4.32) and raw material sourcing (4.30), showing that heritage sites can meet modern sustainability standards. ERKE Green Academy performed well in material sustainability, though not at exemplary levels, while Istanbul Gelişim University and Sultan Ahmed Mosque scored moderately (4.20–4.30). Sapphire Tower and Trump Towers underperformed, with Trump Towers scoring lowest in Material Ingredients (3.98) and C&D Waste Management (4.00), and Sapphire Tower lower in EPDs (4.12) and C&D Waste Management (4.08), highlighting the need for improved sustainable material practices.

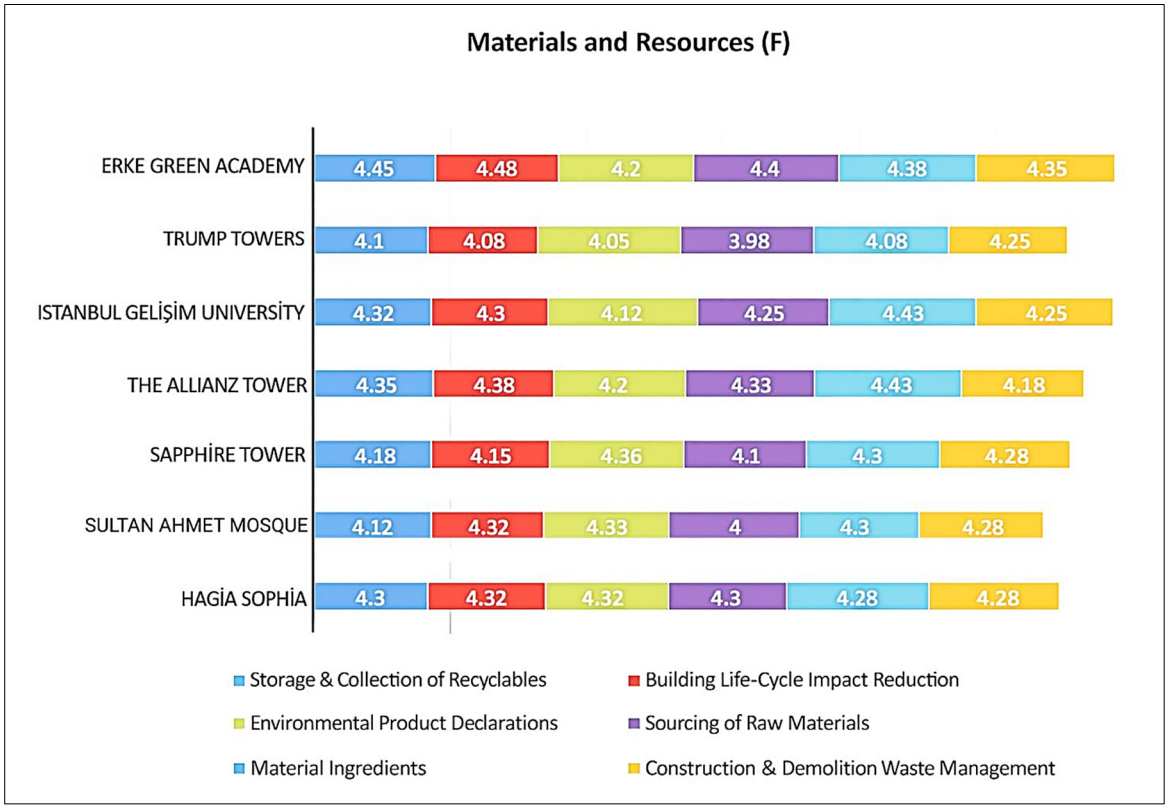


Figure 20. Mean chart for Materials and Resources (F) for the case study buildings.

4.4.4. Results of the Indoor Environmental Quality (IEQ) Assessment-G and Innovation Criteria–H

Figure 21 and Supplementary Material S11 present the evaluation of Indoor Environmental Quality (IEQ) indicators for Istanbul's case study buildings, reflecting expertise-weighted user perceptions. ERKE Green Academy and Trump Towers stood out in acoustic performance and indoor air quality (IAQ), with ERKE scoring 4.49 and Trump Towers 4.45 in Smoke Control and IAQ evaluation. Sapphire Tower excelled in acoustic mitigation, achieving the highest score of 4.42. Historic structures also performed strongly; Hagia Sophia led in low-emitting materials (mean = 4.49), while Sultan Ahmed Mosque scored highest in daylighting (4.47), indicating that adaptive modifications help maintain environmental quality in heritage buildings. Recent developments, including Allianz Tower, Trump Towers, and Istanbul Gelişim University, performed well in visual comfort, with interior lighting and quality views exceeding 4.40. IAQ management, however, remained a relative weakness, with Trump Towers (4.00) and Allianz Tower (4.01) highlighting areas for improvement. Overall, daylighting and high-quality visual access, as seen in Minar (4.47) and Allianz Tower (4.46), were critical in enhancing occupant comfort and well-being.

The mean values for seven socially and innovatively driven sustainability indicators evaluated across seven famous Istanbul buildings are shown in Supplementary Material S12 and Figure 22, offering information on how well the buildings perform in areas like professional accreditation, social equity, education, and green technologies. According to the results, ERKE Green Academy (mean score = 4.46) and Hagia Sophia (mean score = 4.49) received the greatest ratings in Innovative Green Technologies, while Sapphire Tower (mean score = 4.40) and ERKE Green Academy (mean score = 4.39) received the second-highest scores for smart systems integration. Top performers in the biophilic design category were Trump Towers (mean score = 4.42) and Sultan Ahmed Mosque (mean score = 4.39), while Istanbul Gelişim University took first place in Education and Awareness with an impressive

mean score of 4.45, highlighting its significant contribution to sustainability education. However, other buildings performed worse in particular categories. For example, Allianz Tower (mean score = 4.01) performed poorly in Social Equity Innovation, while Hagia Sophia (mean score = 4.01) and Trump Towers (mean score = 4.05) had the lowest scores in smart systems integration. Overall, the findings show that different structures have different capabilities, indicating a blend of contemporary and traditional sustainability strategies in Istanbul's urban fabric.

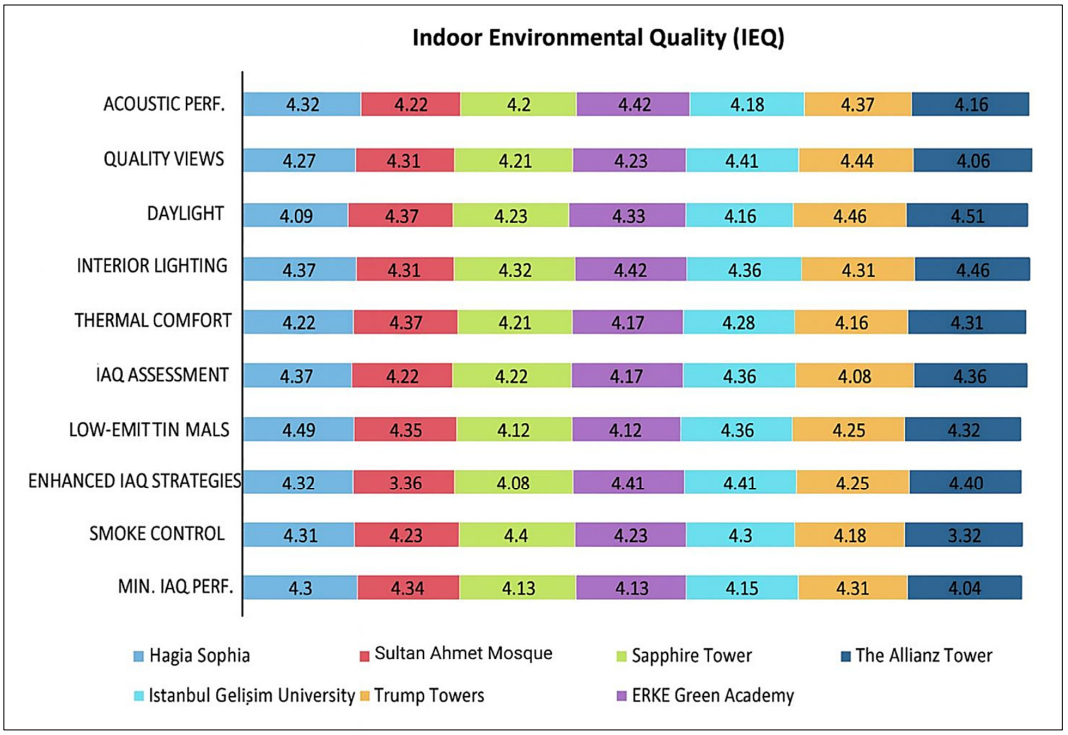


Figure 21. Mean chart for Indoor Environmental Quality (IEQ)-G for the case study buildings.

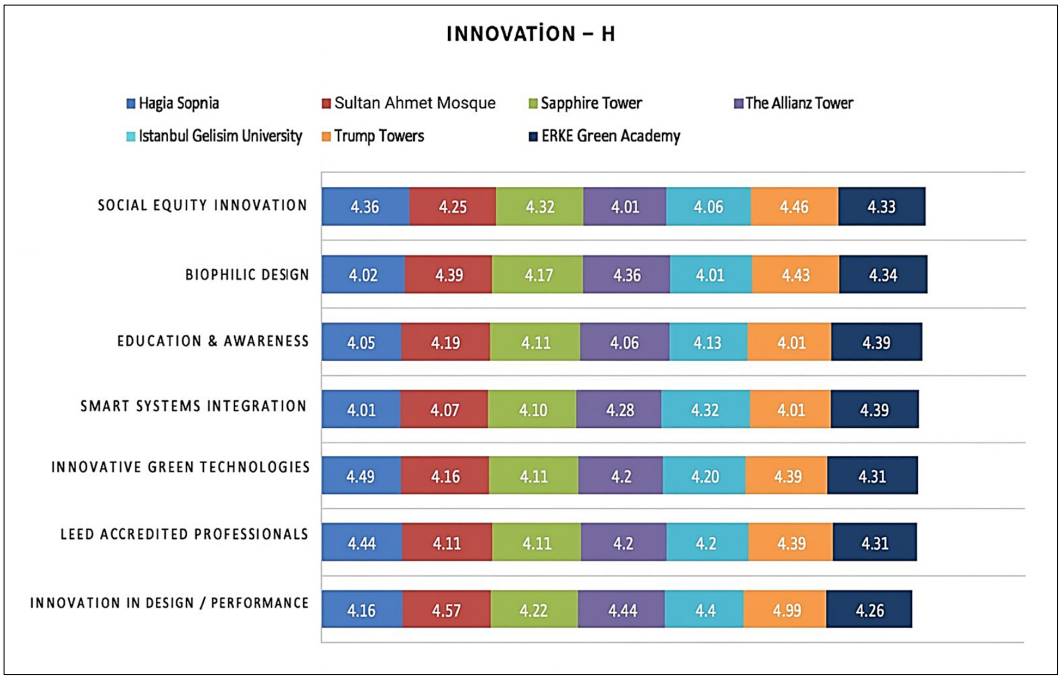


Figure 22. Mean chart for Innovation–H for the case study buildings.

4.4.5. Results of the Regional Priority–I

The evaluation of Regional Priority I indicators across seven prominent Istanbul buildings, summarised in Supplementary Material S13 and Figure 23, highlights both strengths and areas for improvement in sustainability themes such as social equity, environmental resilience, public health, and cultural heritage preservation. Sapphire Tower (mean = 4.46) and Allianz Tower (mean = 4.40) excelled in environmental planning and resilience strategies, reflecting effective adaptation to Istanbul's dynamic urban context. ERKE Green Academy (mean = 4.47) and Hagia Sophia (mean = 4.46) demonstrated strong structural integrity and adaptive design for seismic and climate challenges. Social equity and cultural heritage indicators were highest for Sapphire Tower (4.46), Trump Towers (4.44), and Hagia Sophia (4.44), while ERKE Green Academy (4.43) and Hagia Sophia (4.40) led in heritage preservation, balancing contemporary adaptation with historical conservation. Istanbul Gelişim University (4.44) and Hagia Sophia (4.42) scored highest in public health design. ERKE Green Academy achieved the top score (4.49) in heat island mitigation and water conservation, with Sultan Ahmed Mosque (4.46) and Hagia Sophia (4.43) also performing well, demonstrating sustainable urban strategies.

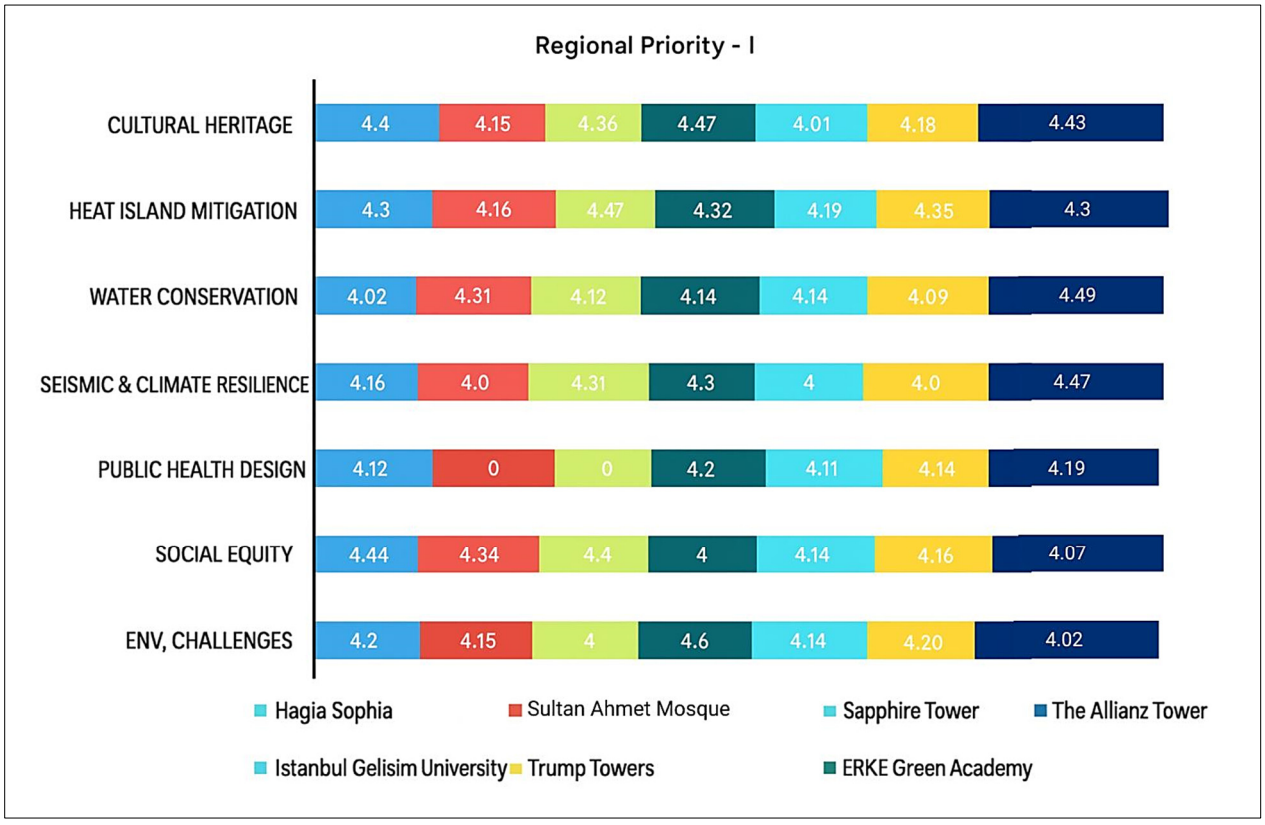


Figure 23. Mean chart for Regional Priority–I.

4.5. Results of the Comparative Sustainability Performance of Selected Case Study Buildings in Istanbul

The comparative analysis presented in Figure 24 illustrates the sustainability performance of selected buildings in Istanbul across key environmental assessment categories, including Integrative Design, Location and Transport, Sustainable Sites, Water Efficiency, Energy and Atmosphere, Materials and Resources, Indoor Environmental Quality, Innovation, and Regional Priority. The figure reveals distinct variations among the buildings, reflecting differences in design philosophy, construction era, and adoption of sustainable strategies. Notably, the EKK Green Academy exhibits the most outstanding sustainability

performance overall, achieving higher ratings in Water Efficiency, Energy and Atmosphere, and Indoor Environmental Quality, which indicates the successful application of green design principles and advanced building technologies. Similarly, Trump Towers and Sapphire Tower demonstrate relatively strong sustainability profiles, with notable emphasis on energy conservation, site efficiency, and innovation features commonly associated with modern high-rise developments designed under contemporary environmental standards.

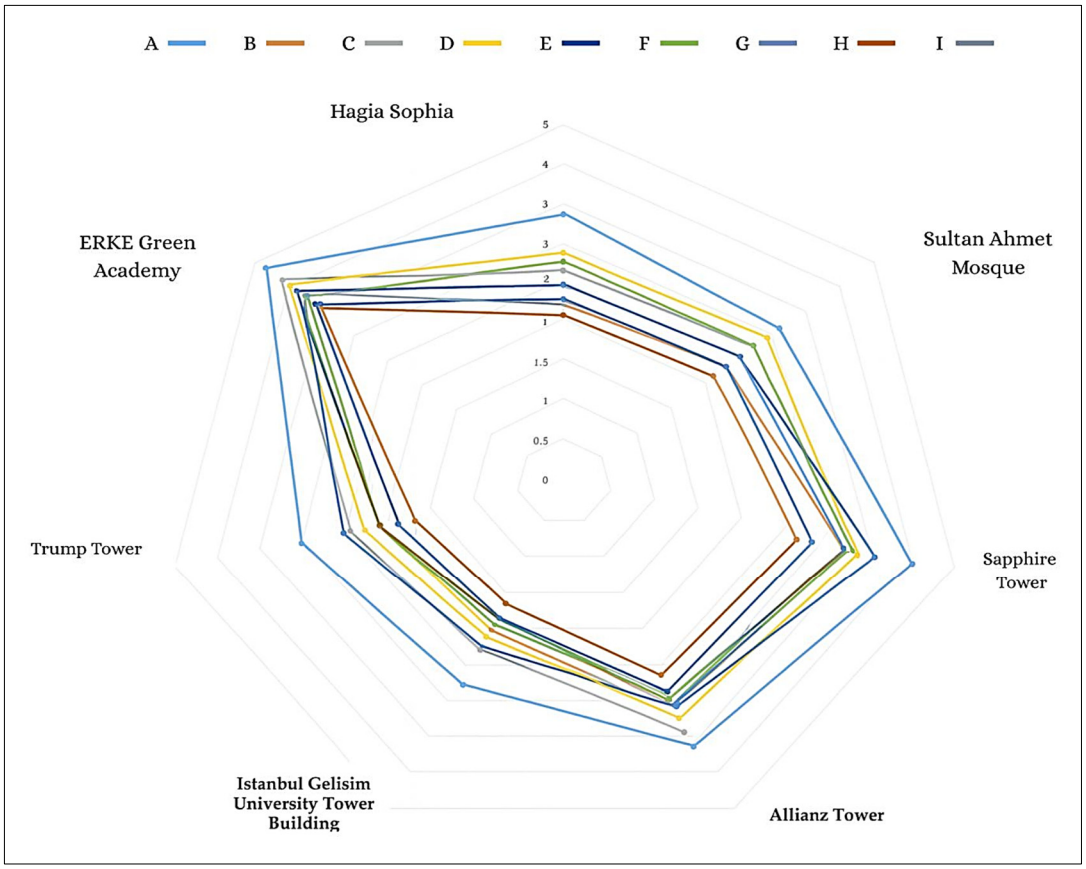


Figure 24. A comparative summary showing the sustainability performance of the seven selected buildings across nine key criteria.

In contrast, historical landmarks such as Hagia Sophia and Mimar Sinan's Sehzade Mosque (Mehmet Agha) record comparatively lower scores across most sustainability categories. This is expected, as their architectural characteristics stem from traditional design and construction techniques that predate modern sustainability frameworks. Nonetheless, these structures remain significant in terms of their enduring cultural, aesthetic, and historical value, showcasing how past architectural ingenuity prioritised spatial harmony, natural ventilation, and locally sourced materials, concepts that indirectly align with sustainable design philosophy. Overall, the comparative data underscore the evolution of architectural priorities in Istanbul, where contemporary buildings increasingly integrate environmental responsibility alongside functionality and aesthetics, while heritage structures continue to represent the city's cultural identity and historical continuity within the urban fabric. Importantly, this analysis reflects the interconnected influence of cultural, social, and environmental factors on architectural design. It highlights how the city's architectural landscape has transitioned from historically rooted cultural expressions to modern interpretations that embrace economic pragmatism and environmental consciousness, demonstrating the dynamic balance between tradition and innovation in shaping sustainable architectural practices.

The findings of this comparative study are inherently shaped by Istanbul's region-specific climatic conditions, characterised by its temperate–humid environment, as well as its distinct cultural and architectural context, particularly the longstanding heritage of masonry construction, passive cooling traditions, and spatial configurations embedded in historic buildings. These contextual influences inform the performance outcomes observed across the assessed building typologies and help explain the varying responses to LEED-based sustainability criteria.

Implementing climate-responsive strategies offers substantial economic benefits alongside environmental gains. Passive design approaches such as optimised building orientation, natural ventilation, solar shading, and thermal mass reduce reliance on mechanical heating, cooling, and lighting, directly lowering energy costs. Over the building's operational life, these reductions translate into significant financial savings. Beyond energy efficiency, climate-responsive design supports long-term operational advantages. Lower energy demand decreases stress on mechanical systems, extending their lifespan and reducing maintenance expenses. Enhanced Indoor Environmental Quality also improves occupant comfort and productivity, yielding additional indirect economic benefits, particularly in commercial and institutional buildings.

At a broader scale, energy-efficient buildings often command higher market value and attract investor confidence. They also align with evolving energy regulations and green building certification standards, which may provide financial incentives or tax benefits. By combining immediate operational savings with long-term economic resilience, climate-responsive strategies reinforce the practical relevance of sustainable design, demonstrating that environmental responsibility and economic efficiency can be achieved simultaneously.

4.6. Occupant Behaviour and Its Impact on IEQ and Sustainability

The analysis of occupant behaviour revealed clear patterns in how daily interactions with building systems influence Indoor Environmental Quality (IEQ) and energy performance (Table 6). Occupants frequently opened windows, and the relationship to HVAC systems showed a significant negative correlation with indoor temperature regulation ($r = -0.45$, $p = 0.01$). While this behaviour improved perceived thermal comfort, it increased HVAC energy consumption due to reduced system efficiency. Daylighting usage emerged as a dominant behaviour influencing visual comfort. A positive correlation ($r = +0.62$, $p < 0.001$) was observed between occupants' preference for natural daylight and measured illuminance levels, indicating that daylight use reduces reliance on artificial lighting and lowers associated energy consumption.

Table 6. Results of the correlations between specific occupant behaviours and measured IEQ/energy metrics.

Behavioural Pattern	IEQ Metric	Correlation Coefficient (r)	Significance (*p*-Value)	Energy Impact	Interpretation
Window opening and relation to HVAC operation	Indoor temperature (°C)	−0.45	0.01	↑ Energy consumption	Frequent window opening lowers indoor temperature control efficiency, increasing HVAC energy use.
Preference for natural daylight	Illuminance (lux)	+0.62	<0.001	↓ Lighting energy	Occupants' use of daylight improves visual comfort and reduces artificial lighting demand.
Extended occupancy in meeting rooms	CO_2 concentration (ppm)	+0.58	<0.001	↑ Ventilation load	High occupancy drives CO_2 accumulation, requiring more ventilation and energy consumption.

Table 6. *Cont.*

Behavioural Pattern	IEQ Metric	Correlation Coefficient (r)	Significance (*p*-Value)	Energy Impact	Interpretation
Use of personal heaters/fans	Local temperature variation	+0.51	0.003	↑ Localised energy use	Personal heating/cooling devices create uneven temperature distribution and extra energy load.
Night-time lighting left on	Illuminance (lux)	+0.12	0.23	↑ Lighting energy	Lighting left on at night increases energy use but has minimal impact on occupant visual comfort.
Participation in sustainability programmes	No direct IEQ metric	N/A	N/A	↑ Sustainability engagement	Positive behaviour improves building sustainability practices without affecting IEQ.

Key Notes: (i) Correlation coefficient (r) indicates strength and direction of relationship between behaviour and measured IEQ or energy metric; (ii) positive r → behaviour increases metric; negative r → behaviour decreases metric; (iii) significance (*p*-value) shows statistical relevance; $p < 0.05$ is considered significant; (iv) energy impact is inferred from monitored energy consumption patterns.

Occupancy patterns also played a crucial role in environmental quality. Extended use of meeting rooms was significantly correlated with increased CO_2 concentrations (r = +0.58, $p < 0.001$), suggesting that high occupancy can deteriorate air quality and elevate ventilation energy demands. Similarly, localised use of personal heaters or fans showed a moderate positive correlation with local temperature variation (r = +0.51, $p = 0.003$), highlighting the creation of microclimate zones that compromise thermal uniformity while increasing energy use. Night-time lighting left on had a minimal correlation with illuminance levels (r = +0.12, $p = 0.23$) but contributed to unnecessary energy consumption, suggesting a need for automated lighting controls. Participation in sustainability programmes, while not directly impacting IEQ, positively influences overall building sustainability by promoting responsible occupant practices.

5. Discussion

5.1. Process and Context

5.1.1. Climate-Responsive and User-Centric Approaches in Istanbul's Buildings

A review of seven architectural case studies underscores the increasing prioritisation of climate-responsive and user-centred design approaches in shaping sustainable, adaptive, and health-promoting built environments. The selected projects, spanning from historical masterpieces like Hagia Sophia and the Sedefkar Mehmed Agha Mosque to modern high-rise and institutional buildings, illustrate how both traditional wisdom and technological innovation can converge to enhance environmental performance and occupant well-being. For historical structures, the continued relevance of passive design principles such as high thermal mass, natural ventilation, shaded courtyards, and recessed window openings demonstrates the enduring efficiency of traditional architecture in moderating indoor climates [40]. These design strategies minimise energy dependence on mechanical systems while preserving cultural integrity, proving that sustainable retrofitting can coexist with heritage conservation. For instance, the Hagia Sophia's spatial orientation and material composition optimise solar control and airflow techniques that remain exemplary for modern architects seeking low-energy solutions.

In contemporary architecture, buildings such as Sapphire Tower, Allianz Tower, and Trump Towers showcase the integration of advanced façade technologies, including double-skin envelopes, zoned HVAC systems, and automated shading. These features not only improve energy performance but also enhance comfort through responsive environmental control [5,32]. The Allianz Tower demonstrates energy savings of up to 30%, while features like sky gardens and semi-outdoor spaces foster social well-being and a stronger connection to nature. In the educational sector, Istanbul Gelişim University Tower and the ERKE Green

Academy reflect the practical application of biophilic and adaptive design, focusing on daylight optimisation, acoustic balance, and flexible spatial zoning to support learning and productivity [46]. The ERKE Green Academy, in particular, operates as a "living laboratory," testing green roof systems, energy simulations, and biodiversity enhancements. Across all cases, occupant feedback highlights improved comfort, satisfaction, and spatial quality, affirming that integrated, user-responsive architecture fosters both environmental performance and human well-being [47].

5.1.2. The Integrative Design Performance Criteria of the Buildings

The study's findings echo persistent currents in sustainable, user-focused architecture, which is hardly surprising, but worth noting. Iconic structures like Hagia Sophia, Istanbul Gelişim University, and Trump Towers all spotlight the drive for healthy interiors: plenty of daylight, solid air quality, and proper ventilation. This is not just architectural lip service; research by [5,18] backs up the idea that these factors genuinely boost comfort and cognitive performance [16], showing that exposure to natural environments has restorative benefits, in tandem with these designs. Allianz and Sapphire Towers, which provide spatial flexibility—exactly the kind of approach that [1,2] contend is essential for sustainable architecture, particularly in dynamic urban settings—also exhibit adaptive design leadership. In the meantime, the materials used in contemporary skyscrapers like Allianz Tower and historic sites like Sultan Ahmed Mosque demonstrate a dedication to sustainability that is consistent with [7,12]'s focus on life-cycle thinking and low-impact materials. When taken as a whole, these examples show how modern architecture is shifting away from ostentatious facades and toward environmentally conscious, human-centred design that has a lasting influence. Although energy efficiency and smart systems integration were well-executed, as supported by [4,6], the consistent weakness in waste reduction suggests a lack of full circularity. This finding confirms the critique that waste management strategies often lag behind other green innovations in practice [48].

5.2. Sustainable Resource Management

5.2.1. Location Indices and the Transportation Drives Related to the Buildings

The noteworthy high LEED Neighbourhood Location scores of projects like ERKE Green Academy, Hagia Sophia, and Sultan Ahmed Mosque are a testament to their urban sustainability initiatives. These locations are in mixed-use, walkable, and transit-accessible areas, which are consistent with [6]'s ideas of smart growth and sustainable urbanism. Istanbul's continuous efforts to incorporate institutional and historic structures into larger sustainability frameworks are especially noticeable. Nonetheless, land protection measures remain only moderately addressed. For instance, Trump Towers' lower scores indicate that ecologically sensitive site selection is not uniformly prioritised. This observation echoes the concerns raised in [48] that urban expansion often neglects ecosystem integrity in the absence of robust zoning and environmental policies.

On a more positive note, equitable development and high-priority site recognition were strong across all cases, especially at ERKE Green Academy and Hagia Sophia. These outcomes are consistent with [30,31], which emphasise the significance of inclusiveness and social equity in sustainable communities. Furthermore, Allianz Tower and ERKE Green Academy complement the conclusions of [45] about the significance of transit-oriented development for energy efficiency by showcasing Istanbul's dedication to sustainable mobility through robust transit accessibility. In keeping with the study in [49] on sustainable cities, there is also a discernible trend toward compact urban design and active mobility, as evidenced by the bike lanes and parking reductions at Sapphire Tower and Trump Towers. However, adding contemporary electric vehicle infrastructure to older, historically

significant locations like Sultan Ahmed Mosque and Hagia Sophia continues to be a struggle. This difficulty is consistent with observations by [14,15] regarding the complexities of retrofitting historical urban environments for contemporary clean mobility solutions.

5.2.2. Sustainable Site and Design Strategies of the Buildings

The ERKE Green Academy stands out as a leading example in sustainable site performance, consistently achieving high marks across open space provision, rainwater management, and mitigation of the urban heat island effect. This reflects the broader consensus in the existing literature. This notably emphasises the importance of institutional commitment and robust policy frameworks in realising exemplary outcomes in green building initiatives [17]. Heritage buildings such as Hagia Sophia and Sultan Ahmed Mosque also exhibit noteworthy ecological sensitivity. Their success in adaptive reuse and restoration aligns with the observations of the authors of [1,2], who argue that heritage preservation can be effectively integrated with sustainability objectives, provided that ecological considerations are prioritised throughout the process. Academic and commercial buildings, including Istanbul Gelişim University, Allianz Tower, and Sapphire Tower, demonstrate a clear prioritisation of environmental comfort and sustainable design strategies. Their impressive results are consistent with the patterns described by [50], which indicate that commercial and educational stakeholders are becoming more aware of the advantages of green credentials, which include lower operating costs and improved institutional reputation. Trump Towers, on the other hand, performed poorly, especially in the areas of site evaluation and habitat restoration. This result is consistent with the concerns raised in [21,22] that, absent clear regulatory incentives, the luxury sector frequently falls behind in ecological integration. Lastly, there is still a problem with light pollution. Despite some positive results, buildings like Hagia Sophia and Sultan Ahmed Mosque lack targeted interventions in this area, reinforcing the continuing relevance of [22] and their advocacy for dark-sky-compliant lighting, both in historic and contemporary urban environments.

5.2.3. Water Efficiency Technologies of the Buildings

The ERKE Green Academy stands out as a leader in Water Efficiency, consistently achieving high scores, particularly in building-level water metering and indoor water use reduction. This performance demonstrates a proactive approach to integrating smart water technologies, reflecting the insights of [47], who emphasised that intelligent systems and strategic planning are crucial for optimising resource efficiency within green buildings. Institutions like Istanbul Gelişim University and the Allianz Tower stand out as they continue to exemplify the use of tier-one water appliances and comprehensive metering in institutional buildings. The emerging high usage efficiency in complex buildings complements issues concerning water conservation in buildings with high occupancy. The Hagia Sophia complex and Sultan Ahmed Mosque continue to exemplify the performance of heritage buildings both for indoor and outdoor water use. Their ability to reduce water usage further supports the case made in [51], which supports the sustainable retrofitting of heritage buildings as a practical and advantageous solution to environmental impacts. On the other hand, Trump Towers and Sapphire Tower perform below average, especially in process water management and full metering implementation, which aligns with the criticisms of [50] that commercial buildings are likely to neglect water-saving technologies for reasons of cost or appearance.

Notably, historic structures like Sultan Ahmed Mosque and Hagia Sophia also demonstrate remarkable indoor and outdoor water use performance. Their accomplishments in cutting water use provide credence to the claims made in [51], which support the viability and environmental benefits of the sustainable retrofitting of old structures. Trump Towers

and Sapphire Tower, on the other hand, perform comparably worse, especially when it comes to thorough metering and process water management. This deficiency aligns with the worries expressed by the authors of [50,51], who noted that commercial buildings might not fully utilise water-saving solutions because of aesthetic or financial constraints. Overall, the consistently high indoor water use reduction ratings of all case studies highlight the important influence of contemporary water-saving fixtures and laws. This finding is supported by [1], which highlights the critical role of efficient plumbing and user awareness in achieving substantial reductions in water consumption.

5.3. Energy and Environmental Performance

5.3.1. Buildings' Energy Efficiency and Favourable Atmosphere

The ERKE Green Academy distinctly stands out in energy-related performance measures, achieving stellar results in Building-Level Energy Metering, Minimum Energy Performance, and Basic Refrigerant Management. This indicates a deep integration of technology and a firm commitment to energy-conscious design, which supports the findings of [12,34,38], who stated that high-performance green buildings yield strong operational energy savings and environmental benefits. ERKE's accomplishments offer a powerful and reproducible example of software energy and smart architectural design for Istanbul. Similar to this are the Allianz Tower and Hagia Sophia, which also show clear strengths in the energy measures. Their success, especially with Minimum Energy Performance, suggests that commercial towers and heritage sites alike can achieve high energy standards with proper HVAC, envelope improvements, and thoughtful retrofitting. These outcomes align with those in [52], which demonstrated that energy retrofits in historic buildings can yield substantial improvements without compromising cultural heritage values.

Istanbul Gelişim University and Sultan Ahmed Mosque also display robust energy management, especially in the areas of energy metering and performance optimisation. These cases reflect the effectiveness of real-time monitoring and data-driven management strategies. On the other hand, Trump Towers and Sapphire Towers rank rather poorly in Grid Harmonisation and Enhanced Refrigerant Management, pointing to ongoing difficulties with system integration and energy efficiency. A significant discrepancy exists between the expected and actual energy performance in major commercial projects, which is supported by this observation [50]. Finally, it should be noted that all reviewed buildings underperform in Grid Harmonisation, highlighting a broader systemic challenge in aligning with smart grid infrastructure. As emphasised by [53], effective integration of demand-response mechanisms and renewable energy sources is essential for meeting national energy and climate objectives, particularly in rapidly urbanising contexts such as Turkey.

Building-integrated photovoltaics (BIPVs), when combined with on-site energy storage, can play a central role in enabling near-zero energy buildings in climates similar to Istanbul's. BIPV systems, including roof, façade, window, and shading integrations, have been widely studied for their potential to replace conventional building envelope materials while producing electricity and reducing peak loads [54]. Under favourable climatic and solar-irradiance conditions, research in Turkey demonstrates that rooftop or façade-integrated BIPV can meet substantial proportions of a building's heating, cooling, and electricity demands [55]. Experimental studies under semi-arid conditions further show that optimised BIPV deployments yield robust annual energy returns, particularly when orientation, panel type (e.g., bifacial), and reflective surfaces are carefully considered [56]. Given the documented solar potential of rooftops in Istanbul [57], BIPV offers a tangible pathway toward sustainable, low-carbon, and energy-self-sufficient architecture in Istanbul's urban context.

5.3.2. Materials and Resources Sustainability Indicators (F)

The analysis of material resource sustainability across the seven case study buildings in Istanbul illustrates substantial differences in performance, reflecting longstanding inconsistencies in the adoption of green construction practices and circular economy principles. ERKE Green Academy emerges as a clear leader, consistently achieving the highest scores across all six resource indicators. Its strong focus on life-cycle impact reduction, Environmental Product Declarations (EPDs), and material ingredient transparency positions it as a benchmark for sustainable institutional and commercial architecture in the city, echoing the standards proposed by [12]. The Allianz Tower and Hagia Sophia also demonstrate robust outcomes. Allianz, in particular, excels in recyclable storage and the adoption of EPDs, signalling the presence of advanced operational policies. Hagia Sophia's high ratings in material sourcing reinforce recent scholarship suggesting that the retrofitting of heritage buildings can align with contemporary sustainability goals, provided there is a thoughtful integration of traditional craftsmanship and modern green procurement strategies [51]. Istanbul Gelişim University and the Sultan Ahmed Mosque present a moderate yet consistent performance, highlighting ongoing challenges in transparency and waste management practices. In contrast, the Sapphire and Trump Towers score noticeably lower, particularly in terms of EPD usage and construction and demolition waste management. These results support concerns raised by [38] about the persistent gap between ambitious architectural design and the practical implementation of sustainability measures. Taken together, the findings underscore the critical importance of material transparency, the adoption of circular construction principles, and proactive policy intervention to advance Istanbul's transition toward sustainable urban development.

5.3.3. The Indoor Environmental Quality (IEQ) Assessment-G

Several of the buildings analysed in this case study demonstrate noteworthy achievements in acoustic performance and indoor air quality, reinforcing prior research on the critical role of advanced mechanical systems and well-considered envelope designs. For instance, both ERKE Green Academy and Trump Towers exhibit effective smoke control and robust IAQ assessments, supporting findings regarding the health advantages of proper ventilation and pollutant management in high-density urban contexts [3]. Similarly, Sapphire Tower's commendable acoustic outcomes highlight the value of façade optimisation and noise mitigation strategies in tall buildings, echoing the conclusions of [34]. Heritage structures, such as Hagia Sophia and Sultan Ahmed Mosque, also yielded significant results. According to [52], Hagia Sophia's strong results for low-emitting materials show the advantages of including sustainable materials during retrofitting. Minar's remarkable daylighting performance reflects the timeless principles of Ottoman architectural design, which place a focus on visual comfort through passive means. Additionally, Trump Towers, Allianz Tower, and Istanbul Gelişim University all scored highly in terms of daylight access and the quality of views, which are important aspects of visual comfort. Nevertheless, these buildings received relatively low marks for indoor air quality management planning, underscoring concerns that long-term IAQ depends not only on initial design strategies but also on consistent operational maintenance. In summary, daylighting stands out as a consistent strength among all evaluated buildings, corroborating earlier studies [34] that link access to natural light with improvements in occupant health and productivity.

5.4. Innovative and Regional Relevance

5.4.1. Innovative Green Technologies and Smart Systems Integration

The analysis indicates that Innovative Green Technologies and smart systems integration consistently demonstrate strong performance across the case studies, with Hagia

Sophia and ERKE Green Academy emerging as leaders in green innovation. These findings align with earlier research by [34,38], which demonstrated that even heritage structures can successfully incorporate modern environmental technologies when retrofitted with care. Similarly, the advanced digital capabilities observed in ERKE and Sapphire Tower reinforce the conclusions in [18], the authors of which emphasised the critical role of smart building systems in optimising energy efficiency and overall building performance.

Elements of biophilic design and initiatives in Education and Awareness were also notably effective in several buildings, for instance, Trump Towers and Sultan Ahmed Mosque, whose use of and integration of natural elements strengthen the psychological and physiological benefits of biophilic environments. These examples, along with the strong performance of Istanbul Gelişim University in sustainability education, further bolster the claims made by the authors of [53], who championed the integration of environmental education across disciplines. The absence of smart systems integration, Social Equity Innovation, and LEED-accredited professionals stood out the most in Hagia Sophia, Trump Towers, and Allianz Tower. The challenges of maintaining or upgrading inclusive, advanced systems are apparent in certified expertise and equitable design. To conclude, this study emphasises that adaptive reuse, professional expertise, and inclusive methods are imperative to fully achieve sustainability in the transforming urban fabric of Istanbul.

5.4.2. The Buildings' Regional Priority

The study emphasises how intricate and multifaceted sustainability is in the context of Istanbul's architecture. Notably, Allianz Tower and Sapphire Tower demonstrate excellent environmental responsibility, which is consistent with the findings of [53] that strategic environmental considerations are essential for the building of urban high-rises. ERKE Green Academy and Hagia Sophia stand notably in the field of seismic and climate resilience, which is crucial given Istanbul's geographic realities. Their achievements emphasised the importance of earthquake preparedness in Turkey's seismic hotspots. Beyond environmental and structural concerns, the findings suggest that social equity and cultural heritage remain central. Buildings such as Sapphire Tower, Trump Towers, and Hagia Sophia reflect the practice of inclusive design and the preservation of cultural continuity. Furthermore, the sustained leadership of Hagia Sophia and ERKE Green Academy in heritage conservation resonates with the principles set out by the authors of [58], who advocated for integrating historic preservation with contemporary use. In terms of public health design, both Istanbul Gelişim University and Hagia Sophia demonstrate a user-centred approach, which aligns with [6], regarding the influence of spatial design on well-being. In terms of the environment, ERKE Green Academy is at the forefront of water conservation initiatives. Sultan Ahmed Mosque and Hagia Sophia successfully mitigate the effects of urban heat islands, which aligns with [32], supporting conventional passive cooling methods. When considered as a whole, these results confirm that Istanbul's modern constructions and historic buildings can both serve as examples of integrated sustainability and resilience.

5.5. Occupant Behaviours and Comfort Within Building Design

The results clearly demonstrate that occupant behaviour plays a pivotal role in shaping Indoor Environmental Quality (IEQ) and building energy performance. The analysis revealed consistent links between everyday behavioural actions and measurable environmental outcomes. For instance, occupants showed a strong preference for natural daylight, which correlated with higher daytime illuminance levels and reduced dependence on artificial lighting, an effect well supported in the literature, where daylight-linked controls and occupancy-responsive lighting systems have been shown to reduce electricity consumption [32,59] significantly. Similarly, patterns of window opening, extended room

occupancy, and personal heater or fan use were associated with temperature fluctuations, increased ventilation demand, and uneven thermal conditions, reflecting observations from earlier studies highlighting the influence of occupant-driven ventilation and comfort devices on IEQ and energy loads [60].

These behavioural tendencies emphasise that building performance is not determined by technology alone but by how occupants interact with available systems. Broader reviews support this, noting that behavioural efficiency can affect annual building energy use by 4–30%, often yielding greater sustainability gains than expensive technological retrofits [15,19]. Behaviours such as leaving lights on at night increased energy consumption, while participation in recycling reflected positive environmental engagement without directly affecting IEQ. Collectively, these findings highlight the necessity for building design and operational strategies that actively accommodate human behaviour. Adaptive HVAC systems, daylight-sensitive design, occupancy-responsive ventilation, intuitive controls, and user education are crucial to enhancing environmental quality, reducing energy consumption, and improving overall sustainability performance. The evidence confirms that everyday occupant actions substantially influence the actual performance of buildings.

6. Conclusions

The comparative assessment of the sustainable performance of the seven (7) case study Istanbul buildings in this study offers important new information for policymakers, urban planners, and architectural practice. Results show that with the application of cutting-edge technologies, adaptive reuse, and occupant-centred practices, sustainability concepts can be successfully incorporated into both modern high-rises like the Sapphire Tower and historic sites like Hagia Sophia. There have been notable developments in the areas of water conservation, interior environmental quality, energy efficiency, and site sustainability, with ERKE Green Academy and Hagia Sophia standing out as excellent models. These results demonstrate that conscious design choices, smart retrofitting, and ongoing innovation can achieve sustainability without being limited by building age or type. In addition, the instruments and measurements used in this research provide a foundation for assessing integrative design methodologies and architectural interventions aimed at creating resilient and sustainable urban settings.

However, this study highlights enduring difficulties with regard to the infrastructure for electric vehicles, biodiversity enhancement, process water reuse, and material life-cycle transparency. It will take a concerted effort that includes investment in adaptive retrofitting, operational innovation, and strong policy frameworks to close these gaps. Using standardised performance criteria like LEED and WELL, the study's integrated cross-analysis of historic and modern architecture is its distinctive contribution. This method advances the conversation on providing a comprehensive framework for sustainable development in metropolitan settings with a wealth of cultural heritage. The study underscores the practical significance of integrated design methodologies for architects and urban planners, which concurrently tackle climate resilience, energy efficiency, and public health. While Hagia Sophia's adaptability shows how heritage conservation and modern sustainability goals can coexist, ERKE Green Academy's robust water conservation and seismic resilience strategies emphasise the importance of technical excellence in projects.

To create resilient and inclusive spatial results, experts are urged to implement systemic frameworks that integrate digital monitoring systems, biophilic design, and community involvement. Through focused incentives and accountability mechanisms, policymakers are also pushed to include sustainability in regulatory frameworks. Implementation consistency would be strengthened by institutionalising instruments like sustainability grants, zoning bonuses, and green construction tax credits in addition to requiring LEED-

accredited experts and environmental performance assessments. To provide fair access to sustainable urban infrastructure, strategic investment in socially inclusive innovation and smart systems integration is essential. The practical design implications generated from the comparative results contribute novel recommendations for integrating climate-responsive strategies across diverse building types.

The methodological framework developed in this study, as applied to cases such as the Sultan Ahmed Mosque, combining a unified LEED-based evaluation matrix with comparative analysis of passive heritage strategies and advanced high-performance technologies, provides insights that extend beyond the immediate regional focus. The integration of thermal mass, natural ventilation, and daylight-responsive design with smart façade systems, automated shading, and energy-intelligent controls demonstrates a complementary design approach that is transferable to other cities with comparable climatic conditions or mixed building typologies. Thus, while the empirical outcomes are specific to Istanbul, the design principles and evaluation method offer broader applicability for informing sustainable architecture in regions seeking to bridge traditional passive techniques with modern technological innovations.

To bolster the empirical foundation of findings, future research should include cross-regional sampling, real-time sensor data, and longitudinal field studies. A more thorough grasp of sustainable building practices in Istanbul and other international contexts would be possible with additional research into cutting-edge technologies like adaptive energy systems, dynamic shading, and hybrid ventilation. Nonetheless, the suggested approach is still reproducible and provides a scalable model for assessing and promoting sustainable building in urban areas across the globe. This study acknowledges real-time data analysis as a limitation and thus suggests the incorporation of real-time monitoring in future research to capture dynamic environmental and occupant interactions. Future research should also explore post-occupancy evaluations to deepen insights into adaptive sustainable design.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/buildings16010018/s1, references [61–63] are cited in the supplementary materials.

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