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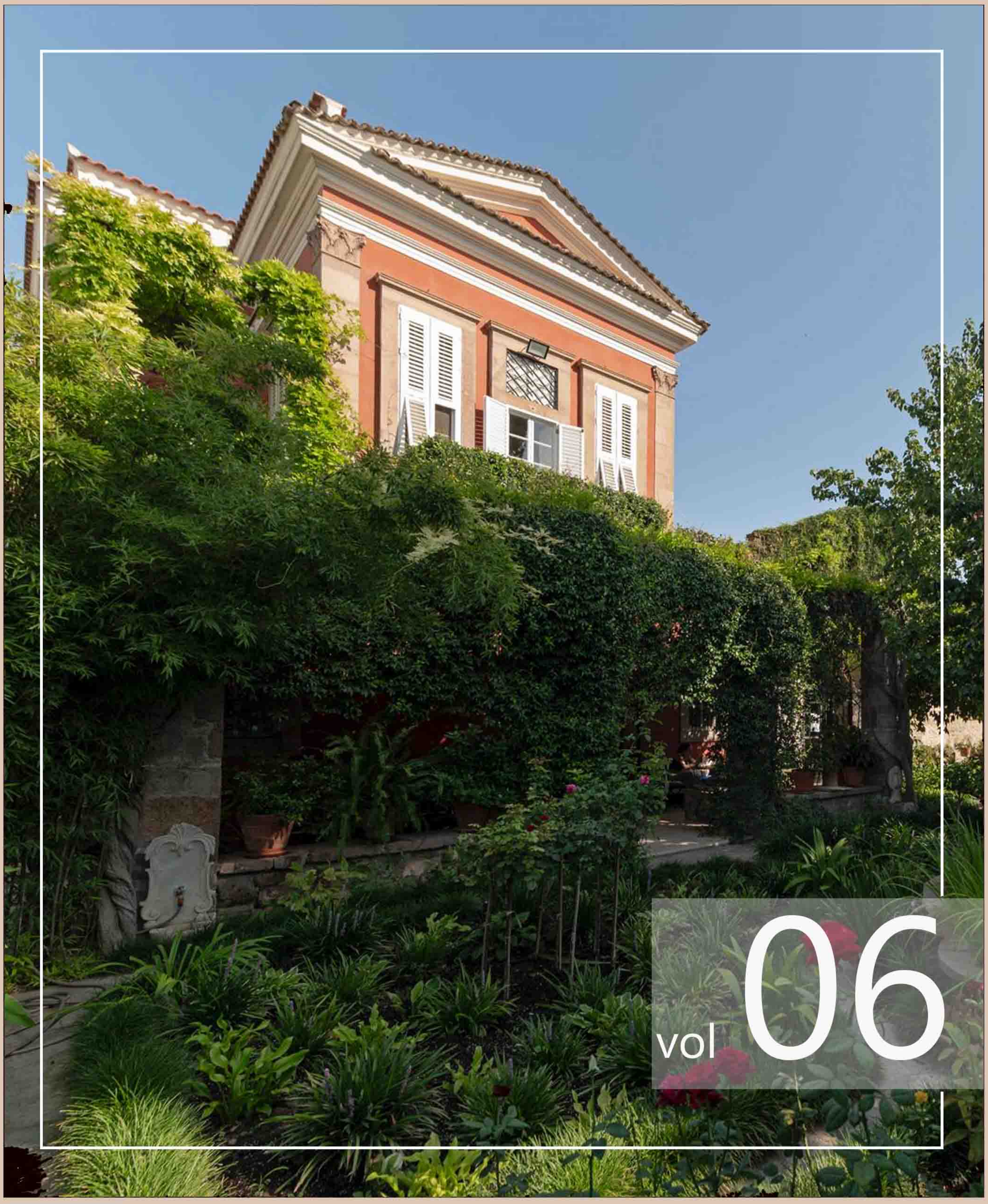

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Editorial

Mehmet Topçu (Editor)

The Journal of Design for Resilience in Architecture & Planning (DRArch) continues its trajectory of growth while steadfastly upholding its commitment to quality and high standards. We are proud to present Volume 6, Issue 2, which features articles of exceptional scientific merit. Staying true to our mission of fostering innovative, interdisciplinary, and resilient approaches to design and urban planning, this issue brings together a collection of scholarly works that explore the dynamic intersections of architecture, resilience, urban transformation, and cultural continuity. This issue brings together contributions from researchers in Singapore, India, Türkiye, and Nigeria, covering a spectrum from historically grounded inquiries to contemporary challenges, including artificial intelligence and the climate crisis.

This volume begins with a study that foregrounds climate-responsive housing, situating thermal comfort within the larger debate on resilience and future-proofing the built environment. “Future-Proofing Next-G Homes: Enhancing Thermal Comfort and Building Energy Performance through Landscape Integration” by Mark Alegbe, Laurence Chukwuemeka, John Lekwauwa Kalu, and Hammed Nasiru investigates the impact of micro-landscape interventions—such as trees, lawns, and water features—on indoor thermal comfort in tropical buildings using dynamic thermal modelling. Findings show that while vegetation can reduce discomfort hours, mechanical cooling remains essential under future climate extremes, highlighting the need for integrated strategies to ensure thermal resilience in Next-G housing. While the first article addresses resilience at the scale of housing performance, the following contribution shifts attention to construction management processes, examining the transformative role of artificial intelligence. In “Artificial Intelligence in Construction Project Management: Trends, Challenges and Future Directions” Sezer Savaş focuses on the role of AI in key functions of construction project management, including time management, cost estimation, quality assurance, occupational health and safety, risk mitigation, resource optimization, and design management, through a narrative literature review. Extending the theme of innovation, the third paper explores design methodologies, focusing on how Interaction Design can enhance Design Thinking in group housing projects. In “Optimizing the Design Thinking Process for Group Housing through Interaction Design Methods” Tadiboina Samantha Kumar and Ramesh Srikonda propose a hybrid approach that combines empathy mapping, interactive prototyping, and real-time feedback systems to optimize DT phases—empathize, ideate, prototype, and test.

From contemporary housing design, the issue turns to cultural heritage, with an article that examines how memory and perception intertwine in the experience of historic buildings. *“Physical Vs Virtual: A Multi-Layered Perception Experience on Memory through Historic Buildings”* by Yekta Özgüven, Asena Kumsal Şen Bayram and Nadide Ebru Özkan investigates the layered relationship between memory and perception through the case of Bostancı Primary School in Istanbul, designed by Architect Kemalettin in the early 20th century. The study highlights how architectural elements, spatial perception, and sensory engagement contribute to memory formation, while also pointing to the potential of virtual technologies in extending architectural experiences beyond physical constraints. In line with the concern for heritage, the next contribution employs a scientific lens to analyze gilded ornamentation using non-destructive testing methods. *“A Non-Destructive Testing Method for the Production Technique of Gilded Ornamentation in a Traditional House: XRF Analysis Method”* by Gamze Fahriye Pehlivan examines yaldızlı ornamentation from a traditional house in Sivas. Using XRF analysis, the study reveals that the gilding is an imitation made from a brass alloy, demonstrating the value of modern, non-destructive methods in conservation and restoration. While the previous article focuses on conserving heritage materials, the following study shifts the discussion to ecological infrastructures, evaluating the long-term performance of rain gardens in the tropics. *“Degradation and Biodiversity of Rain Gardens in the Tropics”* by Lina Altoaimi, Shruthakeerthi Karthikeyan, Akshitha Vadlakunta, Yuting Wang, and Abdul Thaqif Abdul Terawis compares two rain gardens in Singapore—one in Potong Pasir and another in Jurong Lake Gardens—to assess ecological and aesthetic degradation. Using biodiversity and visual indices alongside field observations, the research highlights maintenance and design challenges and proposes strategies to extend rain garden lifespans while supporting stormwater management and urban biodiversity. Continuing with nature-based solutions, the next article investigates temporary, small-scale urban interventions that mobilize civic engagement in transforming overlooked urban spaces. In *“Mobilizing Nature-Based Solutions through Temporary Urban Interventions: A Civic Guide to Ephemeral Landscapes”* Tuba Doğu and Hande Atmaca develop a civic guide through experimental prototyping in three phases—experimentation, fabrication, and dissemination—

integrating material innovation, planning theory, and public participation to advance urban resilience. Broadening the ecological focus from small-scale interventions to larger urban zones, another study examines the role of fringe belt areas in mitigating the urban heat island effect. In *"Urban Heat Island and Fringe Belt Interaction: The Role of the Urban Fringe in Heat Island Mitigation"* Gülnihal Kurt Kayalı, Büşra Gülbahar İşlek, Tuğba Akın, Tolga Ünlü, and Tülin Selvi Ünlü analyze Landsat satellite images from 1985, 2000, and 2025 via Google Earth Engine to show that preserved or minimally developed fringe belts reduce heat accumulation, whereas intensified development exacerbates UHI effects. The study highlights the potential of fringe belts as cooling buffers and calls for their integration into climate-sensitive urban planning. Beyond climate resilience, this issue also addresses the socio-spatial evolution of housing, as explored through the case of Kayseri. In *"Urban Layers and Living Spaces: The Evolution of Housing in Kayseri"* Nihan Muş Özmen and Burak Asiliskender examine housing transformation as a lens to understand broader processes of urbanization, modernization, and socio-spatial change in Turkey. Building on the theme of urban transformation, the following contribution introduces a comprehensive index to assess the vulnerability of Türkiye's cities to climate change. In *"Assessing the Vulnerability of Cities to Climate Change: A New Index Proposal for Türkiye Cities"* Hale Öncel develops an index that evaluates multiple climate risks, including drought, sea-level rise, heavy rainfall, and extreme heat, offering municipalities and researchers a practical tool for climate-resilient planning and decision-making. From contemporary urban challenges, the issue moves back to heritage studies, presenting an analysis of wooden pillar and wooden ceiling mosques of the Seljuk and Principalities period. In *"Analysis of Wooden Pillar and Wooden Ceiling Mosques of the Seljuk and Principalities Period"* Ercan Aksoy and Özlem Sağıroğlu Demirci provide a typological and structural analysis of these mosques, documenting construction techniques and ceiling solutions—some recognized on the UNESCO World Heritage List—through site examinations, archival sources, and 3D modeling.

Turning again to present-day urban issues, another article develops an innovative, participatory paradigm for parking management. In *"A New Paradigm in Parking Management: From Quantitative Models to Stakeholder Participation"* Ecenur Sarıca Karakulak and Görkem Gülhan propose an integrated approach that combines quantitative models with expert and user opinions. Using the Trabzon-Ortahisar case and applying the Analytical Hierarchy Process (AHP), the study demonstrates that conventional methods are insufficient and advocates for participatory strategies better aligned with user behavior and local demand. The issue concludes with a contribution in the field of architectural education, offering a multidimensional analysis of teaching techniques in higher education. In *"Multidimensional Analysis of Teaching Techniques Used in Higher Education: The Case of a Landscape Architecture Department"* Ahmet Akay evaluates teaching effectiveness through student feedback, questionnaires, and course performance. Employing a pretest–posttest design and statistical analyses, the study shows significant knowledge gains across courses, though effectiveness levels vary—being highest in Computer-Aided Design and lowest in Project-I—emphasizing the importance of aligning teaching strategies with student perceptions and curriculum needs.

We thank all contributors for their dedication and hope that this issue inspires new research, collaboration, and creative initiatives. By engaging with these studies, readers are invited to enrich the debate on resilience and design and to help shape a more sustainable future for architecture and planning.

Best regards...

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DRArch's objectives are:

- to question how future building technologies are revolutionizing architectural design, city planning, urban design, landscape design, industrial design, interior design and education,

- to catalyze the processes that lean on interdisciplinary and collaborative design thinking, creating a resilient thinking culture,

- to improve the quality of built environment through encouraging greater sharing of academicians, analysts and specialists to share their experience and answer for issues in various areas, which distributes top-level work,

- to discover role of the designers and design disciplines -architecture, city planning, urban design, landscape design, industrial design, interior design, education and art in creating building and urban resilience,

- to retrofit the existing urban fabric to produce resilience appears and to support making and using technology within the building arts,

- to discuss academic issue about the digital life and its built-up environments, internet of space, digital in architecture, digital data in design, digital fabrication, software development in architecture, photogrammetry software, information technology in architecture, Archi-Walks, virtual design, cyber space, experiences through simulations, 3D technology in design, robotic construction, digital fabrication, parametric design and architecture, Building Information Management (BIM), extraterrestrial architecture, , artificial intelligence (AI) systems, Energy efficiency in buildings, digitization of human, the digitization of the construction, manufacturing, collaborative design, design integration, the accessibility of mobile devices and sensors, augmented reality apps, and GPS, emerging materials, new constructions techniques,

-to express new technology in architecture and planning for parametric urban design, real estate development and design, parametric smart planning (PSP), more human-centered products, sustainable development, sustainable cities, smart cities, vertical cities, urban morphology, urban aesthetics and townscape, urban structure and form, urban transformation, local and regional identity, design control and guidance, property development, practice and implementation.

Editorial Team

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Future-proofing next-g homes: Enhancing thermal comfort and building energy performance through landscape integration

Mark Alegbe*
Laurence Chukwuemeka**
John Lekwauwa Kalu***
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Abstract

Buildings in the tropics are increasingly exposed to intense solar radiation and heat gains that result in extreme thermal discomfort, particularly in naturally ventilated buildings. As climate change accelerates, the Next Generation (Next-G) of housing stock must be designed and integrated with future-proofing strategies to ensure indoor livability. Micro-landscape interventions such as trees, lawns and water features have been found to cool outdoor environments through shading and evapotranspiration. While several studies have explored their role in mitigating outdoor heat stress, with a focus on reducing urban heat island (UHI) effects, the impact of landscape configurations on indoor thermal comfort remains underexplored, particularly in extreme climates. This study employs dynamic thermal modelling in DesignBuilder to investigate the role of micro-landscape elements on indoor thermal performance. A three-phase hypothetical building simulation approach was adopted: (1) without landscape features, (2) with landscape features and (3) with landscape features and mixed-mode cooling. Predicted future climate data for two climatically contrasting locations in Nigeria; Jos (cold) and Sokoto (hot), were used to assess comfort and energy performance. Findings reveal that by limiting solar incidences on the building envelope, landscape elements can reduce indoor discomfort hours by up to 18% in naturally ventilated spaces. However, mechanical cooling remains vital for achieving thermal comfort under future climate extremes. A combined strategy of vegetation and cooling achieved up to a 92% reduction in discomfort hours. Yet, this comfort improvement gave rise to an increased energy demand of up to 48% for the total building and 78% for conditioned spaces. These results highlight the capacity of integrated landscape strategies to support, but not replace, active systems in future-proofing Next-G buildings for thermal resilience.

Keywords: future buildings, future-proofing strategies, micro-landscapes, next-g tropical buildings, thermal comfort

1. Introduction

The rate of urbanisation and the rapid expansion of infrastructures have led to an unprecedented increase in urban heat. This trend is largely influenced by the diminishing presence of greenspaces and the increasing dominance of buildings and paved surfaces (Priya & Senthil, 2021; Wong et al., 2021). Compared to their surrounding rural areas, cities experience more elevated outdoor temperatures, causing severe thermal stress in urban centres (Marcotullio et al., 2021). This phenomenon, commonly referred to as urban heat island (UHI) effect, poses immense challenges for comfort and building energy, especially in regions with extreme year-round temperatures. One of the drivers of thermal stress in urban developments is the scarcity of vegetation which helps regulate outdoor temperatures and reduces a building's cooling load (Aboelata & Sodoudi, 2019; Wong et al., 2021). As urban centres continue to expand globally, heat

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stress is becoming more alarming, buttressing the need for strategies that enhance both outdoor and indoor thermal comfort and energy efficiency.

Cities have become the primary spotlight of research on the impact of vegetation on indoor and outdoor thermal environments. This is not surprising, as the global population is expected to dwell in cities in the coming decades. The focus of research on cities is compelled by the concentration of people, buildings and machines, which emit excessive heat and air pollution (Taleghani et al., 2019). Vegetative elements such as trees, plants and green open spaces have been recognised for their ability to regulate microclimates, thereby alleviating urban heat (Yang et al., 2018; Zeng et al., 2022; Zhao et al., 2018). However, the extent and variation of their impacts are still evolving (Ko, 2018). More so, effective building landscape offers immense cooling benefits to the wider neighbourhood (Wu et al., 2019), since it directly influences shading and evapotranspiration; two key processes that mitigate heat (Aboelata, 2020; Lombardo et al., 2023; Meili et al., 2021; Wong et al., 2021). Nevertheless, the degree of cooling provided by vegetation varies with factors such as climate (Ko, 2018), scale and the level of intervention, whether at the building or urban level (Wong et al., 2021). As a result, understanding these dynamics is crucial for designing effective nature-based solutions.

Despite the growing body of research on energy-efficient buildings, the cooling effect provided by landscape integration has not received the attention it merits in the broader context of delivering the next generation (Next-G) housing stock. The focus of most studies largely dwells on technological solutions and operational energy systems, while natural cooling mechanisms, such as evaporative cooling using water bodies and cooling through trees and plants evapotranspiration, have been somewhat overlooked (Fei, 2024; Hami et al., 2019). Moreover, the effectiveness of greenery in controlling air temperature and reducing the heat stress of outdoor environments cannot be over emphasised, as it has been shown to significantly mitigate heat stress in buildings (Abd Rahman et al., 2022; Darvish et al., 2021). As the climate crisis intensifies, greening buildings has become a non-negotiable mitigation strategy for climate goals realisation (Wong et al., 2021). The increasing dominance of grey infrastructure such as concrete and asphalt in rapidly developing cities has suppressed the potential of green infrastructure (Morakinyo et al., 2021). Given the challenges in retrofitting existing buildings, nature-based solutions offer a suitable way of regulating building comfort and reducing energy consumption (Choi et al., 2021), especially in cities where most of the population of the world is projected to reside in the future (Santiago & Rivas, 2021).

Beyond the immediate benefit of improving indoor thermal comfort, strategically positioning landscape elements such as trees, shrubs, green roofs and water elements plays a critical role in enhancing the resilience of buildings to extreme weather occurrences. These features act as natural buffers that regulate microclimates, reduce surface and air temperature and alleviate urban heat. Consequently, they contribute to sustaining the quality of life, especially in densely built neighbourhoods, by creating more liveable outdoor spaces and reducing the psychological stress caused by elevated heat. In turn, this reduction in ambient temperatures and thermal stress can significantly lower the risk of heat-related illnesses and mortality among vulnerable groups such as the elderly and children among the urban population (Koch et al., 2020). This study seeks to examine the role of landscape features in reducing discomfort in buildings; the primary unit of urban developments, through strategic planning and location of green infrastructures like trees, lawns and pools. If buildings are thoughtfully landscaped, there is an immense potential for cooling load to be reduced and when deployed systematically, these micro-scale interventions may provide a scalable pathway for future-proofing the built environment. For Next-G buildings, designed to be adaptable and climate responsive, this approach offers a practical and scalable design frontier. In extreme future climates where conventional energy systems may falter, effective landscaping will be indispensable for ensuring comfort and efficiency for the survival of the built environment.

1.1. Aim and Objectives

1.1.1. Aim

To investigate the potential of residential landscape features in enhancing indoor thermal comfort and reducing energy demand in Next-G homes under extreme tropical climates, with a focus on developing integrated, future-proofing strategies for thermal resilience.

1.1.2. Objectives

a. To examine the effect of landscape features (trees, lawns and water bodies) on indoor thermal comfort in tropical residential buildings.

b. To compare thermal performance and energy consumption of buildings under different landscape and cooling scenarios in two distinct climates in Nigeria.

c. To assess the potential of integrated landscape elements and mechanical cooling strategies in reducing discomfort hours and energy loads in future climates.

1.2. Study Questions

a. How do different landscape configurations impact indoor thermal comfort in naturally ventilated tropical homes?
b. What is the variation in thermal comfort and energy demand between landscape-only and landscape-plus-cooling scenarios under future climate conditions?
c. To what extent can landscape features contribute to future-proofing strategies for Next-G homes in extreme tropical environments?

2. Literature Review

Greening the building landscape is widely recognised as an effective climate mitigation strategy that yields one of the most thermal and environmental benefits, particularly when combined with other building strategies like solar shading and building orientation (Sharifi, 2021). Such combinations maximise passive cooling potential and reduce reliance on active energy systems. A comfortable thermal environment is generally associated with vegetation, ground surface material, building configuration and wind flow direction and impact (Zhang et al., 2023), as these elements directly influence microclimatic conditions around buildings. The strategic planting of trees around buildings has been shown to alleviate the impact of excessive temperatures, especially in regions with extreme solar radiation (Iyaji et al., 2021). Trees serve as natural thermal buffers that help to moderate indoor temperatures by reducing solar exposure on building envelopes. According to studies by Farhadi et al. (2019) and Yang et al. (2022), optimal indoor thermal comfort is achieved through the shading effect provided by the presence of trees, which limits the impact of solar incidence on buildings. In these studies, the impact of landscape elements in reducing Physiologically Equivalent Temperature (PET) varied. For instance, PET was reduced by 9.36°C mainly by increasing vegetation presence by 10% (Farhadi et al., 2019). On the other hand, PET was reduced by 1.1°C when a water body was evaluated, and up to 1.6°C with all design approaches combined (Yang et al., 2022). This reinforces the potential of vegetative shading as a passive solution to enhance thermal comfort and reduce cooling demand in hot climates.

2.1. The Concept of Next-G Buildings

Next-generation (Next-G) buildings refer to a forward-thinking paradigm in building design and construction practices, encompassing a new wave that prioritises sustainability, resilience, energy efficiency and occupant wellbeing. These buildings are predominantly equipped with advanced features to address the evolving challenges posed by climate change, urbanisation and shifting human needs. For instance, flexible building components, renewable energy systems and integrated monitoring technologies are increasingly central to the design and operation of Next-G homes (Benavente-Peces, 2019; Hao et al., 2023; Plamanescu et al., 2023). The integration of smart systems and adaptive designs enables such buildings to be more resource-efficient, respond to environmental hazards and support user comfort across varying conditions. Certification standards like the WELL Building Standard also reflect this shift by prioritising human health and comfort at the crux of design strategies (Amy, 2019; Hao et al., 2023). Despite the recurring emphasis on technological advancement, there is growing recognition that the advancement of Next-G homes also depends on an integrated approach that factors in the role of vegetative landscape into its overall performance. Landscape features such as plants, water bodies and permeable surfaces, play a crucial role in regulating building microclimates and should not be secondary to recent innovations in future green building discourse. As Gou and Xie (2017) contend, Next-G green buildings must evolve from theatrical expressions of sustainability to biologically responsive systems that leverage passive, nature-based solutions. This ecological framing highlights the necessity for landscape-informed design to complement smart, green future buildings in delivering long-term thermal comfort and climate resilience.

2.2. Strategic Vegetation Placement for Indoor Climate Moderation

Strategically placing trees and vegetation around buildings has shown substantial thermal comfort and energy saving potentials (Ayeni et al., 2019). This effect is more pronounced when vegetation is positioned to intercept prevailing solar angles, reducing the intensity of radiation reaching the building. A study by Darvish et al. (2021) in an academic building in Iran found that well-planned tree landscape contributed to a reduction in energy consumption and a decrease in discomfort hours, consequently enhancing the overall thermal performance of the building. Furthermore, studies by Meili et al. (2021) demonstrate that the cooling effect provided by well-watered trees can reduce surface air temperature by up to 5.8 °C , although the degree of cutback is noted to differ with location. This location-dependent variability emphasises the need for context-specific planting strategies aligned with regional microclimates. Research further suggests that beyond thermal comfort, having trees and vegetation in view of building occupants enhances psychological wellbeing (Wu, 2023). Access to green views has been linked to reduced stress and improved cognitive function, making vegetation a valuable design asset for environmental design of buildings. However, vegetation in users' sight, while psychologically beneficial, must not limit daylight access and ventilation flow. Hussain et al. (2014) in this regard noted that to allow for natural light and air flow, tall trees should be avoided at the south side of the building. This is especially relevant in climates where natural daylight is a vital resource for reducing reliance on artificial lighting.

The inherent qualities of trees further impact on their ability to provide shade and cooling effects. Table 1 represents a selection of locally available trees and shrubs that can be used for landscaping compact plots, highlighting key species characteristics. According to Alexander (2021), tree height and canopy density can directly regulate wind flow and other microclimatic conditions, thereby affecting thermal comfort. This suggests that selection of trees should go beyond aesthetic value to aerodynamic considerations, which could influence convective cooling. This attribute is very important in mitigating heat dissipation limitations caused by obstructed wind movement as emphasised by Meili et al. (2021), who noted that the spacing and orientation of vegetative elements enhance the efficiency of airflow patterns around buildings. Strategically placing trees with high leaf area index (LAI) or high leaf density (HLD) is remarkably effective in providing shading and reducing solar gains (Xiao & Yuizono, 2022; Yang et al., 2022). This effectiveness is extremely critical in dense urban centres where heat loads are often intensified. Moreover, such vegetative features contribute immensely to a decrease in physiological equivalent temperature (PET), as demonstrated by Cong et al. (2022). This approach reinforces the role of trees in enhancing both perceptual and measured thermal comfort conditions.

The higher the LAI or HLD, the greater the shading potential of the tree, which has significant implications for reducing building cooling load (Rahman et al., 2020). In urban landscapes, the arrangement and configuration of trees play a critical role in enhancing the cooling effect. A study by Zhao et al. (2018) suggests that a two-tree equal interval vegetation arrangement is more effective for heat reduction and thermal comfort than a clustered tree arrangement. This points to the influence of spatial uniformity in promoting even shade distribution and uninterrupted air flow. In addition, the orientation of trees relative to prevailing winds is crucial in maximising the cooling effect, with studies by Abdi et al. (2020) suggesting that a rectangular array of trees perpendicular to prevailing winds is more effective for reducing outdoor temperature. This configuration helps direct cooler air across outdoor surfaces and towards buildings, thus complementing passive ventilation strategies and enhancing the microclimatic quality of urban developments.

Table 1 Compact Trees for Small Residential Plots

Species (Taxonomic Name)	Common Name	Nominal Height (m)	Foliage Spread (m)	Leaf Density / Shade Quality	Description	Leaf Transmittance (%)	References
Terminalia mantaly H.Perrier	Umbrella tree or Madagascar almond	10–15	5–8	Very dense, layered canopy	Excellent layered canopy for broad, cool shade; fast-growing and minimal maintenance. Best planted for street sides, driveways, and small yards. Annual pruning required to maintain shape.	Moderate (6%)	(Kimpouni et al., 2024; Owoeye & Hauser, 2023)
Monoon longifolium (Sonn.) B.Xue & R.M.K.Saunders *(formerly known as Polyalthia longifolia*)	False Ashoka Tree or Indian Mast Tree	12–20	1–2	Moderate shade, narrow but thick vertically	Tall, slim, vertical growth. Perfect for tight spaces where horizontal space is limited. Provides moderate vertical shade but less overhead coverage. Very low maintenance.	Low (4%)	(Parkar et al., 2020; Shinde et al., 2023; Taib et al., 2019; WFO, 2025)
Delonix regia (Bojer ex Hook.) Raf.	Flamboyant Tree or Flame Tree	10–15	10–18	Wide spreading, high-quality shade	Stunning bright red flowers with very wide, umbrella-like canopy. Provides excellent shade but needs more lateral planting space. Not ideal too close to buildings.	High (8–10%)	(Havaldar et al., 2024; Taib et al., 2019)
Murraya paniculata (L.) Jack	Orange Jasmine or Mock Orange	2–4	1–2	Dense small canopy, partial shade	Compact tree/shrub with dense leaves and fragrant white flowers. Great for patios, borders, and small gardens. Offers moderate shade and adds fragrance. Easy to trim into hedges.	High (~10%)	(Santhoshini et al., 2022; Taib et al., 2019)
Thevetia peruviana (Pers.) K.Schum.	Yellow Oleander or Lucky nut Tree	3–6	3–5	Light to moderate shade	Fast-growing ornamental tree with yellow trumpet-like flowers. Provides light to moderate shade. Tolerates drought well but seeds and sap are toxic, so caution is needed in residential gardens with kids/pets.	Moderate (6-8%)	(Amulu et al., 2024; Fried, 2019; Owoeye & Hauser, 2023)
Plumeria rubra L.	Frangipani or Temple Tree	5-8	4-6	Moderate density, provides patchy, dappled shade	Beautiful, fragrant flowers; best for small gardens; not ideal if you want deep, full shade. Grows relatively slow.	Moderate (~7%)	(Ramlee et al., 2023; Taib et al., 2019)
Vachellia tortilis (Forssk.) Galasso & Banfi *(previously classified as Acacia tortilis*)	Umbrella Thorn	6-9	6-9	High canopy density, wide spreading, excellent deep shade	Very drought-tolerant, ideal for hot tropical zones; forms a high umbrella-like canopy, good for roof and side wall shading. Needs space to spread.	Low (~4–6%)	(Cheruto et al., 2025; Ella et al., 2018)
Ficus benjamina L.	Weeping fig	10-15	3-6	Very dense foliage, thick, dark, cooling shade	Fast-growing, perfect for tight urban spaces; roots can be aggressive, so plant at least 1.5–2 meters away from foundations or pipes. Excellent for urban shading and air cooling.	Low (~4–5%)	(Mulyani et al., 2021; Orobator & Adahwara, 2022)

2.2.1. Deciduous and Evergreen Species in Residential Landscape

Vegetation selection plays a vital role in landscape-driven thermal regulation, especially in climates that are vulnerable to extreme heat or seasonal variability. One of the most impactful strategies is the deliberate use of deciduous and evergreen trees, each offering unique microclimatic benefits depending on their physiological characteristics and seasonal behaviour. Deciduous trees shed their leaves in the dry or cold season and are valued for their dual-season functionality. In hot climates, such trees offer solar shading benefits during the peak dry season, thereby reducing indoor heat gain and limiting the dependence on mechanical cooling systems (Del Campo-Hitschfeld et al., 2023; Park et al., 2023; Wu et al., 2024). During colder seasons, their leafless canopies permit greater solar penetration, enhancing passive solar heating and daylight benefits (Chen et al., 2025). In Nigeria, where extreme temperatures are recorded year-round, deciduous trees, due to their leaf-shedding attribute, may not be beneficial for long-term shading.

Evergreen species, on the other hand, are characterised by year-round foliage. This advantage is remarkably effective for consistent wind shielding, noise attenuation and maintaining stable cooling effects throughout all seasons (Chen et al., 2025). Their dense canopies help reduce ambient temperatures by increasing evapotranspiration (Wujeska-Klause & Pfautsch, 2020; Yin et al., 2024), improving air quality and acting as natural barriers against solar radiation (Chen et al., 2024; Liu et al., 2020). When planted along west-facing facades or exposed envelope surfaces, evergreen trees provide perennial shading, making them useful in regions with prolonged dry or hot periods (Chen et al., 2024). In Nigeria, deciduous species such as *Albizia zygia* (DC.) J.F. Macbr. and *Terminalia catappa* L. are commonly planted to provide seasonal shading, among other benefits while native evergreens like *Ficus exasperate* Vahl *and Monoon longifolium* are favoured for their aesthetic structure and constant microclimatic buffering. These species, when arranged strategically, have been observed to significantly improve outdoor thermal comfort, shield buildings from direct solar radiation and reduce glare and heat gain in indoor spaces. Studies have shown that based on local climatic profiles and phenological behaviour, a mismatch in species selection can undermine anticipated thermal performance (Morakinyo et al., 2020; Rahman et al., 2020). For example, native or drought-tolerant species often require less irrigation (better water-use efficiency), contributing to low-carbon and sustainable landscape practices (Rötzer et al., 2021).

2.3. Green and Water Features for Building's Thermal Comfort

Studies highlight that green infrastructure, such as green roofs, green facades and water bodies, can further augment the cooling benefits of vegetation around buildings. According to Bach et al. (2023), Chatterjee et al. (2019) and Priya and Senthil (2021), green roofs can effectively regulate outdoor temperatures by providing additional thermal insulation, reducing the need for over-reliance on mechanical cooling. Similarly, green facades are effective at reducing cooling loads and indoor temperatures by absorbing solar radiation through transpiration (Koch et al., 2020; Li et al., 2021; Lombardo et al., 2023; Widiastuti et al., 2020; Zhang et al., 2019), contributing significantly to improved indoor thermal comfort. These features, via their interactions with the built environment, form a critical part of integrated climate-resilient designs. For dry climates, green roofs show more potential for energy reduction and better thermal comfort than green façades (Lotfi & Hassan, 2024), further accentuating the importance of tailored design choices that can maximise environmental benefits across diverse regions.

On the other hand, water features such as pools and fountains also provide significant cooling effects by moderating surrounding air temperature, although their effectiveness is dependent on factors such as size, location on site, shape and climate conditions (Hong et al., 2023; Jandaghian & Colombo, 2024; Liu et al., 2022; Yang et al., 2018). Water bodies, when carefully located, induce evaporative cooling, benefiting both thermal comfort and local microclimatic conditions. Nonetheless, Hong et al. (2023) noted that humidity levels in the vicinity of water bodies can increase, which must be carefully managed in regions prone to high moisture levels to avoid contributing to discomfort and health risks associated with mould growth in buildings.

2.4. Climate Adaptation Potential of Green Infrastructure in Tropical Contexts

Buildings in tropical regions are more susceptible to the impacts of climate change (Méndez-Serrano, 2024), but greening buildings has been found to be a very effective strategy in reducing outdoor temperatures, especially during peak temperature hours (Chatterjee et al., 2019). In addition to reducing the cooling demands of buildings, vegetation plays a critical role in mitigating heat stress by offering shading and regulating the microclimatic conditions (Haruna et al., 2018; Jega & Muhy Al-Din, 2023). These roles not only improve comfort but also reduce the health risk associated with prolonged heat exposure. This is particularly crucial in hot and humid climates like Nigeria, where outdoor temperatures can exceed 35°C (Umar et al., 2020), making both outdoor and indoor spaces almost uninhabitable without shading or cooling interventions. In extreme climates, the growing demand for mechanical cooling, a major requirement for comfort, is not only unsustainable due to its high energy consumption, but also contributes negatively to environmental impacts (Ayeni et al., 2019; Jay et al., 2021; Lundgren-Kownacki et al., 2018). This dependence on active systems can escalate grid stress and undermine national energy goals. Cooling load in such climates accounts for a substantial proportion of carbon emissions, making energy efficiency a central role in the design of tropical buildings (Widiastuti et al., 2020). Thus, integrating passive cooling strategies such as the use of vegetation is paramount in reducing both the immediate cooling needs and long-term environmental impacts.

The potential of green infrastructure to improve the environmental quality of buildings in Nigeria has been cited by researchers (Adegun et al., 2021), but maximising its benefit can be very challenging due to perceived barriers like cost (Adewale et al., 2024), maintenance (Owolabi et al., 2020) and a lack of awareness of its potential values. As highlighted by Ayeni et al. (2019) and Iyaji et al. (2021), green infrastructure for thermal comfort enhancement in Nigeria is yet to be fully harnessed, pointing to a critical gap. Diverse mixes and configurations of landscape elements affect thermal and emotional sensations differently, with the magnitude of impact varying by season (Yan et al., 2023). Despite its recognised promise to improve environmental quality, seasonal differences in the effectiveness of green infrastructure further complicate its impact, as the cooling benefits of green spaces may vary across different seasons (Liu et al., 2022), necessitating dynamic design strategies that account for temporal fluctuations.

To date, numerous studies have focused on the influence of vegetative cover on outdoor thermal comfort and urban heat, while studies on the impact of outdoor landscapes on indoor comfort remain fragmented. Much of the existing literature has prioritised external microclimatic benefits, sometimes overlooking the crucial interconnection between landscape design and indoor thermal regulation. This gap is particularly evident in tropical regions like Nigeria, where intense solar radiation is predominant, making indoor thermal comfort extremely challenging without mechanical ventilation. Addressing this gap will be crucial for green building optimisation to improve both outdoor and indoor thermal comfort, while enhancing energy efficiency and climate resilience. An integrated approach that considers the effects of outdoor landscapes on internal environmental conditions could significantly elevate the performance and sustainability of tropical buildings.

3. Methods and Materials

3.1. Study Approach

This study adopts a simulation-based comparative approach to investigate how the integration of landscape features, especially trees, lawns and water bodies, affects indoor thermal comfort and energy efficiency in future tropical residential buildings. The use of simulation allows for a consistent and controlled assessment of design interventions that would be financially demanding to test using physical experimental setup. As Lin and Brown (2021) point out, accurately modelling microclimatic interactions can be very challenging; however, focusing on landscape elements that are both measurable and thermally influential provides a pathway for meaningful performance.

3.2. Geographic and Climate Overview of Study Locations

The study was conducted in two locations in Nigeria; Jos and Sokoto. Jos, the capital of Plateau State is located at approximately 9.8965° N, 8.8583° E (Figure 1). It is situated on the Jos Plateau in north-central Nigeria at an altitude of about 1295 meters above sea level (masl), making it one of Nigeria's highest urban settlements. This elevation contributes to its temperate microclimate, characterised by, relatively high precipitation from July to September (204 mm - 238 mm) and an annual mean temperature of between 21°C and 27°C (Figure 2), supporting a verdant environment and making it suitable for diverse landscape configurations. According to Köppen climate classification, Plateau state is classified as AW (Figure 3), a tropical wet and dry or savanna climate, with the driest month having precipitation of less than 60 mm. This is further supported by the eco-climatic map (Figure 1), which classifies Plateau State as predominantly a midaltitude and derived savanna region.

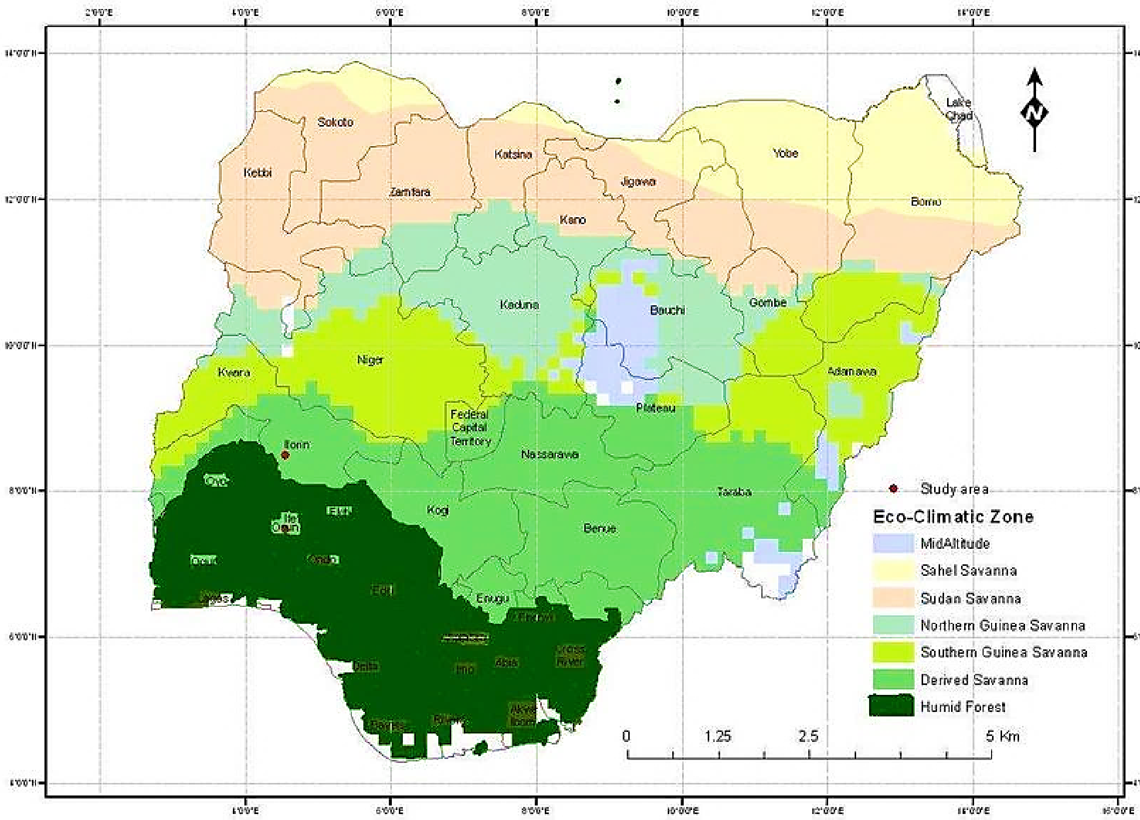

Figure 1 Map of Nigeria showing climatic zones (Source: Maps Nigeria, n.d.)

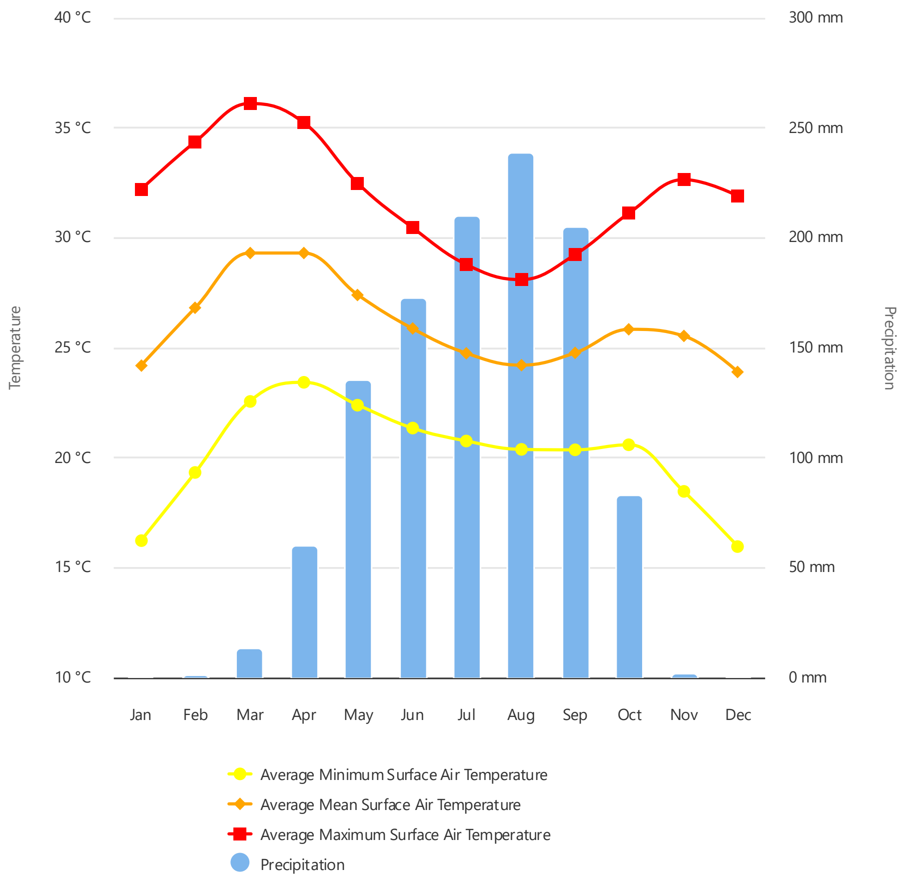

Figure 2 Monthly climatology of air temperature and precipitation 1991-2020 - Plateau, Nigeria (Source: World Bank Group, n.d.)

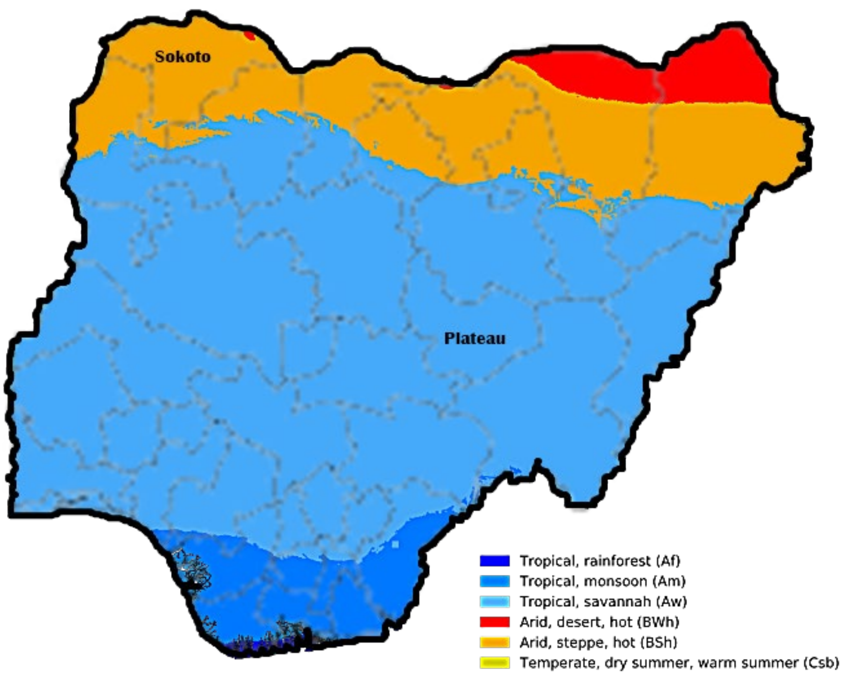

Figure 3 Map showing study locations (Base map retrieved from Beck et al., 2018, modified by authors)

In contrast, Sokoto, the capital of Sokoto state, is located around 13.0059° N, 5.2476° E. It lies within Nigeria's dry Sahelian and Sudan Savanna Zone (Figure 1), typified by an arid (Bsh) climate (Figure 3), sparse vegetation and flat terrain. With average maximum temperature exceeding 40°C

(Figure 4) during peak dry months and rainfall averaging less than 800mm, the environment is markedly harsher and leads to extreme thermal discomfort (Fatima, 2025; Gazettengr, 2025; Olayide, 2025). Urban morphology in Sokoto is compact and utilitarian, shaped historically by adaptive responses to extreme heat, necessitating the use of thick-walled buildings. These climatic and spatial contrasts between Jos and Sokoto present a valuable spectrum for analysing the role of residential garden-based landscape features in improving thermal performance in next-generation housing across different Nigerian climatic contexts.

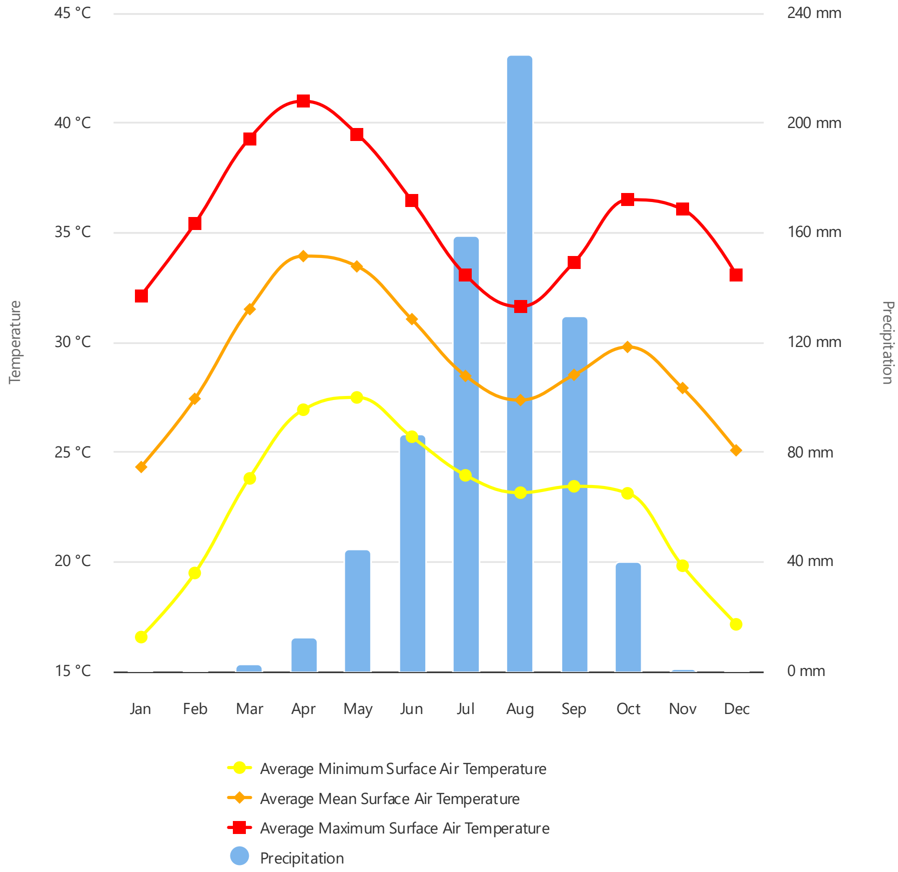

Figure 4 Monthly climatology of air temperature and precipitation 1991-2020- Sokoto, Nigeria (Source: World Bank Group, n.d.)

3.3. Workflow

Stage 1: Building and Landscape Modelling

A hypothetical residential building plan (Figure 5) was modelled incorporating future-proofing strategies suitable for tropical regions. These include enhanced thermal mass, exterior wall insulation, shading devices and strategic window sizing and placement (Figure 6). Landscape elements, such as trees, lawns and a water body, were introduced around the building to simulate their effects on shading and ventilation, forming the basis for subsequent thermal comfort analysis.

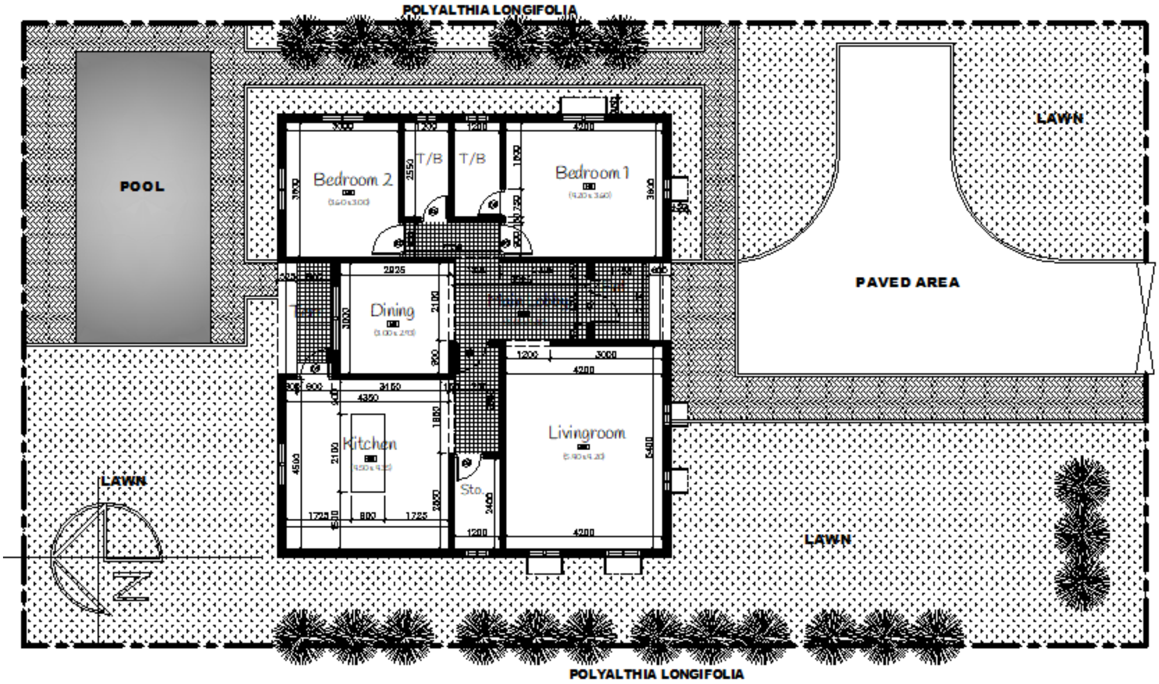

Figure 5 Building and landscape plan

Figure 6 3D view of the hypothetical test building

The building simulations were conducted using EnergyPlus weather data generated using geographical coordinates 9.897° N, 8.858° E, at an elevation of 1295 masl for Jos and 13.006° N, 5.248 ° E, at an elevation of 275 masl for Sokoto. Specific temperature data inputs for the simulations are graphically presented in Figure 7.

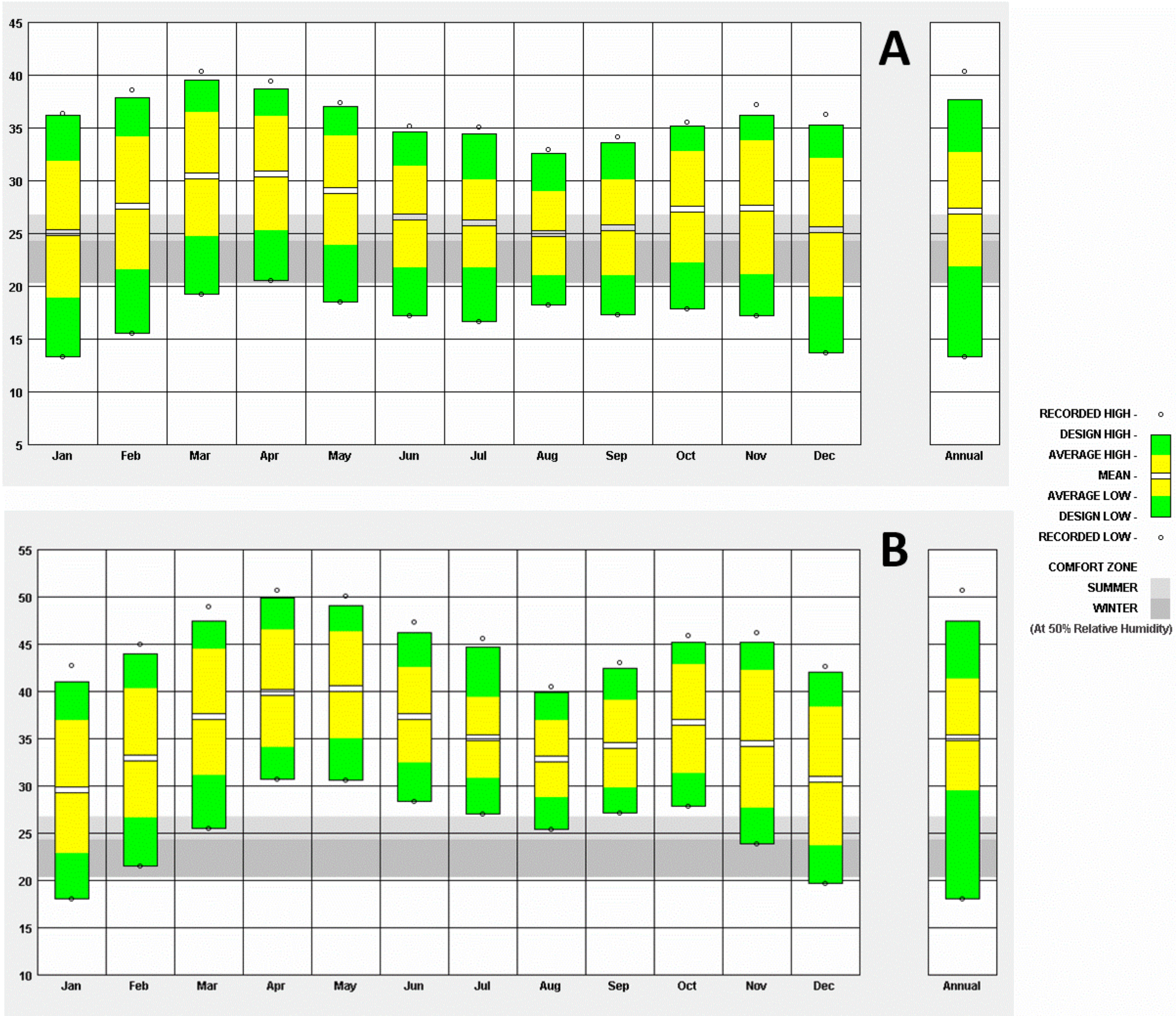

Figure 7 Temperature data for study locations: Jos (A), Sokoto (B). (Source: Climate consultant)

Design strategies such as window shading, thermal mass and evaporative cooling implemented in the design were informed by the adaptive comfort model from the psychrometric charts in Figure 8. The chart shows that cooling is expected to play a more integral role in Sokoto (59%) than in Jos (33%). Additionally, shading of windows is also significant in attaining comfort in these regions as it is needed approximately 33% of annual hours. These charts are integral in determining key strategies, in this case, cooling and shading, to ensure discomfort hours are reduced in the buildings.

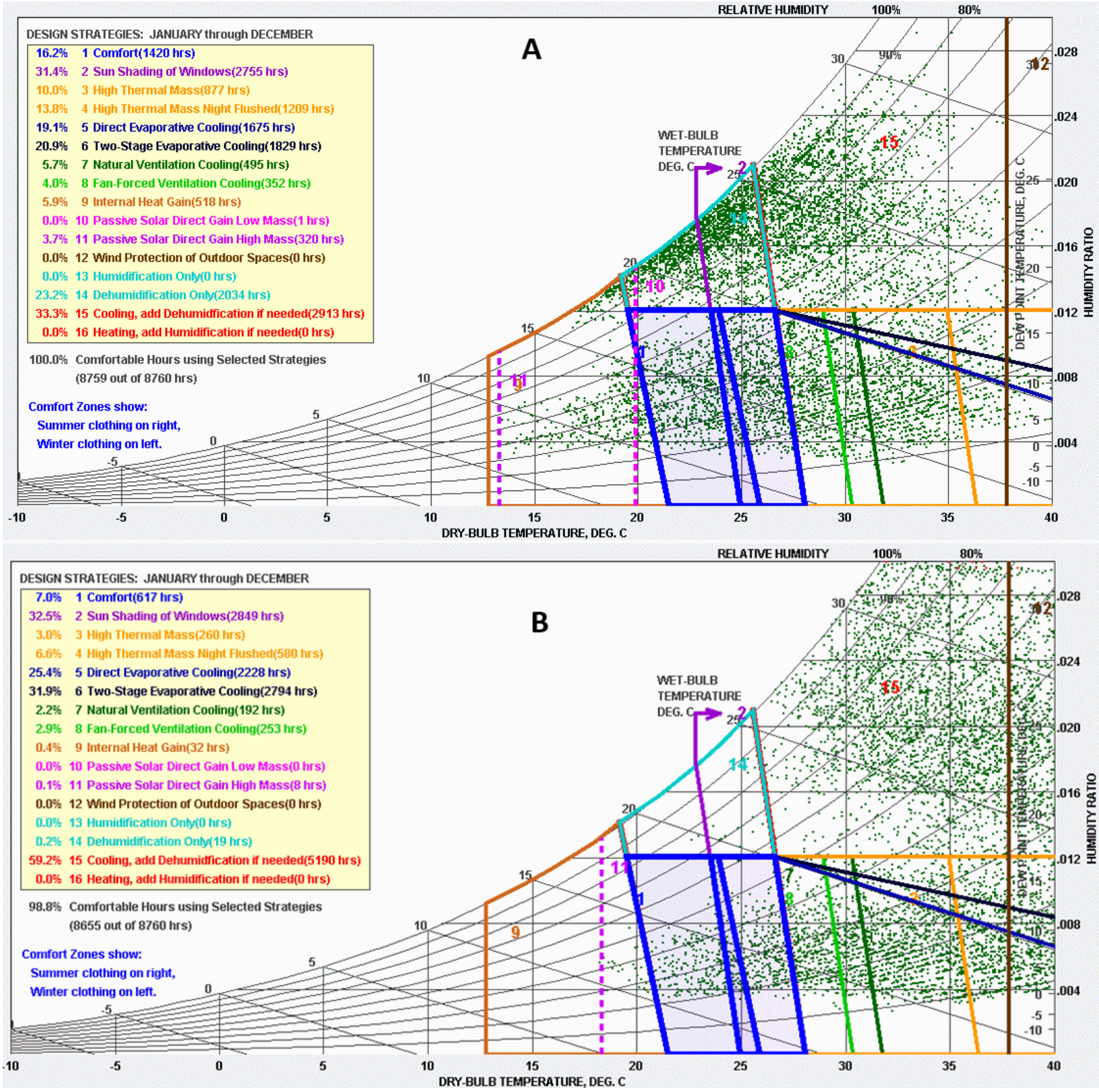

Figure 8 Psychrometric chart showing design strategies for thermal comfort in the locations: Jos (A), Sokoto (B) (Source: Climate consultant)

Stage 2: Landscape Configuration and Optimisation

Different configurations and spatial arrangements of vegetation were simulated to identify the most effective layouts for reducing indoor operative temperatures and minimising energy demands of a building within a 30 m x 15 m residential plot. These configurations were rooted in the spatial constraints of the plot's available setbacks (see Figure 5) and the prevailing South-West wind direction, which informed the strategic positioning of Mast trees (*Monoon longifolium*). The selection and placement of these trees were guided by critical landscape parameters outlined in Table 2, such as thermal conductivity, solar absorptance and canopy height, all of which significantly influence thermal interactions between landscape elements and building surfaces.

The tree's thermal conductivity of 0.2 w/m-k and high solar absorptance of 0.8 suggest that, while the canopy absorbs substantial solar energy, it transmits little heat to adjacent spaces, consequently enhancing its role in passive cooling. Additionally, the specific canopy height of 3.6 m and total height of 5.1 m were calibrated to align with the sun's trajectory during peak temperature periods for the building locations, ensuring maximum shading of east- and west-facing walls. The optimal setback of 2.1 m from the building façade was derived from solar path analysis using the

Curic Sun plugin in Sketchup (Figure 9), which permits precise visualisation of shading overlaps across seasons. These inputs were further validated through DesignBuilder's simulation environment, where exterior temperature and indoor operative temperature were continuously evaluated.

Furthermore, lawn and pool surfaces were considered as complementary landscape elements. The lawn's low conductivity (0.036 W/m-K), moderate density (1050 kg/m³) and specific heat (1850 J/kg-k) made it effective in reducing surface heat re-radiation, thereby regulating near-ground air temperature. In contrast, the pool's higher thermal conductivity (0.6 W/m-K) and remarkably high specific heat (4182 J/kg-K) offered thermal inertia for stabilising microclimate fluctuations during peak solar hours. The absorptance properties of all elements, especially the high visible and solar absorptance (0.95) values for lawn and pool surfaces, influenced radiative interactions within the building's immediate outdoor environment. Initial vegetation layouts were developed in Sketchup using geolocation and solar analysis features to identify effective shading zones across seasonal variations. These insights were later transferred into DesignBuilder for dynamic simulation, where iterative testing of vegetation configurations provided a robust evaluation of the thermal buffering potency of landscape strategies.

Initial vegetation layouts were developed in Sketchup using geolocation and solar analysis features to identify effective shading zones across seasonal variations. These insights were later transferred into DesignBuilder for dynamic simulation, where iterative testing of vegetation configurations provided a robust evaluation of the thermal buffering potency of landscape strategies.

Table 2 Landscape Elements Parameters

Parameters	***Tree***	***Lawn***	***Pool***
Conductivity (w/m-k)	*0.2*	*0.036*	*0.6*
Specific Heat (J/kg-k)	*N/A*	*1850*	*4182*
Density (kg/m³)	*500*	*1050*	*998*
Thermal Absorptance	*0.9*	*0.95*	*0.95*
Solar Absorptance	*0.8*	*0.95*	*0.95*
Visible Absorptance	*0.9*	*0.95*	*0.95*
Canopy Height (m)	*3.6*	*N/A*	*N/A*
Height (m)	*5.1*	*0.15*	*N/A*

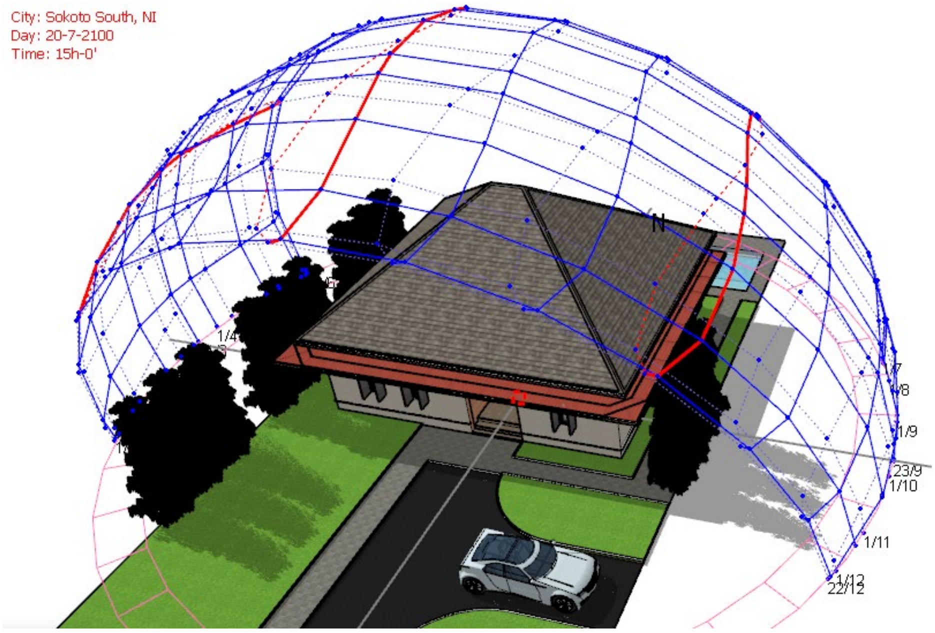

Figure 9 Test building's solar path

Stage 3: Climate-Specific Performance Assessment

The optimised landscaped building configurations were evaluated under the IPCC's extreme climate scenario (RCP8.5-2100) in two distinct locations in Nigeria: Jos, representing a cooler tropical highland climate and Sokoto, representing a hotter, semi-arid region. This comparative analysis seeks to provide insights into how variations in outdoor vegetation impact on indoor thermal performance and energy efficiency in next-generation tropical buildings under future climate conditions.

3.4. Materials and Tools Justification

Previous studies, such as Galal et al. (2020) and Darvish et al., (2021), have employed simulation tools like ENVI-Met for evaluating the environmental performance of vegetation-integrated urban environments. While ENVI-met is effective for broader urban-scale analysis, this study focuses on the building level, necessitating a more tailored simulation approach. DesignBuilder was therefore adopted for its capacity to model dynamic thermal behaviour and energy performance at a detailed building scale.

DesignBuilder's integration with the EnergyPlus engine allows for advanced simulation of passive design strategies and landscape features. Specifically, it supports the incorporation of elements such as shading devices, trees, lawns and pools using Standard and Ground component blocks, making it highly suited for assessing microclimatic interactions on indoor conditions (DesignBuilder, V7.0). To ensure accurate weather inputs, Meteonorm 8 was utilised to generate localised future weather files. The tool synthesises historical meteorological data from a vast network of weather stations and couples it with climate models to provide high-resolution climate projections. The future scenario used in this study aligns with the IPCC's Representative Concentration Pathway (RCP) 8.5 for the year 2100, representing an extreme climate outcome. According to Remund et al. (2020), Meteonorm's method of integrating statistical downscaling with General Circulation Models (GCMs) offers reliable weather data that are tailored to the selected Nigerian locations. Together, these tools permit a robust simulation of how outdoor landscapes can influence building level thermal comfort and energy consumption in extreme tropical climates.

3.5. Future-Proofing Design Strategies

To accurately reflect climate best practices in tropical residential buildings, the hypothetical building model integrates passive design features drawn from contemporary research, particularly the recommendations of Alegbe and Mtaver (2023). These strategies are aimed at reducing heat gains, enhancing indoor comfort and reducing dependency on mechanical cooling systems.

I. **Enhanced Thermal Mass**

The exterior walls were designed with a U-value of 0.517 W/m²·K, achieved through a double-wall assembly composed of concrete hollow blocks and a centrally located insulation cavity. The total thickness of this assembly is 0.35 m. This setup increases the building's thermal inertia, helping to moderate indoor temperature fluctuations by delaying heat transfer through the envelope.

II. **Exterior Wall Insulation**

A 0.05 m thick layer of lightweight Expanded Polystyrene (EPS) insulation was incorporated within the cavity wall. This material minimises conductive heat gain and contributes to maintaining thermal comfort during prolonged exposure to high ambient temperatures.

III. **Window Optimisation**

Window design and placement were tailored to take advantage of the solar orientation and wind direction. Openings on the south and west facades were reduced to 1.20 m x 0.60 m to limit solar heat gain, while those on the north and east sides were extended to 1.20 m x 1.20 m to enhance cross-ventilation potential. This asymmetrical window strategy promotes natural ventilation while managing solar ingress.

IV. **Shading Devices**

Horizontal shading projections of 1.20 m were introduced along the southern, eastern and western facades to obstruct direct solar radiation during peak periods. In addition, rooms with exposed windows on these facades feature 0.5 m vertical side fins and overhangs to further minimise solar penetration and glare. These passive shading elements are incorporated to reduce cooling loads by shielding critical envelope areas from excessive heat gain.

4. Results

The simulation results demonstrate the significant role of outdoor landscape in regulating solar gains, enhancing indoor thermal comfort and influencing energy consumption in residential buildings. A summary of the key outcomes is presented in Table 3. The findings indicate that the impact of landscape features on indoor comfort is highly influenced by the orientation of interior spaces. For example, in both Jos and Sokoto, spaces facing the north, such as Bedroom 2, the Dining area and the Kitchen, exhibited improved indoor temperature performance even in the absence of shading devices. In contrast, rooms with shading devices (e.g., roof overhangs and window fins) but oriented toward the south and west experienced higher indoor temperatures, suggesting the compounded influence of orientation and solar exposure.

Moreover, the performance of landscaped buildings varied greatly between the two locations. The cooler climate of Jos demonstrated a more moderate improvement in thermal comfort compared to Sokoto, where the semi-arid conditions amplified the benefits of landscaping. This location-specific variability aligns with the findings of Ko (2018), Meili et al. (2021) and Liu et al. (2022), who emphasise the specificity of landscape-induced thermal environments to different climatic regions. It is important to note that the recorded energy consumption remained constant across the simulated buildings before the introduction of active cooling systems. This is primarily due to the lighting fixtures, for which the energy load was already accounted, as no mechanical cooling or heating was applied during that phase of the simulation process.

Table 3 Results of Evaluated Metrics across Study Locations

Evaluated Metrics	*Sokoto*			*Jos*		
	No Landscape	*Landscaped*	*Landscaped and Cooling*	*No Landscape*	*Landscaped*	*Landscaped and Cooling*
Operative Temperature – Coldest Month (°C)	34.62	33.95	29.51	32.13	31.44	28.25
Operative Temperature – Hottest Month (°C)	43.46	42.45	32.78	36.70	35.85	30.59
Mean Annual Operative Temperature (°C)	39.40	38.53	31.60	33.97	33.16	29.02
Solar Gain Through Windows (Wh/m² x 10³)	74.91	35.84	35.84	72.29	34.81	34.81
Bedroom 1 – Operative Temperature (Hours Above 32°C)	8619.50	8584.50	3690.50	6552.00	5980.50	605.00
Bedroom 2 – Operative Temperature (Hours Above 32°C)	8595.00	8461.50	3632.50	6794.50	5596.50	525.00
Dining – Operative Temperature (Hours Above 32°C)	8705.50	8614.50	2829.00	7800.00	6575.50	606.00
Kitchen – Operative Temperature (Hours Above 32°C)	8581.00	8477.50	3169.00	6555.00	5686.50	563.50
Livingroom – Operative Temperature (Hours Above 32°C)	8606.00	8577.00	3498.50	6507.50	6090.50	745.50
Energy per Total Building Area (Kwh/m²)	118.28	118.28	228.89	118.28	118.28	194.85
Energy per Conditioned Area (Kwh/m²)	N/A	N/A	539.37	N/A	N/A	459.17
Cooling Energy (Kwh/m²)	N/A	N/A	260.64	N/A	N/A	180.43

5. Discussions

Influence of Landscape Features on Thermal Performance

Results from the simulations affirm the pivotal role of landscape interventions, particularly vegetation, in modulating and enhancing the indoor thermal environment of residential buildings in the tropics. Both locations, Sokoto and Jos, exhibited measurable improvements in thermal conditions due to landscape features, though the magnitude of the impact varied by location. Notably, by simply introducing lawns, solar gains through window openings were reduced by up to 14%, owing to their high reflectivity and low thermal mass, which helped moderate ground-level heat re-radiation. This aligns with the literature that underscores the role of surface albedo and ground treatment in lowering surface temperatures. More significantly, the inclusion of trees, specifically, Mast trees (*Monoon longifolium*), led to reductions in solar gains by up to 52%. This substantial decline highlights the effectiveness of tree canopies in reflecting direct solar radiation, while their transpiration processes also contribute to localised cooling effects, as supported by prior studies such as Yang et al. (2018) and Morakinyo et al. (2018). These biophysical interactions between vegetative elements and their microclimate environments reinforce the argument for green infrastructure as a vital passive strategy in hot climates.

However, the influence of landscape was not uniformly effective across the locations. In Jos, interior spaces oriented towards the north, namely the Dining, Kitchen and Bedroom 2, exhibited a notable reduction in discomfort hours by up to 17.6%, despite lacking direct shading interventions. This substantial improvement in indoor thermal comfort supports the findings of Darvish et al. (2021), who observed similar reductions attributed to tree-induced comfort. The observed enhancement may also be partly attributed to the favourable solar angles in northern orientations, which naturally receive less direct sunlight in tropical latitudes. In contrast, Sokoto, a hotter and more extreme climate, yielded minimal improvements in comparable spaces, with reductions in discomfort hours falling below 2% (Figure 10). This disparity demonstrates the sensitivity of landscape performance to both building orientation and regional climatic conditions, as opined by Liu et al. (2022). Furthermore, the reduction in mean annual operative temperature achieved solely through landscape was relatively modest, with 2.2% and 2.4% decreases observed for Sokoto and Jos, respectively. Although these shifts appear statistically minor, they can play a critical role in nudging thermally marginal indoor environments towards adaptive comfort thresholds, especially when reinforced with complementary passive design measures. These findings reinforce the potential of integrated landscape elements to act as a thermal buffer by intercepting and diffusing solar radiation before it reaches the building façade. This reduces heat conduction through the building envelope and mitigates the thermal load on internal spaces, which is critical in regions like Sokoto, where intense solar exposure is prevalent year-round.

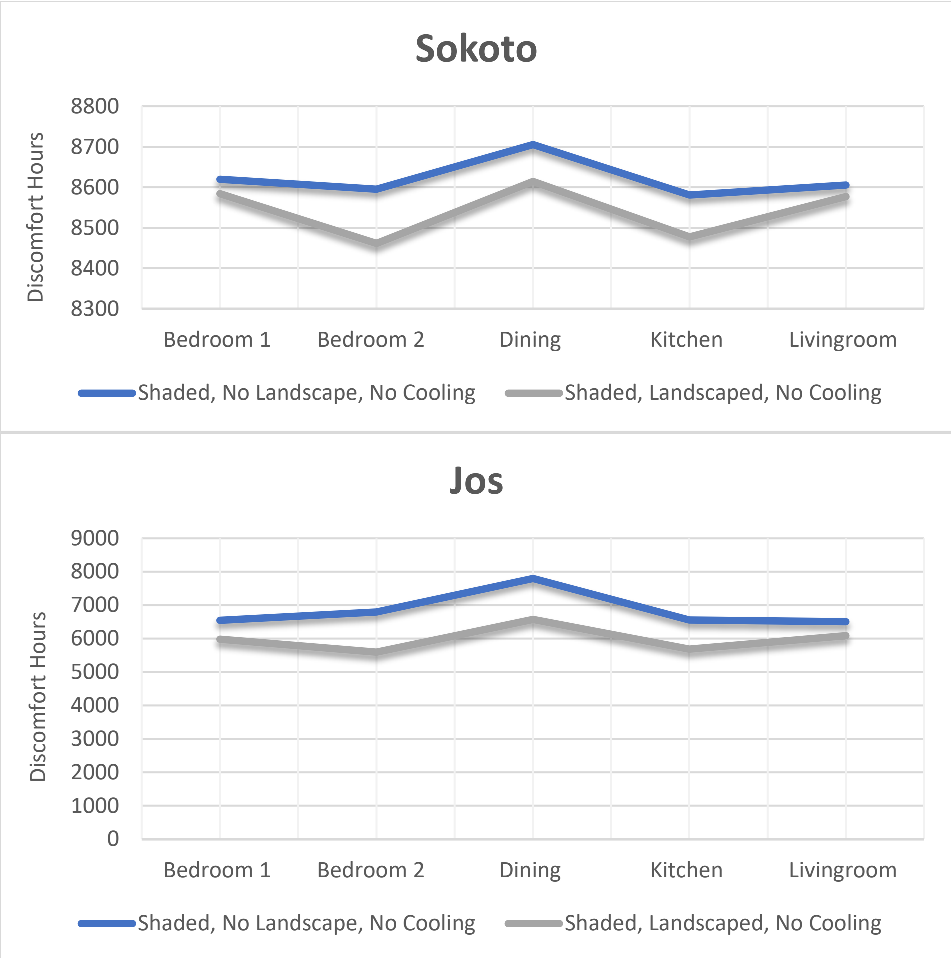

Figure 10 Impact of landscape on thermal discomfort in building spaces across the locations

Landscape and Mechanical Cooling in Future Climates

Despite the growing benefits of landscaping buildings, the results revealed that natural and passive cooling strategies alone cannot guarantee thermal comfort, particularly in the face of projected climate extremes. As observed during the hottest months; May in Sokoto (43.46°C) and April in Jos (36.7°C), outdoor temperatures surpassed the effectiveness limits of natural ventilation and vegetation-induced cooling. These extreme conditions suggest a climatic threshold beyond which passive strategies become thermally insufficient. Moreover, without mechanical intervention, indoor operative temperatures remained remarkably high for comfort, emphasising that passive-only approaches could result in significant heat stress for occupants in these climates. This supports prior assertions that, under extreme climate projections, reliance on passive strategies alone may expose vulnerable occupants to health risks linked to overheating.

However, when mechanical cooling was introduced in a mixed-mode approach (natural ventilation supplemented by scheduled air conditioning), the reduction in discomfort hours was substantial: up to 68% in Sokoto and 92% in Jos (Figure 11). These results are particularly significant for Next-G housing in tropical climates, noting that while passive landscape interventions can alleviate thermal loads, mechanical systems will remain indispensable for ensuring occupant well-being under future climate conditions. Notwithstanding, the reliance on active systems introduces a paradox, where energy consumption rose sharply for indoor comfort to be attained. Buildings without mechanical cooling had an energy use of 118.2 kWh/m², whereas, with mechanical cooling enabled, energy demand increased by 48% across the building area and 78% in conditioned spaces for the building in Sokoto. In Jos, the energy per total building area and conditioned spaces increased by 39% and 74% respectively. These surges in energy requirements across the building locations represent a critical trade-off between thermal comfort and sustainability, necessitating the need for more energy-efficient cooling technologies or adaptive control mechanisms.

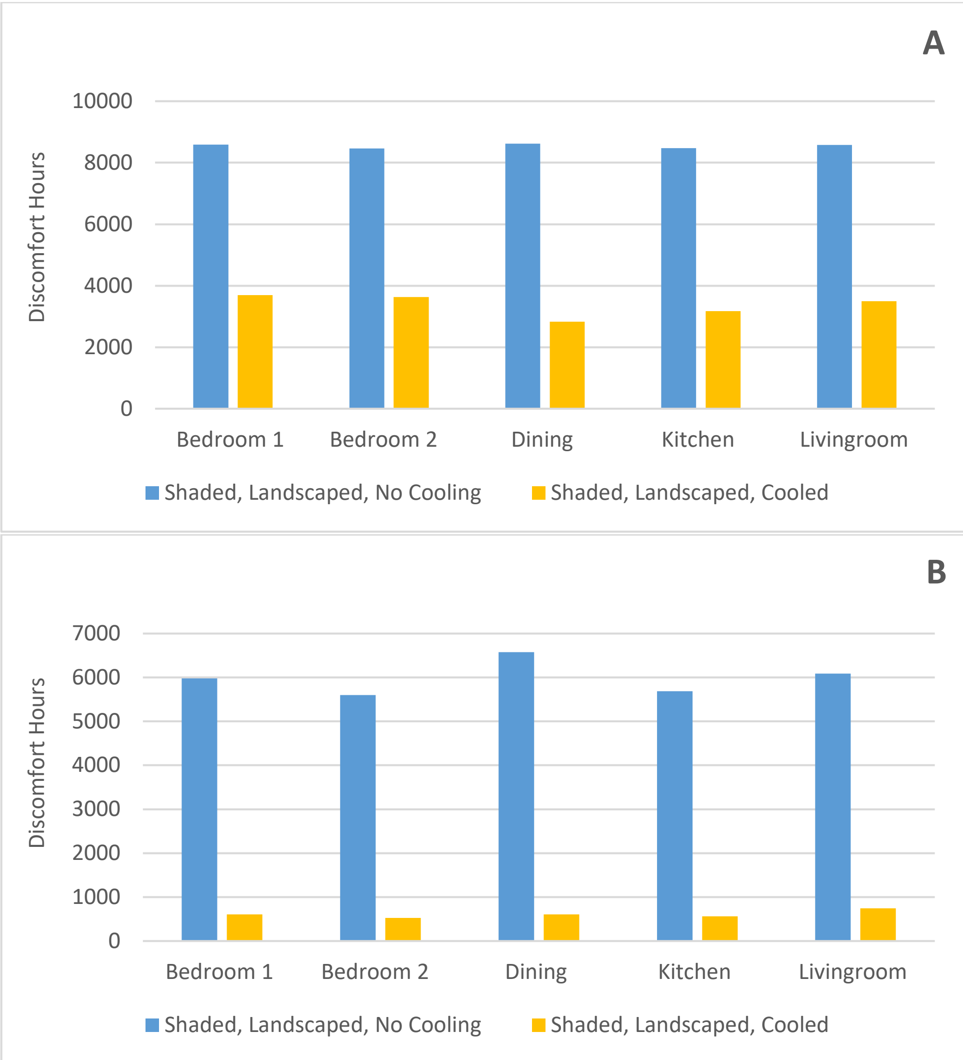

Figure 11 Cooling and landscape impacts on thermal discomfort: (A) Sokoto, (B) Jos

Furthermore, cooling energy demand alone accounts for up to 48% of total energy demand. Jos, despite its current classification as a colder region, exhibited a competing cooling energy demand, compared to the hot climate of Sokoto. This finding supports emerging evidence, including studies by Alegbe and Mtaver (2023), that climate zones such as Bauchi and Jos in Nigeria, traditionally perceived as 'colder' will experience the steepest increase in cooling energy in the future due to shifting climate classifications propelled by extreme warming. Such evolving climatic realities underscore the limitations of historical climate zoning in predicting future performance of buildings. However, in design spaces, as depicted in Figure 12, there were significant differences between observed discomfort hours at the two locations, yielding a percentage variation of between 78.6% (Dining) and 85.6% (Bedroom 2). This challenges conventional design assumptions, and buttresses the exigency of adaptive, future-proofing design approaches tailored to specific regional climate data. Without integrating these future-oriented projections into design frameworks, buildings risk becoming obsolete or thermally dysfunctional over time.

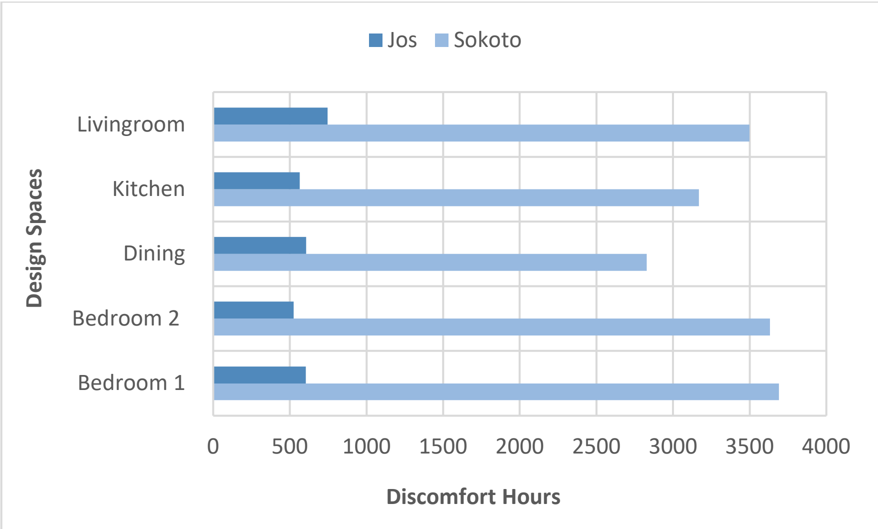

Figure 12 Discomfort hours comparison of landscaped buildings across the locations

6. Conclusion and Recommendations

Conclusion

This study evaluated the influence of landscape features such as trees, lawns and water bodies on the thermal and energy performance of next-generation (Next-G) buildings using a hypothetical residential building in two contrasting Nigerian climates: Sokoto (hot-dry) and Jos (temperate). Dynamic thermal simulations in DesignBuilder were used to assess the variations in impacts across the locations. The study revealed that the inclusion of landscape elements significantly influenced indoor operative temperatures, discomfort hours and energy consumption patterns. In both locations, landscape interventions contributed to a measurable reduction in operative temperatures. Mean annual operative temperature was reduced by up to 2.4% when landscape features were introduced to the building. During the hottest months, peak indoor temperature was reduced by about 2.3%. The effect of landscape on discomfort hours was more pronounced. As observed in the naturally ventilated buildings, discomfort hours reduced by up to 15.8% in Jos.

However, passive landscaping alone was insufficient for attaining the desired indoor comfort range, necessitating the inclusion of mechanical cooling in a mixed-mode setup. With this integrated cooling, discomfort hours significantly reduced by up to 92% in Jos and 68% in Sokoto. These achievements were accompanied by a steep upsurge in energy use per building area, increasing by 48% (118.28 to 228.89 kWh/m²) in Sokoto and by 39% (118.28 to 194.85 kWh/m²) in Jos. In conditioned spaces, the increase was more dramatic, with an observed surge of up to 78% in Sokoto. Moreover, cooling energy alone accounted for 48.3% of total building energy use in Sokoto and approximately 40% in Jos, suggesting that future cooling loads will be substantial, even in regions traditionally considered temperate. This finding challenges the adequacy of relying on passive strategies in tropical contexts, while supporting emerging projections that subtropical zones like Jos will face increased cooling burdens due to climate shifts.

The study confirms that while landscape features can substantially mitigate heat stress and discomfort hours in tropical homes, they cannot independently guarantee indoor comfort under future climate extremes. Consequently, mechanical systems will remain indispensable, but their use must be optimised to avoid excessive energy demand. The integration of landscape and mechanical systems, tailored to local climatic conditions, emerges as an integral pathway for future-proofing Next-G residential buildings in the tropics.

Recommendations

Translating the insights from this study into feasible action requires a multidimensional approach that acknowledges both the technical effectiveness of green landscape features, socio-political and institutional mechanisms to enable their implementation. To ensure future homes in tropical climates, particularly in Nigeria, are truly future-proof, both design practices and policy instruments must evolve in tandem. The recommendations presented below call for a change in basic assumptions about how buildings are conceived, approved and managed in Nigeria's urban and peri-urban contexts, to ensure that the findings of this study can be meaningfully translated into resilient, real-world applications.

I. Integrating Landscape at the Design Stage

A key recommendation is the thoughtful integration of landscape design during the early planning and design stages of building projects. For its effectiveness, it must be upheld as a professional responsibility, enforced by the architect's regulatory body. This measure would ensure that vegetation and green infrastructure are not treated as aesthetic afterthoughts but as integral components of thermal comfort and climate responsiveness. When implemented in unison with building form, orientation and fabric material selection, landscape elements, such as trees, lawns and shrubs can significantly enhance passive cooling and reduce dependence on mechanical systems. To further institutionalise this approach, the submission of a detailed landscape plan should form part of the mandatory building permit application documents. Planning authorities must ensure that projects are evaluated for their ecological performance, while site-level execution must be actively monitored by concerned agencies to ensure that implementation of landscape design does not end on paper.

II. Toward Hybrid Passive-Active Climate Strategies

In the context of the climate crisis, it is no longer enough to rely on passive or active design solutions in isolation. A hybrid approach that combines green landscaping strategies with renewable cooling and ventilation systems is extremely critical. This must be done in a complementary and not competitive manner. For instance, vegetation can be used to shade outdoor spaces to reduce building envelope heat gain during the day, operable windows or ventilated courtyards framed by trees can enable night-time flushing of heat, while energy-efficient systems provide backup during peak thermal discomfort periods. This integrated model should inform future building codes and urban development frameworks.

III. Redefining Climatic Zones and Building Regulations

The current climatic classifications used in Nigeria's planning and building policies are broad and insufficiently nuanced. To guide meaningful low-carbon design responses, a redefinition of climate zones that reflect recent and projected climate realities, including urban heat island effects and microclimate variations across regions, is indispensable. Building regulations should be updated to align with this revised climate classification, with emphasis on green infrastructure, especially in regions where it is most needed. These updated regulations must clearly articulate landscape planning as a performance-based requirement, not merely a decorative element, particularly in housing projects that target low-income and vulnerable populations.

IV. Government Incentives and Local Capacity Building

To support the widespread adoption of these strategies, governments at all levels must provide enabling incentives. These could include subsidised access to ingenious tree species, grants for the installation of water-efficient irrigation systems and reduced development levies for projects that meet defined thermal comfort benchmarks through landscape-based design. To be effective, such incentives must be supported by capacity-building initiatives. Community nurseries and grassroots training programmes should be established to empower residents to plant, maintain and propagate vegetation. Doing so would advance environmental goals, social and economic development by providing green jobs and promoting environmental stewardship at the community level.

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CRediT Authorship Contribution Statement

Mark Alegbe: Conceptualisation, methodology, simulation and results interpretation, writing – original draft preparation. Laurence Chukwuemeka: Supervision, critical review and editing. John Lekwauwa Kalu: Data curation, validation and visualisation. Hammed Nasiru: Literature review and writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing monetary interests or personal relationships that could have influenced the work reported in this paper.

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Data Availability

The data that support the findings of this work are available from the corresponding author upon reasonable request.

Ethics Committee Approval

Approval from an ethics committee was not required for this research.

Resume

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Artificial intelligence in construction project management: Trends, challenges and future directions

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Abstract

Contemporary construction projects are characterized by escalating complexity, voluminous data flows, and stringent sustainability requirements, rendering conventional project management methods increasingly inadequate. In response, artificial intelligence (AI) has emerged as a transformative enabler in construction project management, offering advanced capabilities in predictive analytics, process automation, and intelligent decision support. This paper explores the role of AI in the identified principal functions of construction project management, including time management, cost estimation, quality assurance, occupational health and safety, risk mitigation, resource optimization, and design management through a narrative literature review. Analysis demonstrates that AI-driven approaches significantly enhance operational efficiency and system resilience by enabling proactive identification of schedule delays, cost overruns, and safety hazards. For example, image-recognition systems integrated with Internet-of-Things sensors facilitate real-time monitoring of site conditions and adaptive response to disruptions, while neural-network models trained on historical project data yield more accurate cost forecasts than traditional estimation techniques. In the design management domain, generative design algorithms and AI-enhanced BIM integration have the potential to automate clash detection, optimize form and function, and generate innovative design alternatives that align with cost, energy, and sustainability objectives. Beyond efficiency gains, AI fosters a paradigm shift toward predictive, data-driven, and adaptive management practices that strengthen project resilience, enabling teams to anticipate, absorb, and recover from unforeseen challenges while improving project performance and sustainability. Critical barriers to widespread AI adoption are also identified in this study. Fragmented and non-standardized data ecosystems impede model training and interoperability with legacy systems, while organizational resistance and a shortage of professionals skilled in both AI and construction hinder implementation. Ethical and legal concerns—stemming from the "black-box" nature of many AI algorithms—further complicate accountability in safety-critical decisions. By synthesizing these challenges, the strategic role of AI is highlighted not only as a technological innovation but also as a catalyst for cultural and organizational transformation toward more resilient project delivery. Targeted future research directions include empirical validation of AI tools in live project environments, development of sector-specific AI frameworks tailored to the peculiarities of the construction industry, interdisciplinary collaboration among engineers, data scientists, and managers, and educational initiatives to upskill the workforce. Collectively, these steps will help bridge the gap between theoretical potential and real-world impact, positioning AI as a cornerstone of intelligent, resilient, sustainable, and high-performing construction project management.

Keywords: artificial intelligence, construction project management, digital transformation in construction, smart construction technologies

1. Introduction

Construction projects are inherently complex, involving multiple stakeholders, dynamic environmental conditions, and significant uncertainty across design, execution, and handover phases. Traditional project management approaches—largely heuristic and siloed—struggle to process the growing volumes of data generated by modern Building Information Models (BIM), IoT sensors, and digital records. In response, artificial intelligence (AI) offers transformative capabilities in predictive analytics, process automation, and intelligent decision support. While prior studies

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highlight isolated technical applications—such as computer vision for safety monitoring or neural networks for cost estimation—there is a lack of holistic, function-oriented reviews that map AI across core construction project management domains.

This study fills that gap by conducting a structured narrative literature review to: (1) identify current and emerging AI applications in core domains such as planning, cost control, quality assurance, safety, risk mitigation, resource optimization, organizational learning, information management, design, and sustainability; (2) evaluate the technical and organizational challenges hindering adoption; and (3) propose strategic implications and future research directions. By aligning findings with the PMBOK (Project Management Body of Knowledge) framework, it provides both academic insight and a practical roadmap for integrating AI solutions into real-world construction project management and elucidates the strategic role of AI in advancing the efficiency, resilience, and sustainability of construction project management.

2. Background

2.1. Artificial Intelligence (AI)

Artificial intelligence (AI) refers to machines performing tasks that require human-like cognitive functions—perception, learning, reasoning, and decision-making (Russell & Norvig, 2009). Early AI research in the mid-20th century explored symbolic reasoning, search algorithms, and knowledge representation, but high expectations led to an "AI winter" of reduced funding until advances in algorithms and hardware reignited interest (Russell & Norvig, 2009; Clark, 2015). The advent of big data—massive, high-velocity, high-variety datasets—proved a catalyst for modern AI, as machine learning (ML) and deep learning (DL) algorithms outperformed traditional statistics in pattern detection and prediction (Schneeweiss, 2014; Allam & Dhunny, 2019).

AI is typically categorized by scope and capability. Today's deployed systems are Artificial Narrow Intelligence (ANI)—domain-specific tools that outperform humans on narrowly defined tasks such as image recognition or NLP. Artificial General Intelligence (AGI) remains theoretical, promising human-level cognitive adaptability and reasoning across tasks, while Artificial Superintelligence (ASI) is a speculative future stage exceeding human creativity and wisdom (Microsoft, n.d.). Beyond scope, AI spans a competency spectrum: Analytical AI handles data interpretation and inference, Human-inspired AI adds emotional intelligence, and Humanized AI aspires toward self-awareness (Kaplan & Haenlein, 2019).

Core AI research addresses reasoning under uncertainty, planning, perception, and learning from data (Luger, 2004). These advances have produced daily life tools like virtual assistants, recommendation engines, autonomous vehicles, and diagnostic tools. In industry—particularly logistics, energy, finance, and construction—AI promises efficiency gains, cost savings, and enhanced decision support by transforming raw data into actionable insights (Kowalski et al., 2012). In this study, AI methods—such as neural networks, computer vision, NLP, generative design—that directly impact key construction project management domains were focused.

2.2. Construction Project Management

Construction projects are inherently complex socio-technical systems, requiring the coordination of design, planning, execution, monitoring, and handover under uncertainty. Traditional methods—often siloed, heuristic, and reactive—struggle with today's scale, data volume, and sustainability demands (PMI, 2017; Walker, 2015). AI offers a transformative alternative by converting large, heterogeneous datasets (e.g., BIM models, IoT sensor streams, historical project records) into predictive insights and automated processes.

Key AI benefits in construction project management include proactive risk identification, optimized scheduling, dynamic resource allocation, and real-time quality and safety monitoring. For example, machine-learning models trained on past project data can predict cost overruns and delay risks before they materialize, while computer-vision systems analyze site images to detect safety hazards and quality defects instantaneously (Ekanayake et al., 2024; Lee & Lee, 2023). By integrating AI with legacy BIM and ERP platforms, teams can automate clash detection, perform generative design explorations, and simulate environmental impacts—thereby enhancing both efficiency and resilience.

Despite this promise, the sector's digital maturity remains low and AI in construction remains an underexplored area. Fragmented data architectures, interoperability issues, limited AI expertise, and organizational inertia continue to slow adoption (Toor & Ogunlana, 2010; Bang & Olsson, 2022). Addressing these barriers through standardized data protocols, interdisciplinary training, and executive buy-in is critical to realizing AI's full potential in construction project management.

3. Methodology

The study employs a structured narrative literature review approach with thematic analysis. Unlike a full systematic review protocol (e.g., PRISMA), this method balances rigor and flexibility, allowing thematic depth while ensuring transparency in selection and coding. Although it is particularly effective in emerging fields such as AI in construction project management to synthesize broad and multidisciplinary insights; the study is subject to certain limitations: reliance on secondary sources may exclude recent innovations not yet reflected in published literature, and the rapidly evolving nature of AI technologies may render some findings outdated over time.

A structured yet flexible review process was implemented to identify, evaluate, and interpret relevant studies, with the goal of answering the following research questions: (1) What are the emerging and current applications of AI in core construction project management domains, (2) What technical and organizational challenges hinder AI adoption, and (3) What are the future research and practice directions to maximize AI's impact.

A comprehensive search was conducted across major academic databases, including Scopus, Web of Science, IEEE Xplore, ScienceDirect, and Google Scholar, covering peer-reviewed journal articles, conference proceedings, and industry reports published between 2000 and 2025. Search queries included combinations of keywords as artificial intelligence, construction project management, project management, construction, digital transformation, smart construction, and AI in construction.

Inclusion criteria were: (1) Publications written in English, (2) Studies that explicitly address AI applications in construction project management, and (3) Articles providing empirical evidence, conceptual frameworks, case studies, or reviews. Exclusion criteria included: (1) Studies unrelated to the construction industry, (2) Articles focusing solely on generic AI applications without contextual relevance, and (3) Publications lacking methodological transparency or peer review.

A thematic analysis was conducted using inductive open coding. Eligible studies were manually coded, and codes were iteratively clustered into themes corresponding to project management functions based on their frequency and conceptual relevance. The thematic framework was guided by the PMBOK to ensure alignment with established domains of construction project management. Multiple readings and comparative analysis were employed to ensure consistency and to refine emergent categories. The synthesis of trends, recurring challenges, and practical use cases aimed to evaluate both the maturity and practical relevance of AI applications in the field. The flow diagram of the study can be briefly seen in Figure 1.

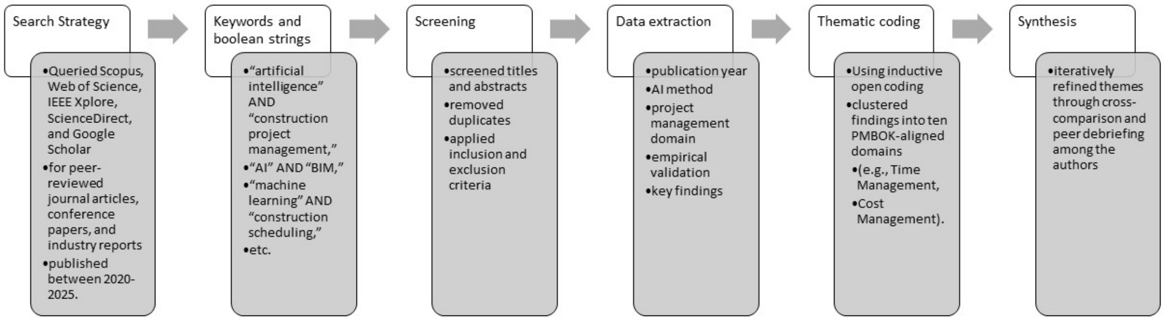

Figure 1 The flow diagram of the study

4. Findings

4.1. Artificial Intelligence in Construction Project Management

The construction sector's complexity, voluminous data flows, and uncertainty make it ripe for AI's pattern recognition, predictive analytics, and automation capabilities. Across planning, monitoring, and control, AI methods—machine learning, computer vision, and NLP—have the potential to contribute to decision-making, proactive delay forecasting, cost and quality alerts, and safety hazard detection, shifting the field from reactive heuristics to data-driven decision support and increasing efficiency across all phases of the project life cycle (Eadie et al., 2013; Bang & Olsson, 2022; Aladağ et al., 2024; Adebayo et al., 2025).

The potential application areas of AI in construction projects are extensive. In particular, AI-supported systems are being applied in critical areas such as scheduling and planning, resource management, cost estimation, quality control, and occupational health and safety. These systems accelerate decision-making processes and reduce the margin of error. For example, Lee and Lee (2023) developed deep learning-based models that detect unsafe behavior and PPE non-compliance in real time using computer vision. Such applications illustrate how AI not only augments on-site monitoring but also enhances overall project control. Moreover, machine learning algorithms trained on historical project data can predict project delays or cost overruns in advance, enabling project managers to take proactive measures. Furthermore, AI technologies such as image recognition, natural language processing, and autonomous equipment can be effectively utilized to enhance safety on construction sites, analyze real-time on-site conditions, and monitor workforce performance.

AI is often confused with automation in project management, but they are distinct. Automation executes predefined, structured tasks based on human-set rules. It has served many project management needs until recently. However, as workflows grow in complexity and data volume expands, automation alone is no longer sufficient. AI systems differ by learning from data, adapting over time, and making decisions without explicit programming (Riter, 2019). In project management, AI evolves from simple task automation to integrated systems that can coordinate teams, suggest process improvements, and make autonomous decisions (Burger, 2017). This shift positions AI as a transformative force—not just a tool—capable of advancing sustainability, safety, planning, risk analysis, cost control, and strategic oversight in construction project management (Bang & Olsson, 2022).

Originally conceptualized in the mid-20th century, AI long failed to meet expectations until recent advances in technology, big data, and machine learning significantly accelerated its development. AI is now seen as a potentially transformative tool for solving persistent problems in the construction industry, such as design errors, delays, inefficiencies, and occupational risks. Its ability to process large volumes of project data, support decision-making, improve cost and quality control, automate repetitive tasks, and enable real-time monitoring highlights its potential. By offering predictive analytics that help project managers optimize resources, manage risks, and enhance project performance, AI is expected to significantly improve productivity, safety, and sustainability in construction. As data volumes in the sector continue to grow, the use of AI will become more widespread, and this technology is poised to become an indispensable tool for successful project management in the future (Aladağ et al., 2024). Tian et al. (2025) further confirm this potential through a bibliometric review, highlighting that AI supports proactive risk mitigation across cost, schedule, safety, and quality domains.

Nonetheless, the integration of AI applications into project management is not merely a technical transformation but also entails a managerial and cultural shift. For successful integration, it is crucial to raise industry professionals' awareness of AI technologies and enhance their digital competencies. Hence, fully benefiting from AI is directly related not only to technological infrastructure but also to the human factor.

Despite its growing promise, the adoption of artificial intelligence (AI) in construction project management faces several critical challenges that hinder its widespread implementation. The adoption of AI applications continues to face challenges such as high implementation costs, a shortage of skilled personnel, data security concerns, and resistance stemming from the industry's traditionally conservative structure (Sacks et al., 2020). One of the foremost barriers is the lack of high-quality, structured, and standardized data, which is essential for training effective AI models but is often fragmented and inconsistent across platforms in construction projects (Khosrowshahi & Arayici, 2012). Moreover, the inherently complex and project-based nature of construction—with its site-specific variables, dynamic workflows, and non-repetitive processes—makes it difficult to generalize or transfer AI models across different projects or contexts. Technological fragmentation and interoperability issues between AI tools and legacy systems, such as Building Information Modeling (BIM) or Enterprise Resource Planning (ERP), also complicate integration efforts (Bilal et al., 2016). Compounding these issues is the shortage of professionals with dual expertise in both AI and construction, which limits practical deployment and innovation.

Furthermore, organizational resistance to change, particularly in firms rooted in traditional project management practices, poses a cultural barrier to adoption, often exacerbated by concerns over automation-induced job displacement (Perera et al., 2020). AI's "black-box" nature, especially in complex decision-making processes, introduces ethical and legal uncertainties surrounding accountability and liability—challenges that are particularly significant in a risk-averse industry like construction (Bai et al., 2020). The absence of standardized benchmarks and publicly available datasets also makes it difficult to validate AI models, limiting transparency and slowing industry trust. Additionally, real-time data collection, essential for many AI applications, raises cybersecurity and data privacy concerns, especially when sensitive project information is shared across cloud-based platforms.

A further challenge lies in the trust dynamic between human decision-makers and AI systems. Even when AI generates accurate recommendations, construction professionals may hesitate to act on them without clear interpretability or user-friendly interfaces. Lastly, the gap between academic innovation and real-world implementation persists, as many AI tools are developed under controlled conditions and lack robust testing in complex, real-world environments. These multifaceted challenges underline the need for industry-wide collaboration, regulatory clarity, improved data infrastructure, and a cultural shift toward embracing data-driven innovation in construction project management and addressing them is essential for realizing the full potential of AI in enhancing efficiency, sustainability, and decision-making in construction project management.

4.2. Key Application Areas of Artificial Intelligence in Construction Project Management

Similar to the construction industry's traditionally slow adaptation to technological advancements, project management as a discipline has also been relatively slow in adopting machine learning and artificial intelligence (AI) technologies (Burger, 2017). However, as the use of AI expands across other industries, its application in construction project management continues to gain traction. In particular, advancements in technology, the emergence of the big data paradigm, and the increasing complexity and scale of contemporary construction projects underscore the necessity of AI implementation in project management. Critical reviews in projects underscore not only the potential of AI for monitoring and control but also the pressing requirement for ethical use, standardized datasets, and explainable systems (Chen et al., 2025).

AI technologies have the potential to transform not only technical processes but also decision-making mechanisms, project management strategies, and on-site operations. Artificial intelligence can be employed throughout the entire project life cycle, contributing to areas ranging from design optimization and resource planning to risk analysis, quality control, and even building life cycle assessments (Akinosho et al., 2020). At a broader level, recent reviews emphasize that AI adoption in project management is contingent on explainable, trustworthy AI systems, clear data governance, and alignment with human decision-making norms (Salimimoghadam et al., 2025).

Although AI-based project management tools remain relatively limited compared to other industries, several experimental applications are emerging. These include: analyzing team productivity to estimate task durations, ranking enterprise-level communication databases, automatically scheduling tasks based on workload and task duration, issuing alerts when budget or schedule overruns are anticipated, predicting the most suitable team member for specific tasks and assigning responsibilities accordingly, automatically distributing information to users based on relevance, visualizing notifications and updates, forecasting unattainable deadlines, and refining task time estimates. There are notable AI implementation attempts across various project management knowledge areas and processes. Among all, the most prominent potential application areas are: time management, cost management, quality management, occupational health and safety management, risk management, resource management, organizational learning, information management, design management and environmental sustainability. A brief summary can be seen in Table 1.

Table 1 Brief Summary of Application Areas of AI in Construction Project Management

Domain	**AI Methods & Tools**	**Key Theme Example**
Time Management	Deep learning, Computer vision	Delay forecasting
Cost Management	ANN, SVM, Regression trees	Real-time budget alerts
Quality Management	UAV imagery + CNN detection	Automated defect detection
Occupational Health & Safety	NLP, Sensor fusion	PPE compliance monitoring
Risk Management	Bayesian networks, NLP	ISO 31000 automated assessment
Resource Management	Predictive analytics	Labor/equipment forecasting
Organizational Learning	NLP, Knowledge graphs	Lessons-learned indexing
Information Management	Ontologies, Semantic indexing	Automated BIM clash detection
Design Management	Generative design, Digital twins	Parametric form finding
Environmental Sustainability	LCA modeling, Optimization algos	Carbon footprint scenario analysis

4.2.1. Time Management

Time management in construction projects is a critical factor in ensuring that the project is completed within the planned timeframe. Project delays can lead to increased costs and contractual disputes (Love et al., 2016). Therefore, planning processes must be managed dynamically and in a predictive manner. Artificial intelligence provides solutions to this need through algorithms trained on historical project data. In particular, methods such as machine learning (ML) and deep learning (DL) can be used to predict potential causes of delay during the project lifecycle and to develop alternative planning scenarios. AI-based systems can analyze project schedules to identify dependencies between work packages, optimize critical path methods, and balance resource utilization in relation to time. For example, a hybrid deep learning model combining neural network demonstrate >93 % accuracy in time estimation for construction projects

(Cheng et al., 2025). Moreover, IoT sensors and on-site observations that provide real-time data streams can be integrated with AI algorithms, enabling continuous monitoring of on-site progress. This allows project managers to make decisions not only based on historical data but also with a forward-looking perspective.

AI's contribution in this area is not limited to the planning stage; it also enhances the accuracy of schedule updates during project execution and enables the creation of early warning systems against potential risks. As a result, more realistic and flexible project schedules can be created, increasing the likelihood of project success. For instance, one of the technologies developed to enhance construction productivity is the Doxel AI system, which utilizes autonomous recorders to capture images and conduct laser scans. It employs AI-based measurements to monitor progress and quality, providing real-time tracking of site status and improving team efficiency. This enables continuous tracking of potential discrepancies between planned and actual project schedules, allowing for more accurate forecasting (Doxel AI, n.d.). In addition, a variety of AI-assisted project management software tools serve professionals in the scheduling and planning domains of construction projects, contributing to the overall value created by the project. These tools help reduce the time and human resources allocated to project planning processes, thereby enhancing overall project efficiency. While tools like Doxel AI exemplify emerging commercial solutions in this domain, peer-reviewed works provides scientific validation of the approach. For example, Ekanayake et al. (2024) developed a deep-learning model for computer-vision based construction progress monitoring, automatically recognizing as-built conditions and reporting real-time status via a web-based platform. Recent advances also include AI-enhanced scheduling tools trained on BIM data and expert planning records, which can automatically sequence activities and predict resource requirements—eliminating the need for manual constraints and significantly streamlining planning workflows (Al-Sinan et al., 2024).

4.2.2. Cost Management

Cost management is one of the most critical processes in ensuring the economic sustainability of construction projects. Deviations in project costs can arise due to various factors such as fluctuations in material prices, labor inefficiencies, planning errors, and unforeseen site conditions (Flyvbjerg et al., 2003). While traditional cost estimation methods often fall short in reflecting this complexity, AI-based solutions have the potential to offer a more dynamic and data-driven approach to the process. As in all profit-oriented industries, the construction sector seeks to maximize the benefits of digital innovations in cost reduction, budget optimization, preliminary cost estimation, and financial planning. In this regard, AI-based project management softwares are increasingly employed to enhance efficiency in construction. For example, a hybrid deep learning model combining neural network demonstrate >97 % accuracy in cost estimation for construction projects (Cheng et al., 2025).

Artificial intelligence can learn from large datasets derived from previous projects to generate more accurate cost forecasts for future undertakings. Machine learning models—particularly artificial neural networks (ANN), support vector machines (SVM), and regression trees—can analyze a wide range of variables, including project size, location, contract type, work items, and procurement processes, to deliver precise cost estimates. Recent comparative reviews show that deep learning and hybrid models outperform traditional ML methods in terms of cost estimation accuracy, achieving up to 90% accuracy in construction project forecasts (Shamim et al., 2025). Moreover, AI can analyze real-time cost data generated during project execution, thus enabling continuous budget monitoring. As a result, deviations can be detected early, and decision-makers can take timely corrective actions. AI-assisted decision support systems can continuously monitor expenditures against the allocated budget and provide cost alerts to project managers. Additionally, proactive scenario analyses can be conducted to anticipate potential price fluctuations in the construction materials and equipment supply chain. Overall, AI applications can contribute to making cost management in construction projects more transparent, data-driven, and predictable, thereby providing a significant advantage in ensuring the financial success of projects.

4.2.3. Quality Management

Quality management in the construction industry is important to ensure that projects are completed within the desired standards, on time, and within budget. Encompassing factors such as material quality, workmanship, structural compliance, and occupational health and safety, quality management is one of the primary determinants of project success. However, traditional quality control methods are often time-consuming, prone to human error, and largely reactive in nature. In this context, artificial intelligence (AI) holds the potential to make quality management processes in construction more efficient, rapid, and proactive.

AI-supported quality management systems can perform real-time inspections and evaluations on construction sites, particularly through the integration of computer vision, machine learning, and big data analytics. For instance, visual data captured by drones and cameras can be analyzed using AI algorithms to automatically detect quality deviations such as surface defects, cracks, or misalignments. This allows for the early identification of errors and deficiencies during the initial stages of the project, enabling timely interventions. Furthermore, by analyzing historical quality data, AI can learn the conditions under which specific defects tend to occur and provide recommendations to prevent similar issues in future projects. Quality checklists, audit plans, and compliance reports can also be automated, saving time and reducing the risk of human error. Another significant contribution lies in predictive quality analytics. AI can assess various variables—including environmental conditions, labor density, and material supply lead times—during the project to anticipate situations that may pose quality risks in specific work packages. This offers managers the opportunity to take preventive action and directly enhances overall project performance. In line with this, recent studies underscore the growing role of AI-based visual inspection, drones, and ML algorithms in real-time quality assurance, particularly for defect detection and site progress monitoring (Hasan et al., 2025).

In terms of practical implementations, one notable example is Doxel AI, a system designed to support product-level quality control by collecting real-time data from the field, identifying faulty work, and verifying alignment between planned and actual production (Doxel AI, n.d.). This system enables immediate error reporting and corrective action. By transforming quality management from a reactive inspection process into a continuous improvement and data-driven decision-making mechanism, AI has the potential to enable the development of more reliable, cost-effective, and sustainable construction projects.

4.2.4. Occupational Health and Safety Management

The construction industry continues to be one of the sectors with the highest rates of occupational accidents. Each year, a significant number of work-related injuries and fatalities occur within the sector, posing substantial risks in terms of occupational health and safety (OHS). The rate of accidents during construction activities is considerably higher than in most other industries. Among the most notable causes are falls from heights, trips and slips, electric shocks, and being caught between objects. Due to factors such as working at height, use of heavy machinery, insufficient safety measures, and human error, accidents frequently occur—resulting not only in loss of life but also in significant financial losses (Hinze et al., 2013). In this regard, making OHS management more proactive and data-driven is of critical importance. Artificial intelligence (AI) has the potential to offer novel solutions in areas such as early risk detection, development of pre-incident warning systems, and the design of safer work environments.

The primary objective of AI applications in construction site safety is to monitor and report safety-related events, alert workers regarding safety protocols, and provide real-time safety cues (Blanco et al., 2017). Current AI-based research in this field mainly focuses on: (1) identifying workers who are not wearing required protective equipment, (2) detecting potential physical hazards on the construction site, (3) analyzing past accidents by comparing incident reports with captured images to predict possible future risks, and (4) generating preliminary warnings for identified potential hazards.

AI-supported computer vision systems and sensor data can analyze workers' movements and their use of safety gear (such as helmets and vests) in real time, promptly detecting anomalies and notifying relevant personnel. For example, using computer vision, unsafe worker behavior or presence in restricted areas can be identified before an accident occurs, allowing for preemptive intervention. In addition, machine learning algorithms trained on historical accident records and site data can predict which types of work, under what conditions and timeframes, are more prone to safety risks. This enables project managers to plan hazardous activities in advance, take necessary precautions, and update worker training programs accordingly. When integrated with virtual reality (VR) technologies, AI can also provide interactive, simulation-based training to workers, enhancing risk awareness and strengthening the overall safety culture. This approach not only helps prevent accidents but also contributes to reducing long-term safety-related costs within the industry.

Moreover, the use of AI in construction safety management significantly enhances efficiency and accelerates decision-making processes for project managers. For instance, in one study, an AI system was able to process 1,080 site photos in under five minutes to detect potential safety risks, whereas a human expert team required over five hours to conduct a similar review (Smith & Kanner, 2017). This finding demonstrates that AI can substantially reduce the time required for implementing safety measures, thereby improving both operational efficiency and on-site safety conditions. More recently, language models such as ChatGPT have also been adapted to extract and explain safety protocols, offering site teams faster and more accessible guidance from regulatory documents (Tran et al., 2024).

4.2.5. Risk Management

Due to their inherent complexity and the involvement of numerous stakeholders, construction projects are characterized by a high degree of uncertainty and risk. These risks can be multifaceted, encompassing cost overruns, schedule delays, quality deficiencies, environmental impacts, and occupational safety threats (Zou et al., 2007). The accurate identification, assessment, and prioritization of these risks is of critical importance for effective project management. At this point, artificial intelligence (AI) has the potential to offer a data-driven approach that enables a more efficient and predictive risk management process. However, despite these capabilities, AI also introduces a new layer of complexity and uncertainty in decision-making. As Kovačević and Bouder (2023) highlight, AEC professionals often encounter “model uncertainty,” “parameter uncertainty,” and “person uncertainty,” making it difficult to trust AI-generated recommendations without extensive validation or contextual awareness.

Machine learning algorithms, trained on data derived from past projects, can predict potential risks likely to emerge in similar projects and analyze their potential impacts (Elghaish et al., 2019). These machine learning algorithms are capable of evaluating numerous variables—including contract type, project scale, supply chain configuration, site conditions, and contractor history—to conduct project-specific risk assessments. In doing so, they provide decision-makers with the opportunity to take proactive measures against high-probability risks. Moreover, natural language processing (NLP) techniques can automatically analyze uncertainty and risk-related statements in project documents, contracts, and other textual records. This enables the systematic identification of sources of uncertainty even during the early stages of the project.

AI-assisted simulation and scenario analysis tools can model how project performance may be affected under various risk conditions, thereby offering project managers a range of decision-making alternatives. However, as Mohamed et al. (2025) point out, the integration of generative AI models introduces new risks—ranging from input data bias and lack of transparency to cybersecurity threats and governance failures. These risks must be addressed to ensure reliable AI adoption in construction project risk management. AI-integrated risk analysis tools also enable project managers to perform dynamic risk evaluations based not only on historical data but also on real-time field information. This capability is particularly valuable in situations that require rapid response, as it supports more accurate and timely decision-making. Emerging research also highlights the use of generative AI tools, such as ChatGPT, for project risk assessment, showing promising results in modeling ISO 31000-based risk decisions (Al-Mhdawi et al., 2023). In this context, AI technologies have the potential to become powerful tools for reducing uncertainties, accelerating risk prioritization processes, and developing decision support systems—thereby enhancing the overall robustness of risk management in construction projects. A recent bibliometric and systematic review of AI-driven risk management in construction underscores growing attention to explainable AI methods and the need to address bias, model transparency, and dataset limitations—suggesting these remain critical challenges for mainstream adoption (Tian et al., 2025).

4.2.6. Resource Management

Resource management is one of the key determinants of success in construction projects. The accurate planning and efficient utilization of resources such as labor, materials, equipment, and time are essential for controlling costs, meeting schedule targets, and achieving quality standards (Kerzner, 2017). However, traditional resource management approaches often fall short in dynamic project environments, resulting in unforeseen deviations. At this point, artificial intelligence (AI) emerges as a promising tool for optimizing resource management through complex data analysis.

AI systems can analyze historical project data to forecast labor and equipment requirements, as well as predict the timing and intensity of resource utilization. This predictive capability helps prevent common issues such as over- or under-allocation of resources, thereby supporting continuous project flow. Furthermore, material procurement processes can be more accurately managed through AI-powered demand forecasting models, minimizing problems such as overstocking or shortages. Machine learning algorithms can analyze real-time data collected from the field to reveal patterns in resource utilization and detect potential bottlenecks at early stages. For instance, AI can identify whether delays in a particular work item are due to labor shortages, equipment malfunctions, or logistical challenges. This enables managers to revise resource plans and optimize operations in real time (Akinosho et al., 2020).

AI-based resource management systems also offer holistic solutions by accounting for interdependencies among different types of resources. For example, how will a delay in one work item cause resource conflicts in other activities? AI systems capable of answering such questions not only analyze the current state but also generate alternative planning scenarios, providing managers with strategic advantages. In this way, AI technologies offer a digital support system that strengthens both strategic planning and operational execution in resource management. As a result, construction projects can benefit from increased efficiency, reduced waste, and more rational resource utilization—ultimately contributing to the overall sustainability of project delivery.

4.2.7. Organizational Learning

Construction projects are inherently complex and dynamic endeavors involving numerous stakeholders working simultaneously, which makes them susceptible to errors and deviations. In this context, documenting and transferring the knowledge and experiences gained at the end of each project for use in future projects constitutes the foundation of organizational learning. Commonly referred to as the "lessons learned" approach, this practice is strategically important for learning from the past and fostering continuous improvement (Ajmal et al., 2010). However, conventional methods of collecting, analyzing, and disseminating such knowledge across the organization are often insufficient. At this point, artificial intelligence (AI) holds significant potential to enhance the effectiveness and sustainability of organizational learning processes. Organizational learning is a critical process within firms as it supports knowledge-based risk management practices (Alashwal et al., 2017), enhances overall performance, and sustains competitive advantage (Zhai et al., 2013). Although the acquisition and reuse of new knowledge are particularly important in project-based industries, knowledge management practices in the construction sector are predominantly informal and human-dependent (Oti et al., 2018). AI tools can offer a more systematic approach, enabling more efficient acquisition and reuse of knowledge. These tools can ensure the retention of learned knowledge within the organization and facilitate its reuse in future projects. They are capable of simulating scenarios and predicting their impact on organizational processes.

With its capabilities in big data processing and natural language processing (NLP), AI can analyze large datasets derived from completed projects—including construction logs, audit reports, site notes, and communication records—to build a robust organizational memory. Pattern recognition algorithms trained on such data can identify frequently recurring problems or successful practices, thus supporting the generation of post-project evaluation reports (Love et al., 2012). In this way, the lessons learned from past experiences can be systematically documented and categorized. Moreover, AI can play a key role in surfacing “tacit knowledge” by facilitating information sharing among project teams. For instance, AI-powered knowledge management systems can analyze the challenges encountered, decisions made, and their outcomes in previous projects, offering guidance for new projects. These systems can also establish learning bridges across different teams within the organization, minimizing redundancy, preventing repeated mistakes, and fostering the dissemination of innovative solutions. AI-assisted organizational learning practices contribute to transforming post-project evaluations into institutional knowledge assets, thereby generating long-term strategic benefits. The support offered by AI in this area not only helps avoid past mistakes but also enables the development of more successful, efficient, and low-risk strategies for future projects. In doing so, AI facilitates the emergence of learning organizations within the construction sector and contributes to the achievement of sustainable success.

4.2.8. Information Management

Construction projects, by their very nature, involve the collaboration of numerous stakeholders and disciplines, resulting in information-intensive processes. From project plans and drawings to contract documents and site data, a wide array of information must be managed effectively to ensure project success. One of the greatest challenges in this process is the inability to store and analyze information in a consistent, accessible, and usable manner. While the goal of information management is to overcome these challenges, artificial intelligence (AI) technologies has the potential to provide significant contributions to this process.

Organizational communication and efficient information flow are crucial components of any operational process. Without proper information flow, financial or material flows cannot occur. An optimally organized flow of information can provide a company with competitive advantages through reduced costs, enhanced customer service, and more efficient business processes (Nousiainen, 2008). The timeliness of information is also of utmost importance because data is continuously updated; staying current in information flow is essential to avoid issues in understanding and interpretation. Consequently, ensuring the transfer and readability of information is the paramount objective in software related to information flow. In construction project management, effective information flow is vital and has become even more important with technological advancements.

AI is revolutionizing information management processes through big data, natural language processing (NLP), and automatic classification algorithms. By integrating with digital technologies such as Building Information Modeling (BIM), AI can automatically organize project documents, detect inconsistencies within documents, and facilitate quicker access to information. Moreover, by extracting meaningful insights from semi-structured data—such as email traffic, site reports, and meeting notes—AI-powered systems can provide decision support to project managers. These systems can also establish contextual relationships among the various datasets generated throughout a project, thereby optimizing search processes for critical information. For example, using NLP techniques, a project team can retrieve related contract clauses, technical drawings, or change records instantly by simply posing a short query (Khosrowshahi & Arayici, 2012). This capability not only contributes positively to time management but also enhances the quality of information-based decision making. Another strong aspect of AI in information management is its role in ensuring data security and version control. By establishing automatic audit systems related to data access permissions, version tracking, and change histories, AI both preserves data integrity and prevents potential information losses. As a result, information flow in complex construction projects becomes more sustainable and transparent. AI-supported information management applications thus make the flow of information in construction projects smarter, more efficient, and more reliable, thereby contributing significantly to overall project success. With rapid access to accurate information, robust validation processes, and powerful analytical capabilities, AI assumes a strategic role in the digital transformation of the construction industry.

4.2.9. Design Management

Creativity is one of the most fundamental attributes of human intelligence and simultaneously represents an inevitable challenge for artificial intelligence (AI). The potential of AI to transform the discipline of architectural design—by introducing novel possibilities and unexplored pathways—remains a subject of ongoing debate. As one of the core phases of construction projects, the design process is critical in determining a project's functionality, aesthetics, and feasibility. It typically involves the simultaneous evaluation of multiple variables and the making of numerous decisions. While traditional design approaches largely rely on professional experience and are conducted through manual methods, the integration of AI technologies promises more rational, efficient, and optimized solutions (Alanne, 2004). AI's iterative, data-driven processes have begun to tackle multilayered design challenges – from form-finding and spatial programming to performance optimization – revealing a rapidly growing body of literature that maps nearly a decade of applications (Bölek et al., 2023).

AI's potential contributions to the design process are multifaceted. Foremost among these is the advent of generative design, an AI-driven methodology that enables designers to define a set of parameters, upon which the system generates a wide array of design alternatives. This approach not only saves time but also facilitates the discovery of creative options that might otherwise be overlooked in conventional design processes. Architectural and engineering solutions can thus be optimized not only for form and function, but also in terms of cost, energy efficiency, and sustainability. A notable example is Autodesk Generative Design, an AI-based tool that generates numerous high-performance design alternatives based on user-defined inputs such as desired daylight levels, orientation toward specific views, or a maximum allowable construction budget. The tool then evaluates these alternatives through AI-driven generative design processes, assessing their functionality accordingly. Furthermore, it provides cost estimates, projected energy consumption metrics, and documentation for quality and budget considerations related to each proposed design (Autodesk, n.d.).

AI-supported design systems can also analyze data from previous projects to highlight the most effective solutions within specific contexts. In this way, systems empowered by pattern recognition and machine learning capabilities not only offer creative suggestions but also support more robust, feasible, and risk-mitigated design decisions by learning from past mistakes. Additionally, AI can be integrated with Building Information Modeling (BIM) platforms to enhance consistency in multidisciplinary design processes. Through such integration, potential clashes between architectural, structural, and mechanical systems can be automatically detected and resolved using AI-generated recommendations. This helps reduce the number of design revisions and prevents errors during the construction phase (Bock & Linner, 2015). AI-assisted design tools can enhance decision quality in the early stages of construction projects, thereby exerting a direct influence on overall project success. While accelerating design workflows, AI can simultaneously foster flexibility, creativity, and sustainability. By combining engineering logic with data analytics, AI contributes to shaping the intelligent buildings of the future. Recent frameworks emphasize the integration of AI with digital twins and real-time data streams, enabling synchronous design, simulation, and performance monitoring across the entire building lifecycle (Jiang et al., 2024).

4.2.10. Environmental Sustainability

The construction sector is responsible for approximately 50% of global resource consumption, nearly 40% of energy use, and a significant share of greenhouse gas emissions (UNEP, 2021). As such, achieving environmental sustainability within the sector is of paramount importance—not only for meeting global climate goals but also as a matter of social responsibility. While traditional construction methods often fall short of supporting sustainability objectives, artificial intelligence (AI) has the potential to offer innovative solutions that contribute to reducing the sector's environmental impact.

AI-supported systems are capable of estimating energy consumption, carbon footprint, and waste generation during construction processes. Based on these data, they can develop alternative scenarios to identify the most environmentally friendly option. For instance, in material selection, AI can holistically evaluate criteria such as recyclability, carbon emissions during production, and the environmental impact of transportation, thereby recommending the most sustainable alternatives. Furthermore, AI systems integrated with sensor data and Internet of Things (IoT) technologies can monitor energy and water consumption on construction sites in real time. These systems can issue automatic alerts in the case of inefficiencies or waste, enabling prompt intervention. Additionally, AI is increasingly used for optimizing sustainability performance by modeling energy usage, emissions, and materials efficiency—especially in green building retrofits (Adebayo et al., 2025). Thus, environmental impact is controlled not only at the planning stage but also during the execution phase.

AI applications can also facilitate optimized waste management by minimizing material waste and promoting sustainable practices throughout the construction lifecycle. Additionally, AI can enable the modeling and enhancement of buildings' energy performance over their entire life cycle. For example, AI-enhanced life cycle assessment tools can forecast the environmental impacts of a building during production, operation, and demolition stages, thereby supporting more sustainable design decisions (Asadi et al., 2012). By promoting the adoption of sustainability principles in construction, AI technologies help reduce environmental impacts, ensure the efficient use of resources, and contribute to the creation of more livable built environments. As a digital enabler of environmentally friendly transformation in the sector, AI is increasingly recognized for its strategic importance.

5. Discussion

The analysis presented in this study affirms that artificial intelligence (AI) holds significant transformative potential in construction project management, particularly in addressing long-standing challenges related to efficiency, uncertainty, risk, and sustainability. Although construction sector is slow in digital transformation, the reviewed literature demonstrates that AI applications are increasingly being adopted across core project management functions, including time and cost estimation, quality assurance, safety monitoring, risk analysis, and resource optimization. These functions are central to project success and have traditionally relied on human intuition and heuristic methods. The shift toward AI-supported decision-making marks a substantial evolution in management philosophy—moving from reactive to predictive and from subjective to data-driven. The practical value of AI in construction project management is most apparent in its predictive and prescriptive capabilities, which allow for proactive identification of risks, optimization of schedules, and real-time performance monitoring. For example, machine learning-based tools exemplify the growing use of autonomous systems for real-time site data analysis and predictive scheduling. These applications mirror the broader trend observed in other sectors, where AI is used not merely to automate but to augment strategic decision-making (Abioye et al., 2021; Burger, 2017).

When compared with previous reviews (e.g., Bang & Olsson, 2022; Aladağ et al., 2024), this study provides a more holistic and function-oriented synthesis, mapping AI applications to specific project management domains. While Bang and Olsson (2022) offered a systematic scoping review, they largely focused on technical implementations. In contrast, this paper extends the discussion to organizational, cultural, and strategic dimensions, highlighting factors such as resistance to change, ethical concerns, and skill gaps—elements that are often underexplored in technologically focused studies. These concerns are echoed in the findings of Kovačević and Bouder (2023), who observe that many construction professionals view AI as ambiguous and overly reliant on visual interfaces that may conceal data weaknesses. Their study reveals that skepticism toward AI stems from a lack of algorithmic understanding and the fear that poorly contextualized AI tools may introduce new risks rather than mitigating existing ones. Moreover, the findings echo the concerns raised by Khosrowshahi & Arayici (2012) and Bilal et al. (2016) regarding data fragmentation and interoperability challenges in the construction industry. These technical hurdles, coupled with organizational resistance and cultural inertia (Perera et al., 2020), illustrate that AI adoption is not merely a technological endeavor but a socio-technical transformation. The need for structured, high-quality datasets is a recurring theme, as poor data quality significantly hampers the training and generalization of AI models, is particularly critical in the construction sector, where project conditions are highly variable and context-specific.

In terms of occupational health and safety (OHS), the study affirms that AI can significantly enhance proactive risk mitigation strategies through real-time monitoring, image recognition, and behavioral analysis. These findings are supported by Smith and Kanner (2017), who demonstrated that AI can drastically reduce the time needed to detect on-site safety hazards compared to human inspection. However, widespread adoption remains limited due to ethical and legal concerns, especially regarding the black-box nature of AI algorithms (Bai et al., 2020), which can undermine user trust in safety-critical decisions. Another noteworthy contribution of this study is the emphasis on organizational learning and knowledge retention, areas often neglected in earlier AI discussions. As Ajmal et al. (2010) and Zhai et al. (2013) suggest, continuous learning from past projects is a key component of project success. AI's role in capturing, structuring, and disseminating tacit knowledge offers a promising avenue for embedding institutional memory into future project planning and execution—thus reinforcing strategic project management capacity. Another thing is, the convergence of AI with digital twins is emerging as a transformative paradigm for construction project control. By combining real-time sensor data, BIM models, and ML algorithms, digital twins enable predictive monitoring, adaptive scheduling, and scenario-based simulation. This integration supports dynamic decision-making and aligns with Construction 4.0 maturity objectives (Jiang et al., 2024).

Despite these advances, the gap between academic innovation and real-world implementation persists. Much of the literature reflects conceptual enthusiasm but lacks empirical validation, particularly in large-scale, diverse project environments. This discrepancy underscores the need for interdisciplinary collaboration, where construction engineers, data scientists, software developers, and project managers co-develop and test AI solutions under field conditions. Hereby, this study underscores that while AI technologies are progressing rapidly, their integration into construction project management is constrained by a combination of technical, organizational, and human factors. The findings support the growing consensus that a multi-dimensional and interdisciplinary approach is essential to unlock AI’s full potential in this domain. For example, Recent studies such as Mohamed et al. (2025) and Al-Mhdawi et al. (2023) highlight the rising use of generative AI and LLMs for automated document analysis, risk prediction, and regulatory compliance. However, concerns over explainability, adversarial risk, and model bias remain major barriers to adoption.

6. Conclusion

This study has provided a multi-dimensional examination of AI in construction project management across core domains—including time, cost, risk, safety, quality, resource and information management, organizational learning, design, and environmental sustainability—through a narrative literature review. It makes three key contributions to the literature on AI in construction project management. First, it offers a comprehensive and function-oriented synthesis—mapping AI methods to core project management domains—thereby bridging the gap between fragmented technical studies and holistic management frameworks. Second, it integrates technical applications with organizational and cultural dimensions, highlighting both AI's transformative potential and the systemic barriers—such as data governance, explainability, and skills gaps—that must be overcome. Third, by grounding the thematic analysis in the PMBOK framework, it adds methodological rigor and produces a practical roadmap that researchers and industry partners can use to scope AI pilots, design live validation studies and evaluate performance using standardized criteria.

Building on these contributions, the study generates clear practitioner takeaways. Project managers are encouraged to move beyond reactive monitoring by leveraging AI-augmented scheduling tools that predict potential delays and trigger early warnings. BIM coordinators can embed generative design plugins within their workflows, automating clash detection and embedding sustainability analyses directly into building models. Safety officers can adopt explainable AI dashboards to visualize hazard predictions and compliance gaps in real time, thereby bolstering stakeholder trust and accelerating on-site implementation of safety protocols. These implications demonstrate how academic insights can translate into actionable strategies, improving both efficiency and resilience on live construction sites.

Beyond practical guidance, the findings underscore AI's broader transformative potential: not merely as a set of tools, but as a catalyst for shifting traditional project management paradigms toward predictive, data-driven, and adaptive practices. Yet, realizing this vision requires overcoming persistent barriers—fragmented data ecosystems, interoperability issues with legacy BIM and ERP systems, limited digital literacy, and organizational resistance deeply rooted in industry culture. To bridge the gap between theoretical promise and real-world impact, future research must prioritize empirical validation of AI applications in diverse project environments, develop sector-specific AI frameworks tailored to construction's unique characteristics, and foster interdisciplinary collaboration among engineers, data scientists, and managers. Parallel efforts in professional education and policy incentives will be essential to upskill the workforce and cultivate a culture of digital innovation.

In sum, AI stands poised to become the cornerstone of intelligent, sustainable, and high-performing construction project management. By addressing both technological capabilities and organizational realities, this study advances theoretical understanding and informs practical strategies, laying the groundwork for resilient, adaptive, and future-ready project delivery ecosystems.

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Resume

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Optimizing design thinking process for group housing through interaction design methods

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Abstract

This research paper investigates the optimization of the Design Thinking (DT) process for group housing projects by using Interaction Design (IxD) methods. Group housing design is increasingly complicated as it attempts to balance individual requirements, community behavior, and sustainability. Through the integration of Design Thinking principles—empathy, ideation, prototyping, and iteration. This article proposes a hybrid approach that combines Interaction Design (IxD) methods, including empathy mapping, interactive prototyping, and real-time feedback systems, to optimize DT's phases (empathize, ideate, prototype, test) in group housing. Through a series of case studies, the research shows how IxD's focus on dynamic user interactions and iterative co-design increases participatory outcomes. Key outcomes are a 30% increase in resident satisfaction with communal spaces, a 25% decrease in design iteration cycles, and enhanced conflict resolution in shared spaces through means such as behavioral analytics and VR-based spatial simulations. The framework not only closes gaps in DT's usage but also encourages interdisciplinary collaboration, allowing architects and interaction designers to co-create flexible, user-oriented living spaces. Practical considerations for large-scale housing solutions are debated, including limitations to cultural responsiveness and resources needed. Recommendations are provided to bring digital-physical feedback tools into policy and practice at the end of the study, which is a path for future work across different socio-spatial environments.

Keywords: interaction design, design thinking, group housing, user-centered design, spatial innovation

1. Introduction

1.1. Context

Growing demand for user-focused and sustainable group housing has led to a transition away from conventional housing structures towards more collaborative living situations (UN-Habitat, 2022). Group housing, such as co-housing, cooperative housing, and shared residences, seeks to reconcile personal autonomy with the good of the group through social engagement, sharing, and environmentally conscious living habits (Akinsulire et al., 2024).

Nevertheless, conventional housing design procedures tend to be inadequate in dealing with the intricate social and spatial relations involved in collective living. Static planning is favored by conventional architectural procedures, making spaces less responsive to changing residents' needs (Eizenberg & Jabareen, 2017). Additionally, the lack of iterative, user-led feedback processes results in design imbalances, eventually influencing resident satisfaction and social cohesion (Díaz & Aedo, 2020).

To transcend these constraints, human-centered design approaches like Design Thinking (DT) and Interaction Design (IxD) are gaining popularity. DT focuses on empathy, ideation, prototyping, and iterative testing, enabling more flexible and inclusive housing solutions (Brown & Wyatt, 2010). In contrast, IxD, originally related to human-computer interaction, applies its principles of

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interactivity, feedback loops, and user experience mapping to designing physical environments (Srisombut et al., 2021). By combining these two fields, architects and urban planners can develop dynamically responsive housing systems that accommodate varied resident requirements while improving social integration and sustainability.

1.2. Problem Statement

Even with the potential of group housing as a sustainable and socially enhancing model, its success hinges on the efficiency of the design process. Conventional architectural practices are frequently lacking in Understand resident needs: Accurately capture the diverse needs, preferences, and lifestyles of prospective residents. Promote collaboration: Facilitate meaningful participation and co-creation among residents in the design process. Optimize shared spaces: Design shared spaces that encourage interaction, foster a sense of community, and accommodate a variety of activities. Balance individual and collective needs: Strike a balance between individual privacy and autonomy and the collective needs of the community. Address potential conflicts: Anticipate and mitigate potential conflicts arising from shared living arrangements. (Wiles et al., 2011).

Additionally, current Design Thinking methods in architecture are more concerned with aesthetics and spatial optimization than user interaction and adaptive co-design. This leads to inflexible housing models that fail to adapt to community needs. Thus, this study aims to redefine the Design Thinking process by incorporating Interaction Design methods, allowing for a more responsive, participatory, and resident-centered housing model.

1.3. Research Objectives

This study seeks to maximize the Design Thinking process for group housing through the incorporation of Interaction Design practices. The particular goals are:

1.3.1. Identify Key Challenges

Determine major challenges in using Design Thinking for group housing through a review of current case studies and literature.

1.3.2. Evaluate Existing Methods

Assess the efficacy of Interaction Design methods (e.g., empathy mapping, interactive prototyping, real-time feedback systems) in improving participatory housing design.

1.3.3. Develop a Refined Framework

Create an evolved framework that incorporates Interaction Design principles into the Design Thinking stages (Empathize, Ideate, Prototype, Test).

1.4. Significance of the Study

This research is a contribution to the innovation in housing design through proposing an holistic framework for improving resident involvement, spatial flexibility, and participatory self-governance. The outcomes are especially applicable to:

1.4.1. Architects & Designers

Delivering a systematic method for developing user-oriented and socially interactive housing typologies.

1.4.2. Urban Planners & Developers

Offering insights into scalable, cost-efficient, and flexible forms of housing.

1.4.3. Residents & Co-Housing Communities

Enabling people to engage actively in the co-creation of their living places.

1.4.4. Policy Makers & Housing Authorities

Guiding policy reforms that promote resident-led housing models and integrating digital feedback.

By bridging the gap between Interaction Design and Design Thinking, this research opens up possibilities for interdisciplinary collaboration, enabling architects, urban planners, and interaction designers to collaborate on designing adaptable, user-oriented, and socially sustainable collective housing solutions.

2. Literature Review

2.1. Design Thinking

Design thinking is an iterative human-centered problem-solving process focusing on understanding the needs of users, creating innovative solutions, and developing them through testing (Lka, 2020). The process is normally divided into five major stages: empathize, define, ideate, prototype, and test (Haryuda et al., 2021). The empathize stage entails intense immersion with users using observation, interviewing, and being in the environment to understand users' needs, behaviors, and motivations (Hou et al., 2019). Empathize phase ensures that real problems are noted by designers as opposed to cosmetic issues (Darmawan et al., 2022). The define phase integrates research insights to create an unambiguous, human-focused problem statement (Tu et al., 2018). An accurate problem gives the next step of the design process direction so that solutions can align with the user's needs (Elsbach & Stigliani, 2018). The ideate stage promotes the examination of several potential solutions through brainstorming, drawing, and other creative methods (Nasution & Nusa, 2021). The ideate stage prioritizes quality over quantity but encourages innovation by focusing on as many ideas as possible (Sari et al., 2020). The prototype stage focuses on creating tangible representations of the solution, from low-fidelity paper prototypes to high-fidelity interactive systems (Johansson & Arvola, 2007). Prototyping facilitates the collection of user feedback prior to full-scale implementation (Häggman et al., 2013). The testing phase tests prototypes against users to establish areas for adjustment (Karnawan, 2021). Testing is done iteratively because learnings acquire result in modifications and iterations in prototyping (Micheli et al., 2018).

Design thinking is used extensively in architecture and urban planning to design spaces that are centered on user experience (Akinsulire et al., 2024). In residential projects, it allows architects to interact with the residents to know their spatial preferences and social behaviors, resulting in solutions that are both functional and aesthetic (Bilandzic et al., 2008). Urban planning is also enhanced by design thinking through the integration of community engagement into planning processes (Caramiaux et al., 2015). For instance, engaging citizens in co-creation workshops ensures that public areas are safe, accessible, and designed according to their requirements (Kappel et al., 2017). Further, sustainability issues, such as energy-efficient construction and green infrastructure, can be resolved through iterative prototyping and user testing (Oluwafeyikemi & Gwilliam, 2015). Through the incorporation of design thinking in housing and urban planning, solutions are more responsive to changing user requirements and urban situations, and hence it is a worthwhile method for modern housing problems.

2.2. Interaction Design

Interaction design (IxD) is centered around designing intuitive and compelling experiences by defining how users interact with products, services, and spaces (Jacko & Sears, 2013). Its main methods—user research, prototyping, usability testing, and scenario-based design—come together to shape refined design results. User research constitutes the process of observing the behaviors, preferences, and needs of users through methods like interviews, questionnaires, and ethnographic studies (Hou et al., 2019). These findings enable designers to design solutions that meet user expectations. Prototyping is an essential IxD tool that allows iterative improvement of design concepts (Johansson & Arvola, 2007). Low-fidelity paper concepts enable users to discover usability problems early in the process (Häggman et al., 2013). Usability testing makes designed solutions accessible to users by obtaining feedback from actual users (Karnawan, 2021). It improves quality of functionality, accessibility, and overall satisfaction of the user.

Scenario-based design entails creating scenarios that illustrate how people engage with a system in varied contexts (De & Carrio, 2009). It is best suited for spatial design because it takes into account real-world interactions and changing environments. Interaction design not only addresses digital interfaces but also has implications on the ways humans engage with environments and societies (Broughton et al., 2009). IxD can add value to social interaction and user-friendliness within common living areas in group housing. As an example, structuring shared environments through interactive spaces—like smart living rooms or social media hubs for resident connection—fosters collaboration in balance with resident privacy (Caramiaux et al., 2015). Similarly, technology governing shared resource operation (i.e., LED bulbs, calendar books for use in shared public space) generates efficiency (Oluwafeyikemi & Gwilliam, 2015).

Interaction design also contributes to solving privacy issues by providing flexible environments in which residents are able to manage their exposure to shared space (Elsbach & Stigliani, 2018). Technologies for intelligent homes, for instance, enable the users to personalize lighting, access control, and sound insulation to strike a balance between community engagement and individual retreat (Broughton et al., 2009).

2.3. Group Housing

Group living is becoming a key solution to urban affordability, loneliness, and sustainability issues (Akinsulire et al., 2024). Co-living units, cooperative housing, and shared housing models are encouraged for their ability to ensure resource efficiency and social interaction at reduced individual costs. Yet the balance between privacy and community remains a problem. Successful design must create private refuge spaces while facilitating shared experience (Kappel et al., 2017). Furthermore, maintaining affordability in group housing models is essential since increasing urban housing prices tend to restrict inclusivity (Srisombut et al., 2021).

Group housing sustainability goes beyond energy efficiency to encompass behavioral and technological interventions promoting responsible consumption of resources (Oluwafeyikemi & Gwilliam, 2015). Smart systems to monitor energy consumption, automate lighting, and enable shared resource management can greatly enhance sustainability performance (Broughton et al., 2009). Through the incorporation of interaction design principles in group housing, digital and spatial interfaces can produce smooth experiences, strengthening social relationships while maintaining privacy and resource efficacy (Caramiaux et al., 2015).

2.4. Identified Gaps

One of the major research gaps is the disjointed application of design thinking and interaction design in housing development. While design thinking presents a comprehensive method to resolve issues, interaction design sharpens the micro-level aspects of the user experience (Micheli et al., 2018). Lack of an organized framework that combines the two approaches means missing chances for improving usability, community engagement, and sustainability. Modern home designs tend to overlook iterative testing available in interaction design methodologies, resulting in less-than-ideal community spaces and waste of resources (Jacko & Sears, 2013). Additionally, the absence of interdisciplinary collaboration among architects, urban designers, and interaction designers impedes comprehensive innovation in group housing.

A possible solution is to have a hybrid system in which design thinking informs the macro-housing strategy and interaction design reworks the micro-level user interface. Moreover, participatory design processes might bridge the gap by engaging residents in co-creating living environments (Caramiaux et al., 2015). By methodically embedding interaction design within the design thinking process, group housing schemes can realize improved social connectivity, eco-friendly living, and responsive environments that accommodate shifting user requirements.

3. Methodology

The following section details the research methodologies used to examine the optimization of the Design Thinking process for group housing using interaction design approaches. The research applies a mixed-methods approach with a combination of case study analysis and participatory action research (PAR) to deliver an extensive overview of the design challenges and possibilities in group housing projects.

3.1. Research Approach

The study employs a mixed-methods research, which combines case study analysis with participatory action research (PAR). Mixed-methods research provides a richer understanding of complex phenomena by merging the strengths of both qualitative and quantitative methods (Sandelowski, 2013). This research approach deals with diversity and complexity, providing several views of the phenomena being studied (Sandelowski, 2013).

3.2. Case Study Analysis

Case study research is an empirical investigation that examines a modern phenomenon in its natural setting. It is especially appropriate for examining complex social phenomena whose boundaries with their context are not sharply defined (Runeson & Höst, 2008). In this study, case studies of 2-3 group housing projects will be undertaken to analyze the implementation and efficacy of the interaction design methods under consideration within the Design Thinking process. Case studies are useful when the practical knowledge is as vital as theoretical knowledge (Flyvbjerg, 2006). Case studies will assist in making sense of whether social designs shall be effective and the living conditions that support the possibility of taking structural opportunities (Deluca & Rosenblatt, 2010). A number of current group housing schemes shall be studied to obtain best practices and lessons learned. The case studies will be chosen from among those that offer innovative design aspects, community engagement strategies, and overall success in serving the requirements of their residents. Case study analysis shall include Studying architectural designs and the design documents. Analysing surveys and interviews of residents. Studying community governance and policies. Evaluating the sustainability and affordability of the schemes.

3.3. Participatory Action Research

PAR is a research strategy that focuses on the active participation of stakeholders within the process of research (Tabroni & Purnamasari, 2022). PAR seeks not only to produce knowledge but to also facilitate action and social transformation (Hays & Singh, 2012). By engaging residents, designers, and other stakeholders in the research process, PAR can make sure that the research is meaningful, relevant, and responsive to the priorities and needs of the community (Blair & Minkler, 2009). PAR with older adults can be an underdeveloped resource for the social gerontology field and for the elders as well (Blair & Minkler, 2009). In group housing, PAR can empower residents to engage in design and decision-making, resulting in more inclusive and sustainable housing solutions (Kapilashrami & Marsden, 2018). PAR may work through steps of religious values, attitudes, spirit doing, daily habits and some skills (Tabroni & Purnamasari, 2022). The PAR will include, Focus groups: Guided group discussions with a small number of prospective residents to discuss their views and opinions towards group housing. Online focus groups can be very effective for qualitative studies. Interviews: Individual discussions with people to have a better idea of their own experiences and insights. Surveys: Statistical questionnaires to get data in greater numbers and discern trends and patterns. Participatory design workshops: Group workshops where future residents collaborate with designers to design and critique design concepts.

3.4. Synthesis of Case Study Analysis and PAR

The combination of case study analysis and PAR enables a complementary method of understanding and streamlining the Design Thinking process for group housing. Case study analysis offers in-depth knowledge of how interaction design approaches are implemented within actual projects, while PAR guarantees that the research remains connected to the experiences and insights of the stakeholders (Elwood, 2009). This unification increases the collaboration and empowerment of stakeholders, in addition to the validity and applicability of the research outcomes (Sixsmith, J.,et al 2017).

4. Results and Findings

4.1. Case Study Analysis

This study analyzes four group housing developments in varied contexts—Italy, South Korea, the United States, and India to assess the ways in which Design Thinking (DT) and interaction design (IxD) (Brown & Wyatt, 2010) practices respond to socio-spatial issues. Through a convergence of user-centric principles with participatory and iterative methodologies, these case studies illustrate routes toward maximizing housing equity, sustainability, and community involvement. The comparative details are presented in Table 1.

4.1.1. Case Study 1: San Siro Neighborhood Revitalization, Milan, Italy

The San Siro public housing project in Milan, an iconic example of 20th-century Italian Modernist architecture, underwent redevelopment to address the dual challenges of socio-spatial inequality and deteriorating building infrastructure (Lucchi & Delera, 2020). The primary focus of the project was retrofitting for improved energy efficiency, while simultaneously fostering social cohesion within a multicultural and intergenerational community. The Design Thinking process was applied throughout the project, beginning with empathy-building through community workshops where residents actively participated in identifying their priorities, such as enhancing the safety of shared spaces and ensuring affordable energy solutions. Moving into the ideation phase, the collaborative efforts of residents and designers resulted in proposals such as modular green courtyards and solar-paneled rooftops. During the prototyping phase, small-scale initiatives like pop-up gardens were introduced to test the community's engagement with newly created green spaces. The testing phase revealed positive outcomes, with post-occupancy surveys indicating a 40% increase in the perceived safety of the neighborhood (Lucchi & Delera, 2020). Interaction Design methods were also employed, with wayfinding systems utilizing color-coded routes to assist older residents in navigating the area more comfortably, and mobile applications providing real-time channels for reporting maintenance needs. While the project successfully integrated both environmental and social sustainability elements, it faced limitations in maintaining scalable resident engagement, suggesting that future initiatives could benefit from more dynamic and continuous feedback loops facilitated by advanced interaction design approaches.

4.1.2. Case Study 2: Seoul, South Korea Public Apartment Housing (Yangnyeong Housing)

A comparative analysis of Design-Build (DB) and Design-Bid-Build (DBB) processes in large-scale public apartment housing projects revealed significant cost and time advantages associated with the DB approach (Park et al., 2015). Within the Design Thinking framework, stakeholder mapping played a crucial role in addressing communication gaps typically found between contractors and residents in DBB projects. The iterative prototyping process was notably enhanced in DB projects, where design teams utilized 3D modeling techniques to modify unit layouts in response to the varied needs of different family sizes. This approach fostered a culture of innovation, encouraging the adoption of advanced design and construction practices aimed at improving both efficiency and overall build quality. Collaboration among designers, contractors, and future residents was emphasized to ensure that the final outcomes reflected a balanced consideration of all stakeholder requirements. Interaction Design methods further strengthened this process, with the use of virtual reality (VR) walkthroughs allowing residents to experience and customize their units before construction commenced. Additionally, community mobile applications enabled residents to participate in decision-making processes, such as voting on preferred communal amenities like gyms or childcare centers. The DB approach ultimately achieved measurable benefits, with a 15% reduction in overall costs and a 30% decrease in project delays (Park et al., 2015). However, the reliance on digital engagement tools highlighted an area of concern, as older residents often faced accessibility barriers due to the inflexible nature of high-tech solutions, underscoring the need for more inclusive, low-tech engagement options in future projects.

4.1.3. Case Study 3: Housing First Initiative, New York, USA

The Housing First initiative focused on providing permanent housing solutions coupled with trauma-informed support services for individuals experiencing homelessness, moving away from punitive policies that criminalized poverty and homelessness (Herring et al., 2019). The Design Thinking approach was integral to the project, beginning with the empathy phase, where in-depth interviews with individuals having lived experiences of homelessness informed key design decisions, such as incorporating private bathrooms within housing units to restore dignity and privacy. During the ideation phase, participatory sessions with residents led to the co-creation of community kitchens, which served to foster peer support networks and collective well-being. Interaction Design strategies were also implemented, with trauma-informed navigation principles guiding the inclusion of softer lighting schemes and clear, simplified signage to minimize anxiety triggers within communal spaces. Furthermore, digital service access points were integrated through in-unit tablets, allowing residents to easily connect with healthcare providers, vocational training, and other essential support services. The initiative yielded significant positive outcomes, with reports indicating a 60% improvement in residents' mental health status. Nevertheless, the project faced challenges related to long-term sustainability, as unstable funding streams limited the broader adoption of advanced Internet of Things (IoT) technologies that could have further enhanced resident engagement and service accessibility.

4.1.4. Case Study 4: Mahila Milan Cooperative Housing, Mumbai, India

In Mumbai, a women-led slum-dweller organization collaborated with non-governmental organizations to successfully construct over 15,000 low-cost housing units using a participatory design approach combined with micro-savings initiatives (SPARC, 2020). The application of Design Thinking was evident from the outset, particularly during the empathy phase, where grassroots workshops highlighted the residents’ priorities, such as the incorporation of flood-resistant construction materials and the provision of dedicated childcare spaces within the housing design. Prototyping was approached through incremental home development, allowing families the flexibility to expand and modify their dwellings over time in alignment with their growing incomes. The project also made effective use of Interaction Design techniques, employing analog-digital hybrid systems, where traditional ledger boards tracking individual savings were progressively digitized through SMS notifications to improve accessibility and transparency. Additionally, simple icon-based community noticeboards were introduced to enable residents to crowdsource maintenance requests, making communication more inclusive, especially for those with limited literacy. The project achieved an impressive 92% resident satisfaction rate, reflecting its success in fostering community-driven housing solutions. However, persistent challenges remained, particularly concerning land tenure security, and the scalability of the model highlighted the need for stronger alignment between policy frameworks and interaction design interventions to ensure long-term sustainability and impact (Datta, 2015).

4.1.5. Case Study Comparative Analysis

Table 1 Comparative Analysis of Design Thinking and Interaction Design Across Case Studies

Aspect	San Siro	Seoul Apartments	Housing First	Mahila Milan
DT Stage Focus	Ideation & Testing	Prototyping	Empathy	Iterative Prototyping

IxD Tools	Feedback Apps	VR Models	Service Portals	Hybrid Ledgers
Sustainability	Environmental	Economic	Social	Socio-Environmental
User Engagement	High	Medium	Medium	High
Key Challenge	Scalability	Tech Accessibility	Funding	Land Rights

4.2. Research Analysis

This section consolidates insights from case studies and user research to present a structured understanding of how Design Thinking (DT) and Interaction Design (IxD) contribute to enhancing group housing projects. Through thematic analysis, comparative assessment, and integration of quantitative user inputs, the DT-IxD integration framework is established. The thematic analysis identifies three recurring challenges. First, the privacy versus community trade-off, where residents struggle to balance personal and shared spaces. In Milan's San Siro project, wayfinding systems and community participation enhanced safety and privacy; in New York's Housing First, private bathrooms promoted dignity; and in Mumbai's Mahila Milan, incremental home extensions allowed privacy customization. IxD solutions like modular layouts and feedback tools help resolve such trade-offs by enabling flexibility and participatory design. Second, sustainability in design and use emerged as a common theme, focusing on environmental, economic, and social integration. Seoul's public apartments used Design-Build for energy efficiency, San Siro applied retrofitting for energy savings and social cohesion, and Mahila Milan achieved low-cost housing through participatory micro-savings. This suggests sustainable design must equally address environmental and social goals through cost-effective, community-driven solutions. Third, user participation and feedback systems highlighted challenges in maintaining active engagement. Housing First showed positive impact through trauma-informed design but faced funding issues; Seoul used VR walkthroughs but struggled with accessibility for older residents; Mahila Milan used hybrid analog-digital noticeboards to broaden participation. This indicates IxD tools must combine low-tech and digital approaches to accommodate diverse user capacities and ensure inclusive, long-term engagement. Table 2 summarizes the key findings from the case study analysis.

4.2.1. Quantitative Insights from User Research

Table 2 Comparative Findings from Focus Groups and Surveys Further Validate Case Study Insights

Key Metric	Survey Finding (%)	Case Study Correlation
Privacy Preference	75% preferred semi-private communal spaces	Milan's modular courtyard approach
Sustainability Priority	70% ranked energy efficiency as a top concern	Seoul's DB model demonstrated cost-energy savings
Digital Accessibility	60% of older residents favored physical feedback systems	Mumbai's hybrid ledgers validated this preference
Community Engagement Tools	65% supported co-design platforms	NYC's service portals enhanced peer-to-peer interaction

4.3. Synthesis: Towards a DT-IxD Integration Framework

The synthesis highlights three core recommendations for improving group housing through Design Thinking (DT) and Interaction Design (IxD). First, empathy-driven IxD involves applying tools like trauma-informed wayfinding from New York City and hybrid ledger systems from Mumbai to promote inclusivity, while digital platforms such as Milan's mobile maintenance reporting help collect real-time resident feedback. Second, iterative policymaking focuses on aligning housing policies with DT-IxD cycles, as seen in Milan's participatory zoning and Seoul's iterative Design-Build refinements, ensuring continuous responsiveness to community needs. Third, scalable feedback systems recommend blending low-tech and high-tech tools, such as Seoul's VR walkthroughs paired with community boards, or Mumbai's analog-digital hybrids, to bridge generational divides and broaden participation. Collectively, these findings establish a DT-IxD integration framework grounded in empathy-driven design, participatory policymaking, and inclusive feedback mechanisms to create adaptable and resident-centered group housing solutions.

5. Framework for Maximizing Design Thinking and Interaction Design

Grounded in the case study analysis and literature review, the following framework is presented to maximize Design Thinking and Interaction Design in the case of group housing:

5.1. Phase 1: Knowing the Users

Empathize: Conduct detailed user research to grasp the requirements, needs, desires, and anxieties of future residents. This could include focus groups [2], interviews, surveys, and participatory design workshops.

Define: Express the major challenges and opportunities of designing group housing that caters to the diverse needs of its inhabitants. This can include the development of user personas, journey maps, and problem statements.

5.2. Phase 2: Generating Design Concepts

Ideate: Create a large set of possible solutions for common areas, privacy, community governance, and other issues of group housing design. This can include brainstorming, sketching, and mood boarding.

Prototype: Develop physical representations of the solutions being suggested to test and iterate on them. This can include making physical models, computer mockups, and interactive prototypes. Low-fidelity prototypes are particularly helpful.

5.3. Phase 3: Refining and Evaluating Designs

Test: Test the prototypes with prospective residents to gain feedback and iterate on the design. This can include usability testing, A/B testing, and surveys.

Refine: Refine the design and develop a final design solution based on the feedback collected during the test phase.

5.4. Phase 4: Implementing and Monitoring

Implement: Put the design solution into practice in a real environment.

Monitor: Track the performance of the design solution and collect feedback from residents.

Iterate: Iterate on the design repeatedly based on the feedback collected during the monitoring process.

5.5. Key Considerations

Along with the above four phases, the following important considerations must be kept in mind while designing the project:

1. Community Governance: Create a fair, transparent, and inclusive community governance structure.
2. Privacy: Provide sufficient privacy to the residents in their personal living areas.
3. Shared Spaces: Make the shared spaces functional, comfortable, and beautiful.
4. Sustainability: Include sustainable design elements in order to minimize the environmental footprint of the project.
5. Affordability: Create affordable housing for varied income levels.
6. Accessibility: Design the housing such that it becomes accessible to those with disabilities. Taking advantage of campus accessibility may increase disability consciousness.
7. Flexibility: Create flexible and adaptable housing to suit diverse needs and ways of life.

8. Technology Integration: Integrate technology to enrich the living experience, e.g., smart home functions and community communication platforms. Internet of Things (IoT) technologies can be utilized in this regard.

6. Challenges and Opportunities

6.1. Challenges

Applying Design Thinking and Interaction Design in the context of group housing has some challenges

1. Diverse Needs: Group housing communities tend to include people with varied needs, preferences, and lifestyles.
2. Conflicting Priorities: Residents can have conflicting priorities for common spaces, privacy, and community management.
3. Budget Constraints: Group housing projects are usually on shoestring budgets, which can limit the extent of design innovation.
4. Community Engagement: Involving residents in the design process can be time-consuming and demand expert facilitation skills.
5. Measuring Success: Measuring the success of group housing schemes may be problematic because it consists of both objective and subjective criteria. Measuring the performance of the building in use can offer much insight.

6.2. Opportunities

Although these problems may exist, adopting Design Thinking and Interaction Design for group housing also offers a myriad of opportunities:

1. Improved User Experience: With understanding and consideration of the requirements of residents, designers can make group housing an effective and enriching living experience.
2. Community Building: Design Thinking and Interaction Design can be employed to create a high level of community and social interaction among the residents.
3. Innovation: These approaches can result in innovative design solutions that respond to the specific needs of group housing.
4. Sustainability: Group housing can be made more sustainable, minimizing its impact on the environment and encouraging responsible use of resources.
5. Affordability: Design Thinking and Interaction Design can be applied to make housing more affordable, thereby making group housing more accessible to more individuals.

7. Future Research Directions

The following areas need to be focused on in future research to better refine Design Thinking and Interaction Design for group housing:

1. Establishing standardized metrics to measure the success of group housing projects.
2. Designing best-practice guidelines for community participation in the design process.
3. Investigating the application of virtual reality and other technologies for prototyping and testing group housing designs.
4. Researching the long-term social, economic, and environmental effects of group housing.
5. Investigating the policy and regulatory framework for encouraging the creation of successful group housing communities.

8. Conclusion

Maximizing Design Thinking for group housing using interaction design techniques can result in more effective, user-focused, and eco-friendly living spaces. By learning about the aspirations and needs of prospective residents, designers are able to come up with creative solutions that work to meet the specific challenges of communal living. This research paper has established a model for maximizing the design process and has made recommendations for establishing successful group housing communities. More research is needed to further streamline these methods and examine the long-term effects of group housing on people, society, and the environment.

The convergence of Design Thinking and Interaction Design provides an effective way to design group housing that not only satisfies the utilitarian requirements of its occupants but also develops a high level of community, supports social interaction, and improves overall well-being. By adopting such methods, architects, designers, developers, and residents can collaborate to design prosperous group housing communities that help make a more sustainable and equitable future.

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CRediT Authorship Contribution Statement

Tadiboina Samantha Kumar: Conceptualization, Methodology, Investigation, Writing – original draft, Writing – review & editing, Data curation, Formal analysis. Ramesh Srikonda: Supervision, Validation, Project administration, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data Availability

The data that support the findings of this study are available from the corresponding author upon request.

Ethics Committee Approval

This study did not involve experiments on humans or animals which require ethics committee approval. Informed consent was obtained from all interview and survey participants. Therefore, ethics committee approval was not required.

Resume

Tadiboina Samantha Kumar is a doctoral research scholar and assistant professor in Department of Architecture at the School of Planning and Architecture, Vijayawada, Andhra Pradesh, India. He holds a Bachelor's degree in Architecture from Jawaharlal Nehru Architecture and Fine Arts University, Hyderabad, and a Master's in Environmental Architecture from the Anna University, Chennai. He began his academic career as an Assistant Professor at the National Institute of Design, Andhra Pradesh, before pursuing his PhD. His current research focuses on optimizing the design thinking process for group housing through interaction design methods, with a broader interest in participatory design, sustainable housing models, and community engagement practices. He has contributed to design innovation projects, user-centered housing studies, and government-supported design research initiatives, reflecting a multidisciplinary approach towards housing design and policy development.

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Physical vs virtual: A multi-layered perception experience on memory through historic buildings

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Abstract

This study investigates the layered relationship between memory and perception through the experience of historic buildings in both physical and virtual environments. Drawing upon theoretical foundations in memory studies and architectural history, the paper aims to explore how architectural elements, spatial perception, and sensory engagement contribute to individual and collective memory formation. The selected case study, Bostancı Primary School building in Istanbul, designed by Mimar (Architect) Kemalettin in the early 20th century, provides a historical context with its architectural and socio-cultural significance. The building has maintained its structural integrity and unique architectural characteristics for years and continues to be used as an educational building today, albeit with a different function. Therefore, it has a strong place in urban memory and provides a strong foundation for exploring the relationship between memory and space through in-situ observations and experiences as a part of daily urban life. The methodology involves a three-phase experiential framework incorporating physical experience (PE), virtual reality experience (VRE), and memory representation through photographs, screenshots, and sketches. Twenty senior architecture students participated in structured experiences within the real and virtual building environments. Data were collected through their drawing of route mapping, image capture, written expressions, and memory sketches. Then they were analysed using a dual thematic framework of Architectural References (AR) and Sensory References (SR), interpreted through episodic and semantic memory models. Findings show that while architectural references were more frequently recalled in both physical and virtual reality environments, VRE yielded higher rates of episodic memory activation due to its ability to eliminate physical barriers and enhance spatial comprehension. Conversely, PE experiences more strongly activated semantic memory, as the embodied tactile nature of physical space provided deeper sensory engagement. Additionally, sketch analyses revealed that participants predominantly recalled historical architectural features, with minimal reference to recent alterations, underscoring the dominance of collective memory imagery over present-day functions. This research contributes to the interdisciplinary discourse on memory and perception by proposing a comprehensive model that evaluates how historic buildings are perceived and remembered differently depending on the mode of experience. It also highlights the potential of virtual technologies in architecture by facilitating complex, layered memory engagements beyond physical constraints.

Keywords: historic buildings, memory, perception, physical experience, virtual reality experience

1. Introduction

Architecture is more than just creating visually appealing images. It establishes connections between individuals and their environment, while conveying the relationships and meanings that arise from these connections (Pallasmaa, 2007, pp. 11). The meanings do not exist concretely in buildings. They are formed during the experiences of spaces by individuals, who perceive them not as mere collections of visual images but as fully embodied material and mental presences

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(Pallasmaa, 2007, pp. 44). Although this experience may initially focus on the sense of sight, as architectural works present pleasingly shaped and moulded surfaces (Pallasmaa, 2007, pp. 12), architecture engages all senses simultaneously. The physical space perceived through the integration of all senses gains meaning in the mind by associating images with experiences. What makes this mental formation possible is the memory.

Memory refers to acquiring, processing, storing, and later recalling information related to the built, natural, and social environment (MEMO, n.d.). Therefore, it is a subject of various disciplines, such as neurology, sociology, psychology, history, literature, and architecture, etc. In architecture, the studies primarily focus on urban memory, in which the city is considered a "collection of objects and practices that enable recollections of the past and that embody the past through traces of the city's sequential building and rebuilding." (Crinson, 2005, pp. xii). In this anthropomorphist concept, "a city remembers through its buildings, so the preservation of old buildings is analogous with the preservation of memories in the human mind." (Crinson, 2005, pp. xii). Urban and architectural memory is created by the physical transmission of architectural artefacts, especially through the historic buildings, from one generation to another. However, architecture and space are not isolated creations; in addition to their materiality, they also have conceptual content (Pallasmaa, 2007, pp. 41-44). This content emerges by recalling the memories on spaces through specific events, general knowledge, and facts accumulated over time, regardless of whether they have been experienced by individuals in the past.

The social environment is crucial in forming individual memory (Assmann, 1997, pp. 39). While societies do not possess a memory of their own, they significantly influence the memories of individuals. Individuals remember what they have personally experienced and the events and facts recounted and attributed meaning by others. This recollection occurs within a semantic context (Assmann, 1997, pp. 40). However, knowledge of human activities from an inexperienced past can be acquired by tracing the concrete remnants they left behind (Connerton, 1999, pp. 25). The more memory is related to unexperienced past and facts, the more it needs concrete traces that are perceptible signs of a fact no longer directly accessible (Nora, 2006, pp. 25; Connerton, 1999, pp. 25). These traces -such as a ruin, a narrative, an inscription, or a historic building- place the memory at the centre of the history as well as architectural history. In this context, architecture is not just a physical entity but a powerful tool in constructing memory, as it provides concrete and abstract links to the past.

In this memory construction, where memory has transformed into a need for history (Nora, 2006, pp. 24), architecture is used in its most concrete and abstract forms because memory emerges with people, time, and space. Historic buildings, in particular, play a significant role in this process, as they serve as physical and societal manifestations of the past, shaping the urban memory. These historic buildings, which are also included as architectural heritage, refer to buildings and/or building groups that reflect and -moreover, embody- the values of the cultural environment in which they exist, which need to be transferred to the future with their unique qualities.

Within this theoretical framework, the paper aims to uncover the relationship between memory and individuals' perception processes and patterns through their experiences in historic buildings. The significance of this study lies in its exploration of how historic buildings are not merely the physical collections of urban memory but also contain references to the multi-component nature of memory as the accumulation of knowledge and culture of the past. Within the scope of the research, the experiences of the Bostancı Primary School building, built by Mimar (Architect) Kemalettin in Istanbul in the early 20th century, in different environments are discussed.

The building was chosen as a case study not only for its stylistic characteristics and its architect but also due to its significance within the realms of architectural, urban, and collective memory. Primarily, the sustained preservation of Bostancı Primary School's original function as an educational building and structural integrity over years has contributed to its profound imprint on urban memory. Furthermore, its current use -albeit under a different function, yet still within the educational facility- provides a strong foundation for exploring the relationship between memory and space through in-situ observations and user experiences. This framework simultaneously enhances the methodological applicability of the study and facilitates systematic data collection.

Buildings like Bostancı Primary School, whose function has changed but which are still a part of urban life, are experienced physically, but the mind and heart remember them through the arrangement, modification, distortion, or erasure of previous experiences (Bastéa, 2004). In this act of remembering, the perception that shapes the experience cannot occur independently of the memories. The source of perception and the recollection of past experiences in memory collaborate to create the experience (Bergson, 2015; Squire, 1987). Memories interconnect them and carry the past into the present in the individuals' minds (Deleuze, 2006). This experience can be a direct physical one with on-site visits to the building, or today, it can be realised as a virtual experience (VRE) through digital technologies and environments (Figure 1).

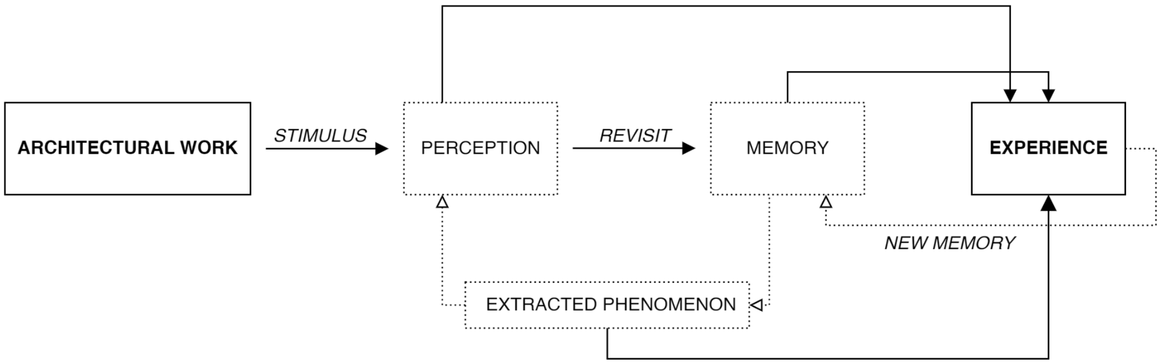


Figure 1 Relation of perception, memory and experience

Technological advances offer various ways to represent historic buildings, serving to preserve, reconstruct and conserve these cultural assets. Digital technologies also enable new possibilities for the sustainability of historical traces by integrating digital content and virtual layers into architectural artefacts. This is based on using computer-based technologies to document, preserve or recreate these artefacts with outstanding historical, aesthetic and cultural values. It also aims to offer digital experiences to a global audience, transcending time and space. Historic buildings bridge the gap between the past and future, representing a diversity of intercultural values including "symbolic, historic, artistic, aesthetic, ethnological or anthropological, scientific and social significance" (UNESCO,2009). Relationships established with historic buildings play an essential role in forming the collective memory of the past and the present. Therefore, studies on historic buildings today should have a multidisciplinary perspective and scope encompassing digital and historical methodologies.

In this manner, this paper presents a more comprehensive understanding of the perception and memorability of a historic building -Bostancı Primary School- in real-life and virtual reality environments. The study employs a three-phase experiential methodology to examine how memory and perception operate in physical and virtual experiences of a historic building, -Bostancı Primary School building. The research consists of a physical experience of the building (PE), a virtual reality experience of the building (VRE), and memory representations of these experiences through sketches, photographs, and verbal expressions. Data were collected from 20 senior architecture students through route mapping, image capturing, and memory sketching.

Thematic analysis was conducted using a dual-coding framework that classified participant responses into Architectural References (AR) and Sensory References (SR). To further explore the relational structures and saliency of these codes, the data were modeled using Graph Commons, a network mapping platform suitable for visualizing qualitative patterns through node-link structures. This visual-relational mapping was then supported by quantitative analysis. The weighted frequencies of each subcategory -AR: elements, AR: spaces, SR: interventions, and SR: materials- were aggregated and compared between two different experiences using the Wilcoxon signed-rank test which is suitable for small sample sizes and ordinal or non-normally distributed data. This two-step analysing approach combined qualitative pattern detection and quantitative statistical validation, yielding a comprehensive framework for assessing how architectural memory is shaped across physical and virtual environments.

The holistic approach of the study will develop a vision-based perception of space and enable the discovery of a comprehensive experience by integrating qualitative and quantitative features. Among all, it is believed that this research at the intersection of digitalisation and architectural history will not only establish a framework questioning the transformative impact of memory, perception, and experience but also ensure a widespread base for the digitisation of a historic building, and the dissemination of a layered perception of architectural history.

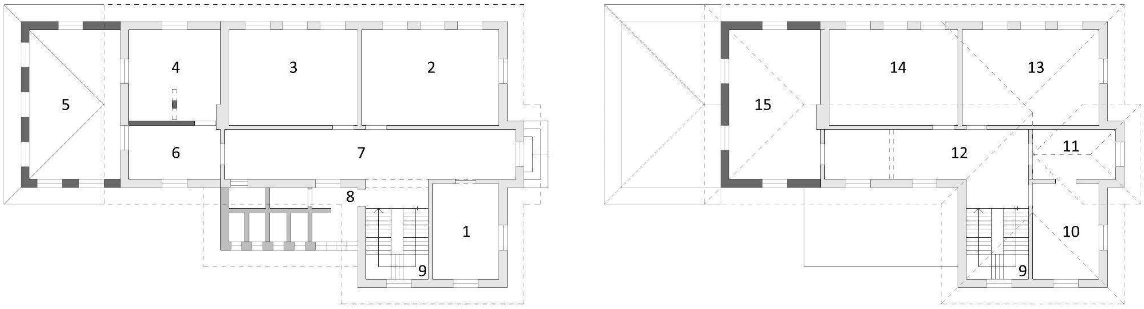
2. The Architectural Features of Bostancı Primary School Building

The school building, named initially İbrahim Paşa or Abdülhamid I Mekteb-i İptidaisi (Primary School), was a unique creation of Kemalettin, designed in conjunction with the Kuloğlu Mosque nearby. The exact construction date is a matter of debate, with some studies dating it to 1913 (Yavuz, 1995, pp. 127) and others to 1914 (Göktürk, 1963; pp. 3001-3002). However, an article from 1913, which reported that education at the school had commenced four months before its publication, suggests a construction date of 1913 (Yavuz, 2009, pp. 215). Today, the building serves as Halk Eğitim Merkezi (Community Center).

Kemalettin's architecture is a theoretical integration of the traditional Ottoman world with the Western world, both of which he experienced during his engineering education at Hendese-i Mülkiye Mektebi (Engineering School) and his studies of architecture in Germany, at the last decade of the 19th century. It emerged as a reflection of modernisation efforts of the Ottomans, primarily aimed to combine the classical elements with modern techniques and materials as an architectural counterpart of the socio-cultural transformations at the turn of the century. It is embodied through the socio-cultural and ideological perspectives of late Ottoman dynamics and incorporates stylistic references to previous eras' architectures, with tiles, wide eaves, domes, and pointed arches (Bozdoğan, 2001, pp. 16).

However, Kemalettin's architecture has a modern approach, aiming to develop an architectural idea with a particular linguistic unity, as well as the buildings' functions and spatial organisation, and how the spaces were used. Although he designed and built many buildings in Ottoman territory, educational buildings are the most prominent ones. The efforts to modernise the traditional education system since the late 19th century physically required new typology of educational buildings, which provided a foundation for Kemalettin to realise his ideas. These buildings architecturally employ new construction techniques and materials for contemporary functions with spatial design. Therefore, the Bostancı Primary School building, which still maintains its structural integrity today and continues to serve public functions despite changes in its original function, continues to exist as concrete traces of past activities that have not been experienced or perceived by the senses.

The school building had an L-shaped plan on two floors (Yavuz, 1995, pp. 127; Yavuz, 2009, pp. 215). The entrance on the short side is accessed with several steps, approximately half a floor in height (Yavuz, 2009, pp. 81). In the building (Figure 2), there was one room on the left side of the main entrance (no. 1) and two rooms on the right side of the hallway (no. 2 and no. 3) on the ground floor. Directly opposite the main entrance is a single-story, pitched-roofed large space at the end of the hallway. Later, it was divided into a secondary corridor (no. 6) and a room with an additional wall and structural column (no. 4). The toilets in the single-story addition next to the stairs on the ground floor (no. 8) are not included in the original drawings, and it is unknown whether they were added during the construction or a later repair. A new large single-story space (no. 5) with a pitched roof has been added at the end of the hallway, facing the entrance. The back door leading to the courtyard directly here is now closed. In the original building, the upper floor plan is the same as the ground floor, consisting of a room on the left side of the hallway (no. 10) and two rooms on the right (no. 13 and no. 14). In a later repair, a space was added to the upper floor of the large single-story area (no. 15). The hallway (no. 12) above the entrance has been partitioned by a wall, transforming it into a closed space, a room (no. 11). Thus, over the years since its construction, the original building has been continuously expanded with additions according to needs, taking on its present form.



Ground Floor: Office (1), Library (2), classroom (3 and 4), atelier (5), open office (6), corridor (7), wc and kitchenette (8), staircase (9); Upper Floor: corridor (12), office (10 and 11), classroom (13 and 15), office -manager room (14).

Figure 2 Floor plans of the current state of the building (Bold parts are later additions)

On the symmetrical front facade (Figure 3), the entrance is extended outwards, rising throughout the entire building height and surpassing the roof level (Yavuz, 1995, pp. 127; Yavuz, 2009, pp. 81). Thus, the main entrance axis of the building was highlighted, as in Kemalettin's other school buildings. The building has brick masonry walls covered with a tiled, pitched wooden roof and wide eaves (Yavuz, 2009, pp. 81-215). On all grouted and mortared facades to give the impression of masonry, there are rows of windows with pointed arches on the ground floor and rectangular lintels on the upper floor (Yavuz, 1995, pp. 127; Yavuz, 2009, pp. 81-215). In the original building, these window rows were in groups of three but were individual in later additions. On the facades, the floors are marked with horizontal mouldings. The mouldings following the pointed arches on the windows on the ground floor are connected at the level of lintels, creating a continuous band around the entire building (Yavuz, 1995, pp. 127; Yavuz, 2009, pp. 81-215). These features, typical to the Ottoman architecture, contribute to the building's unique aesthetic and historical significance.

Figure 3 The facades of the building

Bostancı Primary School building holds a significant place in history due to its unique combination of structural and conceptual aspects, making it a notable representation of the educational buildings designed during this period. It has managed to preserve both its structural and architectural integrity, largely maintaining its originality, and exist in harmony with the environment. Furthermore, its relationship with an important person -Mimar (Architect) Kemalettin-, and an institution also attributes the building more remarkable historical significance in urban memory. The building also holds documentary value regarding the socio-cultural aspects of its era, as well as technical knowledge, skills, materials, and craftsmanship. Even though the building is re-functioned with changing social patterns, the continuity of its usage increases its significance by preventing it from belonging to a specific period historically.

3. Perceptive Memory Framework on Historical Building Experiences: Bostancı Primary School

Despite its close connection with the past, memory is a present action (Nora, 2006, pp. 19). It is a deeply personal process, where facts are stored in memory only after they have been experienced, perceived, and mentally operated by individuals. It involves the merging of concepts and images, making them inseparable (Assman, 1997, pp. 42). This union of concepts activates memory by attributing semantic content to experiences based on senses, further emphasising the personal nature of memory processing.

In architectural literature, the concept of memory is often viewed as an accumulation created by the physical presence of buildings. However, this research takes a different path. It considers "the succession of events as constituting a city's memory, providing a unique psychological context for understanding the city." (Crinson, 2005, pp. xiii). This departure from existing methods and incorporating a broader, multidisciplinary perspective that includes psychological aspects is a step in terms of architecture.

In memory studies, the initial classifications are based on short-term and long-term memory (James, 2007; Radvansky, 2011). Short-term memory is where information is temporarily stored before being transferred to long-term memory and where the information stored at once is limited. Long-term memory, however, enables storing information that a person has acquired, learned and experienced throughout life. The first classifications of long-term memory were declarative and procedural memory (Figure 4). This classification was expanded in subsequent studies to include procedural, perceptual representation, semantic, primary, and episodic memories (Schacter & Tulving, 1994). Since procedural memory lacks a consciously controlled structure and its output is non-cognitive (Schacter & Tulving, 1994), the research focuses on declarative memory and its subtypes shaped by cognitive perceptions. In this manner, declarative memory, where conscious remembering is possible, contains information about experienced events or general knowledge and facts. It has two subtypes: (1) episodic memory which includes memories and events, and (2) semantic memory which includes semantic and factual data.

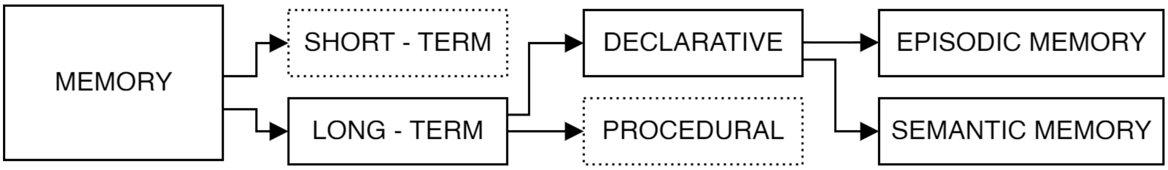


Figure 4 Memory types within the scope of the study

Episodic memory enables storing and recalling experienced events by establishing a relationship with time and space. The reproduced, subjective and spontaneous knowledge of the past includes time and spatial information (Broad, 1925; Brewer & Pani, 1983). However, semantic memory is where general information, facts, definitions, and meanings are stored without being associated with time or space. It is the conscious, objective and spontaneous knowledge of the past, including time and spatial information (Broad, 1925; Brewer & Pani, 1983). In this context, the paper intends to discover how perception transforms architectural experience by working as a memory filter through historic buildings, how this layered reading, created in physical perception, would differ when experienced virtually, and how perception processes transform in different environments. The framework is based on various layers created to explore this dynamic and dialectical process of episodic and semantic perception.

Understanding the complex relationship between these layers necessitates the inclusion of individual memory data for a more comprehensive perspective rather than a linear reading of history. In the theory of architectural history, the dynamic and dialectical context is often presented through a historical montage rather than a linear reading (Coles, 1999). The relationship between past and present is temporal, iconic, and dialectical, replacing the metaphors in discourse with ones akin to memory, perception, and experience. Historical knowledge no longer seeks to retell the sequence of events but compresses them into a dense iconic simultaneity while semantically intertwining them (Benjamin, 2016). Therefore, to enable a multi-layered and dialectical reading of a historic building in the context of episodic and semantic memory, a three-stage experience (Figure 5) has been created based on different layers of experience, perception, and memory, embodying them with various representations.

The experience was carried out with the voluntary participation of 20 architecture students who were carefully selected from the 4th-year grades because of their more comprehensive knowledge of architecture. All the students, aged between 22 and 25, had resided in Istanbul for at least four years and as a result of their academic coursework and daily experiences, they possessed detailed knowledge of historical buildings and could readily recall information related to the architectural features of Bostancı Primary School. Most of them had prior exposure to virtual reality technologies through their coursework or personal interest. Approximately 85% had used VR at least once before. All participants had foundational training in freehand drawing and experience with digital design tools. While this demographic provides consistency in architectural knowledge, it also limits generalizability beyond this population (Mikropoulos & Natsis, 2011).

Firstly, as a preliminary phase, a short seminar session was held by the researchers on the socio-cultural aspects and the architectural features of the period in which the building was designed, as well as the architectural approaches and designs of the leading Ottoman architects. This session aimed to activate short-term memory by having participants recall information they learned in the previous years of their architectural education on late Ottoman architecture and architectural history. Since many of the buildings built during this period still exist in Istanbul, the city where the participants live, and are actively used in daily life, the participants are already familiar with the architecture of this period. With the seminar, their awareness that the architecture of this period is not excluded from today's urban life and architecture was increased. However, Bostancı Primary School was excluded from the scope of this seminar so that it was not directly decisive in memory during experience.

Experience (Mapping with the walking route and stopping points): Subsequently, a visit to Bostancı Primary School, both physical (first phase) and virtual (second phase) was arranged. In order to allow each participant to perceive the building in its unique form, free from the influence of others, these visits were conducted individually under the supervision of the researchers. Thus, in order to enrich the research experience, the diversity of perceptual differences that the effects of spatial experience on memory and recall will cause among individuals were also included in the research.

A study based on on-site observation and experience was conducted in the building for physical experience (PE). During this physical experience, each participant was taken into the building one by one under the supervision of the researchers and wandered freely individually for 15-20 minutes. Moreover, the building was modelled in 3D with all its details and features, and a study was carried out based on observation and experience in the virtual reality experience (VRE). The virtual reality experience was conducted by participants' own computers in an indoor setting. Each participant individually navigated the virtual environment for 15-20 minutes, without external guidance, to maintain experiential authenticity. The VR model was developed using detailed 3D scans and architectural modeling software, ensuring spatial accuracy. The freedom to explore without physical constraints enabled a more holistic perception of spatial configurations. This aligns with current research suggesting that embodied spatial interaction in immersive VR environments enhances episodic memory retention (Slater & Wilbur, 1997).

While the participants were physically and virtually experiencing the building, they were given pre-prepared leaflets and asked to mark the routes on the floor plans of the building they followed and the stopping points on this route. The leaflets included drawings of the building's original floor plans, in particular; thus, it was questioned whether the participants would notice the latter added spaces or changes in the building.

Perception (Photographing selectively and consciously): Participants were assigned to take ten photographs during the PE and ten screenshots during the VRE that attracted their attention or impressed them and mark their exact points on the floor plans of the building.

Memory (Making sketches based on remembering): As drawing activates embodied cognition and spatial recall, providing a bridge between perception and memory (Pallasmaa, 2007), after experiencing the building physically and virtually, they verbally expressed why they took photographs and screenshots and drew four sketches of what they remembered. All memory sketches were completed within 15 minutes after each experience session to capture impressions while memory was still fresh. This timing was consistent for both physical and virtual experiences, which is considered crucial in capturing vivid episodic recall (Epstein & Vass, 2014).

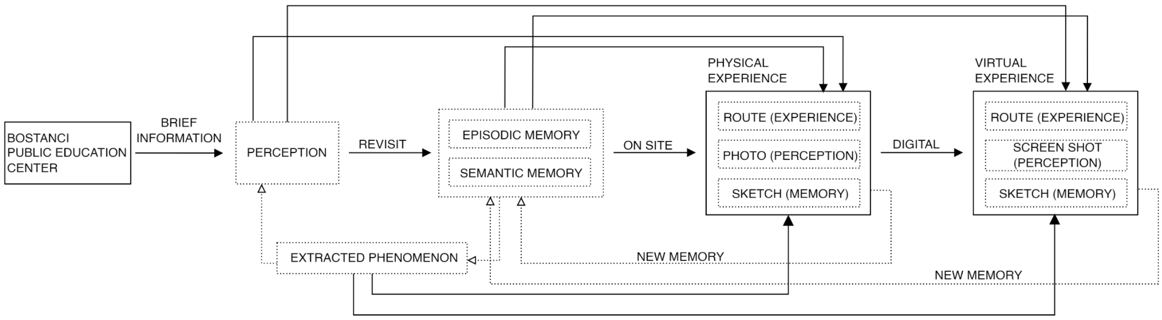


Figure 5 Framework of the experiences

In light of the diverse participant experiences and the variety of outputs collected, a concept-driven analytical approach was employed to identify both episodic and semantic parameters, categorized under two main themes: *architectural references (AR)* and *sensory references (SR).* This dual framework was designed to capture both the objective and subjective dimensions of memory. Through a detailed content analysis of photographs, screenshots, sketches, drawings and textual narratives of the participants, subcategories began to emerge, focusing on *spaces*, *materials*, *architectural elements*, and *interventions*.

To further explore the interrelations between these categories, a relational matrix was constructed. This matrix enabled the systematic categorization of all representational forms, mapping each data point under the broader headings of architectural references and sensory elements, and subsequently organizing them within the aforementioned subcategories. These representations of the participants include *arched window rows*, *staircases*, and *landings*, which are classified as *architectural elements*; *spatial integrity*, *additions*, and *spatial perception*, categorized under *spaces*; *columns*, *decorative objects*, and *furnishings* as *interventions*; and materials such as *wood* and *marble*. However, determining whether a particular item belongs to the domain of architectural references or sensory references necessitates a more nuanced and interpretive analysis.

A holistic examination of participant representations -particularly through semantic analysis of textual expressions- revealed that individual concepts often span multiple categories. For example, *arched window rows* may be associated with both *architectural references -element*, *sensory references -element*, and *sensory references -intervention*. Likewise, the concept of a *wooden staircase* may be interpreted within the contexts of *architectural references* as an *element*, *architectural references* as a *material*, or *sensory references* as a *material*. Similarly, when a drawing and accompanying narrative emphasize *natural light*, the focus may be situated within the *sensory references as spatial* category. The term *room entrance*, depending on the context, can be interpreted either as an architectural element or as a spatial feature.

To deepen the analysis, the study utilizes Graph Commons, a collaborative platform for data mapping and network analysis. This tool enables a sequential examination of parameters through the application of centrality analysis, which helps to sort and identify key nodes within the network. By employing PageRank centrality measures, the most influential parameters in the system are identified. Each code served as a node, while co-occurrences or narrative linkages within individual responses formed the edges. Node centrality and influence were quantified using PageRank algorithms, enabling identification of dominant architectural and sensory elements in participants' memory formation (Brandes & Erlebach, 2005). Additionally, the mappings are interpreted through density zones, defined by the spatial coordinates of the participants' data. Combined with centrality metrics, this spatial analysis offers a comprehensive view of the collective perceptual memory experience.

3.1. Experience 1: Stopping Points of the PE

It is noteworthy that stopping points of the PE accumulate in specific areas (Figure 6). Especially on the ground floor, they spread towards the interiors; however, on the upper floor, they are focused on the entrance areas of the rooms (R). This is related to various new decorative objects in the ground floor hallway (referring to interventions as SR), preventing the holistic perception of the space. The primary stopping point is the central intersection zone on the hallway (Figures 7A & 7B), where the entrances of R2 & R3 (spaces as AR) (Figure 7C) and the staircase (elements as AR) (Figures 8A & 8B) are met. It was decisive that the spatial integrity of rooms (spaces as AR) was perceptible and that the arched window rows (elements as AR) were clearly visible from the room entrances. This intersection, the brightest point of the hallway (elements as SR) due to the natural light from the windows on the wall in the stairwell, also defines a point where the original wooden staircase (elements as AR and materials as SR) is perceived entirely. On the wall surrounding the hallway, there are original arched windows (interventions as SR) that were closed and lost their function due to the latter added toilets (spaces as AR) (Figure 7D).

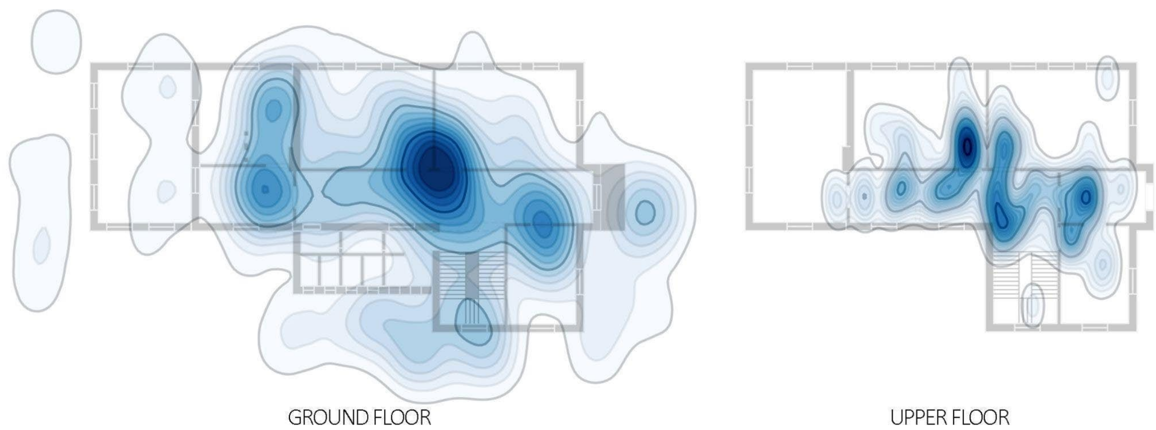


Figure 6 Stopping points of the PE

The secondary stopping points in R4 & R6 (Figures 7E & 7F) seem to be related to changes in the building over time, such as the structural column (interventions as SR), which is a later addition and not present in any of the other rooms, and the lower ceiling height (spaces as SR). While the furnishings (interventions as SR) do not allow easy circulation within R5 (Figures 7G & 7H), the stopping points can be described as the points where the arched door (elements as AR), located between the original arched window rows but closed today (interventions as SR), can be perceived as a whole. However, to a small extent, the others accumulated in the entrance area of R1, which is on the left side of the main entrance. This is related to the bordering wall (elements as AR) at the right side of the main entrance (spaces as AR), and the entrance to R1 (elements as AR) is the first one inside the building. The density of stopping points in the staircase landing (elements as AR) is associated with the windows (elements as SR), that allow the silhouette of the mosque built next to the school building to be seen and perceived from the inside.

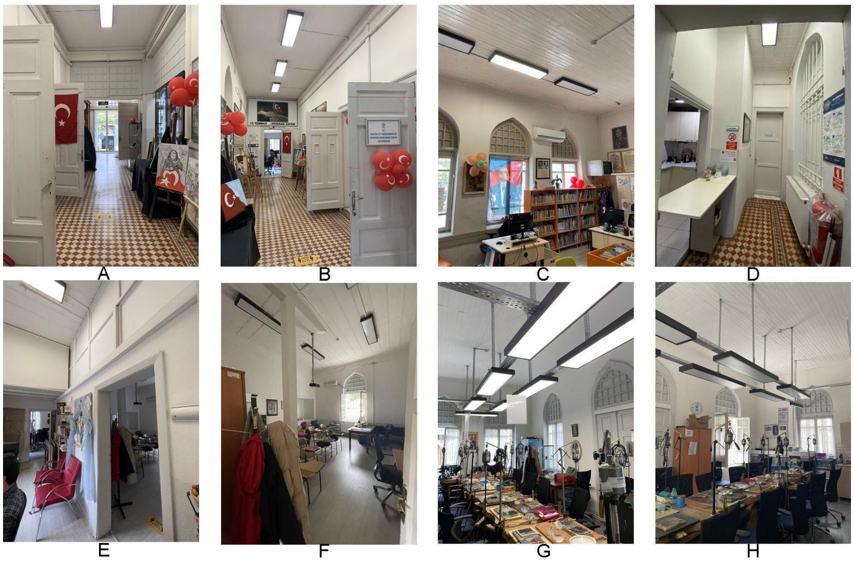


Figure 7 T photographs from the ground floor during the PE

The concentration of stopping points in the hallway on the upper floor is related to its central location within the building, allowing all rooms to be easily perceived from this area (spaces as AR). The window rows (elements as AR) of this narrow hallway (spaces as SR) provide a holistic view of the mosque nearby (elements as SR). The concentration of stopping points in R11 (Figures 8E & 8F) is associated with the changes that have occurred in the building over time, such as the later addition of the wall where the doorway to this room is located and the closure of the original door connecting it to R10 (interventions as SR) (Figure 8C). The concentration in the entrance area of R14 (Figure 8G) is related to its being the first space encountered (spaces as AR) on this floor and receiving ample natural light (spaces as SR).

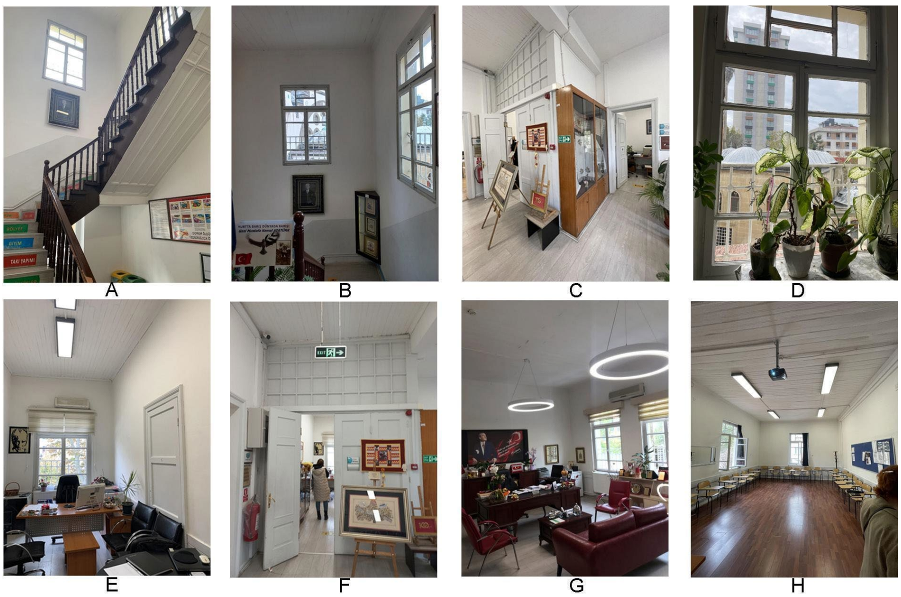


Figure 8 Photographs from the first floor during the PE

Stopping points in the experience outside the building are mainly concentrated on the original few-stepped main entrance (elements as AR) and the courtyard extending from the area between the mosque and the building to the rear. Therefore, the stopping points regarding the PE seem to be determined in connection with the historical architectural references, such as the original elements and materials of the building (elements as SR and materials as SR), original spaces and changes over time, and the historical atmosphere and environment provided by their holistic perception (spaces as SR).

3.2. Experience 2: Stopping Points of the VRE

Unlike the PE, the stopping points of the VRE appear to be more homogeneously distributed inside the building (Figure 9). Architecture students' familiarity with the virtual reality environment and the representation of spaces with 3D digital models might have been decisive due to the computer-based design tools they used. The VRE of the building may have been perceived as a computer game, regarding the similar experiences of spaces in the games they have already played. The opportunity for free navigation within the VRE inside the building without encountering any physical barriers seems to have been utilised as an advantage. Based on the connection between stopping points and the structural features of the building, especially on the ground floor, similar to the PE, the holistic perception of original architectural elements and materials (elements as SR and materials as SR), spaces, and historical references (spaces as SR) is prominent.

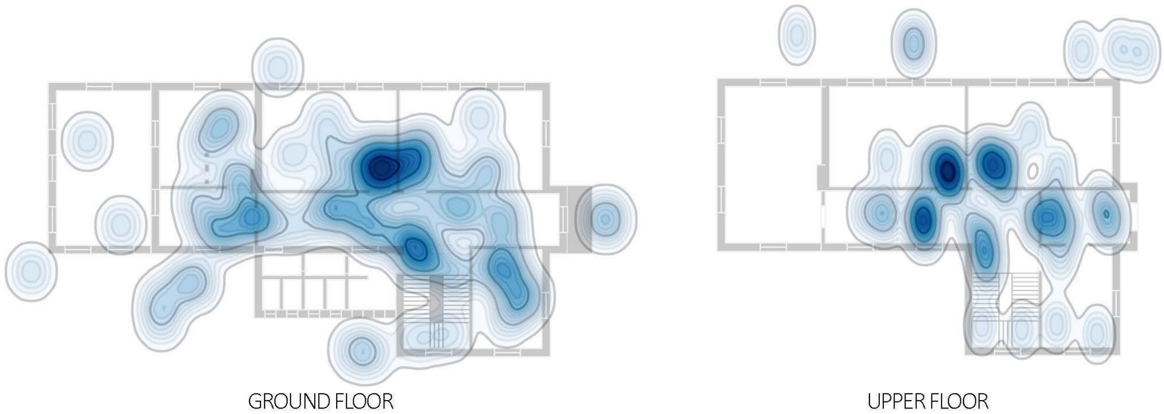


Figure 9 Stopping points of the VRE

The VRE enables spatial exploration by looking from above or outside the building, which is not included in the PE (Figures 13I, 13J, 13K). Significantly, while eliminating physical obstacles such as furnishings in rooms 5 and 11 (Figure 13E), the virtual reality environment allows experiencing some specific areas that cannot be physically experienced (spaces as AR). Even though the movement area during the experience seems more limited in the VRE than the PE, it is associated with the holistic spatial perception in the VR environment, even when stationary at a point.

3.3. Perception 1: Photographing Points of the PE

There is a significant parallelism between the photographing points and stopping points of the PE (Figure 10). The main difference is that various areas within R5 were more accessible for photography due to the closed door between the arched window rows. Another difference is the decreased significance in the photographing points of the entrance area of R14, where the stopping points on the upper floor are concentrated, and a greater concentration of photographing points in the hallway (Figure 8D) leading the stairs. It is due to the perceptibility of the structural integrity of the original wooden staircase (materials as SR), receiving natural light from both sides (elements as SR) and the view towards the mosque. Photographing points are not prevalent in the upper rooms since the window rows are rectangular rather than arched.

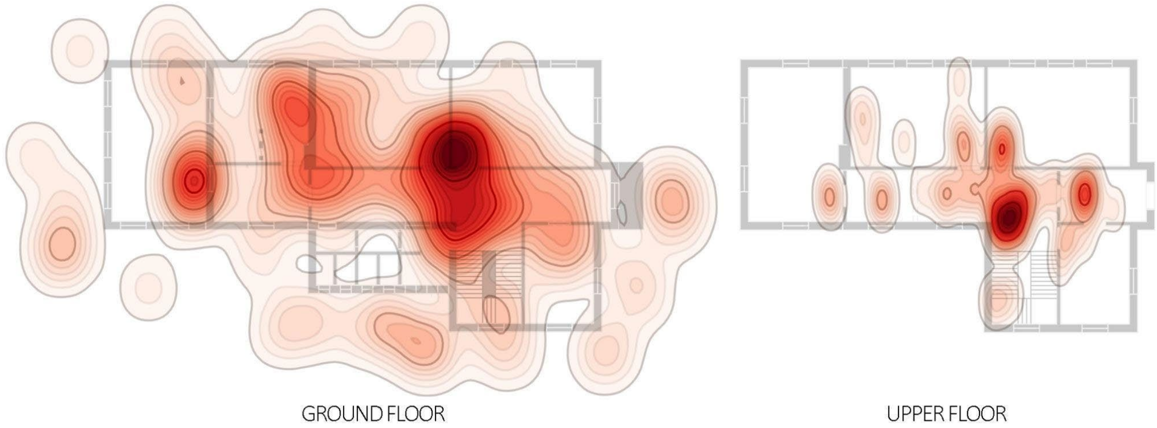


Figure 10 Photographing points of PE

Like stopping points of the PE, the photographing points in the experience outside the building mainly concentrate on the original few-stepped main entrance and architectural details (elements as AR) on the facade (Figure 11). Therefore, the photographing points seem to be determined through the historical view provided by their holistic perception (spaces as SR).

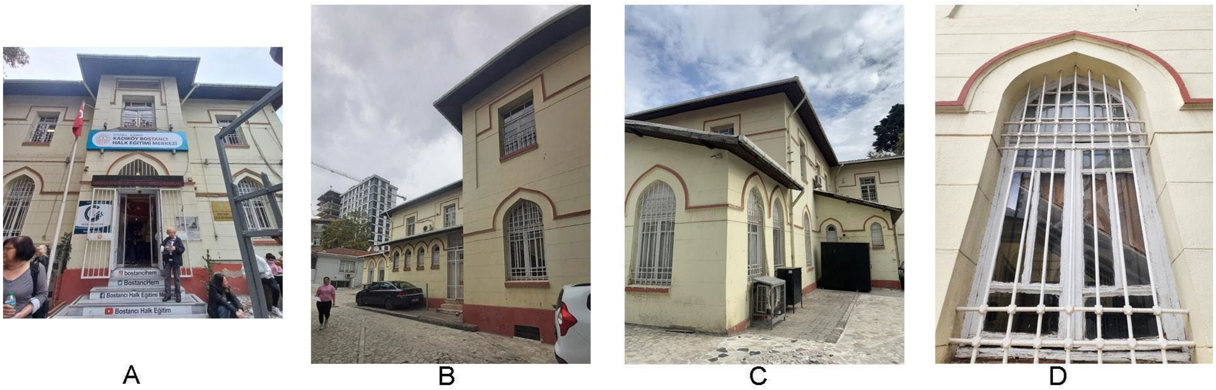


Figure 11 Exterior photographs during the PE

3.4. Perception 2: Screenshotting Points of the VRE

The screenshot points of the VRE are concentrated at a single point (Figure 12) that allows the entire perception of the vertical void defined by the staircase (element as AR and spaces as AR), particularly on the ground floor. The density observed in rooms when photographing physically has become less significant when screenshotting virtually. The density of R2 & R3 (Figure 13E) in virtual stopping points is not included in screenshotting points. No screenshots are taken from the inside of room 5 in the VRE, parallel to the decrease in other rooms. The spatial distribution of photographing points for the building externally tends to decrease in VRE compared to PE, but gathering more specifically at some points.

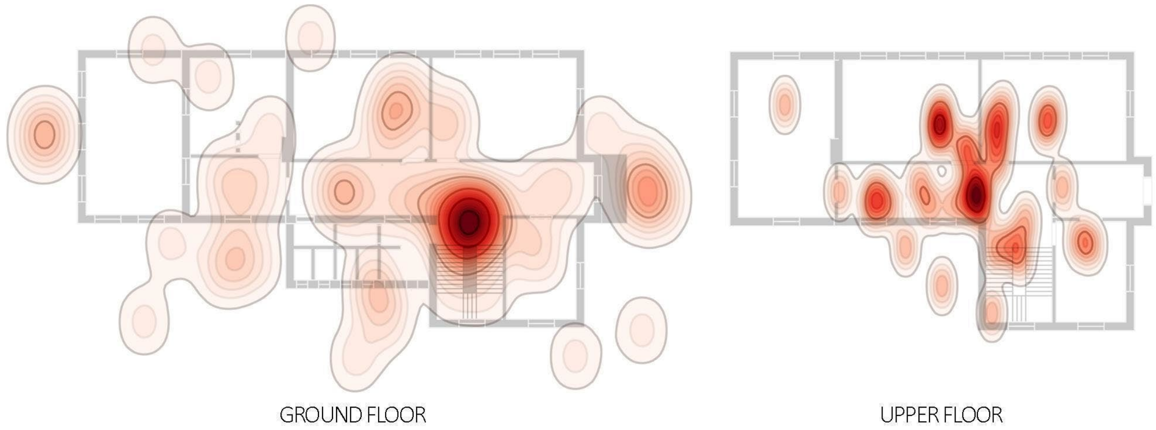


Figure 12 Screenshotting points of the VR

There are no significant differences between the photographing and screenshotting points on the upper floor during both experiences. In the VRE, screenshotting points are concentrated in the area (spaces as AR) leading to the staircase in the upper-floor hallway (Figures 13F, 13G, 13H). The ease of navigating through all spaces without physical barriers in the VR environment has slightly increased the density of screenshot points within R13 & R14. The concentration of photographing points in R12 during the PE has diminished in the VRE by shifting towards R15 along the hallway. The relation to the mosque view through the corridor windows (elements as SR) is also similar when comparing virtual stopping points with screenshotting points.

Despite the virtual stopping points being above the building when perceiving the exterior of the building, they are not included in screenshotting (Figure 13). This seems about the more easily perceivable overall interior in the VR environment. Visuals such as cross-sections and section perspectives of the building among the VRE screenshots have created new perceptions that could never be achieved in the PE.

Figure 13 Screenshots during the VRE

When the written expressions of participants about the reasons for photographing and screenshotting for both PE and VRE are mutually analysed with the visual contents, the senses created inherently by the architectural and spatial references of the building in their memory are remarkable. Among the specified reasons for taking photographs and screenshots, elements, materials (a variety of original ones and later additions), historical details (arched windows and doors, columns, decorative elements), and recent interventions (spatial arrangement of the new function, decorative objects) are included.

3.5. Memory 1 & 2: Sketching Points of the PE & VRE

Two main points are noticeable when the sketches made after PE and VREs are analysed (Figure 14 & Figure 15): (1) details related to architectural elements (elements as AR) and (2) overall views of the facades (elements as AR). Sketches mainly include historic architectural elements such as the original staircase, wooden details, pointed arched window rows and decorative elements (elements as AR). The newly added columns, doors that closed and lost their function, and later additions related to the newly spatial arrangements of the building over time are also prevalent among the sketches (interventions as SR). However, the sketches do not represent any recent architectural interventions.

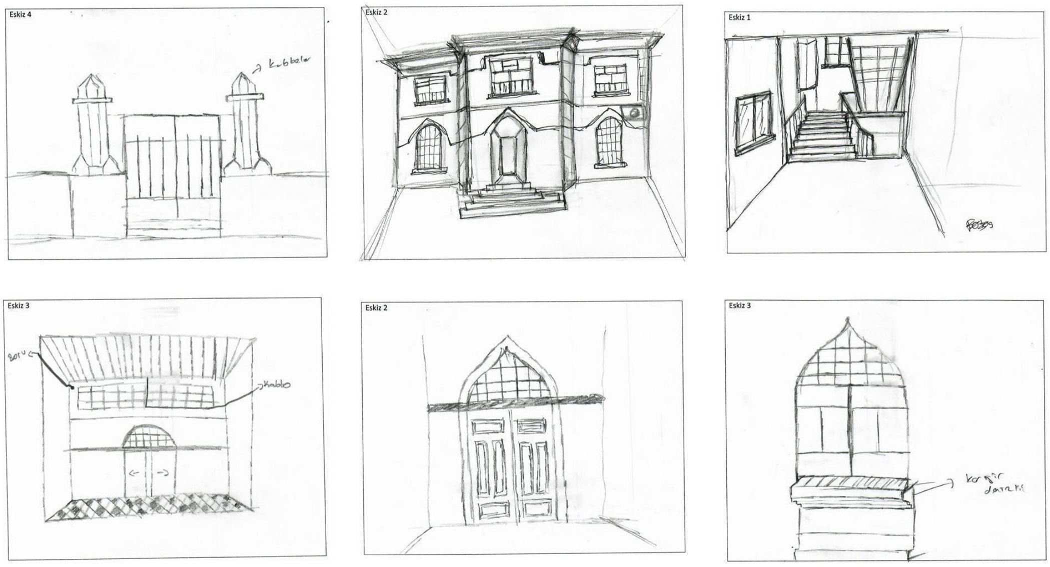


Figure 14 Sketches after the PE

In the sketches of the VRE, the drawings of the facades are included more extensively in a general view concerning the scaling and holistic perception opportunity provided by the virtual reality environment. No significant difference is included between PE and VREs in sketches of the specific spaces containing architectural references. It stands out that the accumulation of historical layers and references in the memory and the reflexes regarding the spatial perception of being an architecture student.

Figure 15 Sketches after the VRE

4. Results and Findings

Experiencing the building both physically and virtually and describing these experiences through multiple forms of representation revealed a multi-layered structure of memory formation, supporting both individual perception and collective accumulation. This framework, where architectural references are interpreted through episodic memory and sensory references through semantic memory (Figure 16) is parallel with Slater and Wilbur (1997), who emphasize that virtual environments foster episodic encoding, while real-world sensory input triggers deeper semantic associations.

EXPERIENCE	TASK	VALUE	OVERALL	VALUE	VIRTUAL/PHYSICAL	VALUE	TASK RELATED	VALUE	OVERALL	VALUE	VIRTUAL/PHYSICAL	VALUE
VIRTUAL	SCREENSHOTS	0,2	ARCHITECTURAL REFERENCES	0,316	ARCHITECTURAL REFERENCES	0,165	ARCHITECTURAL REFERENCES	0,13	ELEMENT	0,202	ELEMENTS	0,11
							SENSES	0,07			SPACES	0,098
	SKETCH	0,05			SENSES	0,085	ARCHITECTURAL REFERENCES	0,035	SPATIAL	0,164	INTERVENTIONS	0,026
							SENSES	0,015			MATERIALS	0,018
PHYSICAL	PHOTO	0,182	SENSES	0,181	ARCHITECTURAL REFERENCES	0,151	ARCHITECTURAL REFERENCES	0,1	INTERVENTION	0,086	ELEMENTS	0,092
							SENSES	0,082			SPACES	0,066
	SKETCH	0,065			SENSES	0,096	ARCHITECTURAL REFERENCES	0,051	MATERIAL	0,05	INTERVENTIONS	0,06
							SENSES	0,014			MATERIALS	0,032

Figure 16 Page rank values of each parameter

When participants' photographs, screenshots, sketches, and verbal outputs were analyzed through their repetition frequency and visual links (as visualized in Graph Commons), architectural references (0.316) emerged 1.74 times more recognisable than sensory references (0.181). This suggests that participants rely more on their episodic memories, regardless of their environment. And it supports Cummings and Bailenson's (2016) observation that spatial legibility and clarity in VR lead to enhanced cognitive mapping and spatial memory, even when multi-sensory feedback is limited. However, the interpretive reflexes of the architecture student participants, as highlighted in Mikropoulos and Natsis (2011), may have played a reinforcing role in prioritizing architectural impressions over sensory ones.

More specifically, architectural references in VRE (0.165) exceeded those in PE (0.151), likely because VR eliminated the physical and perceptual barriers of real-world navigation, allowing the building to be perceived effectively as a whole. On the contrary, sensory references in PE (0.096) were more prominent than in VRE (0.085), which supports Pallasmaa's (2007) assertion that physical experience engages the full body and sensory memory -including touch, atmosphere, and temperature- which VR still cannot fully replicate. Individual internalisation based on direct touch and immersive feeling through the historical atmosphere in-real and the sense of belonging to and the social-cultural awareness of the historic building provided by the PE triggered semantic memory. Moreover, the perception focuses on architectural elements, spaces, interventions, and materials in both experiences (Figure 17), where meaning and materiality become integrated over time.

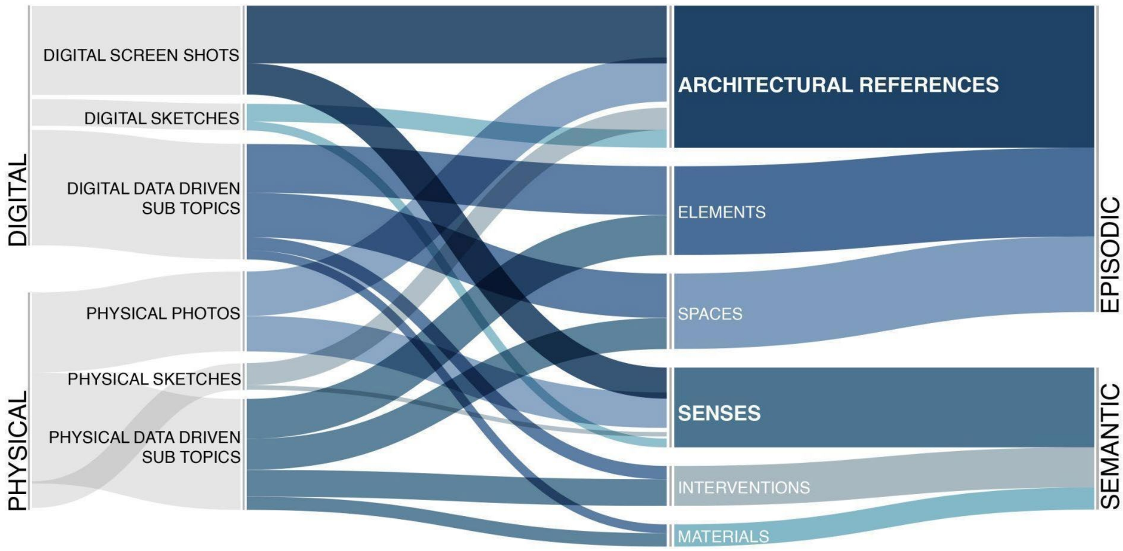


Figure 17 Relational analysis of parameters

In the analysis of subcategories, architectural elements (0.11) and spatiality perception (0.098) were more prominent in VRE, while interventions (0.06) and materials (0.032) were more vivid in PE. This further indicates the episodic and semantic memory distinction and is consistent with Brewer (1986) study that emotionally salient or symbolically charged elements are more likely to be encoded into long-term memory. Despite the dominance of sensory references in both experiences, participants consistently expressed architectural references more frequently in their post-experience sketches, especially in the PE, similar to Pallasmaa's (2007) theory that drawing is an extension of embodied memory and also visual and tactile cognition. Additionally, it reveals the superiority of VRE over PE and episodic memory over semantic memory through the perception of a historical building.

On the other hand, when different representations in PE and VRE experiences such as photographs, screenshots and sketches are examined in detail, architecture is used to activate memory through senses, with all its visual and physical features. In PE and VRE, participants' stopping points are not arbitrary but meaningful about the conceptual content of the architecture and space and its material existence. The exact places they prefer as stopping points are those where they can best perceive the historical and semantic qualities of the space, which is related to the recall and remembering processes of memory. The participants tended to perceive a past physically they had never experienced through these concrete architectural signs on the historical building that do not belong to the present, such as the entrance hall, staircase, courtyard, doors and windows. These were not arbitrary but selected according to their memory's need for symbolic anchors, echoing Assmann's (1997) notion of cultural and collective memory, in which historically embedded architectural elements act as figures of memory that transcend time and space. So these architectural elements, primarily perceived through the sense of sight, have gained a broader content related to semantic memory in the participants' minds beyond visual elements through the images they create by activating the senses.

Since the architectural images photographed focus on the participants' perceptions of the environment, its content is produced consciously and individually. However, although they present a focused view of the widest environment in which the individual is located, they are produced as visual images that will include the space and the unique atmosphere created by this space in the most specific way. In this context, the senses created inherently by the architectural and spatial references of the historic building in their memory individually seem to have been decisive in determining the photographing and screenshotting points. Although there are differences between PE and VRE, the perception of the concreteness of the space by integrating all senses and the determination of the focused vision by associating images with an experienced or inexperienced past in mind are related to memory. However, in this experience, the presentation of focused visions as an accumulation of historical references reveals the relationship of the past established with memory through recalling. Participants' tendency to focus on past-related, historical features of the building (e.g., original windows, materials, decorative elements) instead of recent interventions, and their inclusion only of historical elements in sketches in both PE and VRE, reflect Crinson's (2005) framing of architecture as a palimpsest of memory. Ultimately, the act of sketching and photographing these spaces suggests an attempt to reconcile personal perception with cultural continuity -a process described by Brewer (1986) as the transformation of sensory input into symbolic memory through visual imagery. On the other hand, the holistic presentation of the drawings reveals the role of the visual images and symbol of remembrance in memory recall. Especially given their educational background, it demonstrates how collective memory and architectural training intersect, making the experience both personally reflective and historically rooted. It also refers to Assmann's (1997) view that what is remembered is often shaped by collective references rather than present functionality. This reinforces the idea that participants, even when navigating virtually, were oriented toward memory-laden elements of the architecture, guided by urban memory embedded in Istanbul's architectural fabric, even though they did not spatially experience them before.

To facilitate a clearer comparison of perceptual tendencies across environments, Table 1 summarizes the relative intensity of architectural references (AR) and sensory references (SR), including their subcategories, in both physical and virtual experiences. It also presents Wilcoxon signed-rank test results to evaluate statistical significance (Field, 2018; Gibbons & Chakraborti, 2011).

Table 1 Statistical Comparison of Recognition Intensity (*p < 0.05; †p < 0.10 trend-level significance)

Comparison	PE Mean	VRE Mean	Wilcoxon Statistic	p-value	Significance
AR: overall	0.151	0.165	-	0.036	*
AR: elements	0.0937	0.1058	58.0	0.0826	†
AR: spaces	0.0727	0.0948	20.0	0.0007	*
SR: overall	0.096	0.085	-	0.105	
SR: interventions	0.0611	0.0254	1.0	0.0000	*
SR: materials	0.0347	0.0186	19.0	0.0006	*

The results showed that the difference in architectural reference (AR) recall between PE and VRE was statistically significant (p=0.036), indicating that VRE notably enhanced the recall of architectural elements. For sensory references, the difference was not statistically significant (p=0.105), though a slight tendency toward greater sensory recall in PE was observed. These results align with our qualitative findings suggesting that VRE more effectively triggers episodic memory, while PE engages semantic and sensory memory more.

Analysis of subcategories offers a nuanced understanding of memory patterns. The recall of spatiality perception under architectural references was significantly higher in VRE (p=0.0007), whereas the recall of architectural elements approached significance (p=0.083). In contrast, participants recalled sensory details such as interventions (p=0.000004) and materials (p=0.0006) significantly more in the physical environment. These findings suggest that VRE enhances spatial understanding and episodic recall, while PE provides a richer engagement with tactile and material aspects associated with semantic memory.

5. Discussion

Designed by Kemalettin to serve the needs of a modernizing education system in the early 20th century, the Bostancı Primary School building continues to stand as a well-preserved architectural artifact shaped by the evolving socio-cultural dynamics of its era. Although the building has undergone functional transformations and spatial alterations over the years, its original architectural stylistic characteristics -arched windows and doors, wide eaves, symmetrical facades, wooden staircases, and ornamentations- remain largely intact. These enduring features render the structure not only a representation of architectural heritage but also a mnemonic medium that anchors both individual and collective urban memory.

The findings of this study reinforce the notion that different memory types are activated depending on the nature of the experienced environment, in architectural terms. Specifically, the results indicate that virtual reality experiences (VRE) facilitate stronger recall of spatial and structural aspects (episodic memory), while physical experiences (PE) elicit greater retention of tactile and material details (semantic and sensory memory). These patterns are consistent with recent research suggesting that embodied spatial exploration in VR enhances episodic memory formation through immersive interaction and self-directed navigation (Slater & Wilbur, 1997; Cummings & Bailenson, 2016).

The results demonstrate a precise alignment between the study's methodology and its theoretical underpinnings. The statistically significant enhancement of spatial recall in the virtual reality environment (VRE), particularly for spatial configurations ($p=0.0007$), reflects Pallasmaa's (2007) argument that architecture is not merely visual but multi-sensory and experiential. While VR may lack haptic input, its immersive capacity strengthens episodic memory by enabling embodied navigation supporting Pallasmaa's notion of the "lived body" as the locus of architectural experience. The emphasis on spatial memory in VR also parallels the emphasis on the primacy of atmosphere and spatial continuity in perception.

Participants demonstrated significantly higher recall of spatial features in VRE settings ($p=0.0007$), while materials and interventions were more accurately remembered following physical exposure ($p<0.001$). This suggests that memory recall in architecture is multidimensional, shaped not only by content (what is remembered) but also by the sensory and cognitive characteristics of the medium (how it is experienced). The architectural memory is not merely about recognizing form but about engaging with space through perception, embodiment, and meaning. The richer recall of materials and interventions in the physical experience (PE) -with significant differences ($p=0.000004$ and $p=0.0006$)- echoes Crinson's (2005) view that architecture is always embedded in cultural and material histories. As physical experience triggers tactile sensations, it allows for a more nuanced engagement with textures, interventions, and decay -elements that often resist full simulation in virtual environments. These tactile and body-mediated interactions align more with semantic memory, where accumulated knowledge and cultural context shape perception. This confirms that PE engages long-term memory and knowledge-based recall.

Furthermore, Assmann's (1997) theory of cultural memory becomes particularly relevant in interpreting how specific features of the Bostancı Primary School -such as arched windows, decorative elements, or wooden stairs- were consistently remembered across both mediums. These elements function as "figures of memory" that anchor collective remembrance. The fact that participants retained memory of these symbolic elements regardless of medium suggests that architectural symbols embedded in cultural memory transcend the experiential limitations of either PE or VRE. Thus, the methodology of comparing episodic (VR) and semantic (physical) memory modes not only reflects but also operationalizes Assmann's theoretical separation of communicative vs. cultural memory within a spatial and architectural context.

These findings have significant practical implications for architectural education and heritage preservation. Virtual reality can be a powerful tool for teaching spatial awareness and design principles, especially in settings where physical access to historical sites is limited. However, it should not be seen as a substitute for physical interaction. Instead, it should be viewed as a complementary medium that can enrich architectural pedagogy when integrated alongside traditional site visits and tactile experiences.

By integrating qualitative and statistical analyses, this study does more than comparing positive or negative features of different mediums; it traces how different modalities access distinct layers of architectural memory: VR reinforcing experiential immediacy, and PE reinforcing cultural-physical depth. This layered reading validates the multi-method approach adopted and reaffirms the theoretical foundations laid by key scholars in memory and architecture.

While this study has certain limitations, it also opens up valuable paths for future research. Firstly, the participant sample consisted of senior architecture students with relatively similar backgrounds in spatial cognition and drawing skills. Expanding future studies to include a more diverse participant pool -such as practitioners, non-specialists, or individuals from various age groups and backgrounds- could offer a broader understanding of architectural memory. Secondly, although this research employed a strong qualitative framework and relational mapping tools, incorporating different statistical modelling in future work could enhance the generalizability of the findings. Nevertheless, the relational mapping of memory sketches, verbal descriptions, and image annotations yielded rich, triangulated insights into how individuals encode and recall architectural environments.

The methodology and findings of this research contribute a novel framework for evaluating the memory of historical environments through comparative physical and virtual experiences. As the boundaries between real and simulated environments continue to blur in both education and design practice, understanding how memory operates across these media becomes increasingly relevant. This study lays the groundwork for future explorations on perceptual depth, spatial cognition, and memory formation, potentially extending to interdisciplinary domains such as environmental psychology, digital heritage, and experiential learning.

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CRediT Authorship Contribution Statement

Yekta Özgüven: Writing – review & editing, Writing – original draft, Methodology, Investigation, Analysis, Data curation, Conceptualization, Data visualization. Asena Kumsal Şen Bayram: Writing – review & editing, Writing – original draft, Methodology, Investigation, Analysis, Data curation, Conceptualization, Data visualization. Nadide Ebru Özkan: Writing – review & editing, Writing – original draft, Methodology, Investigation, Analysis, Data curation, Conceptualization, Data visualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

Ethics Committee Approval

Ethics committee permission is not required.

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A non-destructive testing method for the production technique of gilded ornamentation in a traditional house: XRF analysis method

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Abstract

Gold, with its thousands of years of history, has been used across different geographies and with various techniques, carrying diverse meanings beyond being just a metal. Similarly, a variety of techniques can be observed in the production of gold imitation. In cultural heritage buildings, determining whether such ornaments are made of real gold and identifying the production technique are crucial for making correct decisions in restoration. The knowledge and experience of craftsmen can be utilized to determine the content and production technique of the ornamentation in a cultural heritage building; however, this empirical approach is unscientific and prone to error. This study is unique and valuable as it provides information based on definitive results through an analytical and scientific approach. The material of this study is a gilded ornamentation from a traditional house in Sivas. XRF (X-rays fluorescence) analysis method was employed to understand the elemental analysis and production technique of gilded ornamentation. The aim of this study is to determine both the production technique and the elemental structure of the material through XRF analysis of the gilded ornamentation. The absence of gold in the analysis indicates that the gilding was not produced from original gold but is an imitation. When evaluating the gilding imitation techniques, the concentration of copper and zinc elements indicates that the imitation gilding was produced from a brass alloy. The zinc/copper ratio was found to match the ratio used to achieve a gold-like color. Additionally, when other techniques used for gold imitation were evaluated, the absence or trace amounts of other elements excluded those techniques. Consequently, this study presents a new approach to the literature by demonstrating the applicability of modern, non-destructive, contactless techniques like XRF analysis to the science of conservation and restoration.

Keywords: gilding, gilding imitation, gold, NDT, XRF analysis

1. Introduction

In addition to its resistance to atmospheric conditions, oxidation-induced corrosion, galvanic wear, and chemicals, gold's ease of workmanship and its rarity compared to other metals have conferred upon it the symbolic meanings of "value," such as power and wealth. These symbolic attributes have sometimes even made gold a central element in religious ceremonies. The diverse meanings attributed to gold, beyond being merely a metal, have influenced its widespread use across vast geographies, from Europe to Mesopotamia, Egypt to Russia, and even the Far East (Pliny the Elder, Liber XXXIII, i-1, Franklin, 1995; Figueiredo et al., 2010; Klemm & Klemm, 2012; Fomicheva & Valuev, 2021; Ryu, 2022; Miho, 2022; Ulak, 2023).

The term 'gilding' refers to the process of coating an object with gold, either in liquid form or as gold leaf, or with a similar material to give the impression that it is made of or covered with gold. Gilding can also be produced using silver and copper alloys (Sözen & Tanyeli, 1994; Hasol, 2005; Britannica, 2016; Oxford, 2024; TDK, 2024). It can be stated that the use of gilding has persisted from the Bronze Age to the present day. In its early applications, gilding primarily involved directly covering the surfaces of non-gold objects or architectural elements with gold (Pliny the Elder, Liber

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XXXIII, xviii-55; Kalter, 1985; Oddy, 1993; Figueiredo et al., 2010; Klemm & Klemm, 2012; Oktay, 2013).

The earliest examples of gilding, observed around 3000 BCE in the Middle East, are known to have been produced by mechanically securing a thick layer of gold leaf onto the underlying substrate (Figures 1-2). In this method, known as gold leaf gilding, the leaf is pressed and riveted onto the substrate, its edges are folded, or it is placed into a fine groove cut into the surface. By 2000 BCE, gold had been refined and further thinned by hammering. This technique, referred to as leaf gilding, involves the application of an organic adhesive to the underlying substrate or the preparation of a calcite/gypsum ground as an intermediate layer, onto which the thin leaf is applied. Another technique known to have been used since around 1200 BCE is the diffusion bonding technique. In this method, gold and the underlying metal layer are heated together, creating a stronger bond between the two metals through diffusion than with mechanical fastening. While this technique forms a good bond with silver, it is not suitable for use with metals such as tin and lead, which have low melting points (Nicholson, 1979; Oddy, 1981; Oddy, 1993; Oddy, 1995; Figueiredo et al., 2010).

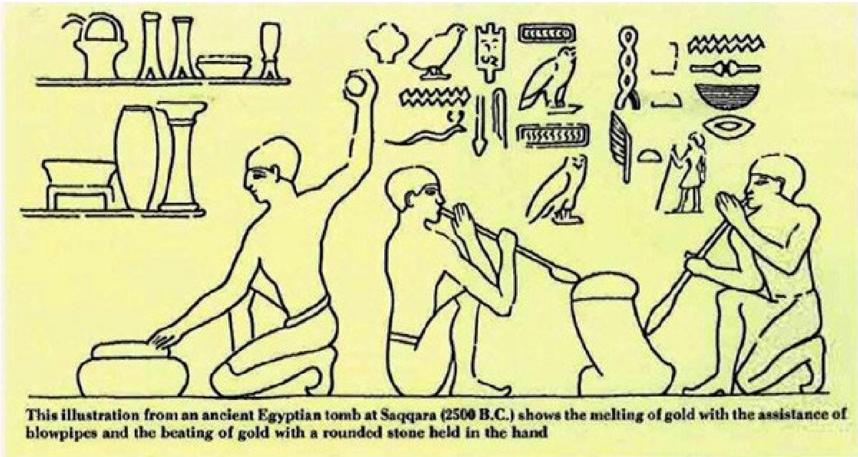

Figure 1 An image found in a tomb in Ancient Egypt from around 2500 BCE: The thinning of gold by hammering (Nicholson, 1979)

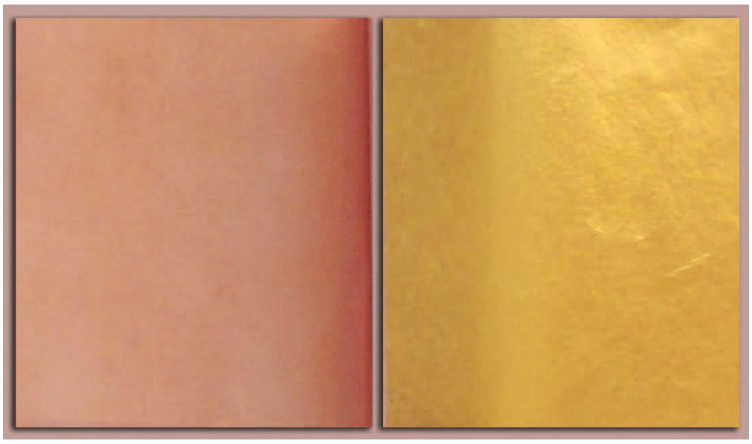

Figure 2 Example of gold leaf (Önel, 2016)

In the 4th century BCE, a new technique was developed in China where gold was combined with mercury amalgam, allowing the mercury to adhere the gold to the surface. In this technique, the mercury-gold amalgam is applied to a previously cleaned surface. The object is then heated (to approximately 365°C) until the mercury evaporates. As the mercury vaporizes, the gold adheres to the surface and is then polished. This technique, known as fire gilding (amalgam gilding, mercury gilding, tombac), became widespread in China during the 3rd century BCE and later spread to Rome and, through Rome, to Europe in the 1st and 2nd centuries CE (Pliny the Elder, Liber XXXIII, xx-64, XLii-125; Oddy, 1993; Anheuser, 1997; Figueiredo et al., 2010; Darque-Ceretti et al., 2013; Britannica, 2016; Önel, 2016; Ortega-Feliu et al., 2017). In addition to this technique, a mixture of honey and gold can also be applied with heat to adhere gold to the surface; however, honey tends to dull the gilding (Balıkçı, 2007). Besides the hot application methods mentioned above, there are also cold application techniques where mercury is used as an adhesive for gold leaf (Darque-Ceretti et al., 2013; Ingo et al., 2013). Another cold application technique involves applying gold in liquid form to the surface using a brush. To provide protection, linseed oil can be applied over the gilding, although this method may cause the gilding to peel off from the surface (Balıkçı, 2007).

Another technique to mention is the gouache gilding (water gilding) method, where gold leaf is adhered using red bole[1]. This technique, which became widespread in the Middle Ages, involves placing a moistened leaf onto a base layer made by mixing bole or red-orange pigments containing lead oxide with animal glue. There are also examples where the leaf is placed on a well-smoothed mixture of glue and gypsum without the use of bole (Hradil et al., 2003; Gulotta et al., 2012). In gouache gilding, it is known that binders such as rabbit skin glue and egg yolk were also used (Toniolo et al., 1998; Gulotta et al., 2012; Brocchieri et al., 2022a; Saggio et al., 2023). In mordant gilding (oil gilding), more durable and higher adhesion applications were achieved by using certain stabilizers such as linseed oil, mineral fillers, and lead white (Gulotta et al., 2012; Steger et al., 2021).

Gold powder gilding is a technique used in China since around 1000 CE, where gold powder is mixed into a binder to create the gilding material (Darque-Ceretti & Aucouturier, 2013). This method involves crushing gold leaf or foil with Arabic gum and applying the resulting fluid mixture to the surface with a brush (Önel, 2016). With technological advancements, fine gold obtained through chemical precipitation from gold-containing compounds is now also used for decorative painting purposes (Darque-Ceretti & Aucouturier, 2013). Another method involves dipping linen into a gold chloride solution, drying and burning the linen, and then transferring the gold flakes that have fallen off to another layer with the help of a leather tool (Oddy, 1995).

Depletion gilding is a technique discovered in the early years of Christianity in Europe and in the same period in Central and South America. It involves the use of chemicals to dissolve other metals in a gold alloy, thereby purifying the gold and using it to gild another object (Bray, 1993; Darque-Ceretti & Aucouturier, 2013). In the 19th century, these techniques were further developed with the introduction of electroplating (Oddy, 1993; Anheuser, 1997; Ortega-Feliu et al., 2017).

Gilding can be produced directly from gold, but gold imitation can also be made from other alloys (Darque-Ceretti & Aucouturier, 2013; Simsek et al., 2015). Copper and zinc alloys (brass) are commonly used for gold imitation due to their cost-effectiveness (Cession, 1990; Scott et al., 2007; Miliani et al., 2009; Sandu et al., 2011a; Gulotta et al., 2012; Simsek et al., 2015; Marchetti et al., 2023). The earliest use of brass, dating back to 4700-4000 BCE in China, was as gold-colored leaf, with similar uses in England around 3000-2000 BCE, in the Middle East around 2000 BCE, and in Anatolia around 1000 BCE (Craddock, 1978; Craddock et al., 2004; Fan et al., 2012; Wei et al., 2022). To achieve a color close to 22-karat gold, the zinc/copper ratio should be approximately 1/5 to 1/6 (14/86). Increasing the zinc content in this alloy, also known as Dutch metal, will whiten the color of the metal. Conversely, decreasing the zinc content will produce a color range from pale gold to reddish pale gold (Britannica, 1998; Craddock et al., 2004; Thornton, 2007; Duran et al., 2008; Steger et al., 2021; Parma et al., 2023).

In addition to using alloys of less valuable metals such as copper and zinc (sometimes lead and tin) in leaf form for gilding imitation, there are also applications of powdered purpurino (porporina)[2] in gilding with gold powder (Duran et al., 2008; Sansonetti et al., 2010; Sandu et al., 2011a; Lalli & Innocenti, 2016). This technique, which involves mixing powders obtained by finely

[1]Bole is fine-grained, velvety red clay used for adhering gold leaf or as a ground layer, composed of natural ferruginous alumina silicates, oils, and other minerals. White bole is a type of China clay made from kaolin (Hradil et al., 2003; Gettens & Stout, 2012).
[2]Purpurino is a yellow metal powder used for gilding imitation (Brocchieri et al., 2022a).

grinding brass leaves or foils with a resin solution and applying it to the surface, was used in the 12th century and is still in use today (Thornton, 1995; Sandu et al., 2011a).

In the 13th and 14th centuries, powdered tin sulfide was also used for gold imitation gilding. This technique, known as mosaic gold, involves heating tin, mercury, and sulfur to different temperatures to achieve yellow hues. Because mosaic gold is unstable and toxic, it was replaced in the mid-18th century by brass powders. Brass, which resembles gold and is finely granulated, became preferable to other copper-based alloys. With the invention of a mill for grinding metal foils in the 19th century, the popularity of metal powders increased further by the mid-century (Duran et al., 2008; Gulotta et al., 2012; Steger et al., 2021; Brocchieri et al., 2022a). Additionally, brass powder paint is used not only for imitation gilding but also occasionally applied over a gold layer (Risdonne et al., 2018).

Another gilding imitation method involves painting silver or tin leaf with yellow varnish (known as the Mecca technique). To make tin leaf resemble gold leaf, a mixture of hydrocerussite, lead oxide, and beeswax was used. Silver, however, tends to tarnish due to oxidation, limiting its use (Mayer, 1951; Thornton, 1995; Fiorin & Vigato, 2007; Duran et al., 2008; Sansonetti et al., 2010; Sandu et al., 2011a; Sandu et al., 2011b; Gulotta et al., 2012). Additionally, gilding imitation has been achieved by painting white metals like lead and polished iron with yellow-orange varnish. There have also been attempts to achieve gold-like brightness using techniques such as sulfidation of silver. Another process, known as anodization, has been used to produce stable and bright-colored oxide layers on metals like aluminum, titanium, and niobium, serving as a gilding imitation. Gilding imitation through vapor deposition and gilded paint production with mica-based bright pigments are also present (Thornton, 1995).

The gilding techniques mentioned above have historically been employed in cultural heritage structures, either using real gold or gold imitations. Attempting to identify the original gilding technique during restoration based solely on personal experience or intuition is prone to human error and may lead to restoration practices that are not faithful to the original.

This study aims to propose a method for identifying the original production technique of a decorative element used for ornamentation in a cultural heritage structure. Within the scope of the study, it was first aimed to determine whether the gilded decoration was produced using real gold or a gold imitation by applying a non-destructive testing method. For this purpose, the XRF (X-rays fluorescence) analysis method was employed to characterize the elemental composition of the gilding. Additionally, a literature review was conducted to investigate traditional gilding production techniques. The data obtained from the XRF analysis were then compared with the traditional gilding techniques identified in the literature, enabling the determination of the original production technique used for the decoration in the examined house.

The material of the study is a gilded decoration located on the wall of a traditional house in Sivas. As the study aims to propose a method for identifying original production techniques, a single case study was selected, thus defining the study's scope and limitations. Expanding the sample to include gilded decorations from different buildings was not feasible due to time constraints and the limitations of the article format.

Based on the elemental composition identified through XRF analysis, certain traditional techniques that could not have been used were eliminated, thereby enabling the identification of the original gilding technique applied to the decoration.

2. Material and Method

The gilded ornamentation that constitutes the material of this study is from a traditional house located at layout 160, block 103, plot 1 in Akdeğirmen Neighborhood, Sivas city center, an area known for its dense concentration of registered traditional houses (Figure 3) (Tapu, 2024).

The house, registered by the Kayseri Cultural Heritage Protection Board with decision number 851 dated October 20, 1990, was later protected by the Sivas Cultural and Natural Heritage Protection Board with decision number 1298 dated July 20, 2009, along with blocks 103, 104, 106, 110, and 114 (Vural, 2018).

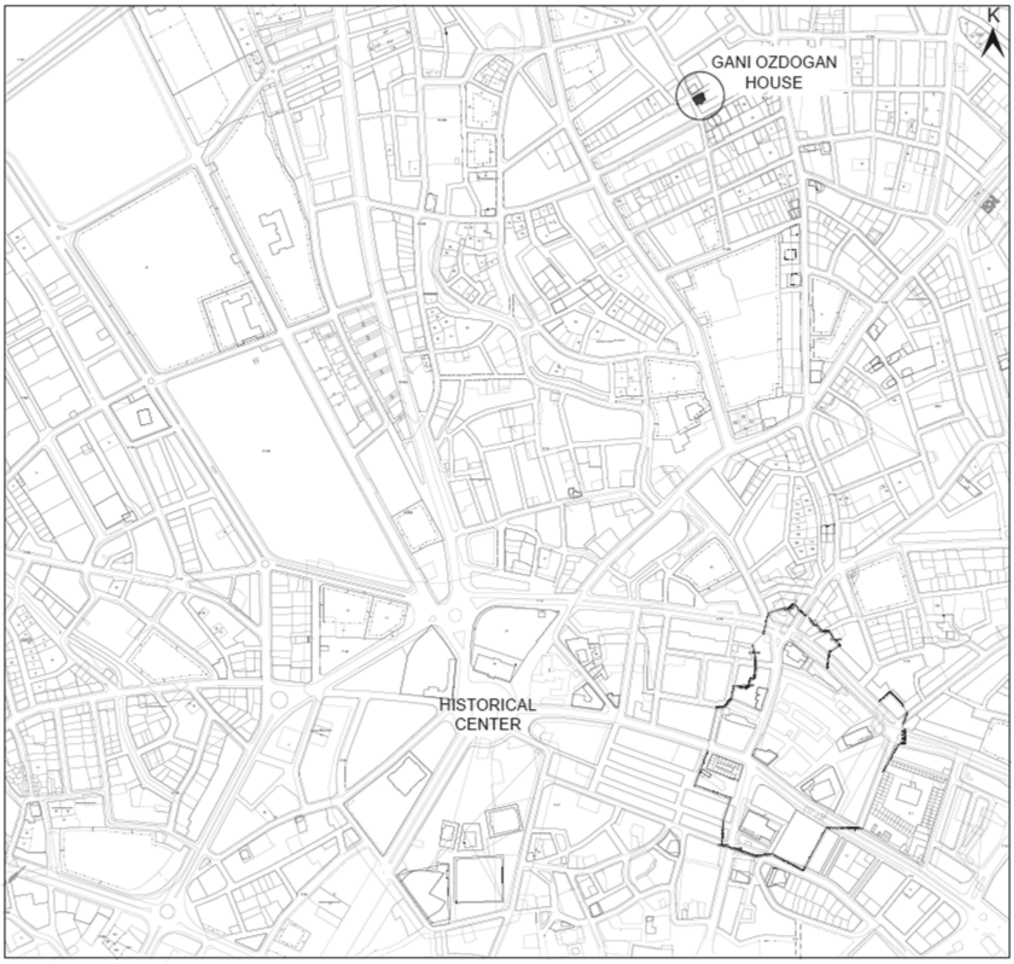

Figure 3 Urban location of Gani Ozdogan house (Sivas Belediyesi Arşivi, 2019)

Figure 4 South facade (Vural, 2018)

The entrance to the house's garden is from 18-Dispanser Street, while the main entrance is recessed into the south facade, positioned between wooden columns. The southern facade is more ornate than the others, featuring an inscription on the gable of the semi-hexagonal bay window (Figure 4). The inscription indicates that the house was constructed in the 19th century and reflects the influences of Westernization Period Ottoman Architecture. The house, with a typical plan, consists of a basement, ground floor, and first floor. The roof is a gabled roof with mission tiles and has broad eaves. The basement is made of stone masonry, while the upper floors are constructed with timber framing and mud brick infill, finished with plaster. Other facades of the house also feature projections, including a small, semi-hexagonal oriel on the north facade facing 18-13 Street. The facades display wooden moldings and profiled columns.

The basement, constructed of rubble stone, consists of a single space formed by floor beams resting on wooden posts and walls. On the ground floor, there are four rooms radiating from the central hall (sofa) and an additional bathroom. The first floor also has four rooms opening to the central hall, along with a modern kitchen and WC (Figure 5) (Vural, 2018). The gilded ornamentation under study is located in the room on the upper floor facing south and west (Figure 5). Above the built-in cupboard and niche, designed along with the northern wall of this room, there is a gilded decoration. This decoration consists of acanthus leaves emerging from a vase and symmetrically arranged floral rosettes filling the spaces created by the leaves as they curve downward (Figure 6). The gilded decoration being studied was made on a lime-plastered wall.

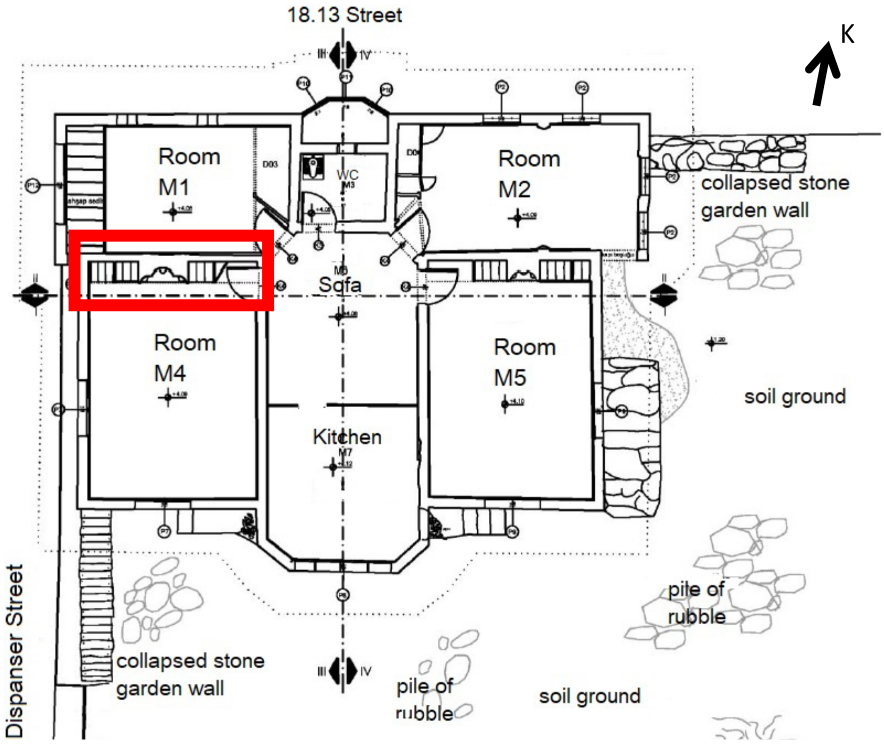

Figure 5 First floor plan of the house (Vural, 2018)

Figure 6 The gilded decoration on the wall of the southwest room (Vural, 2018)

Understanding traditional production techniques of gilded decorations is valuable for preserving traditions, passing them on to future generations, and providing architects with insights into proper restoration practices using traditional methods. Scientifically determining which traditional production techniques were employed in a gilded decoration within a cultural heritage site enables informed decision-making during the restoration process.

Scanning electron microscope (SEM), energy dispersive spectroscopy (EDS), certain applications of Fourier-transform infrared spectroscopy (FTIR), and Raman spectroscopy used for the characterization of gildings cause minor damage to the cultural heritage structure since they require sampling. The use of these methods, which are considered destructive, constitutes an invasive intervention. Therefore, within the scope of this article, a more conservation-oriented approach was adopted, and the non-invasive, non-destructive XRF method was preferred.

2.1. Theoretical Basis of the Methods

Portable XRF devices are portable spectrographs that measure the secondary fluorescence X-rays produced when atoms in a material are excited by X-rays emitted from the device, causing electrons to move from inner orbits to higher energy levels. This measurement is done using energy-dispersive and wavelength-detecting techniques. With this device, measurements can be taken to a depth of several micrometers/millimeters (Figueiredo et al., 2010; Liritzis & Zacharias, 2011; Sandu et al., 2011b; Oyedotun, 2018).

The principle of XRF analysis is based on the ability to identify elements by the unique energy released when an X-ray ejects an electron from the K-band of an atom, and another electron from the L-band transitions to the K-band to stabilize the atom (Çetinkaya, 2010). This non-destructive and non-invasive method allows for the in-situ, rapid, and highly accurate characterization of cultural heritage without causing damage. As a result, it has been adopted in the fields of architectural and archaeological conservation (Frahm & Doonan, 2013; Acquafredda, 2019; Leone et al., 2019; Li et al., 2020; Bersch et al., 2021; Pecchioni et al., 2021; Pehlivan, 2022a; Pehlivan, 2022b; Pehlivan, 2023; Zhang et al., 2024).

Although analyses conducted with portable XRF devices are non-invasive, contactless, non-destructive, and do not require sampling or surface preparation, making them easy to apply and offering straightforward data processing, it is essential to consider that the device can measure depths greater than 100 µm when interpreting the results (Figueiredo et al., 2010; Sandu et al., 2011b).

Another limitation of XRF analysis is surface contamination. Atmospheric pollution, particularly on façades located in urban centers, can be a common issue. Another source of contamination arises from human contact with the surface. Such pollutants may not always be visible but can appear in XRF analysis results. Therefore, unless a patina that must be preserved is present, surface cleaning is recommended prior to analysis. Since the likelihood of surface contamination is higher in the case of light elements, this factor must be considered during experimental studies. Several studies have highlighted this issue by reporting the presence of anachronistic elements (Pahlke et al., 2001; Ogburn et al., 2013; Tissot et al., 2018; Bicchieri et al., 2020). Furthermore, on surfaces exposed to moisture, salt deposits may remain after the evaporation of water, which can also interfere with XRF analysis (Di Castro Silva et al., 2025).

2.2. Application of the Method

Numerous experimental studies have employed the XRF method for gilded or gold-containing cultural heritage. Miliani et al. (2009) conducted XRF analysis on the surface paints of a group of ceramics and identified examples where gold, brass, or a combination of both were used. Figueiredo et al. (2010) used XRF analysis to perform the elemental characterization of a gilded nail and, unusually, concluded that the gold-gilded nail was made of copper rather than the more commonly used bronze. Simsek et al. (2015) applied XRF to study the gilded decorations in Early Böttger ceramics, while Gao et al. (2016) and Colomban et al. (2020) used it for the characterization of gold leaf. Pessanha et al. (2019), Barcellos Lins et al. (2020), and Orsilli et al. (2023) utilized XRF to measure the thickness of gold leaf. Hinds et al. (2014) employed XRF to detect platinum content in Roman gold coins. Schwantes and Trachet (2020) experimented with XRF analysis to distinguish whether a yellow-painted surface pigment was iron (III) oxide-based, or ochre, successfully making the identification with XRF. Fanti and Furlan (2020) applied XRF for provenance analysis of gold particles found on a shroud. Brocchieri et al. (2022b) demonstrated through XRF analysis that a group of gilded lead artifacts at the Royal Palace in Caserta were gilded with real gold. Margreiter et al. (2022) produced amalgam gilding experimentally to prove that XRF can be used as a non-destructive inspection method. Tissot et al. (2018) and Guerra and Pagès-Camagna (2019) used XRF to determine the gold content of jewelry, Steger et al. (2021) to detect the elements forming gilded metallic pigments in stained glass, Brocchieri et al. (2022a) for the characterization of gilded decorations, Marchetti et al. (2023) for elemental analysis of gold flakes, Gattia and Seccaroni (2023) for identifying gilded threads in silk and carpets, and Vadrucci et al. (2024) for the characterization of a gilded leather artifact. Povolotckaia et al. (2025) employed XRF analysis to prove that a rare technique called "mizunotype" applied on a wooden panel was created using gold.

In this study, the portable XRF device used was the Thermo Scientific Niton XL3t analyzer with a GOLDD+ detector. Its resolution is below 185 eV, with a measurement rate of 60,000 cps and a shaping time of 4 µsec. The X-ray tube operates with a silver anode at 50 kV and 200 µA. The device is capable of measuring elements from magnesium (Mg) to uranium (U) with a resolution of 5 mm. It features a self-calibration function that utilizes measurements from a standard metal.

Since the gilded decoration is located indoors, the risk of atmospheric pollution was low. Nevertheless, to prevent contamination from surface contact, a simple cleaning was performed. The surface was wiped with a lightly dampened cloth, dried, and subsequently measured by positioning the device approximately 1 mm from the decoration at a 90° angle for about 125 seconds, generating spectra for the 60-Light Range, 90-Low Range, and 120-Main Range.

Data processing was carried out using the "Standard Thermo Scientific™ Niton Data Transfer (NDT™) PC software" developed by the manufacturer and compatible with the device. The software provided the intensity of the detected elements in counts per second (cps), which were then converted into parts per million (ppm) and presented in column charts.

The data obtained from XRF analysis were evaluated within the context of the literature review on traditional gilding techniques. The absence of certain elements led to the elimination of some techniques, while the consistency of the detected element ratios with those reported in the literature helped identify the original gilding technique used in the decoration.

3. Findings

The XRF spectra obtained from the gilded ornamentation analyzed using the p-XRF device were converted into graphs in terms of keV for the spectrum and ppm for the element concentrations. Elements that could not be detected in the analysis were not included in the graph.

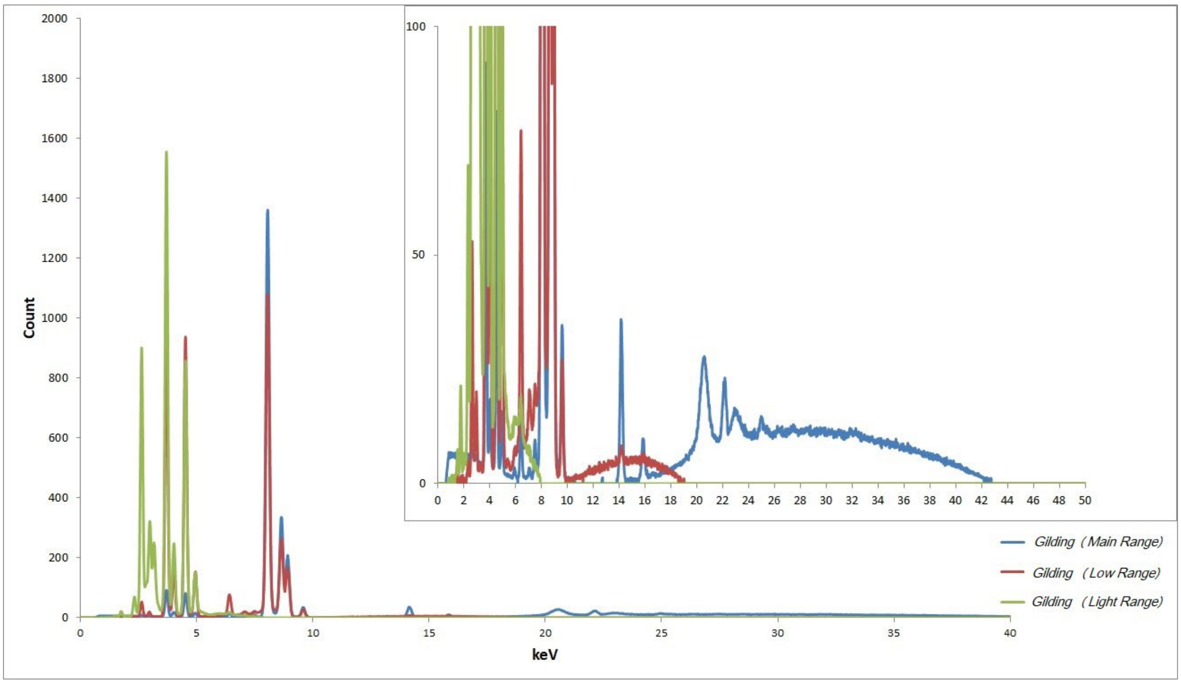

Figure 7 XRF spectrum of the gilded ornamentation

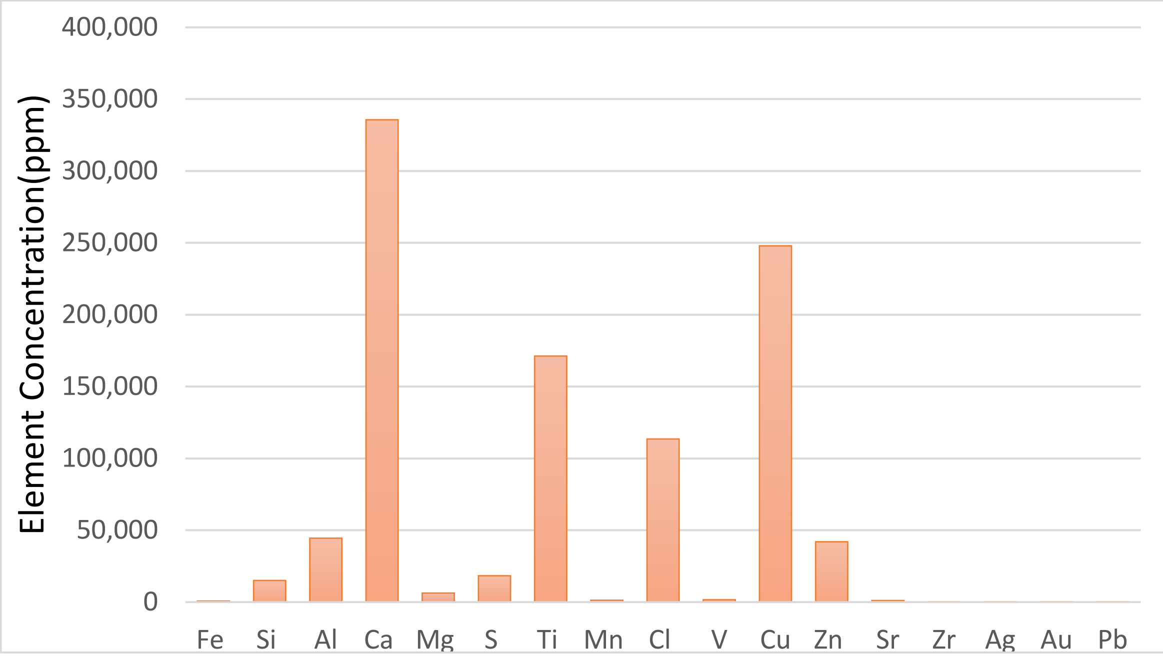

Figure 8 Graph showing the elemental concentrations in the gilded ornamentation

According to this, it is observed that the element with the highest concentration is calcium, followed by copper, titanium, chlorine, aluminum, and zinc. The analysis revealed that certain elements such as mercury, chromium, tin, cadmium, and bismuth were not present. Gold, silver, lead, zirconium, iron, strontium, vanadium, and manganese were found in negligible amounts (below 0.2%), while silicon, magnesium, and sulfur were present in concentrations below 2% (Figures 7 and 8).

4. Discussion and Conclusion

Gold is typically not found in its pure form in nature. Particularly, gold without silver indicates refined gold. Copper is not commonly used as an alloy in gold because it makes the metal harder to be forged; however, natural gold does contain a small amount of copper. Natural gold typically contains approximately 40% silver, 5% iron, and 1% copper (Figueiredo et al., 2010; Sandu, 2011b).

To determine whether the gilding is made of real gold, the presence of the aforementioned elements should be checked. In the examined artifact, gold is found at 0.0026%, silver at 0.0131%, and iron at 0.0762%.

The negligible amount of gold confirms that this ornamentation was not produced from real gold but is a gold imitation. When analyzing the graph in Figure 8, the proportions of copper and zinc—elements commonly used in imitation gilding—are noteworthy. The ratios used to achieve a gold-like color are known to be approximately 1/5 to 1/6 (14/86) (Britannica, 1998; Craddock et al., 2004; Thornton, 2007; Duran et al., 2008; Steger et al., 2021; Parma et al., 2023). The zinc/copper ratio in the examined gilded ornamentation is found to be 1/6 (14/86), consistent with the literature (Figure 9).

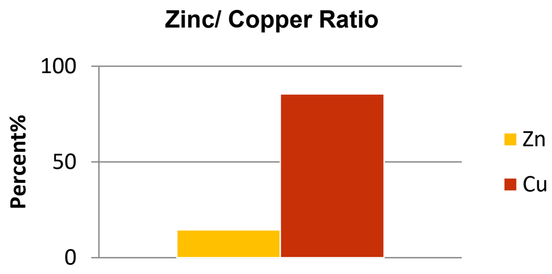

Figure 9 Graph showing the zinc/copper ratio in the gilded ornamentation

In addition to copper and zinc, other techniques used for gilding imitation were also evaluated. For the powder tin sulfide application, the presence of tin, mercury, and sulfur is required; however, the absence of tin and mercury, along with the trace amount of sulfur, eliminates this technique. The use of tin and silver leaf as another gilding imitation technique is not feasible due to the absence or trace amounts of these elements.

Some yellow-orange pigments used in gilding production include: iron oxides (madder colors), minium (Pb3O4), chrome yellow (Paris Yellow—PbCrO4), chrome orange (PbCrO4•PbO), vermilion (α-HgS), and Pb-Sn yellow (gialolino) (Cavallo & Verda, 2008; Duran et al., 2008; Rampazzi et al., 2008; Sansonetti et al., 2010; Perez-Rodriguez et al., 2013; Kekeç, 2022). Another pigment used to produce metallic yellow is orpiment (As2S3) (Jackson & Jackson, 1976). Another pigment used for gold imitation is zinc potassium chromate (Śwituszak et al., 2023). Nickel antimonate, cadmium pigments, bismuth vanadate, and bismuth molybdate are also other yellow pigments (Tunçgenç, 2004).

Elemental analysis shows the absence of the aforementioned arsenic, chromium, potassium, mercury, and tin; lead and iron are found in negligible amounts. Therefore, the presence of yellow-orange pigments used in gilding production cannot be confirmed. Additionally, since cadmium, nickel, antimony, and bismuth are absent, and vanadium is present only in trace amounts, the presence of other yellow pigments cannot be discussed either.

The density of copper and zinc in the elemental analysis and their conformity to the ratios reported in the literature confirm the use of a brass alloy for gilding imitation. It is important to focus on whether brass leaf or brass powder paint was used. It is known that brass leaf surfaces are burnished. However, in the ornamentation, there is no evidence of burnishing; instead, there are traces of a liquid paint consistency (Figure 6). Therefore, it can be concluded that the ornamentation consists of a brass powder-based gilding imitation paint.

In gilding imitation paints, in addition to copper and zinc, elements such as tin and nickel may occasionally be present in small amounts (Steger et al., 2021); however, none of these elements were found in the examined artifact.

When evaluating the findings, it is necessary to address certain characteristics and limitations of the XRF analysis. As mentioned above, XRF can measure depths greater than 100 µm (Figueiredo et al., 2010; Sandu et al., 2011b). This feature explains the high concentration of calcium observed in Figures 7 and 8. The high concentration of calcium is due to the traditional lime mortar layer beneath the gilding. This is because the XRF device can analyze down to a few micrometers below the gilding.

To reduce the risk of contamination, surface cleaning was performed prior to analysis. Moreover, most of the elements detected in this analysis are heavy elements, which are less susceptible to surface contamination (Pahlke et al., 2001; Ogburn et al., 2013; Tissot et al., 2018; Bicchieri et al., 2020). The concentration of aluminum and silicon elements is likely due to the presence of aluminosilicate within the mortar. The concentration of titanium is probably derived from titanium dioxide pigment, which is commonly used in white paint applied over the lime mortar and known for its high opacity (Middlemas et al., 2013; Karlsson et al., 2018). The presence of chlorine indicates the accumulation of salts on the surface (Di Castro Silva et al., 2025).

Portable XRF analysis (p-XRF) is effective in detecting a wide range of metals and non-metals; however, due to its low sensitivity for elements smaller than magnesium, it has limited ability to detect organic pigments containing C, H, and N. The pigments used for imitation of golden yellow are mentioned above. Since the pigments commonly used to imitate gold do not contain these elements, the study was not adversely affected by this limitation of the XRF technique.

Based on the analysis, it has been done that a lime mortar layer and paint be applied to the wall surface first, followed by brass powder paint for gilding imitation. A restoration approach in accordance with this technique is advised.

This study presents a non-destructive, contactless, and non-sampling method for understanding the content and production technique of gilded ornamentation in a cultural heritage. It is suggested that portable XRF devices and the units using them (such as laboratories, centers, university-affiliated institutions, and advanced technology offices) be more widely disseminated. Furthermore, it is recommended that the Cultural Heritage Preservation Regional Board Directorates make the use of such methods mandatory through a policy decision. This would enable restorations to be carried out in a manner that is scientifically accurate and true to the original, beyond the intuitions and personal knowledge of the restorers.

Due to the limitations of the study, the research focused on the gilded decoration of a traditional house in Sivas, serving as an example of the applicability of a new technique, namely non-destructive XRF analysis, to the field of conservation and restoration science.

This study, constrained by time, working conditions, and the format of the article, addressed a single case study. For future research, it is recommended to expand the sample size by analyzing a greater number of gilded decorations and conducting comparative analyses. As such studies increase, documenting the elemental composition of gilded decorations will contribute to building a significant database for understanding the production techniques of the period and the distribution networks of these techniques.

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CRediT Authorship Contribution Statement

Gamze Fahriye Pehlivan: All prepared by Pehlivan. Investigation, writing, review & editing, methodology, data curation, conceptualization etc.

Declaration of Competing Interest

The author declare that she has no known competing financial interests or personal relationships about this paper.

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Data Availability

Data will be made available on request.

Ethics Committee Approval

An ethics committee decision is not required.

Resume

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Degradation and biodiversity of rain gardens in the tropics

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Abstract

Rain gardens are commonly applied as a nature-based stormwater management method in urban areas, yet the long-term impacts, possible degradation, and effects on biodiversity as a type of green infrastructure remain underexplored. By comparing two rain gardens in Singapore– one of the earlier prototypes in a neighbourhood managed by a local town council in Central Singapore at Potong Pasir, and a more recent one managed by the National Parks in the West at Jurong Lake Gardens, the ecological and aesthetic functions are investigated. Thus, the rain gardens are explored through the lenses of both functional and aesthetic degradation. Quantitative methods, including the Shannon Biodiversity Index, Green View Index, Colourfulness Index, and surface heat mapping, are applied. Observational methods, including spatial configurations of the rain gardens, plant health, and soil conditions, were also explored to understand the extent of degradation. Common challenges encountered in rain gardens included poor or improper maintenance, poor aesthetic and visual engagement, as well as improper design. Through the findings, comprehensive design and maintenance suggestions are provided for designers and planners to improve existing rain gardens and extend the lifespan and function of future gardens. Rain garden lifespans can be lengthened to reap long-term benefits like effective stormwater management and habitat creation for local biodiversity. Maintenance suggestions build upon existing grey infrastructure and nature-based solutions routine maintenance protocols, tackling the four key functions of a rain garden: sedimentation, filtration, infiltration, and bioretention. Design suggestions are drawn from the data analysed, including potential tree planting configurations and the use of groundcover to reduce surface temperature.

Keywords: design maintenance, ecosystem services, green infrastructure, landscape degradation, rain gardens

1. Introduction

Water Sensitive Urban Design (WSUD) is a nature-based solution for combating climatic risks such as flooding, environmental pollution and high urban heat (Chen et al, 2022), whilst also creating aesthetic benefits for urban populations (Healthy Land and Water, 2020). One example of a WSUD feature often used in small-scale urban spaces is a rain garden. The Public Utilities Board (2024) defines rain gardens as "vegetated land depressions" designed to hold and filter stormwater runoff. As illustrated in Figure 1, surface runoff is first filtered through a layer of mulch and plants, then infiltrates into bioretention soil. A layer of pea stone and a layer of gravel filter out excess sediment. Usually, a perforated pipe within the gravel layer carries excess filtered water to a catchment area.

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Rain gardens are regarded as an efficient stormwater management measure while also being low-cost and environmentally sustainable. However, inadequate maintenance can render them ineffective (Vineyard et al., 2015). This can lead to both the aesthetic and functional degradation of the rain garden. Aesthetic degradation refers to the human perception that the rain garden is no longer able to fulfil scenic, care and knowledge, and ecological value requirements. Functional degradation refers to a decline in the hydraulic and ecological performance of the rain garden. There is a general shortage of research which assesses the degradation of rain gardens, especially using aesthetic metrics such as the Green View Index, Colourfulness Index, or plant health and ground coverage assessments. This also indicates a lack of studies on the visual and aesthetic qualities of rain gardens.

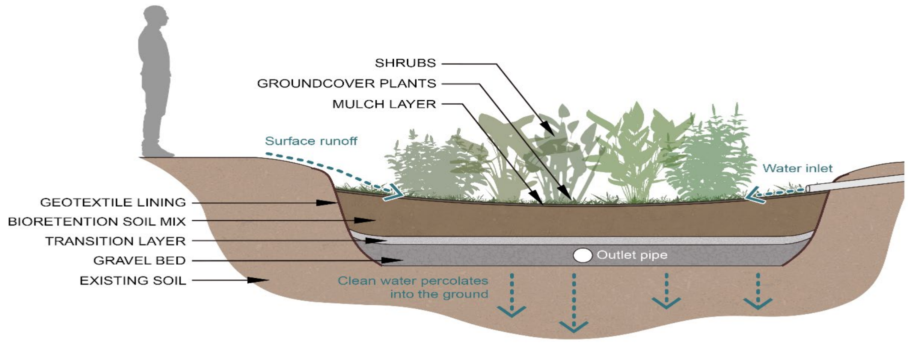

Figure 1 Layers and functions of a rain garden (Original illustration, adapted from Massachusetts Department of Environmental Protection (2006))

The objective of this study is to understand the aesthetic and functional degradation of rain gardens and its implications using both qualitative and quantitative methods, including the aesthetic metrics of Green View Index and Colourfulness Index, to then provide recommendations for extending existing and future rain garden life spans. Three main research questions are listed as follows:

1. How can rain garden degradation be measured and comparatively assessed?
2. What environmental, maintenance, and design factors affect the degradation of rain gardens?
3. How may research inform existing rain garden maintenance practices, and improve future rain garden designs for longevity of functions?

Two rain gardens in Singapore are selected for a comparative study: a rain garden at Potong Pasir and a rain garden located in Jurong Lake Gardens, due to differences in their maintenance, planting strategies, and age. In this comparative study, the Shannon Biodiversity Index of the plant species at the respective rain gardens will be measured to understand plant diversity. The Green View Index and Colourfulness Index will also be used to quantify plant growth and floral colours in the rain gardens, from a human perspective. Additionally, surface temperature will be taken within and around the rain garden to understand shading conditions. Finally, analysis focusing on observations of spatial configurations, plant health, and groundcover conditions will be conducted and compared to the quantitative data collected.

2. Literature Review

2.1. Spatial Design and Function of Rain Gardens

Rain gardens originated as an alternative for stormwater drainage in the 1990s for a development project which aimed to reduce the costs of drainage systems by mimicking natural water flows and retention (Green Building Alliance, n.d.). Rain gardens are typically advised to include a soil mix of 50%-60% sand, 30%-40% silt or loam topsoil, and 10%-20% organic matter or compost (ibid.). Multilayered planting within these gardens can lower the Urban Heat Island effect of a space (Shi et al., 2024). Furthermore, Ge et al. (2023) explain how the public may perceive the thermal comfort of a space to be more regulated if multilayered planting is implemented. Rain gardens also provide a cooling effect during the nighttime as it facilitates water transpiration (Shi et al., 2024). The pollutant-capture capacities of rain gardens depend on the plant species and soil quality within the garden; Singapore National Parks Board suggested plant palette was tested to remove up to 95% of Nitrates and 100% of Phosphates (Loh, 2012). Through a variety of plant species, rain gardens have been found to benefit ecosystem restoration projects, as they provide habitats for pollinators and other animal species (Morash et al., 2019; Dunnett & Clayden, 2007). When implemented on the larger urban scale, improved nature-space connectivity and ecosystem resilience are observed (Hanumesh et al., 2024).

From the cited literature, the studies conducted either assess rain gardens independently as a single variable or made a comparison between rain gardens on their planting palettes. These studies do not typically evaluate rain gardens in the context of WSUD. Instead, some of the sources determine the perceptive value of rain gardens in comparison to more conventional landscape features such as streetside planting and turfed areas. They recommend high maintenance requirements for the rain gardens and their surrounding spaces. Thus, one key focus of this study is to provide design guidelines for both new and existing rain garden projects to improve their effectiveness, longevity and sustainability.

2.2. Aesthetic Degradation of Rain Gardens

Dobbie and Farrelly (2023) explain the human perception of rain gardens to be dependent on four aesthetic lenses: scenic, care and knowledge (e.g. maintenance), identity of the space, and the perceived ecological value. They suggest that the aesthetics of function, i.e. the perceived function of a space, is equally as important as the four other lenses. Users of a space often perceive rain gardens to be a positive addition, in comparison to regular tree-lined streets (Dobbie, 2016). Furthermore, the educational function of a rain garden is suggested to add value to the space and increase public acceptance of rain garden installation and use (Church, 2015). Varying colours and textures of the plant palette of a rain garden is highly important to improve the scenic aesthetics and provide an identity for the space (Doğmuşöz, 2024). Overall, the sources assess the perceptive value of rain gardens as a comparison to more conventional street planting or turfed areas and suggest high maintenance requirements for the spaces.

Based on the above literature, the aesthetic degradation of rain gardens can be defined through the aesthetic lenses identified by Dobbie and Farrelly (2023), focusing specifically on the lenses of scenic, care and knowledge, and perceived ecological value. When the rain garden is perceived as no longer being able to fulfil the above functions, it is considered aesthetic degradation. Focus will be placed on analysing how biodiversity plays a role in this aesthetic degradation, specifically, plant species that are both intentionally planted as part of the rain garden function and design, as well as plants that have emerged during the rain garden's lifespan, such as weeds, which were not part of the design intent. The Shannon Biodiversity Index will be used in this paper to quantify the biodiversity at the chosen sites.

There is a lack of studies on the implications of the Green View Index (GVI) and Colourfulness Index (CI) on rain gardens, which are useful methods of quantifying visual greenery and plant diversity. Currently, studies on GVI and Colourfulness Index tend to focus on urban streetscapes rather than rain gardens specifically (Zhu et al., 2023; Ma et al., 2023). Furthermore, another metric for rain gardens that is understudied is surface temperatures. Although Chen et al. (2024) studied the effect of rain gardens on surface temperatures, they only accounted for the surface temperature of the rain garden and surrounding impermeable pavement rather than the surface temperature of different materials, shaded and unshaded conditions and the effect of plant palette on rain garden temperatures. Therefore, this study aims to tackle these gaps in knowledge through the comparison between two rain gardens of different ages and site contexts, to understand how degradation occurs over time.

2.3. Functional Degradation of Rain Gardens

The degradation of Water Sensitive Urban Design (WSUD) features often results in degraded stormwater quality, with increased pollutant loads reaching the receiving catchment (Xiao et al., 2017). When assessing the hydraulic performance and water quality impact of different WSUD features, bioretention basins, which are functionally similar to rain gardens, perform well and hence, are preferred over other filtration features when water quality is the primary concern (Liu et al., 2022). While the effectiveness and performance of rain gardens or similar features are well documented, the same is not true for their degradation. However, similar to a constructed wetland, the lifespan of a rain garden is influenced by factors such as filter media, type of runoff pollutant, inflow water quality, management level, etc. (Guo et al., 2018). A case study of a bioretention basin in Westbury Place, Brisbane, showed that the overgrowth of weeds and grass in the basin resulted in many issues, including clogged filter media, a lack of filtering plants, and no inlet scour protection (Tara & Thrupp, 2018). The outlet was also prone to blockage. As a result, the Brisbane City Council replaced all the vegetation as well as replenished the system to reinstate its functionality. Thus, based on the existing literature on the degradation of Water Sensitive Urban Design ('WSUD') landscape features similar to the rain garden, the functional degradation of rain gardens can be defined as the gradual decline in their hydraulic and ecological performance, leading to a decrease in their lifespan.

The performance of a rain garden, especially infiltration, does not decline abruptly. Research indicates that infiltration-based blue-green infrastructure can lead to a significant reduction in flooding despite low saturated hydraulic conductivity and weed growth, provided that the infiltration cells have been designed and installed effectively (William et al., 2019). However, there is still a lack of research on how this degradation can be alleviated or alternatively planned to increase the lifespan of a rain garden. Furthermore, though there is a general understanding that the efficiency of rain gardens reduces over time without appropriate maintenance and replacement of filter media (William et al., 2019), a comparison of such a feature with more recent rain gardens would offer insight into better planning and design for longevity of rain gardens and propose alternative uses for the WSUD feature over its lifetime.

2.4. Rain Garden Improvement Methods and Techniques

In general, Bąk and Barjenbruch (2022) describe maintenance methods of rain gardens to include the upkeep of the rain garden irrigation, pruning of invasive vegetation, removal of dead plant matter and rubbish, replenishing the mulch layer, preventing erosion and accumulation of sediment, and management of the surrounding landscape. Meanwhile, based on existing literature, techniques for improving rain garden effectiveness can be categorised into digital simulations, infrastructural techniques, and planting techniques. Digital techniques can be utilised through simulation modelling and computer algorithms. For example, Li et al. (2020) ran a hydrology simulation, simulating the effects of water volume and nitrogen regulation of rain gardens to improve their design parameters. Similarly, McGuire et al. (2021) conducted a simulation using green stormwater infrastructure models to understand various stormwater variables in relation to rain garden catchment.

Infrastructural techniques involve engineering solutions such as installing a cap orifice in the underdrain pipe to control water outflow and constructing a two-stage tandem rain garden that can better reduce surface runoff (Guo & Luu, 2015; Tang et al., 2024). Lastly, various studies have investigated planting techniques and their effect on rain gardens. Yuan et al. (2017) studied how vegetation types affect the hydrological performance of rain gardens, concluding that a mixed variety of forb-rich perennials were most effective in reducing surface runoff. Likewise, Johnston et al. (2020) show vegetation types can change the bioretention capabilities of rain gardens, determining that plants with higher leaf area and rooting mass such as shrubs and prairie vegetation were most effective in improving soil-water storage and soil drainage.

3. Methodology

3.1. Data Collection Methodology and Site Selection

Following site selection, both quantitative methods– Shannon Biodiversity Index, Green View and Colourfulness Indices, and surface temperature– and observational data– spatial configurations of the sites, plant health, and groundcover and soil conditions– are collected. As suggested in Figure 2, the parameters across the two categories are interdependent; for example, observed issues with plant health may affect the Shannon Biodiversity Index through observed plant death, while surface temperature may be influenced by different soil conditions, such as compacted soil versus loose soil. Similarly, the spatial configurations of the rain gardens may affect the Green View and Colourfulness Indices through visibility of different vegetation. Following the data collection a comparative analysis between the two rain gardens will be made. From the analysis, design suggestions for new rain gardens and maintenance suggestions for existing rain gardens will be discussed. The methodology of this study is represented in Figure 2.

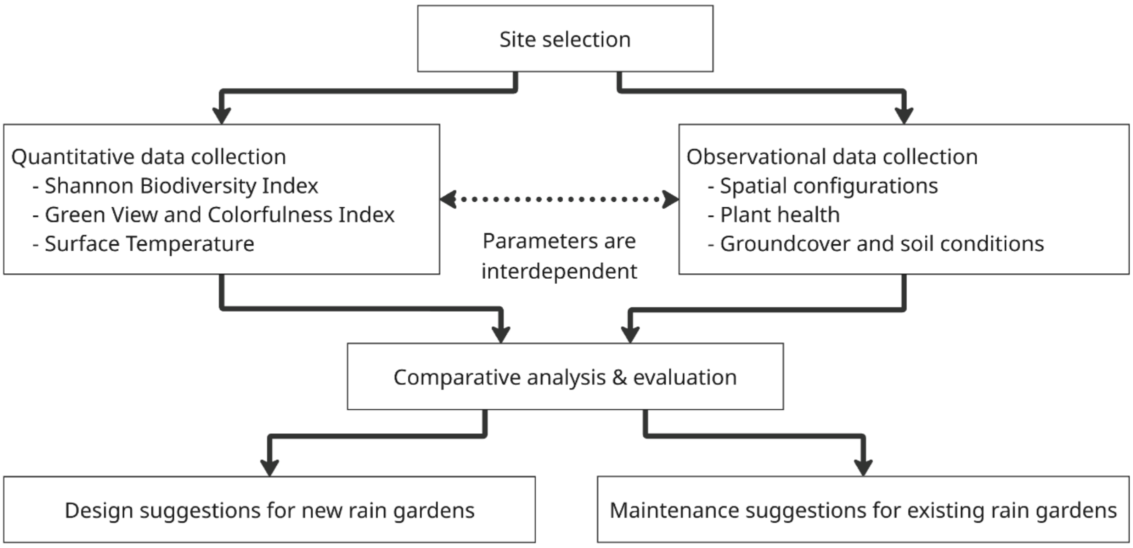

Figure 2 Methodology for data collection and analysis

Two rain gardens from different sites were chosen for this study. The first rain garden is located within Lakeside Garden at Jurong Lake Gardens, spanning approximately 478 square meters, and the second is located at Potong Pasir Avenue 3, where the rain garden and the swale together span over 700 sqm, in that particularly the rain garden spanning over 100 sqm. Both rain gardens are located in Singapore and were built as part of the Active, Beautiful, and Clean Waters programme– 'ABC Waters'– which promotes the integration of sustainable water management within urban landscapes (Public Utilities Board, 2024). The two rain gardens were chosen for several notable differences that will aid in the investigation of rain garden degradation and allow for comparative discussions between them.

First, the differing socio-economic and governing contexts of the two rain gardens suggest reason for comparative study. Because of the recent rejuvenation of the Chinese and Japanese Gardens within Jurong Lake Gardens (National Parks Board, 2024), the gardens are likely to receive more attention in terms of higher footfall and maintenance, compared to the Potong Pasir rain garden, which resides in a mature residential estate. The differing socio-economic contexts of a public park in the case of Jurong Lake and a small neighbourhood park connector in the case of Potong Pasir have implications on the use and perception of the gardens; the image of the Jurong Lake rain garden may be reflected in a national lens, while the Potong Pasir rain garden fulfils neighbourhood functions, as it is incorporated in a community learning trail (The Institution of Engineers Singapore, 2016). Additionally, another important difference to take into context is the differing governing authorities; while the rain garden in Jurong Lake Gardens is managed by the National Parks Board– 'NParks'– the rain garden at Potong Pasir is managed by the Jalan Besar Town Council. The differing management authorities have implications on funding available for the upkeep of the respective rain gardens, and it can be assumed that less funding is provided to the neighbourhood-scale Jalan Besar Town Council than the national-scale NParks.

Second, through initial observations, the differing planting strategies and age of either rain garden suggest different outcomes of aesthetic and functional roles of the gardens. The current planting palette of the Potong Pasir rain garden only consists of ground cover, while the Jurong Lake rain garden has more shrub coverage. The Potong Pasir rain garden is older than the Jurong Lake rain garden by approximately 14 to 17 years; the Potong Pasir rain garden was initiated between 2006 to 2008, at a similar time as the launch of the ABC waters programme (Public Utilities Board, 2024), while the Jurong Lake rain garden was constructed between 2022 and 2023.

Finally, design strategies implemented for the rain gardens differ in purpose and in connecting to the wider ecological and hydrological contexts, as seen in figures 3 and 4, providing basis for comparison of rain garden performance and intended function. The Potong Pasir rain garden was implemented using a 3P strategy– People, Public, and Private; it serves educational functions as well as hydrological and ecological functions to collect, filter, and convey stormwater, as well as to enhance biodiversity (The Institution of Engineers Singapore, 2016). On the wider scale in figure 3, the rain garden at Potong Pasir is connected to a series of vegetated swales and other rain gardens along Kallang River that filter stormwater before discharging into a canal (Public Utilities Board, 2024, p. 84-85). The Jurong Lake rain garden, a more recent project, intends to restore the landscape heritage of the freshwater swamp forest on site; thus, site-specific habitat zoning plans encapsulate different deconstructed freshwater swamps (Ecotones and Habitats, 2019). The specific rain garden chosen for this analysis is within the shaded woodland zone near Jurong Lake, as seen in figure 4. On the wider scale, Jurong Lake Gardens integrates a network of bioretention basins and rain gardens designed to manage approximately 20% of surface runoff, thereby alleviating pressure on conventional drainage infrastructure (AECOM, n.d.). Therefore, the differing spatial and design qualities of the two rain gardens provided reason for comparative assessment.

Figure 3 Satellite image of Potong Pasir rain garden and wider context (Google Earth, 2025a)

Figure 4 Satellite image of Jurong Lake rain garden and wider context (Google Earth, 2025b)

3.2. Hypotheses

Based on the literature review and site selection, the following were the hypotheses for the study:

1. The newer rain garden (Jurong Lake Garden) would be less visually degraded due to routine maintenance and early care, as opposed to the Potong Pasir rain garden. The rain garden in a larger public park, therefore, will be in better condition than the one in a residential neighbourhood. (Xiao et al., 2017)

2. The newer rain garden, due to its age and location, will have a wider variety of species suited for water filtration, whereas most of the intended plant palette would have been replaced for the Potong Pasir rain garden.
3. The newer rain garden would have higher GVI and CI due to diversity in species and more closely planted groundcover, lowering surface temperatures (Doğmuşöz, 2024).

3.3. Quantitative Data-Biodiversity, GVI & CI, and Surface Temperature

First, the Shannon Biodiversity Index was calculated to measure the diversity of plant species by sampling two quadrats on each rain garden site. At Potong Pasir, the plants generally consisted of ground cover, hence two 1x1 meter quadrats were sampled. At Jurong Lake, the plants were mostly shrubs, hence two 3x3 meter quadrats were sampled. For both sites, one quadrat in an edge or corner of the rain garden and one quadrat in the core or centre of the rain garden were sampled, such that the different conditions can be considered. The Shannon index is calculated for each quadrat using the formula below:

$$H' = -\sum_{i=1}^{S} p_i \ln(p_i)$$

Where:

S indicates the total number of species in the community, i.e. species richness.

p_i indicates the proportion of the i-th species. This is calculated as the number of individuals of species i divided by the total number of individuals in the community, pi = ni / N.

ln as the natural logarithm.

A higher value in the Shannon Biodiversity Index indicates greater diversity for both richness and evenness of the species. This metric gauges the distribution and diversity of the flora of selected rain gardens. Since plant selection plays an essential role in water filtration and quality (Chaves et al., 2025; Laukli et al., 2022), the index allows us to determine the functionality of both sites.

After calculating biodiversity metrics, the Green View Index (GVI) and Colourfulness Index (CI) of the overall spaces are quantified based on images taken from eye-level around each of the rain gardens. The GVI aims to compute the greenery along the rain gardens and is defined as the ratio of vegetation area within human view to the total human view area, given as a percentage (Zhu et al., 2023). Next, the CI aims to complement the GVI by analysing the level of ecosystem service that can provide scales with trait diversity; the more diversity of a trait is present, it results in more service provided (Behm et al., 2022). Hence, in this case, rain gardens with a diverse disposition of plant growth form and floral colours can be associated with a higher delivery of aesthetic ecosystem services as compared to gardens with single-growth forms and colours. 10 images were taken at eye-level at Potong Pasir, while 14 images were taken at Jurong Lake to account for the larger area, then, using those images, the GVI and CI were calculated by a Grasshopper code shown in appendix A. The code calculates the GVI and CI as a percentage of the images processed; the higher the value, the better the GVI or CI score. This allows us to understand and quantify the visual diversity of spaces, as a higher GVI value suggests that more vegetation is in view, and a higher CI value represents more contrasting colours in the vegetation.

Measuring the surface temperature allows the identification and understanding of the effects of UHI on the site (Lau & Lin, 2023). These measurements under different shade conditions and materials provide a distinguished identification of disparities between the two rain gardens to focus design suggestions. Additionally, it allows for further inferences about the environment for plant growth, medium compaction, which affects water filtration, and thermal comfort. The measurements of surface temperature were collected using a thermal image sensor FLIR TG165 under various conditions, including unshaded barren ground, unshaded ground cover, shaded ground cover, plant surface, paved surface and the centre of the rain garden.

3.4. Observational Data-Spatial Configurations, Plant Health, and Groundcover Conditions

The spatial configuration of each rain garden is mapped out to understand the clustering of plants, canopies, and groundcover. Overlapping canopies are noted, as unintentional shading of the rain garden may affect performance. As Puppala et al. (2022) highlighted that the GVI does not report on the health of plants; observational data is collected on site to identify issues with plant health. Potential issues of plant death, stunted growth, and pest infestations are noted and discussed in relation to the spatial clustering of plants within the rain garden. Invasive and spontaneous-growing species and their effects are explored as well. Similarly, groundcover conditions are noted, where patches of exposed soil and rocks are investigated in relation to quantitative data such as surface temperature. Soil quality and erosion are also noted and their implications on rain garden performance are discussed.

4. Results

4.1. Quantitative Data-Biodiversity, GVI & CI, and Surface Temperature

The data collection method was designed to capture representative samples of plant diversity across different spatial conditions within each rain garden. By sampling both central and peripheral zones, the method accounted for potential microhabitats and differences that could influence species distribution. The use of different quadrat sizes tailored to vegetation type (shrubs vs. ground cover) ensured scale and accuracy in capturing species composition and abundance. This analytical approach allowed a nuanced interpretation of biodiversity in relation to ecological function, thus supporting a better understanding of how plant diversity may influence hydrological performance across different rain garden designs. Sampling biodiversity responds to the hypothesis that the newer rain garden is expected to have a wider variety of species suited for water filtration.

While initial results suggest higher species evenness and diversity at Potong Pasir, with a Shannon Index of 1.62, compared to Jurong Lake Gardens of 1.2, this changes significantly when weeds and unintended species are excluded, as seen in table 1. Potong Pasir's index drops to 0, leaving only one species, whereas Jurong Lake Gardens rises to 1.66, indicating a more purposeful planting palette due to its increased diversity. Figure 5 illustrates the plant configurations at Potong Pasir, and figure 6 illustrates that of Jurong Lake, based on species listed in tables 1 and 2.

Table 1 Species Identified at Jurong Lake Gardens Rain Garden and Potong Pasir Rain Garden-Species Considered as Weeds are Highlighted in Red

Jurong Lake Gardens Rain Garden		
Species	**Quadrat 1 (Corner)**	**Quadrat 2 (Center)**
Cheilocostus speciosus (J. Koenig) C. Specht	-	5
Pandanus amaryllifolius Roxb.	-	9
Calathea lutea	21	2
Rhapis multifida	3	12
Osmoxylon lineare	-	14
Thalia geniculata (red-stemmed)	-	12
Arostichum speciosum	9	-
Axonopus compressus	1320	-
Phyllanthus debilis	-	338
Spermacoce latifolia	-	1125
Cyperus mindorensis	-	450
Hydrocotyle sibthorpioides	-	56
Phyllanthus urinaria	240	-

Cyanthillium cinereum	120	-
Overall Shannon Index	**0.76**	**1.20**
Shannon Index without weeds	**0.136**	**1.66**
Potong Pasir Rain Garden		
Species	**Quadrat 1 (Corner)**	**Quadrat 2 (Center)**
Commelina diffusa	93	-
Cyperus mindorensis	105	294
Axonopus compressus	50	56
Nelsonia sp	20	130
Solanum sp	35	-
Phyllanthus urinaria	2	37
Medicago lupulina	5	2
Spermacoce ocymoides	97	162
Eragrostis tenella	145	185
Overall Shannon Index	**1.40**	**1.62**
Shannon Index without weeds	**0**	**0**

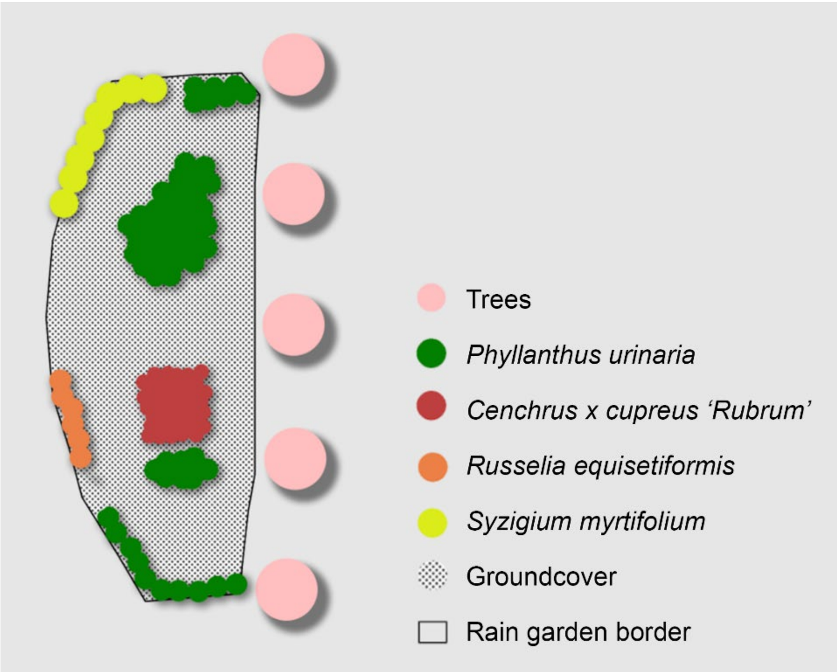

Figure 5 Potong Pasir rain garden plant configuration

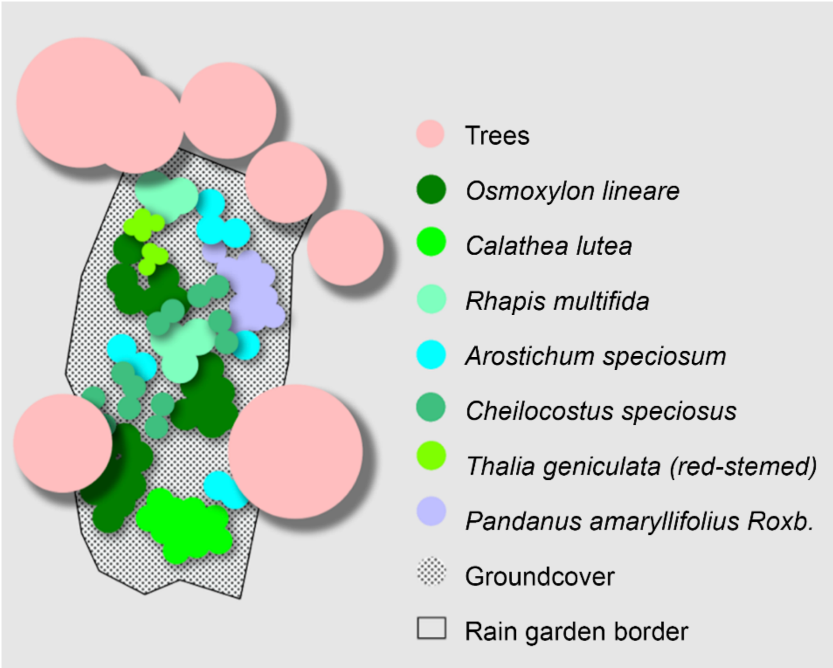

Figure 6 Jurong Lake rain garden plant configuration

For the Green View Index (GVI) and Colourfulness Index (CI), data collection relied on capturing multiple eye-level images that reflect the everyday human experience of the rain garden (appendix B and C), ensuring consistency in perspective across both sites. These images served as the visual dataset for further analysis, and to respond to the third hypothesis that the newer rain garden is expected to have higher GVI and CI values. The computational approach by processing the images through a Grasshopper script (appendix A) minimised human bias and allowed for objective comparison of GVI and CI. The GVI and CI percentages for each of the images and the averages are represented in table 2.

Table 2 Green View Index (GVI) and Colourfulness Index of Jurong Lake Gardens and Potong Pasir Rain Gardens

Image No.	GVI (%)		Colourfulness (%)	
	Jurong Lake Gardens	Potong Pasir	Jurong Lake Gardens	Potong Pasir
1	26.86	73.15	35.65	48.44
2	29.39	45.49	33.16	44.12
3	30.26	33.01	32.41	46.40
4	34.61	16.48	33.82	40.26
5	49.82	30.59	40.30	55.86
6	34.18	29.77	37.42	61.03
7	30.36	40.38	35.48	50.69
8	40.04	40.09	38.71	45.63
9	45.83	26.22	37.30	37.08
10	35.07	24.95	38.30	39.15
11	40.67	-	43.41	-
12	38.04	-	41.92	-
13	42.62	-	35.32	-
14	35.29	-	39.81	-
Average:	**36.64**	**36.02**	**37.36**	**46.89**
Std Deviation, σ:	**6.36**	**14.77**	**3.16**	**7.12**

While both the GVI and the CI are on average higher for Potong Pasir as compared to Jurong Lake Gardens, there is a higher variance in the values as seen in figure 7, compared to those at Jurong Lake in figure 8. This indicates that GVI and CI are unevenly distributed across the rain garden at Potong Pasir, while the distributions and variation are more even at Jurong Lake.

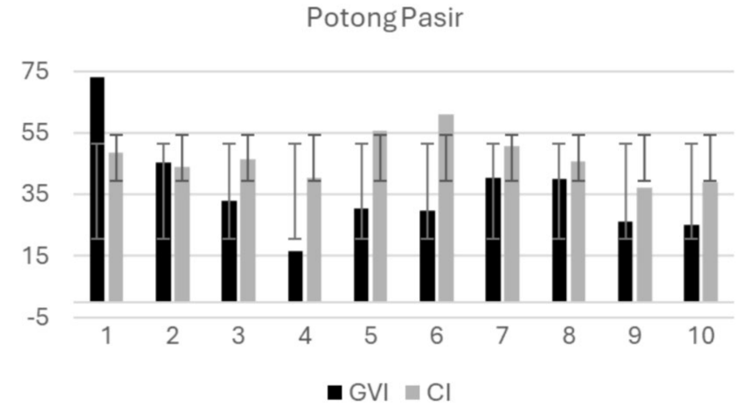

Figure 7 Graph showing GVI and CI of the Potong Pasir rain garden with standard deviation

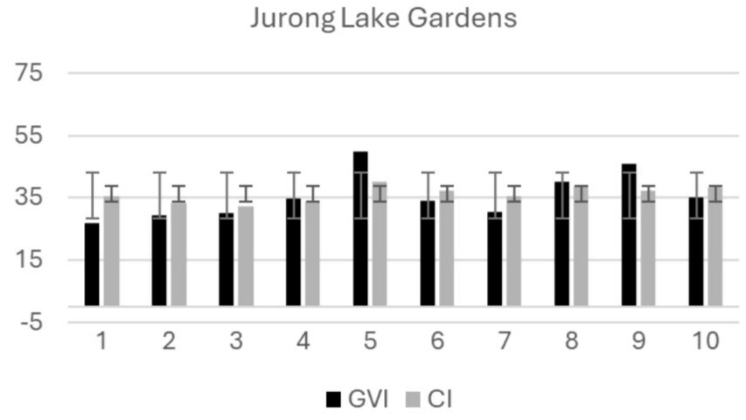

Figure 8 Graph showing GVI and CI of the Jurong Lake rain garden with standard deviation

Surface temperature data was collected systematically across different material and shade conditions to capture a comprehensive thermal profile of each rain garden. Both rain gardens were visited in mid-March 2025, with surface temperatures measured between 12-2 pm during the peak heat period. Although mild rain occurred prior to data collection at both sites, the similar weather conditions ensure a valid comparative analysis. By targeting consistent surface types under comparable conditions, the method minimised external variability and ensured reliability. The analysis approach involved comparing temperature ranges across both sites to identify microclimatic differences and infer their implications on thermal comfort and hydrological performance. This comparative approach underscores how planting design and material choices influence heat retention, which may help inform better landscape strategies.

The Jurong Lake rain garden recorded a higher average surface temperature of 51.36°C, compared to 41.14°C at Potong Pasir. Despite having more shade, the newer Jurong site showed higher temperatures, likely due to sparse ground cover at its core, as shown in figure 10 (iii). In contrast, Potong Pasir's established ground cover appears to lower surface temperatures by around 20°C on average, as shown in figure 9 (iii).

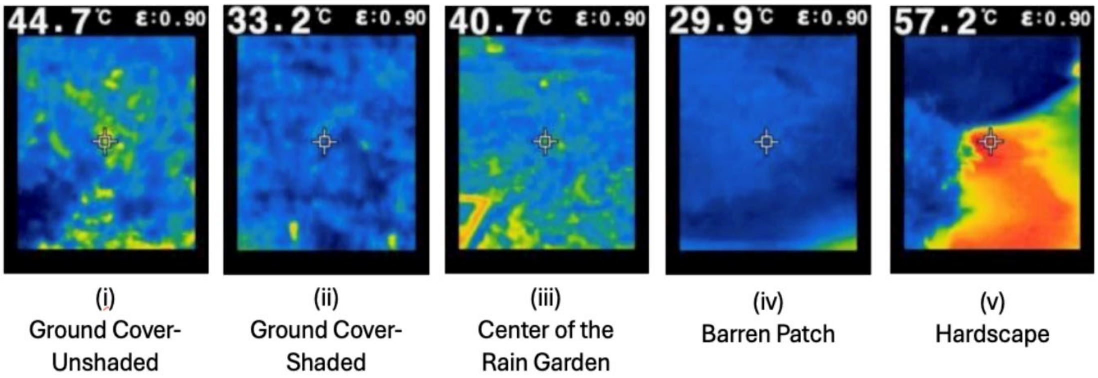

Figure 9 Surface temperature images of Potong Pasir rain garden

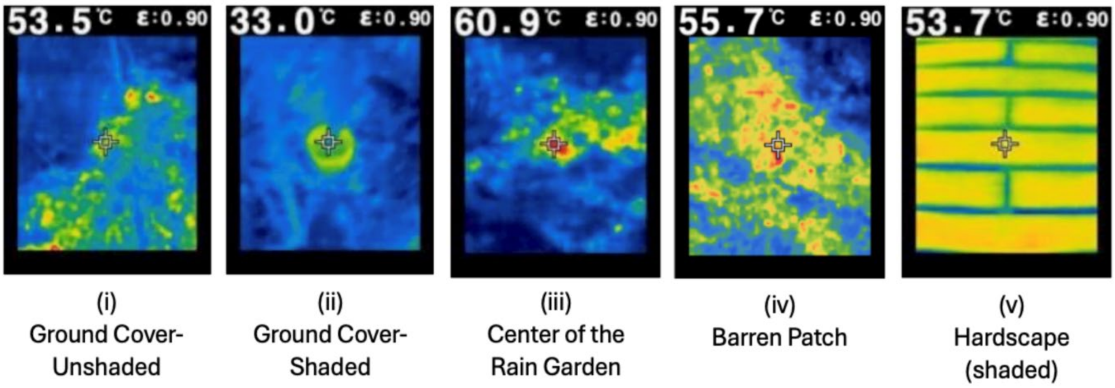

Figure 10 Surface temperature images of Jurong Lake Gardens rain garden

4.2. Observational Data-Spatial Configurations, Plant Health, and Groundcover Conditions

Spatial observations were gathered through on-site walkthroughs, focusing on visual assessment of planting structure, soil conditions, and infrastructure performance, such as inlet function. Selected patches were examined to represent broader patterns across the rain gardens. The analysis approach involved linking these qualitative observations, such as overgrowth, soil patchiness, and clogged inlets, to broader maintenance and design outcomes. By correlating spatial layout and vegetation health with signs of neglect or poor establishment, the analysis provides insights into how site conditions impact long-term performance of rain gardens. This aims to respond to the first hypothesis statement that the newer rain garden is expected to be more visually diverse and less degraded due to routine maintenance and early care.

Both rain gardens showed signs of poor maintenance, including overgrown plants, dried patches, and clogged inlets. As seen in figure 11, Potong Pasir mostly has even ground cover, while patchy ground coverage was observed at Jurong Lake, shown in figure 12, indicating inadequate early-stage care, which is critical for healthy vegetation establishment. This has likely contributed to weed growth in parts of the rain garden. There is also an overall lack of visual harmony within either garden; without seasonal bloomers or focal plants, rain gardens fail to serve their educational or recreational role. The general observations also reflect an overarching theme of disconnect from the communities using the rain garden. Without interpretive signage, benches, or pathways, rain gardens feel like passive infrastructure rather than public green assets.

Figure 11 Site images of Potong Pasir rain garden

Figure 12 Site images of Jurong Lake Garden rain garden, showing patchy ground cover

Infections like leaf blotching and stem browning, shown in figure 13, indicate inadequate pest control and mulch renewal, contributing to habitat degradation and visual neglect. This weakens ecosystem resilience and may even reduce community engagement. Despite Potong Pasir's higher GVI at (73%), uneven plant coverage results in visual imbalance, which users often perceive as neglect or poor design (Church, 2015).

(a) (b)

Figure 13 Poor plant conditions at **(a)** Jurong Lake Gardens, and **(b)** Potong Pasir

Poor soil quality and unsuitable plant selection were observed to compromise key rain garden functions. Sediment buildup and root blockages hinder infiltration, leading to surface pooling and increased mosquito breeding risk. The absence of proper elevation zoning (inflow-mid-outflow) disrupts water movement and filtration. This, along with compacted soil, limits percolation and thus reduces microbial activity and weakens plant anchorage.

5. Discussion

The following discussion aims to evaluate the conditions of the two rain gardens through comparison across the various parameters. Existing routine maintenance and design guidelines will be explored alongside possible inadequacies in current practices. By deducting and analysing likely reasons for different aspects of degradation at both rain gardens, detailed design and maintenance suggestions are provided.

5.1. Comparative Discussion

A summarised comparison between the Jurong Lake rain garden and the Potong Pasir rain garden is shown in Table 3 below, addressing the first research question on how rain garden degradation may be measured and comparatively assessed.

Table 3 Summarised Comparison Between Jurong Lake Gardens and Potong Pasir Rain Gardens

Parameter	Jurong Lake Gardens rain garden	Potong Pasir rain garden
Shannon Biodiversity Index	***1.66*** The diversity and evenness of species are high. As a newer rain garden, the shrubs and plants for filtration are maintained. However, there is a notable lack of ground cover.	***0*** The original plant palette of the rain garden has been replaced with weeds; as a result, the distribution of rain garden-specific plant species is missing.
Avg. Green View Index (GVI)	***36.64%, with a σ: 6.36*** The GVI is similar for both rain gardens. However, the standard deviation indicates evenness in the different views of the garden.	***36.02%, with a σ: 14.77*** The GVI is similar for both rain gardens. However, the higher standard deviation shows more variation in the level of greenness in various views.
Avg. Colourfulness Index (CI)	***37.36%, with a σ: 3.26*** Despite the higher species diversity, JLG has comparatively lower CI due to the lack of flowers in flowering species and surrounding objects.	***46.89%, with a σ: 7.12*** Potong Pasir rain garden has a higher CI with a greater standard deviation. The presence of buildings and other elements gives it an edge despite the lack of a diverse planting palette.
Avg. Surface Temperature	***51.36 °C*** The lack of ground cover contributes greatly to its increased average surface temperature. Thus, the JLG rain garden is less effective in mitigating UHI.	***41.14 °C*** Weed growth in the old garden has contributed to a dense ground cover that helps lower the overall surface temperature of the garden and its surrounding surfaces, contributing to reducing the area's UHI.
Spatial Configuration	Lacks visual harmony Over-shading by large tree canopies	Lacks visual harmony Lacks water-filtering shrubs and plants Connected to bioswales and series of other rain gardens
Plant Health	Leaf blotching Stem browning	Leaf blotching Leaf defoliation
Ground Cover Conditions	Low Ground Cover Compacted soil High sediment content	High Ground Cover Loose soil Low sediment content

To address the second research question– what environmental, maintenance, and design factors affect the degradation of rain gardens– a comparative discussion of the two rain gardens' conditions is explored. Although the rain garden at Jurong Lake Gardens was constructed at least 14 years after the rain garden at Potong Pasir, it appears to have degraded faster, as highlighted in the results discussion parts 5.1 – 5.3. This may be attributed to a few challenges that were identified based on the results of the study, which include low diversity in species selection, overshading of trees in the surrounding landscape, and heat retention due to soil compaction. In addition to these challenges that could have increased the rain garden deterioration rate, another challenge rain gardens may face is the lack of visual identity, resulting from its degradation.

The quicker degradation of the rain garden at Jurong Lake Gardens may be attributed to poor plant selection. According to the results of the Shannon Biodiversity Index, the Jurong Lake rain garden scored lower when weeds are included in the count. While the Jurong Lake rain garden scores higher than the Potong Pasir rain garden when weeds are removed from the count, the plant diversity in the Jurong Lake rain garden is extremely concentrated in one location, causing the score in one quadrat to not be significantly higher than the score of 0 in the Potong Pasir rain garden. These results demonstrate that, regardless of the presence of weeds, rain gardens appear to perform better with higher plant species diversity that is more evenly dispersed throughout the rain garden. This is supported by Yuan et al. (2017), who suggest that planting more diverse species rather than monocultures or restricting plant mixtures can improve the hydrological performance of rain gardens in terms of stormwater detention and retention capabilities. Furthermore, it appears that forb-rich perennials are effective in slowing surface runoff and increasing stormwater detention time due to their higher leaf area and deeper rooting mass (Ibid.), such as weeds like Commelina diffusa, Cyperus mindorensis and Eragrostis tenella in the Potong Pasir rain garden. Another benefit of the deeper rooting systems of such plant species is improved biofiltration and nutrient removal of nitrates and phosphates (Loh, 2012). Additionally, a diverse planting palette also strengthens the plants' resistance to disease and insect infestations (Ibid.). Apart from forb-rich perennials, prairie vegetation is also similarly effective in providing these benefits, a category that the weed species fall into as well (Yuan et al., 2017). Hence, it appears that the lack of diversity in plant species selection may have reduced the hydrological performance of the Jurong Lake Gardens rain garden over time, as there are lesser forb-rich perennials or prairie vegetation planted, thus contributing to its degradation.

As part of the biodiversity evaluation conducted during the assessment of the Shannon Biodiversity Index, the current plant configuration of both rain gardens is evaluated in figures 5 and 6. In figure 6, the growth of the tree canopies have likely shaded the vegetation within the rain garden at Jurong Lake, in comparison to figure 5 where the trees have been planted further away. Thus, the spatial layout and design of not just the rain garden but also its surroundings play a crucial role in its performance and degradation. This highlights a potential challenge in which trees planted too close to the edges of a rain garden may cause overshadowing, preventing sunlight from reaching the plants within the rain garden and affecting their growth. Furthermore, this is supported by observations of plants such as the Rhapis multifida in the Jurong Lake rain garden, which may have deteriorated due to the lack of sunlight. Therefore, improper tree planting near a rain garden may cause the issue of overshading from trees as the canopies expand, affecting plant growth in the rain garden and affecting its performance over time.

The higher surface temperatures observed within the rain garden at Jurong Lake Gardens, especially in areas without ground cover, could result in soil compaction, which in turn can appear higher in temperature. This is observed in figure 9(iii), where compacted soil and larger rocks were found at the core of the Jurong Lake rain garden, measuring upwards of 60ºC surface temperature when under direct sunlight. Soil compaction may significantly impact the performance of rain gardens as it can reduce the level of moisture in the soil, affecting plant health, and affect the soil's ability to retain water (Kelishadi et al., 2018). Without ground cover covering the soil in the rain garden this increases exposure to sunlight, thus resulting in soil compaction. As Attah and Etim (2020) show, high temperatures can influence soil compaction, which also decreases its moisture level. With less access to water in the soil, this may negatively impact the health of plants in the rain garden and exacerbate the decline of the rain garden. Moreover, heat also reduces the water retaining capacity of soil, thus less water is saturated within it (Kelishadi et al., 2018), which may impact the rain garden's bioretention functionality.

Lastly, both rain gardens scored approximately 36 GVI, while Jurong Lake scored 37 CI and Potong Pasir scored 46 CI (where 100 indicates the highest value). As Jurong Lake scored lower on CI, it may represent a lack of a clear visual identity. This may affect a rain garden's ability to provide cultural ecosystem services, such as aesthetic and educational services, while also decreasing spatial identity. According to Doğmuşöz (2024), varied textures and colours of the plants in a rain garden help to increase aesthetics and form a spatial identity. Thus, this absence may cause monotony and decrease the strength of the rain garden and its surrounding area's identity. The higher standard deviation in the GVI results of the Potong Pasir rain garden also suggests a visual imbalance in the greenery, which may further impede its aesthetic values. Additionally, without seasonal bloomers or focal plants, the rain garden at Potong Pasir also fails to serve enhanced educational and recreational purposes, especially since it is used in educating students from nearby schools. This lack of visual identity and reduced educational value may also reduce the impact of rain gardens as sites for engaging with communities on biodiversity and water management.

5.2. Suggestions for Planners and Designers

This section explores the third research question of how research may inform existing maintenance practices and future designs of rain gardens. Based on the data collection and analysis of the two rain gardens, the following are suggested maintenance and design guidelines to increase the lifespan of rain gardens and to design for longevity.

Table 4 suggests the basic routine maintenance in ensuring that conventional system components in grey infrastructure remain highly functional. The above maintenance for grey infrastructure is largely done by Town Councils for areas within Housing & Development Boards (HDB) estates (Housing & Development Board, 2024) and by contractors employed by developers or property owners of private developments (Public Utilities Board, 2018).

Table 4 Routine and Remedial Maintenance on Infrastructures to Manage Stormwater-Text Marked with an Asterisk Indicates Practices Observed to be Inadequate on Site

Conventional system component	**Routine maintenance**
Pipelines and storage basins	Inspecting surface above pipelines for sinkholes, wet spots and tree growth
Inlets / outlets / manholes	Removal of litter and debris Cleaning of screens to remove moss Cutting grass, removing weeds
Nature-based solutions practice	**Routine maintenance**
Sedimentation	Cutting grass, removing weeds Removal of litter and debris Pruning trees, maintaining vegetation
Filtration	*Cleaning and removing build-up of geotextile or filter
Infiltration	Cleaning gutters Cleaning and removing build-up of geotextile or filter
Bioretention	*Assessing vegetation for disease, infection or poor growth *Maintaining plant density *Mulching and replacing top layer of soil
Nature-based solutions practice	**Remedial / Occasional Maintenance**
Sedimentation	Reseeding areas Repairing erosion damage Realigning riprap Re-levelling uneven surfaces
Filtration	Removal or control of tree roots Replacing geotextile or filter
Infiltration	Clearing sediment deposits Replacing geotextile or filter Repairing cracks, depressions
Bioretention	Fixing holes in filter media Maintaining erosion protection *Removal of invasive species Repairing cracked or disturbed inlets

However, Rain Gardens – a Nature Based Solution (NBS) make the focus of this study. The maintenance of rain gardens depends on their location and ownership. The Potong Pasir rain garden is located within HDB estates. It is maintained by the respective Town Council – Jalan Besar

Town Council – which manages the common property in public housing areas (Housing and Development Board, 2024). The JLG rain garden falls under the care of the National Parks Board (NParks), which is responsible for the upkeep of ecological features that promote stormwater management and enhance biodiversity (National Parks Board, 2024).

In table 4, the entries marked with an asterisk indicate maintenance practices that were observed to be either inadequate or entirely absent during field observations. As a result, the following design recommendations have been proposed to address these maintenance gaps and to inform future iterations of rain garden implementation in the tropics. These suggestions are grounded in field observations and aim to enhance the long-term functionality and resilience of rain gardens, contributing to the objectives of the study on the degradation and performance decline of such systems across the nation.

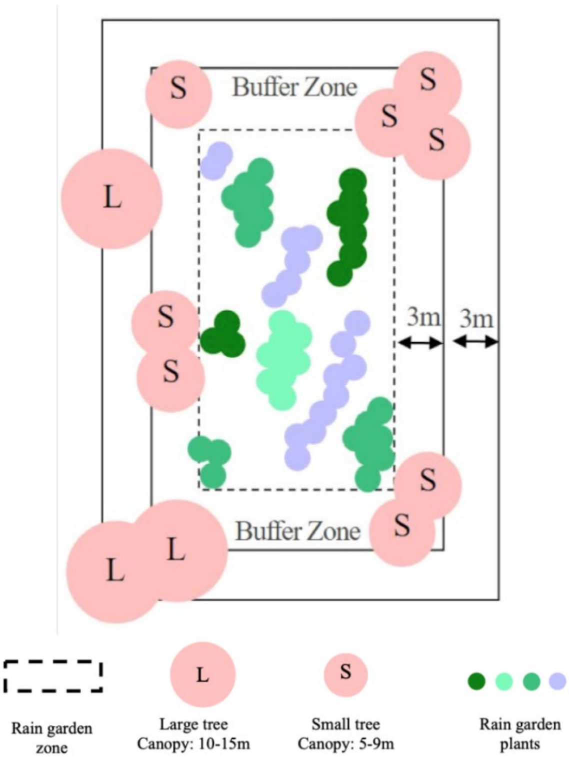

Figure 14 Design suggestions to prevent over-shading by trees

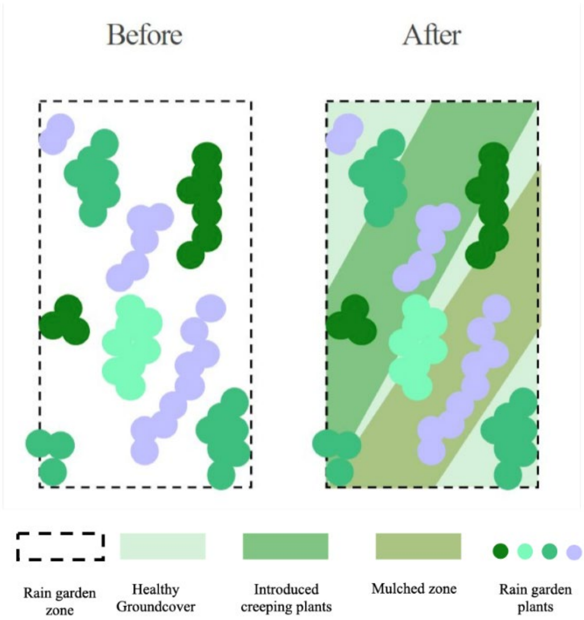

Figure 15 Design suggestions to improve temperature regulation

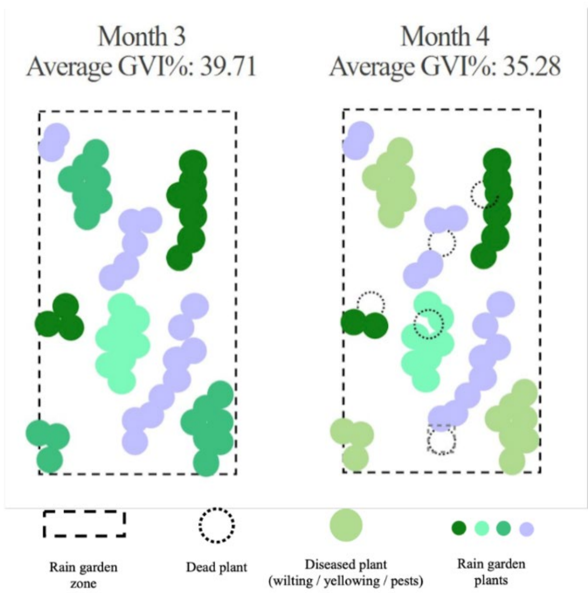

Figure 16 Design suggestions for weed and pest control, and for easier regular visual assessment

Table 5 Design Suggestions Based on Field Observations, Correlating with Figures 14, 15, and 16 Above

Fig. No	Reason	Recommendations / suggestions
14	**Preventing over-shading by trees.**	
	Rhapis multifida in JLG rain gardens were suspected to die over time due to the over-shading of trees that grew larger over time (refer to fig. 6).	Planting large trees at a minimum of 3 meters away from rain garden zones. Smaller trees can be planted just within the buffer zone. No trees should be planted within rain garden zones.
15	**Improving surface temperature regulation**	
	JLG rain garden was observed to have higher surface temperature on bare grounds and areas with a lack of ground cover (refer to fig. 7 and 8).	Applying mulch – of 50% sand, 30% loam and 20% compost (Green Building Alliance, n.d.)– and planting creeping groundcovers to reduce surface temperature. Introduce phase-based maintenance (see table 4).

	The quick degradation of this rain garden could indicate a lack of initial maintenance.	Year 1 to year 2: Routine health screening of plants Year 3 onwards: Increased remedial maintenance
16	**Improving surface temperature regulation**	
	Potong Pasir rain garden is a place of learning for students (Ying, 2019). Overgrowth and infestation were observed on some plants (refer to fig. 13).	Introduce community weeding activities – spearheaded by Jalan Besar Town Council – to remove invasive species Monthly image inspection through the measurement of GVI for early identification of plant issues and preparation of plant disease mitigation methods.

Thus, to enhance the longevity and functionality of rain gardens in the tropics, it is quintessential to address key design and maintenance challenges identified during field observations of this study. These strategies aim to mitigate degradation over time and contribute to more resilient, low-maintenance rain gardens in urban environments.

5.3. Limitations

Various methodological and interpretive constraints limited the study. Methodological constraints include the small sample size in which only two rain gardens were compared, and the data collected was limited to the rain gardens themselves, not incorporating the surroundings and conditions of the wider context (e.g. swales and catchment linked to the rain garden). The study was also limited by time-based and seasonal variables; there was limited time to assess rain garden performance, hence the majority of the data collected was static. Similarly, there was a lack of control over environmental variables, such as seasonal changes which affected the spontaneous vegetation growing during the monsoon season. In the results for the surface temperature on hardscape material at Jurong Lake Gardens, there may be some inconsistencies due to significant shade cast on the hardscape and edges of the rain garden.

Both rain gardens are situated in public spaces, making it accessible for the visual analysis methods employed in this paper. However, the study was limited from exploring various sub-soil parameters, such as monitoring filtration and infiltration of water, measuring extents of water purification, and inspecting sub-soil qualities, due to the limited access to the rain garden ground. Interpretive constraints of this study included potential observer bias in qualitative observations, such as when noting plant health and ground coverage. Potential bias may have also been translated into the images captured for GVI and CI calculations.

6. Conclusion

Rain garden degradation was measured through both quantitative measurements of biodiversity, Green View Index, Colourfulness Index, and surface temperature, as well as qualitative assessments of the spatial configurations, plant health, and groundcover conditions. The various measurements allowed for a rich comparative assessment. The study thus concludes that tackling key issues that accelerate rain garden degradation through maintenance and design suggestions allows rain garden lifespans to be lengthened and reap long-term benefits like effective stormwater management and habitat creation for local biodiversity. Common challenges encountered in rain gardens included maintenance issues, poor aesthetic and community engagement, as well as improper design. Maintenance suggestions tackled four key functions of a rain garden: sedimentation, filtration, infiltration, bioretention. Design suggestions included tree planting configurations and using ground cover to reduce surface temperature and visual inspections. This, in turn, allows for improved visual quality and a higher greenery in view.

Further studies are suggested to account for more diverse rain garden planting palettes in the tropics, and a longer time frame to monitor rain gardens and their degradation from their installation date, while also factoring in more data regarding the user experience of the rain garden. User experiences can link back to the assessment of GVI and CI to understand the visual perception of rain gardens and may be incorporated through usage data of rain gardens, community engagement analyses, and user perception surveys. This is encouraged to be carried out as a longitudinal study with standardised data collection methods, including regular biodiversity surveys as well as plant and soil quality monitoring, and statistical testing for comparison between rain garden conditions. Future studies should continue to employ mixed-method approaches to capture the relationship between ecological and socio-economic dimensions of rain gardens, especially as the governmental and managerial contexts of rain gardens heavily affect the conditions, as shown in this paper.

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Appendix

Appendix A– Grasshopper (Rhinoceros 3D) script for calculating Green View and Colourfulness Indices

```
# Source: https://github.com/kowalski93/Green-View-Index-for-QGIS/blob/main/greenviewindex/calculate_green_view_index_algorithm.py
import os
import clr  # Add the clr import to access .NET libraries
clr.AddReference("System.Drawing")  # Import the System.Drawing assembly
from System.Drawing import Bitmap, Graphics, Color  # Import Bitmap, Graphics, and Color classes

input_folder = InputFolder  # Folder containing the images
output_folder = InputFolder  # Folder for saving masked images (optional)

write_masked = False  # No longer saving masked images
algorithm = "Li"  # Algorithm to extract vegetation pixels: "Li" or "Dong"

# Function to resize the image to 1000x1000 pixels
def resize_image(img, target_width=1000, target_height=1000):
    resized_img = Bitmap(target_width, target_height)
    graphics = Graphics.FromImage(resized_img)
    graphics.DrawImage(img, 0, 0, target_width, target_height)
    graphics.Dispose()
    return resized_img

# Function to calculate Excess Green Index (ExG) for vegetation detection
def calculate_exg(img):
    width, height = img.Width, img.Height
    exg_values = []

    for x in range(width):
        for y in range(height):
            pixel = img.GetPixel(x, y)
            r, g, b = pixel.R, pixel.G, pixel.B
            exg = 2 * g - r - b
            exg_values.append(exg)

    return exg_values, width * height

# Function to apply Li et al. or Dong et al. vegetation algorithms
def apply_vegetation_algorithm(exg_values, algorithm, width, height):
    vegetation_mask = []
    for exg in exg_values:
        if algorithm == "Li":
            # Li et al. algorithm: simple threshold for ExG
            vegetation_mask.append(255 if exg > 50 else 0)
        elif algorithm == "Dong":
            # Dong et al. algorithm: Example HSV-based threshold (not included in Rhino)
            # Replace with a direct RGB-based rule for compatibility
            vegetation_mask.append(255 if 50 < exg < 150 else 0)
    return vegetation_mask

# Function to calculate Sky View Factor (SVF)
def calculate_svf(img):
    width, height = img.Width, img.Height
    sky_pixels = 0
    total_pixels = width * height

    # Assume sky pixels are those with high R, G, B values (near white or light blue)
    for x in range(width):
        for y in range(height):
            pixel = img.GetPixel(x, y)
            r, g, b = pixel.R, pixel.G, pixel.B

            # Simple threshold to identify sky pixels
            if r > 200 and g > 200 and b > 200:  # Example for white or light blue
                sky_pixels += 1

    # Calculate SVF as the percentage of sky pixels
    svf = (sky_pixels / total_pixels) * 100
    return svf

  # Function to calculate colourfulness
def calculate_colourfulness(img):

    width, height = img.Width, img.Height
    rg = []  # To store rg values for all pixels
    yb = []  # To store yb values for all pixels
    # Calculate rg and yb for each pixel
    for x in range(width):
        for y in range(height):
            pixel = img.GetPixel(x, y)
```

```
                r, g, b = pixel.R, pixel.G, pixel.B
                rg.append(r-g)
                yb.append ((r + g) / 2 - b)

            # Calculate the mean values
                Urg = sum(rg) / len(rg)
                Uyb = sum(yb) / len(yb)

            # Calculate the standard deviations
                Qrg = (sum((value - Urg) ** 2 for value in rg) / len(rg)) ** 0.5
                Qyb = (sum((value - Uyb) ** 2 for value in yb) / len(yb)) ** 0.5

        # Compute the colourfulness metric
        colourfulness = (Qrg ** 2 + Qyb ** 2) ** 0.5 + 0.3 * ((Urg ** 2 + Uyb ** 2) ** 0.5)

        return colourfulness

# Function to process images and calculate GVI and SVF
def process_images(input_folder, write_masked, algorithm):
    all_files = [f for f in os.listdir(input_folder) if f.endswith(".jpg")]
    results = []

    for file in all_files:
        filepath = os.path.join(input_folder, file)
        img = Bitmap(filepath)

        # Resize the image to 1000x1000
        resized_img = resize_image(img, target_width=100, target_height=100)

        # Calculate Excess Green Index
        exg_values, total_pixels = calculate_exg(resized_img)

        # Apply vegetation classification
        vegetation_mask = apply_vegetation_algorithm(exg_values, algorithm, resized_img.Width, resized_img.Height)

        # Calculate GVI as the percentage of vegetation pixels
        green_pixels = sum(1 for value in vegetation_mask if value == 255)
        gvi = (green_pixels / total_pixels) * 100

        # Calculate Sky View Factor (SVF)
        svf = calculate_svf(resized_img)

        # Calculate Colourfulness
        colourfulness = calculate_colourfulness(resized_img)

        results.append((file, gvi, svf, colourfulness))

    return results

# Main execution
results = process_images(input_folder, write_masked, algorithm)

# Output results to console or Grasshopper panel
for file, gvi, svf, colourfulness in results:
    print(f"Image: {file}, GVI: {gvi:.2f}%, SVF: {svf:.2f}% , Colourfulness:{colourfulness:.2f},")
```

Appendix B– Images taken at Jurong Lake rain garden used to process Green View and Colourfulness indices

Appendix C– Images taken at Potong Pasir rain garden used to process Green View and Colourfulness indices

CRediT Authorship Contribution Statement

Lina Altoaimi: Writing - Review & Editing, Writing - Original Draft, Investigation, Methodology, Project Administration. Shruthakeerthi Karthikeyan: Writing - Review & Editing, Writing - Original Draft, Investigation, Formal Analysis. Akshitha Vadlakunta: Writing - Review & Editing, Writing - Original Draft, Conceptualization, Investigation. Wang Yuting: Writing - Review & Editing, Writing - Original Draft, Investigation, Data Curation. Abdul Tha'Qif bin Abdul Terawis: Writing - Review & Editing, Writing - Original Draft, Investigation, Visualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. The authors declare that this study has received no financial support.

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Data Availability

Data will be made available upon request.

Ethics Committee Approval

An ethics committee approval was not required for this study.

Resume

Lina Altoaimi is a graduate of the Bachelor of Landscape Architecture programme at the National University of Singapore. Her research interests include spatial degradation and transformation, as well as the influence of policy on urban spaces. She is currently pursuing independent research projects exploring architectural degradation and related policies in the tropical built environment.

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Mobilizing nature-based solutions through temporary urban interventions: A civic guide to ephemeral landscapes

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Abstract

The potential of permeable urban landscapes has gained increasing attention in contemporary academic scholarship on nature-based solutions (Nbs). The common thread of these solutions is related to pressing issues arising from responses to climate change caused by urban densification, necessitating innovative strategies for enhancing environmental resilience. However, these strategies often require extensive timeframes and large-scale implementation. In contrast, temporary approaches to urbanism have the potential to provide answers to these strategies by focusing on citizen-engaged, small-scale, low-cost and low-tech actions. This study engages these two planning approaches in dialogue by focusing on overlooked urban interstices—small and unnoticed impervious spaces that have significant potential to become permeable. Developing a conceptual framework, the research explores how ephemeral installations can transform these interstices into nature-based, scalable and socially engaged landscapes. Applying this framework, the study adopts prototyping as an experimental research method, structured around three phases: (1) experimentation: incorporating nature-based aggregates, (2) fabrication: forming scalable and modular tiles, and (3) dissemination: creating social value with workshops. Building over the findings of these phases, the paper concludes with a proposal for a civic urban guide that outlines all these practical strategies for activating underutilized spaces through accessible and low-maintenance interventions. The guide aims to inspire civic engagement and environmental awareness, offering a model for small-scale, bottom-up interventions in line with broader Nbs objectives. In doing so, the research proposes a comprehensive approach to urban resilience that bridges planning theories, material experimentation, and public engagement.

Keywords: civic engagement, ephemeral landscapes, nature-based solutions, temporary urbanism, urban permeability

1. Introduction

In late October 2024, the flash floods in Valencia[1] once again rendered visible the vulnerability of cities in the face of climate change. While such urban vulnerabilities are largely associated with impervious surfaces, it is widely accepted that these types of events are not local but global in nature (Seddon et al., 2021; Kabisch et al., 2017). Over the past decade, the fields of design, architecture, and planning with a focus on environmental concerns have become more prominent in response to these threats due to fast-forward and uncontrolled urbanization (Cuff & Sherman, 2011). In this context, nature-based solutions (Nbs) have become an umbrella concept in capturing the ecological and societal challenges foregrounding urban ecosystem-based approaches (Keeler et al., 2019; Bush & Doyon, 2019; Frantzeskaki et al., 2019). Nbs demonstrate the appealing potential of permeable landscapes with varying motivations for the re-naturalization of urban spaces, such as tackling stormwater drainage (Biswal et al., 2022), preserving ecosystems (Dorst et al., 2019) or reducing flood risk (Vojinovic et al., 2021). These motivations on urban resilience have also been

[1]It is important to recognize that the severe flooding in Valencia was not an isolated incident, but part of a wider series of catastrophic floods that also occurred in many other European countries. For further details, *see*. " How Cities Are Using Nature-Based Solutions to Tackle Floods". Retrieved December 20, 2024, from https://time.com/7202917/cities-nature-based-solutions-floods/.

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incorporated into urban design and architectural practices at various scales globally, ranging from responses in the context of revitalizing brownfields or wetlands, to seeking solutions at the building scale by redefining underutilized rooftops.[2] However, the larger scale nature of these projects and the search for long-term re-naturalization of cities makes the widespread application of Nbs in practice questionable in terms of how to scale up their measures to achieve wider benefits for society, biodiversity and the climate (Odongo et al., 2022).

From this end, temporary urbanism has the potential to offer insights with a focus on improving ecological performance (Kay et al., 2019; Mata et al., 2019). Characterized by bottom-up and short-term actions that are small-scale, low-cost, and low-tech in enhancing urban resilience (Lydon & Garcia, 2015), temporary urban design practices range from community gardening in vacant spaces, pop-up green spaces in parking lots to simply planting into small lots that go unnoticed in everyday rush.[3] Despite the fact that the initial objectives of temporary urban practices may diverge from Nbs in terms of revitalizing lands left vacant due to regulations or financial constraints (Oswalt et al., 2013), providing a creative tool for urban branding and foster urban entrepreneurship for global competitiveness of cities (Thorpe et al., 2017; Colomb, 2012), and exploring the potential of democratic production of urban spaces (Andres, 2012; Bradley, 2015; Parker et al., 2019), the design responses concerning these practices coincide with nature-based solutions.

The growing interest in the adoption of Nbs in urban practice and the relevance of temporary urbanism create opportunities for rethinking urban ecosystem approaches. Following this path of possibilities, this article explores how the approach of temporary urbanism complements Nbs by introducing creative ways of imagination through examples of projects realized in urban spaces. Departing from the proposition that citizen-engaged, small-scale and short-term urban interventions can mobilize Nbs in practice, we argue that rather than expanding the scope of Nbs, scaling down its measures through the implementation of temporary urban interventions may facilitate the integration and widespread adoption of Nbs in urban contexts. Recognizing that natural responses in the urban environment cannot be conceptualized in isolation from social resolutions (McGrath et al., 2023), this study examines how communities can play a role in catalyzing Nbs through temporary interventions.

The paper engages with the intersecting literature on nature-based solutions (Dorst et al. 2019; Kabisch et al., 2016) and the practical dimensions of temporary urbanism (Stevens & Dovey, 2022; Lydon & Garcia, 2015; Bialski et al., 2015; Oswalt et al., 2013), bringing them into dialogue to inform a new conceptual approach. Structured as a two-part research study, the first part develops the theoretical groundwork, while the second presents product-oriented research that builds upon the insights derived from the theoretical exploration. Regarding the former, the paper acknowledges the recent trends and traits of temporary interventions in urban space within the context of nature-based urban solutions, with a particular focus on the motivations and processes in creating permeable urban grounds. In terms of the latter, through practice-based research and adopting prototyping as an experimental research method, it further situates these concerns within urban interstices that go unnoticed in everyday life—along roadsides, between cracks in the pavement, unattended urban planters that become dumping grounds—such minuscules that are overlooked by local authorities due to their small scale. Exploring the potential of spontaneous propagation and ephemeral nature of plants in these urban interstices, the study attempts to respond to how such spontaneity can be further cultivated through civic imagination, and how these nature-based temporal interventions in the urban environment strive without human assistance for maintenance.

[2]These Instances include the Grand Canal Linear Park designed by 128 Architecture and Urban Design in Mexico City, Sankt Kjeld's Square & Bryggervangen designed by SLA in Copenhagen, Rachel de Queiroz Park designed by Architectus S/S, in Fortaleza, Brazil, Qunli Stormwater Wetland Park designed by Turenscape, in Haerbin City, Northern China.

[3]These instances include but are not limited to transforming car-oriented landscapes by offering permeable platforms, redefining vacant spaces with gardening practices and community gardens, turning underutilized water basins into learning spaces, and pavement guerilla gardening practices located at various urban spaces. For a detailed catalogue of temporary urban interventions, *see*. Ho and Douglas, (2012). *Spontaneous Interventions: Design Actions for the Common Good*, Washington, DC: Architect/Hanley Wood.

The article unfolds in five sections: Following this introduction, Section 2 sets the ground for Nbs and temporary urbanism as two planning approaches addressing global challenges. It further visits a diverse array of temporary urban interventions tackling permeable urban grounds, and develops a conceptual framework at the intersection of nature-based solutions and temporary urbanism, grounded in the shared concerns and intentions of these fields. Section 3 operationalizes this framework by discussing the phases of a research experimentation covering its objectives, processes and outcomes. This experimentation focuses on the integration of ephemeral landscape installations aiming to explore innovative strategies for permeable surface solutions in urban spaces. The culmination of these research phases constitutes a civic urban guide discussed in section 4, proposing temporary nature-based interventions to enhance urban resilience, aspire people to engage with their environments, to foster a sense of ownership, with the potential for a lasting, albeit temporary, impact. These potentials are tested in practice through a workshop held in Izmir, Türkiye, the points of which we close in the concluding section 5.

2. Nature-Based Solutions and Temporary Urbanism: A Conceptual Framework for Integrating Two Planning Approaches as Solutions to Global Challenges

The dominant urban growth model seen globally in the 21st century has entered a critical period marked by climate change, loss of biodiversity, and other human-induced environmental crises, creating significant challenges (Mahmoud et al., 2022; Dorst et al., 2019; Bush & Doyon, 2019). In contrast to the predominant urban development model, nature-based solutions (Nbs) have emerged as an important planning approach that seeks solutions to these global issues. Introduced by the International Union for Conservation of Nature, Nbs are defined as "actions to protect, sustainably manage, and restore natural or modified ecosystems, that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits" (IUCN, 2017). This approach seeks to improve urban resilience, looking for ways to replace the reliance on hard and grey infrastructure with green and blue alternatives (McPhearson et al., 2023, p. 2).

Notable projects such as the Grand Canal Park in Mexico City, which reclaims a neglected 70,000 square-meter canal through environmental regeneration and reforestation, or the Stormwater Wetland Park in Harbin, China, which revitalizes a dying wetland by transforming it into a green sponge supporting multiple ecosystems, have become emblematic examples of Nbs. While these examples could be expanded further, they clearly demonstrate the long-term benefits of ecological restoration without ignoring the needs of local communities. However, a common feature and a mentioned discussion among these renowned projects is their larger scale, which requires extensive planning and implementation timelines (EEA, 2023; Odongo et al., 2022; Vojinovic et al., 2021). In connection with these concerns, the literature also emphasizes the lack of a systematic approach (Odongo et al., 2022) and the absence of clearly defined principles (Kabisch et al., 2022; Dorst et al., 2019) in Nbs, thereby highlighting the need for a conceptual framework, which is addressed in this section.

Building on these concerns, this section is grounded in the main premise that Nbs can be mobilized through temporary urbanism, a planning approach that engages with small-scale, low-cost, low-tech and experimental planning approaches. In conjunction with recent international scholarship discussing the field, temporary practices are approached from different perspectives, summoned as tactical (Rossini, 2018; Stevens & Dovey, 2022; Lydon & Garcia, 2015), guerrilla urbanism (Hou, 2010; Hardman et al., 2018; Mikadze, 2015), interim (Colomb, 2017), or indeterminate (Groth & Corijn, 2005). These varying connotations affirm that temporary interventions offer alternative approaches to addressing shortcomings in traditional urban development, including unsanctioned, unexpected, and meanwhile operations. The rationale for integrating temporary urbanism into Nbs lies in the practices' inherently temporality. This temporality becomes both an instrument and an asset in the reimagining of urban space

(Madanipour, 2017), allowing for the rapid implementation of short-term experimental projects. Examples such as guerilla gardening, pop-up parks, and community gardens are both well-established labels and forms of temporary urban interventions, often driven by ecological imperatives in response to climate change adaptation (Stevens & Dovey, 2022, p. 42).

Consequently, although these fields may initially appear distinct, this section identifies their commonalities and argues that their convergence holds significant potential for advancing climate resilience and spatial justice in urban environments. While this study particularly focuses on the contribution of temporary urbanism to Nbs, it should also be acknowledged that bridging these two fields offers mutual benefits: temporary urban interventions can act as catalysts for short-term and small-scale strategies within Nbs, while Nbs can provide ecologically embedded solutions for temporary practices.

The growing body of Nbs literature emphasizes the potential of Nbs (1) to provide sustainable and resilient innovations for incorporating elements of nature into urban areas (McPhearson et al., 2023; Bush & Doyon, 2019); (2) be cost-effective and applicable at multiple scales by replacing hard and grey with soft and green urban infrastructure (Vojinovic et al., 2021); (3) and respond to societal challenges rather than aiming only at technological solutions (Almenar et al., 2021; Kabisch et al., 2022). These three interconnected potentials - natural elements, scalability and social challenges - are also explicitly or loosely relevant to temporary urbanism. Among them, natural elements and scalability are implicitly linked with temporary urban interventions, while addressing social challenges are intrinsic to the bottom-up character of such practices. The following subsections draw on these three common threads, providing information from the literature on temporary urbanism and related urban implementations to discuss how these practices may mobilize Nbs in practice.

2.1. Natural Elements

As with Nbs, incorporating elements of nature into urban areas to increase urban density is among the concerns of temporary urban interventions. Just as urban intensification in temporary interventions refers to harnessing the potential of vacant or underutilized urban spaces by enhancing "both the volume and the variety of users and uses", renaturalization of urban spaces also becomes "a form of intensification because of its focus on improving ecological performance" (Stevens & Dovey, 2022, p. 35). Such renaturalization of urban spaces as a temporary form of urban intensification is evident in the replacement of parking lots with parklets as small parks, the transformation of waste sites into wild landscapes, or the introduction of pop-up parks and guerilla gardening practices. While these practices depart from different concerns and premises, such as the revolts against the car-dependent urbanization in the parklet movement (Lydon & Garcia, 2015, p. 132) or the renegotiation of spatial rules through the appropriation of public spaces in guerrilla gardening (Mikadze, 2015), the environmental concerns that encompass these practices have been further interpreted by temporary urbanism scholarship as "transitional ecology" (Kay et al., 2019) or "civic ecology" (Krasny & Tidball, 2012).

An example relevant to this scholarship is the practices of the Depave,[4] a citizen initiative launched in Portland in 2006. Depave has been removing asphalt and concrete surfaces in order to restore the natural environment, thus reducing the risk of flooding by creating alternative drainage areas for stormwater. To this day, Depave continues to collaborate with local governments, enabling communities to respond to climate change through urban re-greening and address environmental and social inequities. In a similar vein, tile-popping[5] campaign, which started as a playful idea by civil society organizations during the Covid-19 period, has become a rivalry between the two Dutch cities of Rotterdam and Amsterdam. The competition, which involves replacing

[4]To view the practices of Depave organization, visit the link at https://www.depave.org/, Accessed December 15, 2024.

[5]Although there are guidelines organizing the Tile-Popping campaign, residents can remove tiles from their front yards without any consent by the relevant municipalities. See https://www.rotterdam.nl/geveltuinen. https://www.theguardian.com/environment/2024/apr/04/we-need-to-accept-the-weeds-dutch-towns-compete-to-remove-the-most-garden-paving, Accessed January 20, 2025.

pavement tiles with shrubs, grass or other greenery, becomes a way of empowering residents to create more permeable surfaces and to promote natural spaces in the cities (Figure 1).

Similar concerns are addressed at the material scale in the works of Urban Reef,[6] which incorporate bio-based algorithms and 3D printing techniques to prototype reef-like structures. The designs of Urban Reef explore how such forms can generate diverse microclimates and capture rainwater, complementing existing urban drainage networks. These explorations are also spatialized in the public realm through innovative construction approaches, such as the Hi-Fi project,[7] a zero-carbon, compostable cluster of circular towers made from discarded corn stalks and mycelium. Altogether, these instances demonstrate that temporary practices in the urban areas provide environmental benefits that are also recognized for their contribution to reducing the heat island effect, balancing microclimate and stormwater surges (Mata et al., 2019; Stevens et al., 2024).

Figure 1 De-tiling practices in the Netherlands (left column) and practices of depave (right column) (Source: https://www.nlvergroent.nl/ & https://www.depave.org/)

2.2. Scalability

While these instances in the context of environmental restoration might remain limited in providing a thorough perspective on the full scope of temporary urbanism, they do underline the potential of spatial and temporal scale in these practices (Stevens & Dovey, 2022, p. 17-32). Consequently, the question of scalability is implicitly linked to the nature of temporary interventions, as small-scale actions encourage quick and tactical implementations alternative to larger-scale urban strategies that take time, while short-termism allows for the escape of master plans that address global capitalism respectively (Oswalt et al., 2013). Responding to these two dimensions of scale is the practice of guerrilla gardening, a label associated with temporary urbanism that emerges as a direct and unauthorized response to neglected spaces (Douglas, 2014, p. 10). Bringing nature to vacant or abandoned spaces, guerrilla gardening practices are largely small in scale in terms of seed bombs being practiced in sites with limited spatiality, transforming them into spaces of nature with basic tools needed (Mikadze, 2015). These practices of sowing the

[6]Urban Reef is a research and design platform that creates open-ended habitats to encourage the growth and diversity of life in urban settings. For further information, visit https://www.urbanreef.nl, Accessed July 25, 2025.
[7]Hi-Fi project has received an award for sustainable construction https://www.holcimfoundation.org/projects/hy-fi, Accessed July 25, 2025.

seeds of seasonal plants, are also of a temporal scale, dependent on the legal status of the vacant land that is in limbo and the ephemeral landscape they offer.

The state of in-betweenness, both spatially and temporally, also becomes a tactical approach, where modularity is a common design response in temporary practices. An instance of modularity can be traced in the ECObox project, with recycled wooden pallets defining the basic module of a community garden on a derelict site (Petrescu, 2013). The creation of a public space that the community can build with pallets allows the spatial scale to expand over time, but also encourages the dismantling of the design due to the limited temporal scale offered by the space (Figure 2). As well as being linked to the design response to a problem or defined by the material chosen, modularity can also be determined by the imposed architectural and urban standards. In another temporary practice, the Urban Hives project, the scale of the incorporation of urban gardens into the hard surface of public spaces is determined by the size standards of car parks (Figure 3). By offering an elevated modular structure, the project can grow with the occupation of further car parks, as well as being easily assembled and disassembled. In this respect, modularity could hold potential for the further development of nature-based solutions, with innovative and creative responses that are scalable in public spaces.

Figure 2 Ecobox project, realized by aaa, 2001-2006 (Source: www.urbantactics.org)

Figure 3 Urban hives, realized by Natalie Harb, 2018 (Source: www.nathalieharb.com)

2.3. Social Challenges

A third and a final commonality between Nbs and temporary approaches lies in their response to societal challenges. Nevertheless, the manner in which social challenges are addressed is slightly different in the two approaches. In the context of Nbs, climate change and extreme weather events pose major threats to urban systems, necessitating solutions that go beyond ecology to also consider the long-term impacts on urban communities (McPhearson et al., 2023). In this regard, social challenges arise as consequences of global environmental crises and are addressed within nature-based projects as part of a broader response to these issues through the promotion of equity and enhancement of urban liveability. While Nbs treat social challenges as secondary effects of global environmental crises, serving social needs, in contrast, become primary triggers for action through temporary interventions.

By directly shaping and encouraging practical solutions in the city, temporary interventions are known to deliver "less tangible changes and more socially aware practices" (Tardiveau and Mallo, 2014, p. 456). Social awareness can take place through temporary urban interventions that are directly initiated by residents, as well as through participatory processes that are initiated by designers and trigger the engagement of the community. Consequently, the social role of temporary interventions is contingent upon an underlying sense of socio-political agency and involves efforts to revise or reinterpret existing structures (Wortham-Galvin, 2013, p. 23). These efforts to (re)define public spaces for social encounters can be seen in the practice of guerrilla gardening, or in the closing of laneways and the creation of parklets. Similar concerns have recently started to be addressed in the Nbs scholarship as "social-natural solutions", which refers to the consideration of material solutions where socially produced spaces and natural processes intersect (McGrath et al., 2023). In this context, and as seen in the aforementioned instances, temporary approaches that provide unexpected events and social encounters in public spaces foster new social relationships in urban public spaces (Rossini, 2018), thereby strengthening community engagement by providing less hierarchical relationships and welcoming underserved groups.

2.4. Researching the Materiality of the Conceptual Framework

As discussed in the introduction, despite the varying scopes and objectives of Nbs and temporary urban practices, a literature review and an overview of selected works across diverse scales and contexts reveal the emergence of a common trajectory underlying both fields. While the instances illustrated in this section are not exhaustive, they serve as a departing point for identifying the commonalities that give rise to them. These common concerns demonstrate how temporary interventions can potentially mobilize Nbs in practice, thereby playing a critical role in raising awareness and fostering engagement with the global challenges addressed by Nbs. Furthermore, the increasing recognition of Nbs not only at the macro scale, but also at the meso to micro scales (Tozer et al., 2023), from green roofs and walls to planters on apartment balconies, further reinforces the potentials for practical openings that temporary urbanism can offer in the field of Nbs. From this perspective, therefore, it is possible to acknowledge that temporary interventions that address the renaturalization of urban spaces in their concerns can also be considered as Nbs.

With these commonalities forming a conceptual framework, this study outlines the early-stage development of a product solution. The product development process serves as a means of operationalizing the proposed framework, translating theoretical insights into practical strategies that address both ecological concerns and urban adaptability. Emphasis is placed on identifying spatial and material strategies, with the intent to test how such an approach might function at a smaller, replicable scale within the urban fabric. Nonetheless, it is important to mention other areas, such as biomaterials and parametric research, that could trigger nature-based solutions in urban environments. These fields have the potential to provide information for temporary approaches, yet they largely remain context-free. Although acknowledging these fields, this study excludes them from its scope.

While the preceding subsections attempt to construct a conceptual framework that concurrently outlines a corresponding product vision, it is equally important to interrogate how these ideas materialize through practice. Therefore, it should be acknowledged that the components of the framework should be evaluated not only as separate stages in the research process, but also as defining features of the final product, which aims to raise social awareness on ecological issues. This dual role, both analytical and generative, positions the framework as a guide for action-oriented inquiry. In the following section, the focus shifts toward the experimental research phase, where each design move is examined in relation to its conceptual underpinnings and practical implications. By tracing the material development and implementation processes, this phase aims to ground abstract theory in lived, spatial interventions, further reinforcing the civic relevance of the work discussed in Section 4.

3. Ephemeral Landscapes: Prototyping Nature-Based Solutions via Temporary Interventions

Situated within these literature intersections, this section takes a closer look at how temporary urbanism in the context of Nbs may potentially unfold. It introduces Ephemeral Landscapes, a project that is developed as a continuation of research-oriented and product-oriented experimentations, integrating these approaches into practice.

In Ephemeral Landscapes, research-orientation stands for the exploration of how nature emerges in impervious urban landscapes. This approach is parallel to the recognition and understanding of urban wildlife, which has been a subject of interest since the 1970s (Page & Weaver, 1974) and continues in contemporary temporary urban practices (Seiter & Future Green Studio, 2016). Emphasizing the important role of urban weeds in erosion control, stormwater management, and climate mitigation, this orientation extends beyond mere research by exploring the ways to harness the potential of not only wild plants, but also urban plants in general, through their practical application in urban landscapes, leading to product-oriented implementations. In temporary urban practices, product-oriented approaches generally experiment with nature-based interventions, embedding them within urban landscapes in more exploratory ways. While some works question the quality of soil and water in urban spaces and raise awareness of growing food in public spaces, others fall into the exploration of material development, critiquing urban waste at the nexus of industry and ruins, giving new life to industrial by-products through the mixing of nature. Despite the different objectives in product-orientation in temporary interventions, a common goal is to allow nature to take root within built environments, creating dynamic vegetation systems through material experimentation.

The Ephemeral Landscapes project is developed against this backdrop as a continuation of research and product-oriented experimentation. As discussed in the previous section, guerrilla gardening practices were the inspiration for this project (Mikadze, 2015), and an important component of these practices, seed bombing (Marris, 2013), in which seeds are placed in clay and compost to protect them from environmental conditions and promote germination, was adopted. The Ephemeral Landscapes project follows this simple yet effective technique for the introduction of vegetation in impermeable urban environments, with a particular focus on overlooked urban interstices—small and unnoticed spaces with significant potential. To achieve this goal, the aim is to develop a versatile tile that can come in multiple forms and with flexible condiments which can function both on vertical and horizontal surfaces. Facilitating plant growth on impermeable urban materials like concrete without requiring substantial soil depth, seed-embedded tiles offer a bottom-up approach to urban natural restoration, bridging research and product-oriented experimentation while extending the possibilities of Nbs through temporary urbanism.

This section explores the integration of nature-based temporary installations into urban landscapes through the processes and outcomes of the Ephemeral Landscapes project. Adopting small-scale, low-tech and low-cost approach, the project includes innovative alternatives for permeable surface solutions that can be adapted to urban environments. The research and product-oriented studies consist of three stages that correspond to the three key themes derived from the literature in the previous section: (1) experimentation: incorporating nature-based aggregates, (2) fabrication: forming scalable and modular tiles, and (3) dissemination: creating social value through workshops. The following subsections discuss these stages separately. However, it is important to remember that these stages are interrelated, creating a nonlinear process in which each stage informs the others.

3.1. Experimentation: Incorporating Nature-Based Aggregates

Starting from the concern of unlocking the potential of urban interstices that go unnoticed in everyday life —along roadsides, cracks in the pavement, derelict urban planters that turn into landfills that become dumping grounds— the main objective of the project is to develop a nature-based aggregate that is capable of creating durable yet biodegradable surfaces that support plant growth. Since the literature overview has demonstrated the potential benefits of integrating vegetation into urban infrastructures, highlighting its role in enhancing environmental resilience (Mata et al., 2019; Stevens et al., 2024), the project aimed to identify an optimal solution through design innovation in material experimentation.

To start the research process, initial experimental studies were carried out in a controlled environment. The selection of appropriate materials formed a critical step, with ceramic clay—both in its solid and liquid forms—chosen as the primary binding agent due to its formability, durability, environmental sustainability, and moisture-retention properties. These potentials of the clay made it easier to combine the seeds as the green agent without harming them. Furthermore, feeder agents of soil and peat were added to improve the mix's properties for seed propagation, aerator agents such as straw, sawdust and perlite were added to improve the permeability and texture of the design (Figure 4). The initial seed selection focused on plant species known for their resilience and ability to adapt to different environmental conditions. Various seed combinations, including quinoa and lentil seeds as legumes, were tested to assess their suitability. By systematically measuring variables such as soil and binder composition, frequency of watering and sunlight exposure during a series of controlled trials, the most suitable seed varieties for the ideal clay-to-seed ratio and ideal tile sizes were identified (Table 1).

Figure 4 Initial experiments in Ephemeral Landscapes (Source: Authors)

Table 1 Key Components for a Seed Tile

RATIO	Key Components for a Seed Tile			
	1	2	3	4
	Binder Agent	Feeder Agent	Green Agent	Aerator Agent

	45-50%	25-30%	5-10%		15-20%
	Liquid Clay	Peat	Edible	Microgreens	Mist of Water
	Solid Clay	Soil		Quinoa	Perlite
		Egg Shells		Lentil	Straw
		Coffee Grounds		Wheat grass	Wood chips
			Non-edible	Wildflower seeds	
				Clover seeds	
				Groundcover mix	

The process of achieving an optimal mix is influenced by several key factors, including the choice of plants (e.g. seeds, legumes, edible greens or flowering plants), the type of soil and peat as nutrients, and the aeration agents (e.g. sawdust or wood chips) in appropriate proportions. The following is a discussion of the efficacy of these different blends that have been tested with different ratios and in different contexts.

3.2. Fabrication: Forming Scalable and Modular Tiles

Once the settling of the ideal ratio of materials and the optimization of the conditions for securing seed propagation, product-oriented explorations were initiated. To ensure that the seeds remain viable and the tiles retain their structural strength, the production procedures are based on two standard methods of ceramic production: slab making and slip casting. In the former, the mixture was formed into triangles by hand, while in the latter, the slip-casting technique, liquid clay was poured into triangular plaster molds to form the tiles (Figure 5). The triangular shape of the mold was chosen for its ability to create different patterns when assembled in different ways. Circular shapes were not preferred because of the difficulty in creating interconnected patterns as they do not line up smoothly. However, fragility was evident at the corners of the preferred triangular and polygonal shapes.

Figure 5 Experiments with liquid clay, lentils and mixed seeds (Source: Authors)

As for the thickness and the size of the tiles, liquid mixture was poured into a plaster mold with thickness of approximately 2.5 cm, with an additional half-centimeter drying allowance. In contrast, handmade slab tiles were shaped into equilateral triangles with sides measuring 10 cm. To assess plant growth, soil stability, and watering frequency requirements, prototype tiles were then placed outdoors over a soil ground, with some covered by a membrane underneath and others left directly on the ground. The process was analyzed through direct observation and taking notes. Within a few weeks, seeds sprouted rapidly, and as rainfall gradually dissolved the tiles, they adapted to their surroundings, forming a uniform green layer (Figure 6). The tiles attracted stray animals, but unlike traditional open-field seed dispersal, which is often disrupted by animals, the tiles provided a protective structure that prevented seeds from being scattered or consumed.

Figure 6 First experiments of vegetated tiles with quinoa seeds (Source: Authors)

Building on these initial insights, the trial extended to the urban landscape in the Bostanlı district of Izmir, specifically targeting the impermeable, unattended concrete grounds. A neglected urban planter that turned into a dumping ground was identified as problematic where vegetation also struggled to thrive due to insufficient soil depth. To overcome these challenges, the project aimed to offer a practical and sustainable solution by placing the fabricated seed tiles in this urban setting and monitor their performance, particularly focusing on how they respond to natural irrigation (Figure 7). In this regard, the field testing provided a comprehensive opportunity to assess the tiles' effectiveness in fostering plant growth while also proving their potential to address urban environmental issues, such as limited vegetation growth, and the enhancement of soil permeability.

Figure 7 Field test in a neglected urban planter in Bostanlı, Izmir (Source: Authors)

3.3. Dissemination: Creating Social Value with Workshops

The research conducted in the previous subsections on nature-integrated, scalable, and modular solutions led to the development of the "seed tile", where sharing it with the public was planned as the next step. To trigger public engagement and the potential for a bottom-up adoption, a workshop was organized as a part of the World Creativity and Innovation Day designated by the United Nations. This special day not only played an important role in sharing the results of the research as an innovative natural solution in the city, but also provided an opportunity to disseminate a bottom-up approach to the production of seed tiles. The goal was to share the methodology and allow participants to replicate the production process within their own communities and urban environments. Organized in an academic setting, the full-day workshop brought together a diverse group of participants, including students and academic staff. During the workshop, various tile options were explored, including the assessment of different clay types and their compatibility with various soil and seed compositions (Figure 8-9-10-11).

Figure 8 Workshop materials: Various types of clay, seeds and soil (Source: Authors)

Figure 9 Workshop with high school students interested in studying design: Preparation phase at the Faculty of Fine Arts and Design, Izmir University of Economics

Figure 10 Workshop with high school students: Production phase at the Faculty of Fine Arts and Design, Izmir University of Economics

Figure 11 Workshop with administrative and academic staff during the seed selection phase, conducted at the Faculty of Fine Arts and Design, Izmir University of Economics

About 15 participants took part in the morning and afternoon sessions, preparing mixtures of different types of clay and applying them to printed patterns. Afterward, the tiles were placed on the gravel floor of a roof garden (Figure 12-13). It was at this point that the effectiveness and adaptability was tested, particularly in terms of engaging participants via a collaborative working environment and fostering a sense of ownership for the project. However, the lack of rainfall during the extremely hot summer month became a research limitation and the intended goal of promoting a natural environment over the impervious roof garden was not realized. Nevertheless, the active involvement in product fabrication and the positive reception of the activity demonstrated the potential for broader public engagement and interest in the project as some participants took seed tiles to their home environments to test their effectiveness, further extending the experiment beyond the workshop setting.

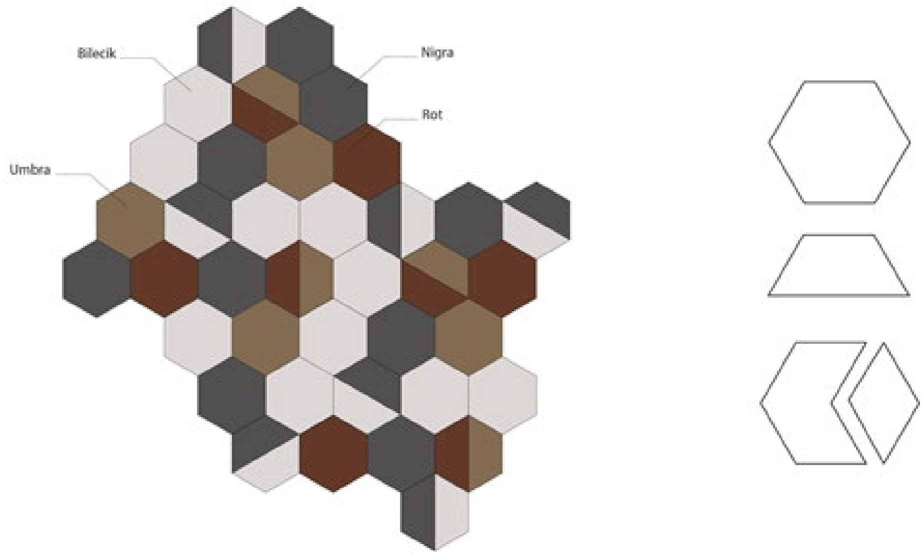

Figure 12 Tile pattern alternative (Source: Authors)

Figure 13 Testing the tiles on the roof garden (Source: Authors)

4. Learning from Ephemeral Landscapes

The research and product-oriented experimentation phases mentioned above revealed several lessons about the limitations and potentials of the project, including the diversity of the seeds and the performance of the seed tiles. Regarding the former, and relevant with the experimentation phase of seeking the optimum aggregate, tiles containing seeds such as lentils exhibited the fastest growth rate. However, larger seed's strong root systems have been the cause of tile cracking. In contrast, smaller seeds, such as chia seeds, produced weaker root systems that spread over the top and bottom surfaces, effectively covering the tiles and demonstrating their permeability while maintaining structural integrity. The larger and smaller seed types thus have distinct advantages and disadvantages: the mix with the larger seeds promotes rapid vegetative growth but damages the tile integrity, while the smaller seed mix maintains the tile's shape and provides a uniform ground cover without causing breakage.

In terms of the latter factor, tiles produced with slip-casting technique demonstrated greater fragility and were more prone to breakage compared to those handmade slab tiles. Although the problem of fragility is a disadvantage in the transportation of tiles, the slab technique remains more advantageous than slip casting because it requires less equipment and therefore less intensive human labor. Yet, the efficiency of the fabrication processes depends on the surface area desired to be covered, thus the number of people involved in the production, how fast the results are aimed and the desired thickness.

Despite these two limitations, small-scale production still makes the transportation of the tiles viable, while their modular structures make them adaptable to the context. Timing and outdoor conditions also remain critical for optimal results. Along with these advantages, the process of tile making demonstrates the potential for social awareness of the presence of neglected urban spaces and their impervious conditions. A series of further workshops, organized with participants coming from different backgrounds and age groups,[8] aimed for social awareness where participants began to recognize design not only as a formal practice but also as a playful reconnection with social and environmental relevance. These findings, both from the material experimentations and engagement with participants, reveals a pathway to promoting innovation in design through community-driven approaches. Although such urban interventions remain temporary in nature, inspiring public engagement can foster a sense of ownership that can potentially have a lasting impact.

Together, these learnings from the Ephemeral Landscapes project present the possibility of a civic guide that can foster bottom-up, nature-based temporary interventions, where citizens produce tiles by their own means due to material simplicity. The proposed civic guide has the potential to work as a how-to manual, and by following these steps, it bears the potential of becoming a speculative tool for engaging with urban interstices. In Table 2, these steps are presented through actions, descriptions and considerations to simplify the product-oriented process. This civic guide is planned to be disseminated through community workshops, printed distributions in relevant contexts, or digital platforms. Through this dissemination, the project aims to raise public awareness of nature-based solutions, as well as to build collective imagination for the long-term vision of permeable urban landscapes.

Table 2 Step-by-Step Urban Civic Guide for Ephemeral Landscapes

Step		Action	Description	Considerations
1	Spotting Urban Interstices	Identify underutilized urban spaces	Unattended planters, removed tiles, cracked surfaces, etc.	Scale, accessibility, and environmental conditions
2	Taking an X-Ray of the Spot	Estimate the rough volume & scale	Spatial dimensions to determine material needs	Sketches and photos from the site
3	Preparation of Ingredients	Mix materials	*See* Table 1. for details	Seeds selection in line with climatic conditions
4	Deciding the Form	Determine modular & small-scale units	Simple forms for small spots, multi-edged for larger spots	Stacking potential and water retention efficiency
5	Curing & Drying	Solidify tiles	A few days is necessary to ensure durability	Test for brittleness before installation
6	Urban Installation	Deploy intervention	Documenting growth & transformation	Vehicular traffic & human flow

[8]These workshops include a Children's Day event held in the same location and year, specifically organized for earthquake victims.

Civic guides, or as they are called - how-to manuals, handbooks, design guidelines or specifications - are already playing an important role in the implementation of temporary urban approaches.[9] These guidelines are increasingly being adopted by urban institutions and local governments,[10] and the tactical urbanism literature is recognized as a primary reference for presenting intervention models and their implementation (*see.* Lydon & Garcia, 2015; Stevens & Dovey, 2022). However, despite their institutional recognition, many of these guides run the risk of failing to engage directly with urban users, as they primarily inform designers rather than interacting directly with users. In contrast, the civic guide proposed by the Ephemeral Landscapes project seeks to bridge this gap by directly proposing an engagement with city users, empowering them to take action. In this regard, the guide proposed in the Ephemeral Landscapes remains analogous to open-source temporary interventions, such as those prompted by Recetas Urbanas,[11] wherein the project itself can be regarded as a toolkit that can be customized.

5. Conclusion

In the face of increasing threats from climate change and extreme weather events, this study acknowledges the inevitable role of nature-based approaches in increasing the permeability of urban landscapes. However, it emphasizes that this role can be further strengthened through temporary interventions. While we recognize that such temporary measures alone cannot solve the problems, by embracing transitional and civic ecology practices (Kay et al., 2019; Krasny & Tidball, 2012), they may serve a critical function in raising awareness in the long run, as they can be easily replicated and disseminated compared to many nature-based solutions.

As a response to this concern, the paper explored the intersection of literature on nature-based solutions and temporary urbanism approaches in the context of impervious urban landscapes through the Ephemeral Landscapes project. In doing so, it makes two key contributions to these seemingly disparate fields: first, by integrating them through the proposal of a novel conceptual framework; and second, by introducing a design-based method that operationalizes this framework.

Firstly, regarding the conceptual framework developed in this study, impervious urban landscapes can be approached through three key themes: incorporating natural elements into the design process, providing small-scale yet scalable solutions, and addressing social challenges through community-driven processes. While these themes contribute to ongoing discussions in the nature-based solutions literature, the exemplified global temporary urban projects upon which this framework is founded are only the starting point in imagining how temporary strategies can complement long-term nature-based interventions. In this regard, while the conceptual framework is open for contextualization, its themes are likely to be expanded and/or further refined as more practice-based approaches continue to be developed.

From this perspective, the case of Ephemeral Landscapes presented in this study derives its context from overlooked small urban interstices—impervious spaces that often escape the attention of planners and authorities due to their small scale. By exploring the spontaneous propagation of urban flora, particularly within guerrilla gardening practices (Hou, 2010; Hardman et al., 2018; Mikadze, 2015), it questions how temporary green interventions can be fostered through civic imagination.

The conceptual framework holds potential for adaptation across various urban and design studies: as this study has attempted, it can inform the objectives and phases of design research at the product scale; determine the contents of an urban guide that could play a critical role in urban

[9]For the most well-known ones, *see.* A Tactical Urbanism Guidebook, Mohankumar (2020); The Planner's Guide to Tactical Urbanism, Pfeifer, (2013).

[10]This is especially true of the parklet movement, which has been embraced by renowned cities such as San Francisco, Milan, Minneapolis, and Los Angeles.

[11]Recetas Urbanas, translated as *Urban Recipes*, is a collective founded by renowned guerrilla architect Santiago Cirugeda. For more information, *see*. www.recetasurbanas.net, Accessed January 2025.

policymaking; or serve as a pedagogical tool in design education. Covering these areas, the civic guide proposed in this study is a first step toward applying the conceptual framework in practice, and can be adapted to suit different contexts and uses. Since temporary urban guidelines are already integrated as tools in planning practices (Pfeifer, 2013), the informal and not widely adopted approach in the study also holds promise for future integration into policymaking processes as it gains recognition and support from local authorities.

This brings us to the second contribution of the study. Through the conceptual framework, which facilitates the dissemination of nature-based solutions via temporary interventions, this research also explores effective strategies for transforming hard-to-implement surfaces due to their scale. In this regard, operationalizing the conceptual framework via a design-based prototyping method assumes a dual role: it demonstrates how the conceptual framework can lead to practical spatial solutions, and how in turn this practical solution can contribute to environmental awareness via a civic guide.

By directly linking ecological awareness to the materiality of urban spaces, the project demonstrates how research-oriented product experiments can translate into low-cost, modular infrastructures that increase permeability and support the development of green spaces in urban voids. By integrating seed-infused tiles into urban landscapes, the study demonstrates how such innovations can support the natural and aesthetic diversity of cityscapes. Therefore, the environmental role of the seed tiles extends beyond their immediate function as a building material, aligning with the growing concerns of incorporating nature into urban design. The results of the product-oriented research process suggest that the appropriate selection of seed mixtures and their application during optimal seasons plays a crucial role in ensuring favorable plant growth, with plants thriving even in difficult environments such as concrete and low soil depths.

By simultaneously addressing both theoretical and practical approaches to the problem of impermeable urban landscapes, the civic guide that operationalizes the conceptual framework proposed in this study serves as a practical tool, bridging academic discourse and practice. While it is only a small incentive toward a nature-based, modular, bottom-up approach, it provides practical steps that can serve as a valuable entry point into the broader discussions on urban resilience at the intersection of nature-based solutions and temporary urbanism.

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CRediT Authorship Contribution Statement

Tuba Doğu: Writing – review & editing, Writing – original draft, Resources, Methodology, Conceptualization, Data curation. Hande Atmaca: Writing – review & editing, Writing – original draft, Investigation, Methodology, Conceptualization, Data curation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data Availability

Data will be made available upon request.

Ethics Committee Approval

An ethics committee decision is not required.

Resume

Tuba Doğu received her B.Arch from Middle East Technical University and M.Sc. from The University of Sydney. Earned her PhD. in architecture from Izmir Institute of Technology. Currently works as an Assistant Professor at Izmir University of Economics and continues her research at UrbanTank (www.urbantank. org) since 2013, developing research and intervention projects for human-oriented and participatory urban environments. Major research interests include social interventions as a form of alternative spatial practices, centering on questions of human and material agency.

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Urban heat island and fringe belt interaction: The role of the urban fringe in heat island mitigation

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Abstract

Fringe Belt (FB) areas are transition zones located between successive areas of urban development. They are typically characterized by open spaces, industrial and institutional areas, and low-density residential areas. An Urban Heat Island (UHI) is a microclimate phenomenon caused by urbanization, characterized by higher surface temperatures in city centers compared to the surrounding area. The primary factors exacerbating the UHI effect are dense development, reduced green spaces and the heat-retaining properties of surface materials. FB areas can mitigate the UHI effect by limiting heat accumulation due to their relatively natural and permeable surfaces. This study aims to analyze temporal changes in FB areas and evaluate their impact on the UHI effect. For this purpose, Landsat satellite images from 1985, 2000 and 2025 were processed using the Google Earth Engine (GEE) platform to obtain land surface temperature (LST) values and map UHI distribution alongside delineation of fringe-belt plots. The results indicate that the UHI effect is relatively low in areas where fringe belts are preserved or minimally developed. Additionally, it was observed that the UHI effect increases as these areas become more developed over time. The study reveals that fringe-belt areas can play an important role in reducing the UHI effect, suggesting that these areas should be integrated into urban planning as cooling buffers. The study emphasizes the necessity of climate-focused approaches in urban planning and suggests evaluating fringe belts as potential microclimatic mitigation areas.

Keywords: fringe belt, urban heat island, remote sensing, land surface temperature, google earth engine

1. Introduction

The Urban Heat Island (UHI) effect is a significant environmental phenomenon characterized by higher temperatures in urban areas than in their surrounding rural areas. This temperature increase is attributed to various factors, including impervious surfaces, energy consumption and anthropogenic heat flux. Understanding the interaction between urbanized areas and their peripheries is crucial for reducing UHI through effective urban planning and landscape strategies that incorporate the urban periphery.

Urban areas tend to have higher surface temperatures due to changes in land cover and settlement density that retain heat. For instance, urbanization significantly contributes to heat retention by reducing vegetation cover and increasing impervious surfaces (Liao et al., 2017; Sobrino et al., 2012). The difference in temperature between urban and rural areas can sometimes exceed several degrees at night when stored heat is released, reaching significant levels (Levermore

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& Cheung, 2012; Dou et al., 2014). As cities expand, the urban fringe — the transition zone between urban and rural areas — plays a crucial role in mitigating these temperature differences. Studies indicate that the careful management of the urban growth — including the expansion of green spaces and water features — can mitigate some UHI effects (Li et al., 2013; Yang et al., 2022; Wang et al., 2019).

1.1. Definition and Importance of Fringe Belt (FB) Areas

Fringe belts (FBs) are transitional zones that emerge between successive settlements during the historical and geographical development of cities, when their growth comes to a halt (Conzen, 1960; Whitehand, 2001). The structural and functional heterogeneity of FBs is contributed to by the diverse land uses that contain open spaces, industrial and institutional areas, as well as low-density residential areas. This diversity characterizes FBs as morphological and historical traces in the interpretation of urban form (Conzen et al., 2012).

FB plots are sparser than residential areas due to their larger sizes and provide important clues for understanding continuity and discontinuity in urban form. They are not merely physical buffers, but also morphological thresholds conducive to explain the direction, timing and strategy of urban growth (Whitehand & Morton, 2006; Ünlü, 2013). Sometimes indicating a pause or change in direction in a city's expansion, FBs also bear traces of planning policies, property structures and socio-spatial dynamics (Barke, 1974).

However, the importance of fringe belt areas is not limited to providing historical insights. These areas can also play a critical role in enhancing urban ecological resilience. In particular, their contribution to urban air circulation, high permeable surface ratios and favorable locations for green space continuity make these areas effective at balancing the urban microclimate. Using the example of Birmingham, Hopkins (2011) stated that fringe belts are stable and continuous natural areas that contribute to urban ecosystem integrity, emphasizing that these areas should be prioritized for protecting urban air movement and ecosystem services.

With their ability to follow the natural topography, high permeable surface ratio, distance from artificial heat sources and wide-open spaces, FBs can provide microclimatic areas that enable air circulation within the city, support biological diversity and balance the heat island effect (Hopkins, 2011; Görgülü & Görgülü, 2021). Therefore, fringe-belt areas should be considered in contemporary planning approaches as components of the future climate-sensitive urban form, not merely as remnants of the past. Similarly, Kirby et al. (2024) demonstrated that unbroken green belts influence temperature distribution at the urban scale and alleviate thermal loads on settled areas.

In the Turkish context, Hazar and Özkan (2020) argues that fringe belts offer significant potential for restructuring urban landscapes through nature-based solutions. This is particularly due to their capacity to create permeability, continuity and climatic buffer zones. These areas should therefore be integrated into spatial planning tools. Görgülü and Görgülü (2021) define fringe belts as critical threshold areas that enable permeability between the built environment and natural systems, providing microclimatic balancing and ecosystem services. In this context, fringe belts are indispensable components of climate-resilient urban planning.

1.2. Theoretical Foundations of the Interaction Between UHI and FB

The interaction between the UHI effect and green infrastructure areas is addressed within a spatial theoretical framework based on urban form and land use diversity. The UHI effect is a well-documented climatic phenomenon characterized by higher temperatures in urban areas compared to rural surroundings. It results from heat emitted by human activities, reduced vegetation cover and the density of impervious surfaces (Oke, 1982; Voogt & Oke, 2003). The intensity of this effect is influenced by various factors, including surface temperature, the heat storage capacity of building materials, and the spatial arrangement of building density.

In contrast, fringe-belt (FB) areas are defined as transition zones that have developed at different stages of urban growth. They are characterized by fragmented land use patterns, low building densities, and relatively high proportions of open and green spaces (Conzen, 1960; Whitehand, 2001). Thanks to these structural characteristics, FBs provide microclimatic advantages such as higher evaporation potential, lower heat absorption, and better air circulation. This makes them a significant contributor to thermal comfort compared to densely built-up urban centers.

In theory, FBs function as morphological and ecological buffer zones and have the potential to mitigate the urban heat island (UHI) effect. These areas are an important component of the historically layered urban form and have played a balancing role against urban pressures over time. Furthermore, urban metabolism and thermal zoning approaches show that the distribution of vegetation and open spaces can significantly impact urban thermal regimes (Grimmond, 2007; Emmanuel & Krüger, 2012).

In this context, integrating FBs into climate-sensitive urban planning can help preserve historically shaped urban structures while reducing heat-related environmental stress. The theoretical basis of this interaction emphasizes the strategic importance of canopy belt zones for long-term climate adaptation and urban thermal comfort.

1.3. Literature Gap and the Aim of This Study

Studies of FB areas have largely focused on their morphological evolution and historical development processes within urban growth models (Conzen, 1960; Whitehand, 2001). However, the environmental regulatory capacities of FB areas, particularly with regard to their potential role in mitigating the UHI effect, have not been sufficiently addressed in the literature. Studies on the UHI effect have generally focused on city centers and densely built-up areas, largely neglecting the potential contributions of fringe-belt areas.

This study aims to reveal how fringe-belt areas can reduce the UHI effect by considering their morphological, socio-economic, and environmental functions. To this end, the relationship between the spatial structure of fringe-belt areas and their thermal behavior is analyzed using satellite images and surface temperature data from different periods. The study intends to provide a new perspective on UHI literature and contribute data-driven insights to urban planning and climate adaptation strategies.

2. Methods and Materials

2.1. Study Area

This study examines Adana, one of Turkey’s largest metropolitan centers. Situated in the south-eastern region of the country, it lies within the fertile Çukurova (Cilician) Plain. Characterized by rapid urbanization, diverse land use patterns and a significant historical and geographical context, Adana is an ideal case study for analyzing fringe-belt areas.

Throughout the 20th and 21st centuries, Adana has experienced significant urban sprawl, particularly to the north, east, and west. This provides a dynamic context for examining the spatial, ecological, and socio-economic characteristics of FB. Various factors have influenced urban development, including its strategic location, regional migration movements, and infrastructure investments. However, Adana's climatic characteristics also significantly influence its urban and ecological structure. According to the Köppen climate classification, the city exhibits the characteristics of a hot Mediterranean climate, with hot and dry summers and mild and rainy winters. During the summer months, especially July and August, temperatures frequently exceed 35°C, while in winter, temperatures rarely drop below 5°C. The annual average rainfall is approximately 650–700 mm, with most precipitation occurring between November and March. These climatic conditions support vegetation in the surrounding areas and directly influence land use preferences in the surrounding areas, particularly with regard to green spaces.

In other words, due to its rapid urbanization, climatic characteristics and morphological structure, Adana is a relevant example for studying fringe-belt dynamics, enabling research into the relationships between urban growth, ecological resilience and socio-spatial transformation (Figure 1).

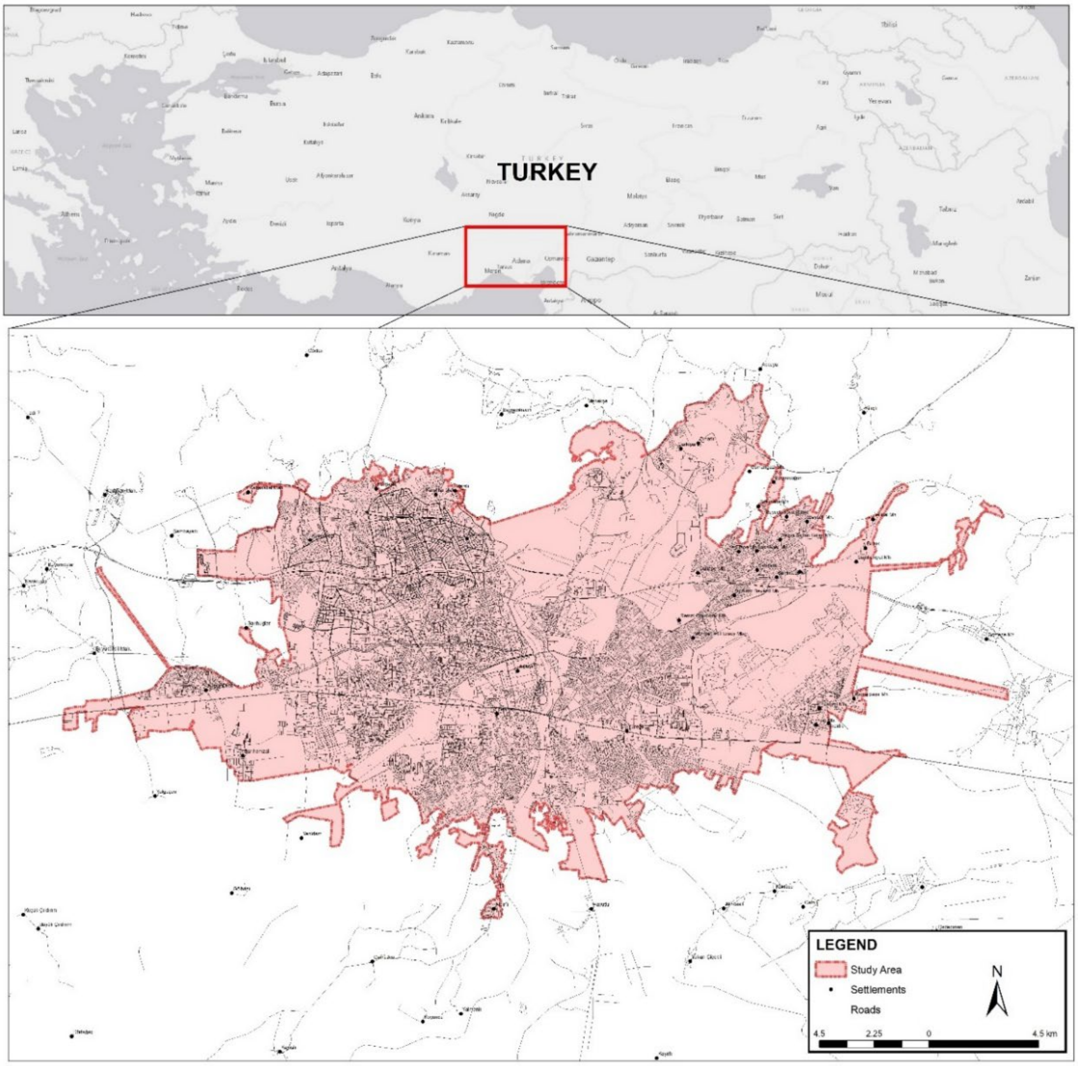

Figure 1 Location of study area

In the first step of the study, the fringe belts were digitized and Landsat 5 TM, Landsat 7 ETM+ and Landsat 8 OLI/TIRS satellite images from 1985, 2000 and 2025 were used to calculate the normalized UHI index. The images were obtained through the Google Earth Engine platform. The UHI value obtained for each fringe-belt plot was then manually assigned to that plot for each analyzed year, in order to investigate the temporal variation of the UHI effect within different land types (Figure 2).

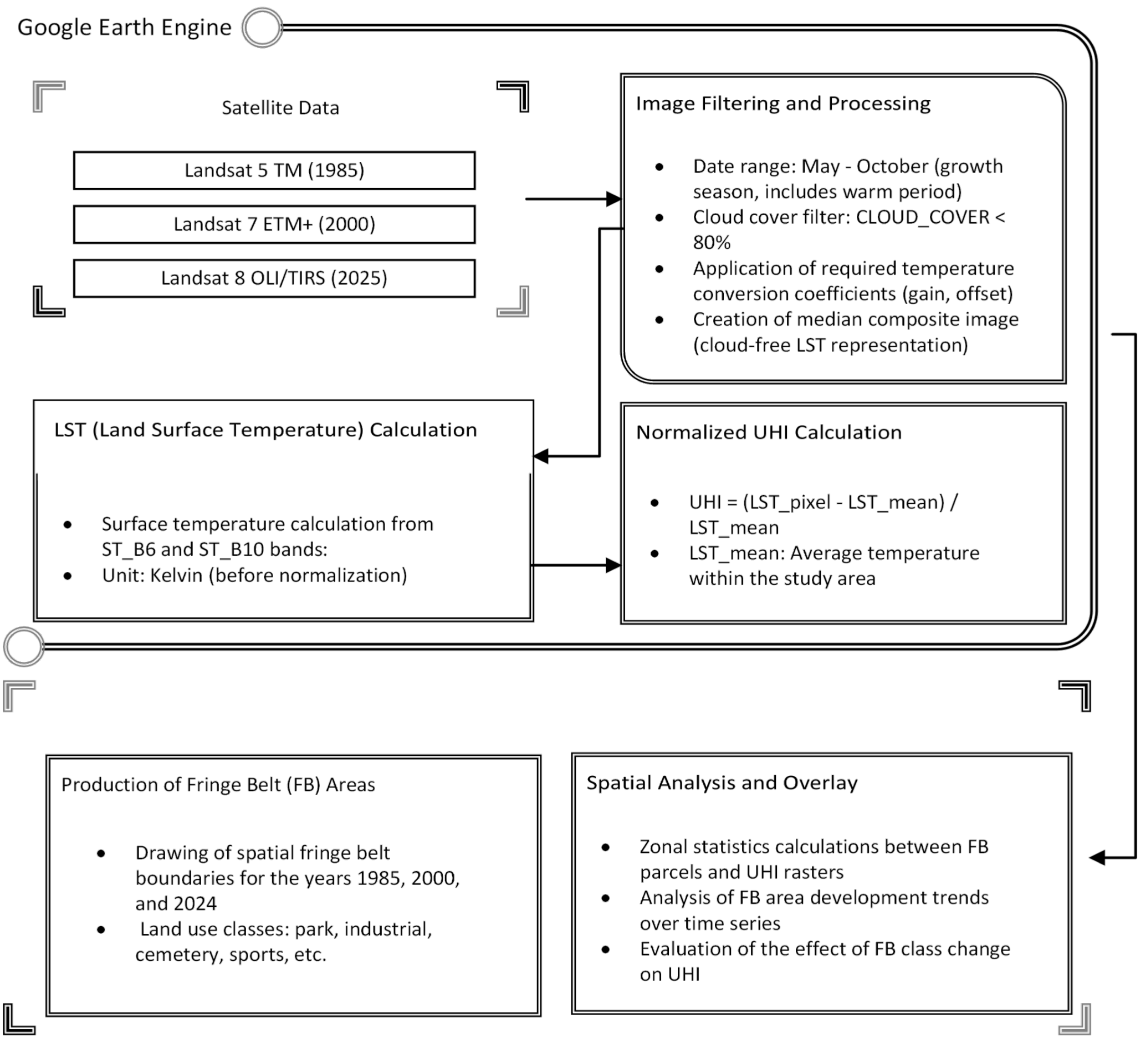

Figure 2 General framework of the study

2.2. Analysis of Fringe Belts

The fringe-belt analysis comprises three main stages. The first stage involves delineating the fringe-belt plots. The next stage is identifying their land uses and determining the changes they have undergone. As this research relates to the UHI effect, the focus is primarily on the first two stages.

Fringe-belt plot delineation is conducted for the years 1985, 2000 and 2025 within the scope of time series analysis. To this end, information was collected from old maps and records, aerial images, and field observations. Alongside today's digital maps, historical maps such as land registry maps, city plans and land use maps from 1985 and 2000 were utilized. However, one of the biggest challenges was the lack of necessary data for creating fringe-belt plots in these historical maps. This issue was resolved by redrawing the land boundaries of the relevant periods using existing digital maps. Additionally, high-resolution aerial photographs from 1985 and 2000, as well as current photographs, were used to clarify the land boundaries. Analogue maps from 1985 were digitized and georeferenced. Data from 2000 and 2025 were evaluated using satellite imagery and urban datasets.

Periodic urban growth data obtained from time series analysis was overlaid with fringe-belt land uses, enabling comparative evaluations of changes in these areas. Accordingly, fringe-belt plots were categorized into four main land-use classes: industrial areas, institutional areas, open areas and other uses (storage, temporary settlements, mixed uses, etc.). These categories enabled the effects of changing urban form on the fringe belt to be interpreted in more detail over different periods (Table 1).

Table 1 Fringe-Belt Classification

Industrial Areas	Institutional Areas	Open Green Areas	Other Areas
Industry	Administration	Public Park	Sports Areas
Warehouse-service	Government	Cemetery	Undefined Area
Medium-sized industry	School		Abandoned Area
Manufacturing	University		Commercial Area (shopping mall, business center)
Transport	Hospital		
	Community Center		
	Military Zone		
	Religious		

Following this arduous and protracted process, the fringe-belt areas of Adana for the years 1985, 2000 and 2025 were delineated. Subsequently, the inner, middle, and outer environmental belts within the built-up area were mapped for these periods using ArcGIS software.

2.3. Urban Heat Island (UHI) Mapping

The study also examined the fringe-belt patterns formed in 1985, 2000, and 2025 by conducting UHI analyses simultaneously. In this process, satellite images, orthophotos, existing maps, and urban plans were interpreted collectively; raster-format data were digitized in GIS-based environments and integrated into the analysis process. Consequently, both the spatial spread of urbanization and the formal and functional characteristics of fringe-belt areas were clearly demonstrated.

The present study utilized satellite imagery from various years to analyze the long-term alterations in the UHI effect, employing land surface temperature (LST) data as the primary investigative metric. In this context, satellite data from Landsat missions in 1985, 2000, and 2025 were utilized to examine the temporal development of the UHI effect in Adana province. The Landsat satellite is part of the Earth Observation Program, the world's longest-running and most comprehensive satellite-based Earth observation program, conducted by the U.S. Geological Survey (USGS) and NASA. Initiated in 1972, this program furnishes a significant data source for the monitoring of alterations in land cover and land use over time. Landsat images are utilized in a variety of disciplines, including urban studies, environmental monitoring, agriculture, forest management, water resources, and climate change, due to their medium spatial resolution of 30 meters (NASA, 2022; USGS, 2023).

The relevant images were obtained through the Google Earth Engine (GEE) platform, which has cloud-based computing and large-scale data processing capabilities. In selecting the images, priority was given to scenes exhibiting high representativeness of the study area, favorable atmospheric conditions, and low cloud cover. The 1985 image was obtained from the Landsat 5 Thematic Mapper (TM) sensor, as demonstrated in Figure 1. This date is significant as it marks the initial stage of Adana's post-industrial urban expansion. The second image, acquired in 2000, was also obtained from Landsat 7 ETM+ and reflects the transformations in land use that occurred during the intermediate stage of urban development. The most recent image was acquired from the Landsat 8 Operational Land Imager/Thermal Infrared Sensor (OLI/TIRS) satellite in 2025, enabling analysis of heat distribution (Table 2).

Table 2 Satellite Sensors, Acquisition Dates, and Spatial Resolutions Used for UHI Analysis

Satellite Name	Date	Resolution
Landsat 5 TM	1985	30 meters
Landsat 7 ETM+	2000	30 meters
Landsat 8 OLI/TIRS	2025	30 meters

Land surface temperature (LST) calculations were performed with consideration for the technical characteristics of each satellite platform. Initially, top-of-atmosphere (TOA) radiance values were calculated from the thermal bands; subsequently, the brightness temperature was obtained using these values.

All processing steps were executed within the GEE environment, utilizing the JavaScript programming language to ensure that data from different years was processed using a consistent method. The LST layers obtained were analyzed comparatively in both temporal and spatial contexts in order to assess changes in heat distribution in urban areas. The LST formula calculated from the thermal bands of the Landsat 5 satellite was utilized for Landsat 5, while the surface temperature for Landsat 8 was obtained directly from the "ST_B10" band provided in GEE. The difference between the LST value of each pixel in the study area and the average LST value of the surrounding reference non-FB areas was calculated by converting the values from Kelvin to °C. Consequently, the temperature values were subjected to standardization, thereby facilitating the creation of UHI maps. In order to evaluate the UHI effect in fringe belt plots, normalization was performed by comparing the average of the non-fringe-belt regions within the study area. This approach yielded anomalies in the fringe-belt plots. The UHI effect was calculated using the following equation:

$$UHI = \frac{T_{pixel} - T_{mean\_non-FB}}{T_{mean\_non-FB}} \tag{1}$$

Where T_{pixel} is the temperature of the plot in the fringe-belt and T_{mean_non-FB} is the average temperature outside these areas. The normalized UHI maps were divided into five classes according to the lowest and highest pixel values in the region (Table 3).

Table 3 Classification Scheme for Normalized UHI Effect Used in This Study

Classes	UHI Range	Label
1	< - 0.030	Very Cooling Effect
2	-0.030 – 0.000	Cooling effect
3	0	Neutral Zone
4	0.010 – 0.020	Warming Effect
5	> 0.020	Very warming effect

3. Results and Findings

3.1. Urban Growth and Fringe-Belt Formation

In the early 20th century, Adana was a small city located in the fertile agricultural region of Çukurova, where irrigation-based agricultural production was prevalent. The initial significant development took place in the late 19th century, coinciding with the emergence of commercial activity centered on cotton farming and the augmentation of railway connections (Sönmez, 2011). Subsequently, the urban area expanded in a northerly direction, traversing the initial fringe belt – the inner fringe belt – to reach its current extent. The initial urban development plan, formulated by Hermann Jansen and promulgated in 1940, designated this particular area of the city as the primary development zone.

Following the 1950s, urban expansion was propelled by the development of irrigation technologies and the substantial increase in agricultural productivity. The establishment of the Mersin Port and the subsequent intensification of trade relations with Mersin further contributed to Adana's rapid development. The 1967 urban development plan sought to address this rapid growth by proposing new residential areas, with planning focused on expanding toward the northern and northwestern peripheral areas (Altunkasa, 2004). Between the years 1940 and 1967, the city of Adana underwent significant urban development, particularly in terms of its peripheral infrastructure. During this period, the city established its second fringe belt, which was developed in close proximity to the railway line. In the absence of alternative explanations, it can be posited that the industrial uses present in the western region, in conjunction with the airport area, have contributed to the formation of the second fringe belt, which is otherwise referred to as the middle fringe belt.

By 1985, the formation of a middle fringe belt persisted, and a third belt – the outer fringe belt – became apparent in the built-up area. Notwithstanding the occurrence of urban expansion, particularly in the northern and western directions, new development areas have not been fully incorporated into the built-up area. During this period, there was an increase in the number of larger fringe-belt plots, particularly in industrial areas, military areas, the airport, and university areas. Despite the larger plots being located in the outer fringe belt, institutional uses, including education, healthcare, and administrative functions, predominated in the former fringe belts (Figure 3).

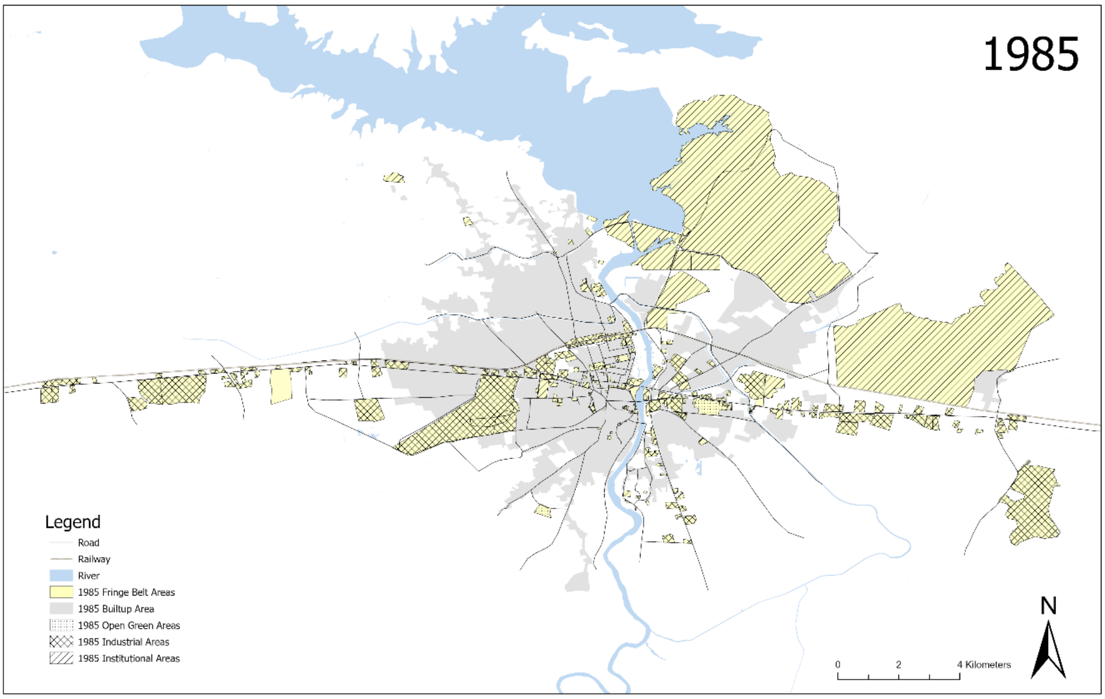

Figure 3 Fringe belts of Adana and the built-up area in 1985

In the late 1990s and early 2000s, an increase in urban density and a trend towards a multi-centered structure were observed in Adana. In the 1990s, a series of revisions to urban development plans resulted in a comprehensive restructuring of the urban structure of Adana. This restructuring was underpinned by a strategic framework comprising five distinct development sectors: northeast, northwest, southeast, southwest, and central (Altunkasa, 2004). During this process, the city incorporated peripheral settlements such as İncirlik, Balcalı, Yeşilbağlar, and Buruk and faced intense development pressure, particularly on the areas around the Seyhan Dam Lake in the north (Zorlu & Sögüt, 2019). While the inner and middle fringe belts were consolidated, the outer fringe belt continued to form, especially through large-scale public investments (Figure 4).

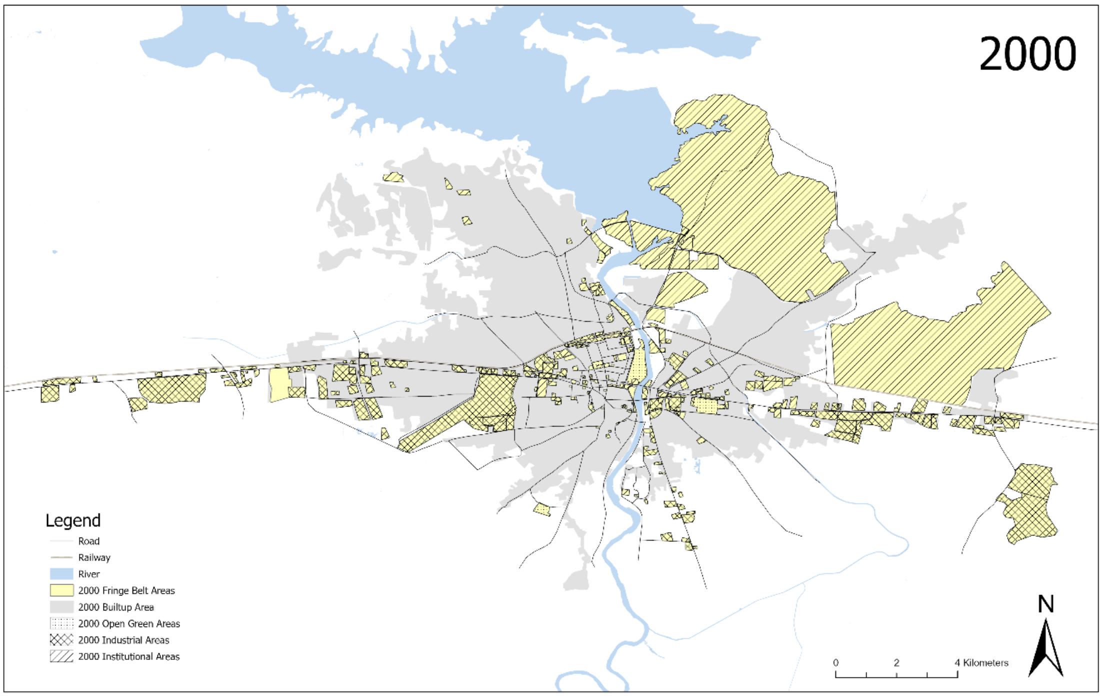

Figure 4 Fringe belts of Adana and built-up area in 2000

By 2025, significant changes in the inner and outer fringe belts were observed. Firstly, there was fringe-belt alienation, which refers to a change in FB use to non-FB use. Secondly, there was a change in land use from one FB use to another. The former is evident in the middle fringe belt, where a process of industrial transition has occurred, with older factories being converted into shopping centers. In contrast, the latter is observed in both the inner and middle fringe belts, as evidenced by the transformation of some industrial plots into institutional use. Conversely, the outer fringe belts are still undergoing a development phase, with the emergence of new institutional structures (Figure 5). The natural threshold areas in the north and west have been subject to high-density development over time, which has also exerted development pressures on the fringe belt areas. This situation has had a detrimental effect on the climatic and ecological characteristics of settlements, thereby increasing the UHI effect.

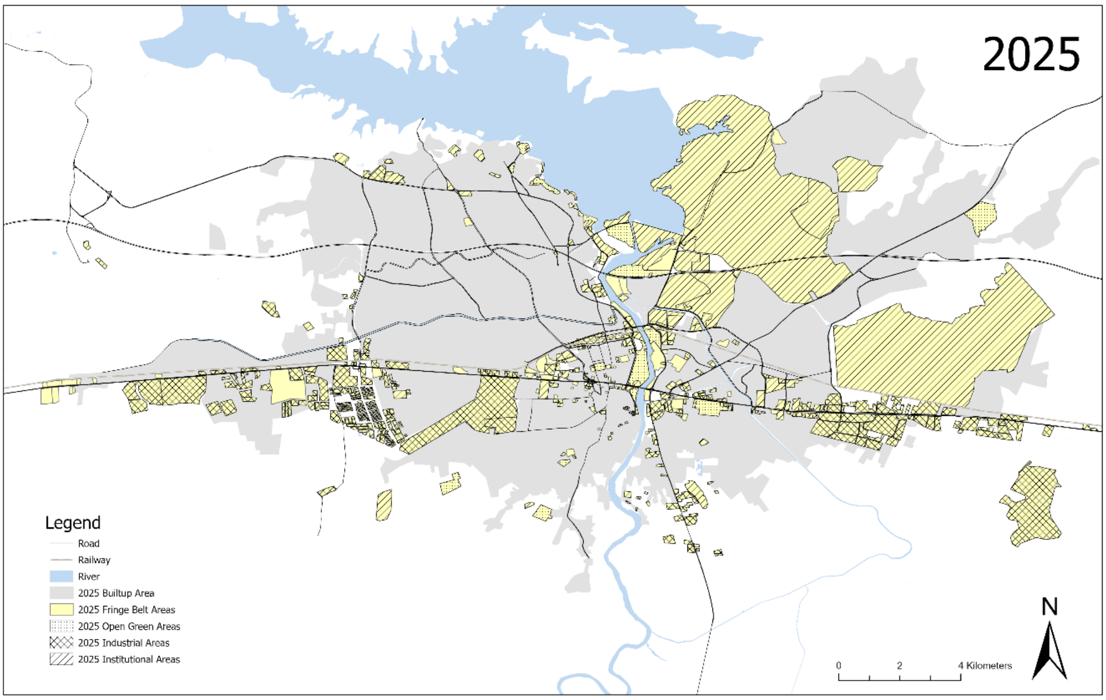

Figure 5 Fringe belts of Adana and built-up area in 2025

The sparse structure of fringe belt areas underwent a gradual densification between 1985 and 2025. This transformation was characterized by the aggregation of building complexes, the augmentation of building footprints, and the reduction of open spaces. Consequently, fringe belt areas underwent a degradation not only in their spatial characteristics but also in their functional and environmental attributes.

3.2. Changes in the Size and Characteristics of the Fringe Belt Between 1985–2000–2025

Between 1985 and 2025, the city of Adana underwent substantial urban expansion. While urban development was primarily focused on the city centre and its surroundings until 1985, the city began to extend to the north and west in the 2000s; the 2025 built-up area exhibits a more intense, dispersed, and fragmented structure in these directions. This phenomenon has precipitated not only an alteration in the boundaries of built-up areas but also a substantial modification in the spatial relationship between the fringe belts and the city (Figure 6).

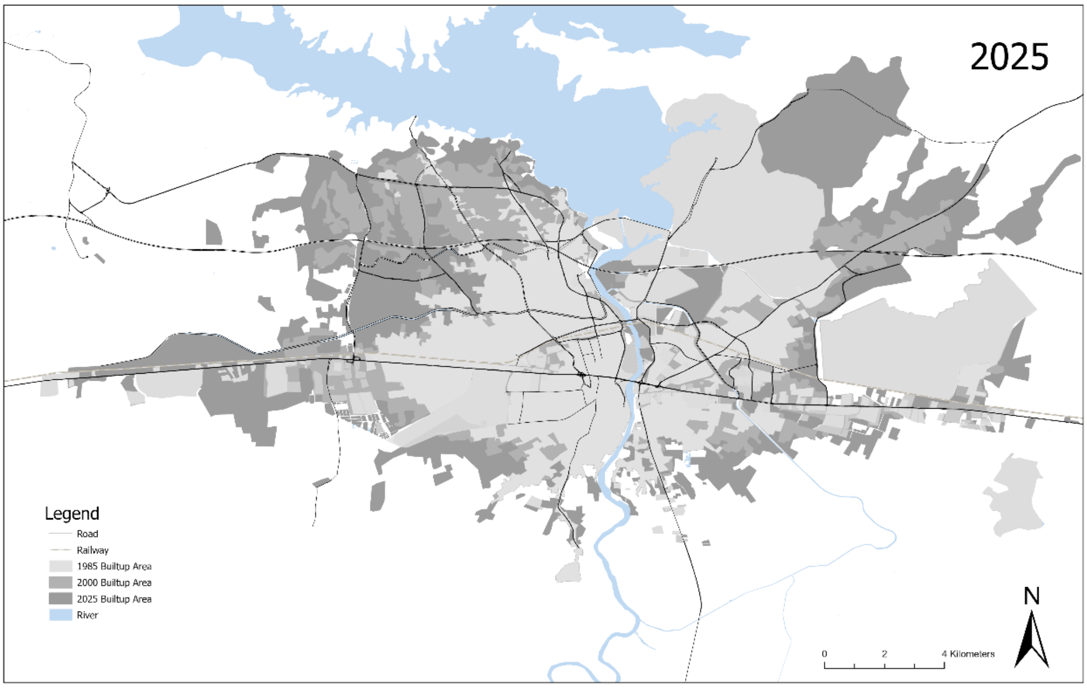

Figure 6 Changes in built-up area by the years

Spatial analyses and quantitative comparisons have been used to reveal changes in the size and functional distribution of fringe-belt areas. As demonstrated in Figure 1, the area of the fringe-belt area increased from 54.3 million m² in 1985 to 55.9 million m² in 2000, and further to 83.3 million m² in 2025. However, it should be noted that this change is not only quantitative but also qualitative (Table 4 and Figure 7).

In 1985, the predominant land use in fringe belts was institutional areas (e.g. universities, hospitals, administrative units) at 71%, while industrial areas ranked second and formed a functional buffer, delineating the urban centre and the environmental threshold. During this period, open green spaces occupied a very limited area and were scattered within the fringe belt (Table 4).

Table 4 Land Use Distribution Over the Years (1985, 2000, 2025)

Year	Land Use	Area (m²)
1985	Industrial Areas	14.216.190,84
	Institutional Areas	38.629.686,56
	Open Green Areas	1.151.142,12
	Other	305.254,76
	Total	54.302.274,28
2000	Industrial Areas	14.882.844,00
	Institutional Areas	39.122.200,48
	Open Green Areas	1.683.973,00
	Other	204.733,67
	Total	55.893.751,15
2025	Industrial Areas	32.363.140,00
	Institutional Areas	44.207.321,00
	Open Green Areas	5.183.881,00
	Other	1.608.919,00
	Total	83.363.261,00

By the year 2000, while the dominance of institutional areas persisted, an increase in the absolute size of industrial areas was observed. However, a decline was observed in the "others" category (storage, temporary settlements, undefined areas, etc.), although not a dramatic change.

The 2025 fringe belts mark a pivotal moment in which both spatial and functional intensification become evident. In particular, there has been a marked increase in development pressure in the older fringe-belt areas, which are located within the inner city. A significant proportion of these areas have undergone a transformation, resulting in the loss of their original functional character and subsequent transformation into service areas for commercial, service and administrative functions. It is indeed noteworthy that high-density developments, including shopping centers, multi-store business centers, and private healthcare facilities, have become pervasive in these areas. This phenomenon underscores the turning of fringe-belt areas from mere transition zones to focal points of urban transformation, leading to increased plot density.

It is evident that industrial areas have attained approximately 32.4 million m², constituting the predominant share within the fringe belts. Institutional areas have undergone continuous expansion, with open green spaces reaching a substantial magnitude, amounting to 5.1 million m². This increase is primarily attributed to the development of previously vacant areas located outside established urban areas. The percentage distributions presented in Figure 7 provide a clearer visualization of this structural change. In 1985, approximately 71% of the fringe belt consisted of institutional uses, while this ratio decreased to 53% in 2025; during the same period, the ratio of industrial areas increased from 26% to 39%. Warehouses and associated service activities were predominant within industrial areas, superseding the presence of factories. Conversely, the proportion of open areas exhibited a marked yet modest rise, from 1.5% to 6.2% of the total area.

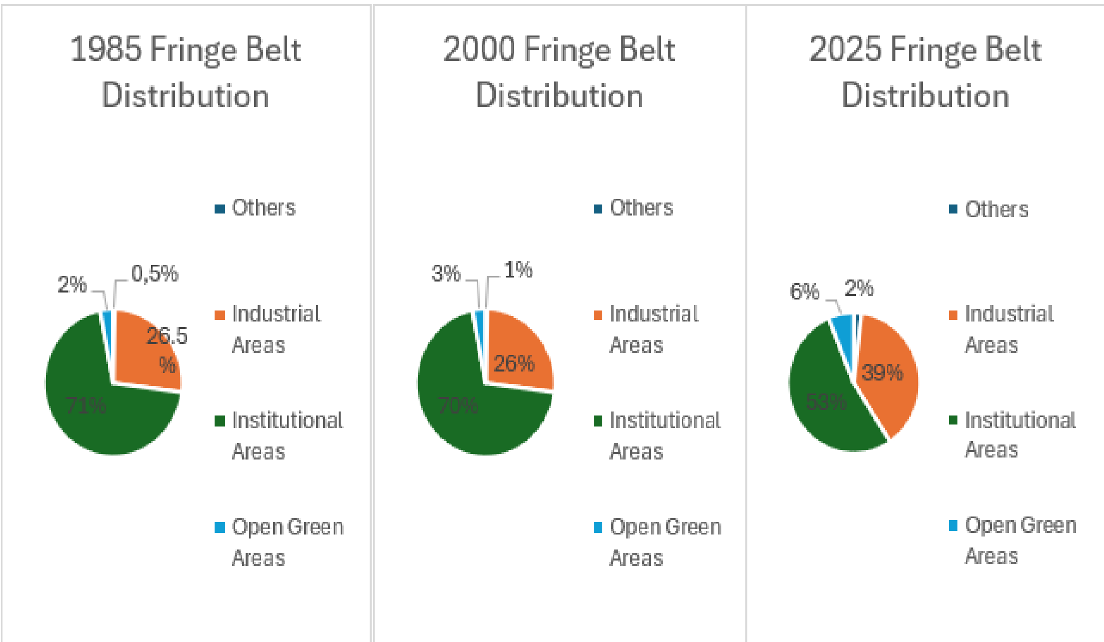

Figure 7 Distribution of FB plots over the years

3.3. Analysis of UHI Within FB Plots

In this study, the interaction between FB plots and surface UHI was assessed by overlaying normalized UHI data and FB vector data using the zonal statistics method, and the average UHI value was calculated for each FB plot. Consequently, the microclimatic characteristics of FB plots were quantitatively obtained, thereby revealing their heating or cooling effects within the city. In the cartographic documents created within the specified scope, the following colour-coding system was employed: "Very Cooling" (dark blue), "Cooling" (light blue), "Neutral" (yellow), "Warming" (orange), and "Very Warming" (red). The boundaries of residential areas were delineated in grey for each period.

It has been observed that areas within the city centre which have experienced a significant cooling effect tend to be located in proximity to green spaces, sports facilities, and institutional areas characterized by a high ecological capacity. Open spaces and parks, in particular, were identified as areas that reduced the UHI effect in the city centre. These areas, delineated in dark and light blue, were observed to have a cooling effect within the urban fabric. In a similar manner, public institutions with large permeable surface areas also exhibit a significant cooling effect. It has been established that such areas exert a positive influence on the microclimate, both within their own boundaries and in the surrounding areas.

The magnitude of the cooling effect increased in plots located in close proximity to the city centre between 1985 and 2000, owing to alterations in land use. Notwithstanding the occurrence of urban expansion, the cooling effect has been sustained as a consequence of the augmentation in the utilization of sports facilities and open green spaces. However, a marked increase in the proportion of plots categorized as "warming" or "very warming" has been observed in plots located to the east and west of the city center (Figure 8).

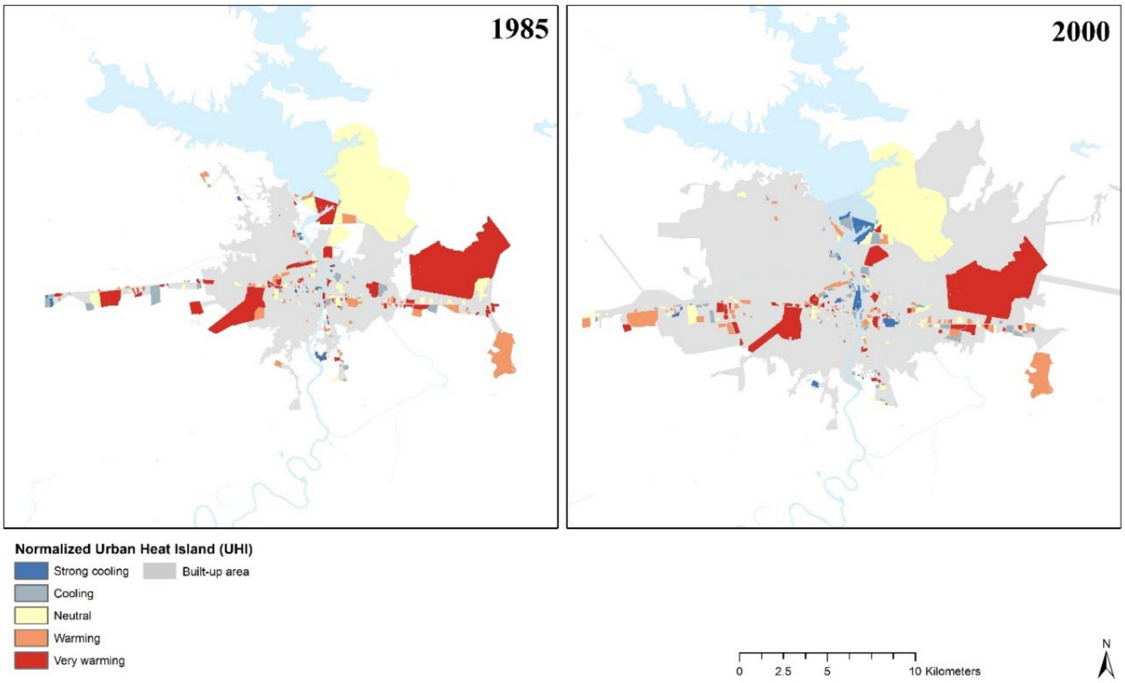

Figure 8 Spatial distribution of normalized UHI classes in 1985 and 2000

By 2025, there is an expectation of an increase in the UHI effect. In comparison with the year 2000, both the city centre and the peripheral areas located outside the city centre have experienced an increase in the categories of 'very warming' and 'warming'. The UHI effect has been observed to increase in the peripheral plots located on the southern and western peripheries of the city. Furthermore, the UHI effect formed during this period has contributed to an enhancement of this effect. While parks, institutional complexes, and sports facilities located in the city center remain the focal points of the cooling effect, the UHI effect stands out as the period during which it spread over the widest area in the analyzed years (Figure 9).

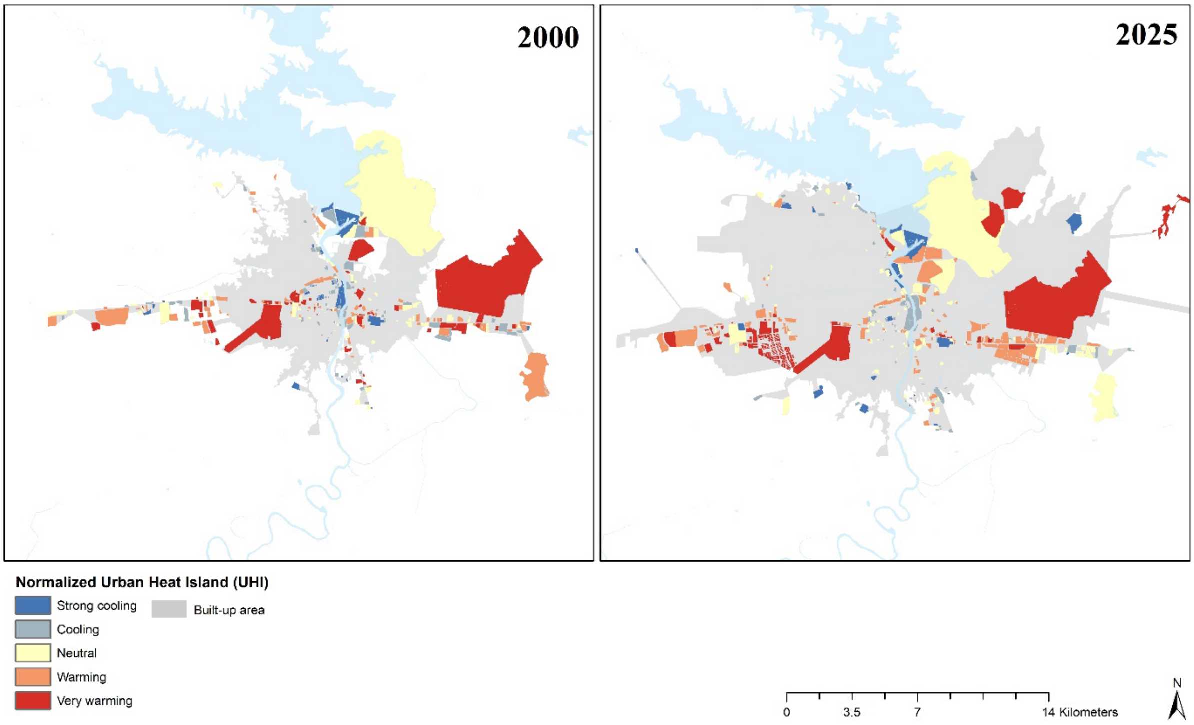

Figure 9 Spatial distribution of normalized UHI classes in 2000 and 2025

In 1985, 53.61% of fringe-belt plots were classified as "Warming", while the "Very Warming" class accounted for a mere 12.17% of the area. During this period, the total area exhibiting "Neutral" and "Cooling" effects exceeded 34%. This result suggests that fringe-belt areas exhibited greater resistance to the UHI effect in 1985, or alternatively, that these areas experienced less dense development.

A significant transformation is observed in 2025, with the proportion of areas classified as "Very Warming" increasing to 43.99%, while the proportion of areas classified as "Neutral" decreased to 6.73% and the "Cooling" class to 0.24%. This percentage change indicates that fringe-belt areas have undergone increased urbanization, with higher impervious surface ratios and significantly elevated surface temperatures. Nevertheless, this phenomenon suggests that certain marginal belts have transitioned from being transient to permanent, characterized by substantial heat accumulation.

The structural transformation observed between 1985 and 2025 demonstrates that urban sprawl is not merely a spatial expansion but also has profound effects on the thermal environment. In this context, the temporal analysis of the UHI effect on fringe belt areas is of critical importance for developing climate adaptation strategies in urban planning processes. Of particular note is the accelerated rise in the "Very Warming" category, which signifies the potential for exacerbation of the deleterious effects of these regions on ecosystem services and the loss of thermal comfort (Table 5).

Table 5 Proportion (%) of Fringe Belt Plots in Each Normalized UHI Class for the Years 1985, 2000, and 2025

Year	Very Cooling (%)	Cooling (%)	Neutral (%)	Warming (%)	Very Warming (%)
1985	0	2.2	31.94	53.6	12.17
2000	0	4.26	38.36	44.59	12.79
2025	0	0.24	6.73	49.04	43.99

The central question guiding this study, namely, "How has the spatial and structural transformation of FB areas during the urban development process affected the UHI effect?" has been largely addressed and validated by the study's findings. The hypothesis developed in this context suggests that the alienation, shrinkage, and increase in building density observed in fringe-belt areas alongside urban development contribute to the increase in the UHI effect by altering the thermal properties of these areas.

In the present study, the statistical significance of the relationship between UHI values and various land-use types (for example, open space, sports area, institutional area, etc.) in fringe-belt plots was analyzed using the Kruskal-Wallis H test. This non-parametric variance method is favored when data do not conform to a normal distribution and group sizes vary. For each year, the FB plots were classified according to the corresponding year's land use, and the Kruskal-Wallis test was employed to ascertain whether there was a significant difference between land use and UHI values. The fundamental hypothesis of the test is that the distributions of all groups are equivalent; a low p-value signifies a substantial discrepancy between at least two groups.

In the analysis conducted for 1985, $p=0.003$ ($p<0.05$) was obtained, indicating a significant difference between land use and UHI values. The statistical evaluation of land use and UHI for the year 2000 yielded $p < 0.001$, while for the year 2025, $p < 0.001$ was found.

In the evaluation of fringe-belt plots in 1985, 2000, and 2025, considering land use types, the mean, median, minimum, maximum, and standard deviation of UHI values and the number of plots were provided. In 1985, the areas with the highest average UHI values were found to be those designated for industrial land use (0.0142). The second-highest UHI values were exhibited by institutional areas (0.0106), followed by industrial areas. Conversely, open areas demonstrated the lowest UHI values (0.0093). Despite the relatively limited number of plots classified as "other", the average UHI value remained at an intermediate level of 0.0119.

In the year 2000, a substantial decline in UHI values was documented across all land use categories. Institutional areas exhibited an average UHI decrease to 0.0086, while open areas demonstrated a decline to 0.0031. Industrial areas, however, exhibited an increase to 0.0141. The relatively high UHI effect persists in industrial areas. However, the decline in the UHI effect in open areas suggests an augmentation in the cooling effect within the urban environment. In 2025, an increase in the UHI effect was observed again for all land use types, especially in industrial areas, where the average UHI rose to 0.022 and the maximum value (0.0348) remained quite high (Table 6).

Table 6 Descriptive Statistics of Normalized UHI Values by Land Use Type for 1985, 2000, and 2025

Year	Land Use	Number of Plots	Mean	Median	Min.	Max.	Std.
1985	Open Space	9	0.0093	0.0081	-0.0105	0.0289	0.0111
	Institutional	94	0.0106	0.0117	-0.0037	0.0239	0.0062
	Industrial	150	0.0142	0.0143	-0.0046	0.0324	0.0068
	Other	4	0.0119	0.0135	0.0021	0.0187	0.007
2000	Open Space	12	0.0031	0.0031	-0.0074	0.015	0.0064
	Institutional	11	0.0086	0.0089	-0.0053	0.0232	0.0052
	Industrial	165	0.0141	0.0143	-0.0051	0.0294	0.0068
	Other	3	0.0047	0.0033	0	0.0108	0.0056
2025	Open Space	43	0.0136	0.0142	0.0003	0.0251	0.0053
	Institutional	181	0.0181	0.0179	0.0062	0.0358	0.0048
	Industrial	180	0.022	0.022	0.0036	0.034	0.0061
	Other	12	0.0144	0.0155	-0.0009	0.0212	0.0062

A spatial evaluation indicates that fringe-belt plots displaying industrial usage demonstrate the highest mean UHI across all three designated periods. The cooling effect of institutional and open areas is maintained until 2000 but begins to be lost in 2025. Despite the limited number of plots classified as "other", a substantial increase in the UHI effect is evident by 2025 (Figure 10).

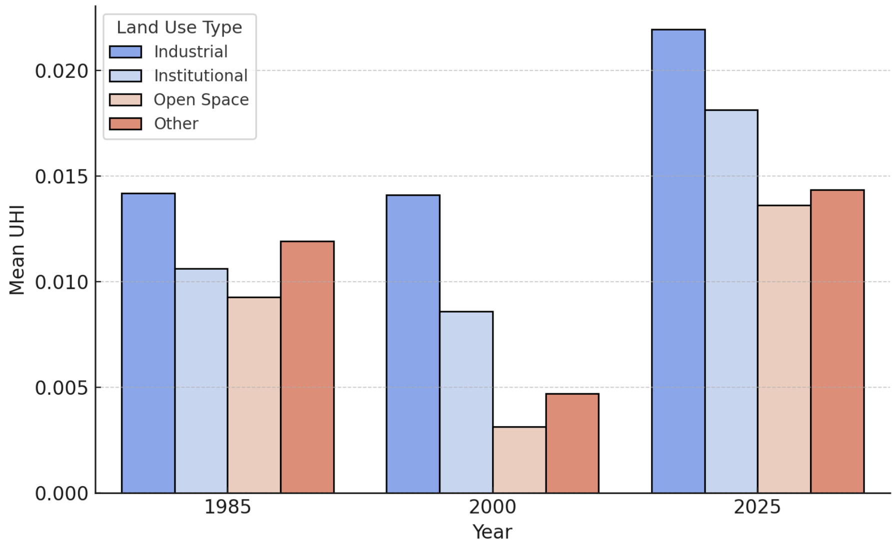

Figure 10 Mean UHI values by land use type (Industrial, institutional, open space, other) for 1985, 2000, and 2025

4. Discussion

The fringe-belt concept, which delineates morphological areas formed during historical urban growth processes and reflects urban development, also indicates that these areas should be reconsidered in urban planning not only for their physical but also for their environmental functions (Ünlü, 2022). The UHI effect, which has brought the increasing thermal pressure in urban areas to the forefront, highlights the microclimatic role of fringe-belt areas. However, a comprehensive study is absent from the extant literature that examines the direct relationship between the fringe belts and the UHI effect. This finding underscores the study's distinctive approach in evaluating fringe-belt areas at both the spatial and microclimatic levels.

In the relevant UHI literature, the principal strategies for reducing urban heat islands are listed as follows: increasing green space ratios, preserving permeable surfaces, reducing building density, and adopting street designs that support air circulation (Jusuf et al., 2007; Bhargava et al., 2017). However, the evaluation of such strategies is typically conducted through the utilization of green infrastructure elements dispersed throughout urban areas. Consequently, fringe-belt regions are not directly addressed within this context. However, fringe belts, due to their historical nature as permeable, green, or low-density areas in the peripheral lands of the city, have lower surface temperatures than city centers and thus have the potential to act as buffers against thermal stress.

Conversely, fringe-belt literature has focused predominantly on the examination of morphological continuity, functional transformation, and historical development periods. However, the recommendations available for the evaluation of these phenomena in planning remain limited. Recent studies have begun to define fringe belts not only as threshold areas but also as ecological and microclimatic green corridors. Hazar and Özkan's (2020) study emphasizes the role of these areas in terms of urban biophysical integrity, while Görgülü and Görgülü's (2021) study states that fringe belts should be evaluated as ecological thresholds that provide interrelationships between the built environment and natural systems. In his preliminary study on the ecological significance of fringe belts, Hopkins (2011) emphasized that these areas support biological diversity, provide ecosystem services, and connect urban natural areas. However, these approaches do not directly link the effects of fringe belts in the UHI context with data-based analyses.

This study is among the first to analyze fringe-belt areas by matching them with UHI effects, with a particular focus on Adana across three distinct periods. In the context of urban planning, fringe belts are regarded not only as spatial transition zones but also as microclimatic resilience points. These belts are considered strategic areas that can be utilized to reduce urban heat pressures. In this regard, the study serves to bridge the gap between the UHI and fringe belt literatures, offering a comprehensive framework that integrates these two approaches. From the perspective of urban planning, the proposal calls for the redefinition of fringe belts not only as areas earmarked for future development, but more significantly and crucially as components of climate-sensitive planning.

In this study, an examination of the period between 1985 and 2000 reveals that changes in land use in plots adjacent to the city centre have had a mitigating effect on the UHI effect. The augmentation in the prevalence of sports facilities, parks, and green spaces within the urban landscape, in conjunction with the proliferation of institutional areas in proximity to the city centre and the peripheral belt regions, has precipitated this outcome. The restructuring of institutional areas in their current locations, or the avoidance of intensive development in new institutional areas, may have been effective. This finding suggests that these areas have been effectively preserved in terms of their spatial integrity and that their cooling effects have been sustained despite urban expansion. Consequently, it can be posited that UHI pressure was constrained during this period. The area encompassing the fringe-belt region, which was 54.3 million m² in 1985, exhibited a 53% increase, reaching 83.3 million m² by 2025. However, this increase is not solely quantitative in nature; it also encompasses qualitative dimensions, including functional diversification, increased density, and structural alienation. The composition of fringe belts was initially dominated by institutional areas; however, these belts have gradually experienced increasing pressure from industrial, commercial, and high-density mixed-use developments. Consequently, they have undergone a significant shift in their original threshold functions. By 2025, industrial areas accounted for the largest share in fringe belts, indicating a reshaping of the periphery.

During the 2000–2025 period, the propagation of the UHI effect across a substantial geographical area is evident, encompassing both urban centers and peripheral suburban regions. It is evident that the increase in the "very warming" and "warming" categories in fringe-belt plots in the southern and western peripheries of the city is indicative of a disruption in the spatial continuity of these areas. This disruption suggests that these areas are subject to development pressure. As demonstrated in the study conducted by Zorlu and Söğüt (2019), utilizing the case study of Adana, following the year 2000, there has been a notable increase in urban density, particularly in threshold areas along the periphery. This phenomenon can be attributed to frequent alterations in master plan decisions, heightened development pressure through plan revisions, and the conversion of green areas into residential and mixed-use zones. This transformation has laid the groundwork for the disruption of not only the physical structure but also the microclimatic balance. In this context, the protection of fringe belt areas through sustainable planning decisions and their development using ecological planning approaches should be considered an important strategy for controlling the UHI effect.

UHI analyses have yielded definitive insights into the repercussions of this spatial transformation on the city's microclimate. In 1985, 34% of fringe-belt plots exhibited a cooling or neutral effect, while this rate fell below 7% in 2025. Concurrently, the proportion of areas classified as "Very Warming" exhibited a marked increase, rising from 12% to 44%. Industrial uses with high impervious surface ratios have consistently exhibited the highest UHI values in all three periods, while the cooling effect observed in open and institutional areas in 2000 began to weaken by 2025. Statistical analyses conducted on fringe-belt plots (Kruskal-Wallis H test) revealed significant differences between land use types and UHI values. The present study has revealed a significant increase in the UHI effect in industrial areas in 2025, whilst a decrease was observed in institutional and open areas. The findings demonstrate that structural transformation in fringe belts exerts not only functional but also climatic consequences, thereby causing the UHI effect to spread towards the city periphery.

5. Conclusion

The present study set out with the objective of unveiling the spatial and functional metamorphosis of fringe-belt areas in Adana between 1985 and 2025, whilst concomitantly analyzing the repercussions of this transformation on the UHI effect. A comparative analysis conducted over three periods reveals significant transformations in both size and quality in fringe-belt areas.

Consequently, fringe-belt areas have evolved from being merely urban threshold zones to becoming direct targets of urban pressures, intensification, and thermal stress. This transformation necessitates the re-evaluation of fringe belts as critical areas in urban planning processes, particularly in terms of climate adaptation, permeable surface conservation, and cooling area strategies. In this context, fringe-belt areas should be regarded not only as vestiges of historical urban form, but also as a high-priority component of climate-resilient urbanization policies in the future.

The findings reveal that the function of fringe-belt areas within cities has changed significantly over time and that this transformation has had a substantial impact on the thermal environment. The intensive development that has been observed in industrial areas, coupled with the increasing UHI effect, indicates that impermeable surfaces have increased and that green infrastructure is inadequate in these areas. In particular, by 2025, some fringe belt areas are expected to transform into areas with high thermal load accumulation and exposed to urban density pressure. This indicates that these areas are no longer merely transition zones but have become focal points of urban growth. This situation highlights the importance of incorporating fringe belt areas into future planning processes alongside climate adaptation strategies. It is evident that solutions such as the preservation and enhancement of the cooling effect of open and institutional areas, in addition to the integration of green corridors and heat-absorbing surfaces, can play a critical role in the balancing of the UHI effect in these areas. Moreover, the preservation of the functional diversity of fringe belt areas is of significance not only for microclimatic benefits but also for sustainable urbanization. In this context, planning policies must redefine fringe belts as spatial thresholds, establish specific land use decisions, and set development limits for these areas.

A comprehensive approach has been adopted to reveal the temporal change of fringe-belt areas, land use transformation, and their spatial relationship with UHI. However, in order to interpret the findings in greater depth, it is recommended that multivariate spatial statistical methods and advanced interaction models be used in future research. In particular, an examination of the structural relationships between the transformation of fringe-belt areas and urban dynamics, such as demographic structure, accessibility, property regime, and investment trends, will provide a more complex and meaningful analytical framework. The execution of comparative studies in cities exhibiting divergent climatic and morphological characteristics is of paramount importance for the elucidation of the universal principles that govern the fringe belt phenomenon, whilst concomitantly accounting for its site-specific variations. Furthermore, the increased precision afforded by high-resolution remote sensing data could facilitate more robust understanding of the temporal and spatial variations of the UHI effect. The development of scenario-based spatial simulations and decision support systems to test the effects of planning policies also presents a critical potential for future studies in terms of translating theoretical knowledge into practical applications.

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CRediT Authorship Contribution Statement

Gülnihal Kurt Kayalı: Writing – review & editing, Methodology, Investigation, Analysis. Büşra Gülbahar İşlek: Writing – original draft, Visualization, Data curation. Tuğba Akın: Writing – original draft, Visualization, Data curation. Tolga Ünlü: Conceptualization, Methodology, Writing – review & editing. Tülin Selvi Ünlü: Project administration, Investigation, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data Availability

Data will be made available on request.

Ethics Committee Approval

Since this study does not involve human participants, animals, or any sensitive personal data, an ethics committee decision was not required, and this has been stated accordingly in the manuscript.

Resume

Gülnihal Kurt Kayalı is a landscape architect and researcher with a focus on Geographic Information Systems (GIS), remote sensing, and ecological landscape planning. She received her bachelor's and master's degrees in landscape architecture from Çukurova University, where she is currently continuing her doctoral studies. Her academic path has been shaped by an interest in understanding the interaction between urban development and natural systems, and by exploring methods that can contribute to more sustainable and resilient urban environments. Her research covers topics such as ecological networks, habitat connectivity, and urban resilience, with particular attention to how spatial data and landscape metrics can inform planning decisions. She has contributed to different research projects and has presented her studies in national and international academic settings. These experiences have supported her interest in applying interdisciplinary approaches and technology-based methods to issues of urban and environmental sustainability. She continues her academic work with the aim of combining scientific analysis and practical perspectives to support more balanced relationships between cities and natural landscapes.

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Urban layers and living spaces: The evolution of housing in Kayseri

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Abstract

This study examines the transformation of housing in Kayseri as a case through which to understand broader processes of urbanization, modernization, and socio-spatial change in Turkey. Once defined by inward-oriented courtyard houses constructed from local materials—reflecting values of privacy and communal life—Kayseri's domestic architecture has undergone significant transformation across four historical periods: the pre-Republican era, the early Republican period, the post-1950 expansion, and the post-1980 neoliberal era. Each phase reflects a distinct interplay between national policy directives, global urban trends, and local adaptations. Early Republican reforms introduced Western-oriented architectural ideals by promoting detached houses and low-rise apartments. This trajectory accelerated in the post-1980 period when neoliberal policies prioritized high-rise residential development driven by private capital and speculative investment, often at the expense of cultural continuity and human-scale urban design. Employing an interdisciplinary methodology, this research integrates archival analysis, oral histories, spatial observations, and visual documentation. Drawing on architecture, sociology, and history, it investigates how built forms mediate tensions between tradition and modernity, memory and transformation, and local identity and state ideology. With its long-standing strategic and cultural significance, Kayseri provides a compelling case for examining how urban development is shaped by structural forces and lived experience. The study argues that the housing transformation in Kayseri is not a linear progression, but a contested and layered process shaped by evolving economic structures, governance models, and cultural logic. By combining textual, visual, and experiential knowledge, the research offers a deeper understanding of how domestic space reflects and constructs shifting urban realities.

Keywords: city, housing culture, Kayseri, modernization, urban transformation

1. Introduction

The housing transformation in Kayseri functions as a microcosm of Turkey's broader urban modernization, shaped by evolving cultural norms, technological innovations, and changing spatial practices. Traditionally, housing in Kayseri was characterized by inward-oriented courtyard houses constructed from local materials, reflecting privacy values, familial hierarchy, and environmental adaptability. These houses facilitated multifunctional living and fostered strong neighborhood relations within a compact urban morphology.

Following the foundation of the Turkish Republic, a new phase of urban development emerged in Anatolian cities. Industrialization, state-led infrastructure investments, and early planning initiatives introduced detached modern houses and low-rise apartment buildings by the mid-20th century (typically limited to three or four stories rather than the high-rise blocks familiar today). These new housing forms embodied a national orientation toward Western ideals articulated by modernist discourse, particularly hygiene and rational planning, the latter referring to the systematic organization of residential space through functional and standardized layouts. The apartment, in particular, emerged as a marker of modern urban life and middle-class identity.

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The post-1980 period witnessed an intensified urban landscape transformation under neoliberal economic policies and the growing influence of private capital. High-rise apartment complexes, frequently driven by speculative development, replaced traditional neighborhoods and reconfigured the urban fabric. While these developments responded to housing demand and introduced modern amenities, they also brought gradual shifts that disrupted established cultural practices, weakened neighborhood-based social ties, and compromised the city's traditional human-scale morphology.

This article traces the evolution of housing in Kayseri across distinct historical periods—from the pre-Republican era to the present—demonstrating how national policies, economic transformations, and global urban trends have continually reshaped domestic architecture. By positioning Kayseri within both historical and contemporary contexts, the study explores how the built environment mediates tensions between tradition and modernity, local identity and state ideology, and memory and urban transformation.[1]

2. Methodology

This study offers a historical reading and analysis of housing transformation in Kayseri, examining how architectural forms, spatial practices, and social meanings have evolved. It adopts a multi-layered approach that mirrors the one used in Bozdoğan's work (2001)—rooted in urban studies and drawing from architecture, sociology, and history— through an approach that refrains from privileging a single discipline while actively engaging others (Repko & Szostak, 2017). Archival research, spatial analysis, literature review, and interviews are integrated to explore the city's socio-spatial changes.

Historical materials—urban plans, drawings, maps—form the foundation of the analysis (Çabuk, 2012; Sönmez & Alper, 2012; Yücel et al., 2020), complemented by academic studies highlighting the spatial impact of political and economic shifts (Kasap, 2017; Kocatürk & Yücel, 2012). The methodology blends documents, photographs, oral histories, and field observations to uncover the layered meanings of housing, especially since the mid-20th century (İmamoğlu, 2006; Çelik, 2017b).

Key to the analysis is the shift from inward-facing courtyard houses to modern apartment blocks (Bektaş, 2013; Bozdoğan, 2001), examined through visual materials that reflect changing domestic organization and socio-cultural values. The study is structured around four transformation phases: pre-Republican period, the early Republic, post-1950 expansion, and post-1980 neoliberalism (Kocatürk & Yücel, 2012; Yücel et al., 2020).

Photographs—archival and fieldwork-based—document changes in style, technique, and domestic life. To understand intergenerational transmission, semi-structured interviews were conducted with participants from different generations, through which oral history captures diverse experiences and cultural meanings of house, spatial belonging, and lifestyle shifts. The study incorporates an embodied perspective informed by local familiarity, contributing to its engagement with the local context. In addition to interviews, participants drew floor plans of their past homes, producing memory-based spatial representations and revealing emotional attachments. These drawings contributed user-centered insights to the spatial analysis, illustrating typological change and lived experience.

Rather than presenting a linear transformation, the study frames morphological changes in the houses as a contested process shaped by tradition, governance, economic restructuring, and global trends. Through interdisciplinary tools—visuals, narratives, and field experience—it highlights how the built environment reflects and shapes social change. This approach underscores the value of

[1] Despite their long presence in Kayseri, detached garden houses had limited impact on urban form during the key transformation periods. The analysis focuses on apartment buildings, which shaped the built environment and spatial practices during the Republican and post-1980 neoliberal phases. Although garden houses gained prominence after COVID-19 and the 2023 earthquake as socio-economic markers, they remained marginal to earlier urban restructuring.

combining visual, textual, and lived knowledge in urban research, offering a historically grounded account of Kayseri's housing transformation.

3. Urban Development of Kayseri

Tuna (2017) examines the historical evolution of urbanization by contrasting modern and traditional cities. Modern cities, shaped by the Industrial Revolution, emerged as industrial and commercial hubs, whereas traditional cities—particularly in Islamic contexts—developed around religious institutions and trade networks. Thinkers like Marx, Lefebvre, and Pirenne offer divergent interpretations of this transformation, emphasizing class conflict, spatial production, and the rise of the merchant class, respectively. Urbanization restructured cities socially and economically, deepening class divides and weakening rural ties. As cities gained autonomy and civic participation expanded, urban life became increasingly organized around economic and administrative functions (Tuna, 2017). Complementing this structural perspective, Louis Wirth (1938) conceptualizes urbanization as a distinct mode of life characterized by heterogeneity, anonymity, and impersonality—conditions that foster social fragmentation and erode traditional forms of solidarity.

As Özmen (2021) argues, modern urban identity emerged through the rise of the bourgeoisie, who challenged feudal authority and reconfigured urban space. In contrast, traditional cities were shaped by local elites embedded in established religious and economic networks. However, as cities across the globe—including those in Turkey—became integrated into the capitalist system, the distinction between traditional and modern urban forms began to blur. This dynamic is particularly evident in cities such as Kayseri, where modern economic structures coexist with deeply rooted cultural traditions.

One of the earliest architectural manifestations of this shift in urban identity was the apartment building, which first emerged in late 19th-century Istanbul, particularly in the Galata-Beyoğlu district. Driven by expanding trade and the residential demands of embassy staff, foreign merchants, and Levantines, these structures—often designed by Greek and Armenian architects—reflected the city's increasing multiculturalism (Pulat Gökmen, 2011; Tanyeli, 2004; Öncel, 2010). While initially inhabited by foreigners, Muslim residents gradually adopted apartments as symbols of modern comfort and progress, mirroring broader transformations in social life and domestic spatial practices.

During the Republican era, apartment buildings symbolized modernization. Influenced by European ideals, housing reforms promoted concrete construction over wood and prioritized hygiene over tradition (Bozdoğan, 2001; Bertram, 2008). The state supported this ideological transformation by training architects abroad and hosting European experts like Egli, Wagner, and Taut (Tekeli, 2010). Cubic-style houses and modern apartments emerged, with the latter proving more adaptable to Turkish domestic life (Bozdoğan, 2001). Subsequent reforms—particularly those introduced by the Democratic Party in the 1950s and the enactment of the 1965 Condominium Law—enabled mass apartment construction (Balamir, 1994), reshaping urban housing norms. Apartments redefined spatial practices, introducing shared maintenance systems and transforming prevailing notions of privacy and identity, though cultural adaptation remained uneven (Pulat Gökmen, 2011). Rooted in late Ottoman Westernization, this trajectory continued under the Republic and was reinforced by post-1980 neoliberal policies that turned high-rise apartments into speculative assets. Cities like Kayseri followed this path, reflecting broader tensions between tradition, modernity, and the evolving conditions of urban life.

This study takes Kayseri as a case to examine broader urban and architectural transformations. With a history extending back to before the Common Era, Kayseri has long served as a strategic hub along military and trade routes. Since Roman times, it has hosted several civilizations and emerged as a key urban center during the Seljuk period. At that time, the city was spatially organized into three zones: the castle, the urban core, and the surrounding outskirts, forming a tripartite structure (Cömert, 2006).

While the Ottoman period was marked by limited state investment, the early Republican era represented a turning point characterized by rapid development driven by state-led industrialization. Factories such as Tayyare [Airplane] (1926) and Sümerbank Textile (1935) played a pivotal role in this transformation, while the arrival of the railway facilitated urban expansion, particularly toward the city's northern periphery. Kayseri's urban evolution, therefore, resists linear narratives of either uninterrupted tradition or abrupt modernization. Instead, it reflects a complex and layered process in which spatial form, social structure, and cultural memory are in continuous interplay.

Between 1882 and 1945, Kayseri underwent significant processes of modernization. Sönmez and Alper (2012) contrast the organic urban fabric of the Ottoman period with the more structured and formalized layout of the Republican era. Although early planning initiatives in the Ottoman Empire can be traced back to the Tanzimat reforms, their spatial impact remained limited in interior trade cities such as Kayseri, where transformation occurred gradually and with greater restraint (Çabuk, 2012). The 1933 Çaylak Plan marked the first urban planning attempt, followed by the 1945 Oelsner-Aru Plan, which introduced zoning principles and laid the foundation for a modern urban structure.

Until the mid-20th century, Kayseri maintained a compact urban form. Subsequently, changes in transportation infrastructure and planning policies encouraged linear expansion (Yücel et al., 2020). Industrialization played a central role in reshaping the city's morphology and housing practices. Onsekiz (2016) identifies three key phases—1923–1960, 1960–1980, and post-1980 period—each marking distinct shifts in urban function and morphology. Sönmez (2012) further highlights how industrialization altered everyday life, especially housing patterns.

Between 1930 and 1970, houses in Kayseri began integrating traditional and modern elements. Oral (2006) identifies the period from 1950 to 1970 as particularly significant for housing design, during which neighborhoods such as Sahabiye emerged as early examples of modernist planning (Güler, 2019). These developments illustrate the continuity between past and present, reflecting broader social and spatial transformations.

Drawing on Tekeli's framework, Kocatürk and Yücel (2012) identify four distinct phases in Kayseri's spatial development over the 20th century. This periodization is based on the city's master plans and their influence on spatial organization. The **National Investment Period** (1923–1945) lacked formal planning but was marked by major state-led development projects. The **Planned Period** (1945–1975) introduced urban renovations and grid-based layouts. During the **Second Planning Period** (1975–1986), the city experienced increased density, the rise of mass housing, and the emergence of a linear urban structure. **From 1986 onward**, Kayseri underwent its most significant spatial transformation (Figure 1).

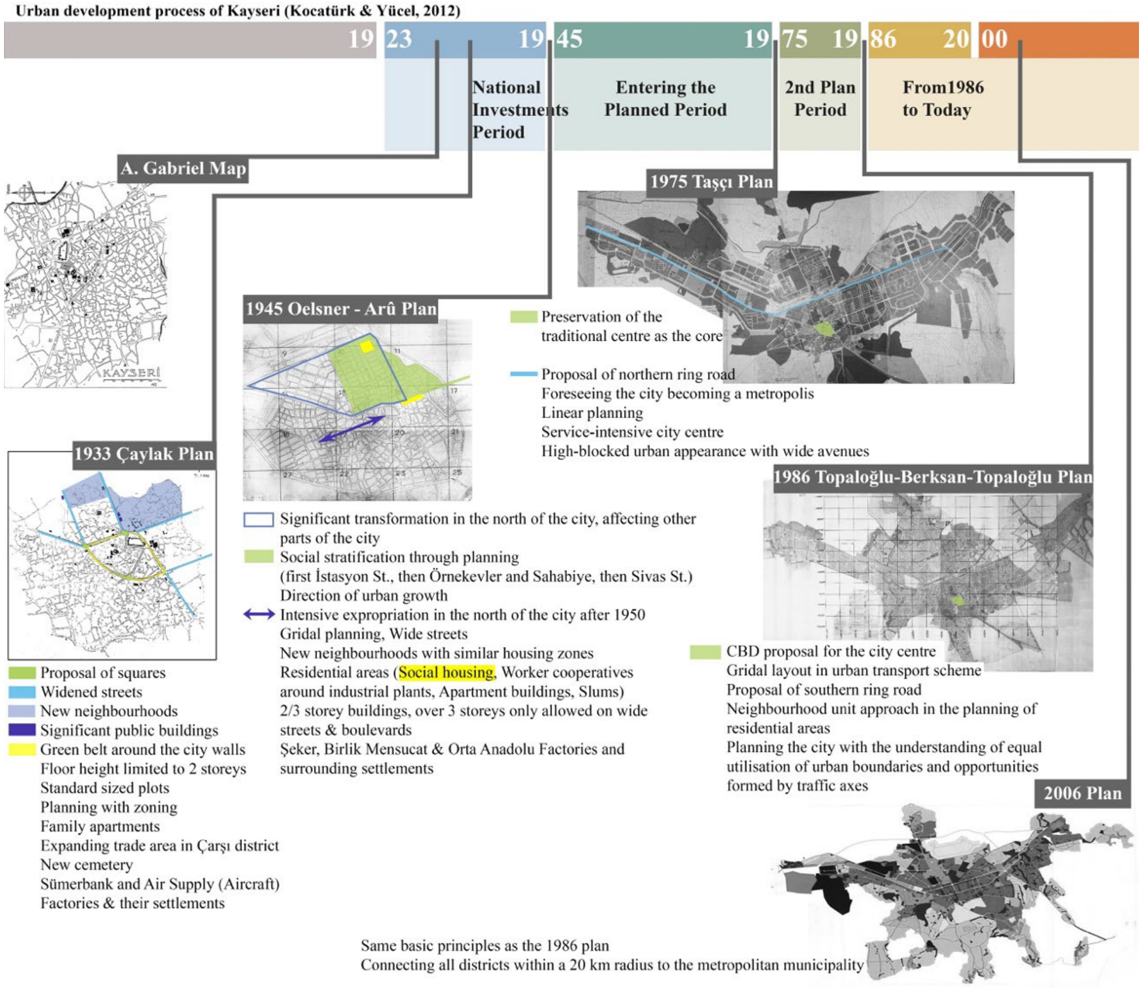

Figure 1 Summary of Kayseri development plan applications (Sources: Demir & Çabuk (2012), Asiliskender (2008)) (Other sources: Tekinsoy, 2011; Çabuk, 2012; Sönmez & Arslan Selçuk, 2021; Yücel et al., 2020; Yılmaz Bakır et al., 2017)

Gabriel's 1927–1929 map documents Kayseri's organic urban fabric, while the 1945 Oelsner-Aru Plan—considered the city's first comprehensive urban planning initiative—significantly departed from traditional spatial forms. The 1975 Taşçı Plan reinforced a centralized business district and relocated industrial activity to the urban periphery. By the 1980s, Kayseri had transitioned mainly from low-rise neighborhoods to block-style apartment developments. The 1986 Topaloğlu-Berksan-Topaloğlu Plan further encouraged high-density residential expansion and centralized commercial zoning. These dynamics were reinforced by the 2006 plan, which supported the east-west urban expansion and consolidated the city center, structuring much of the contemporary urban landscape despite subsequent revisions (Yücel et al., 2020).

4. Housing in Kayseri

In Kayseri, as in many Anatolian cities, the neighborhood has historically functioned as both a spatial and social unit, fostering solidarity, mutual respect, and close-knit neighborly relations (İmamoğlu, 2006) (Figure 2). These communities facilitated coexistence among individuals of different religions and cultures, who often lived in similar ways and comparable housing typologies (Ateş, 1997).

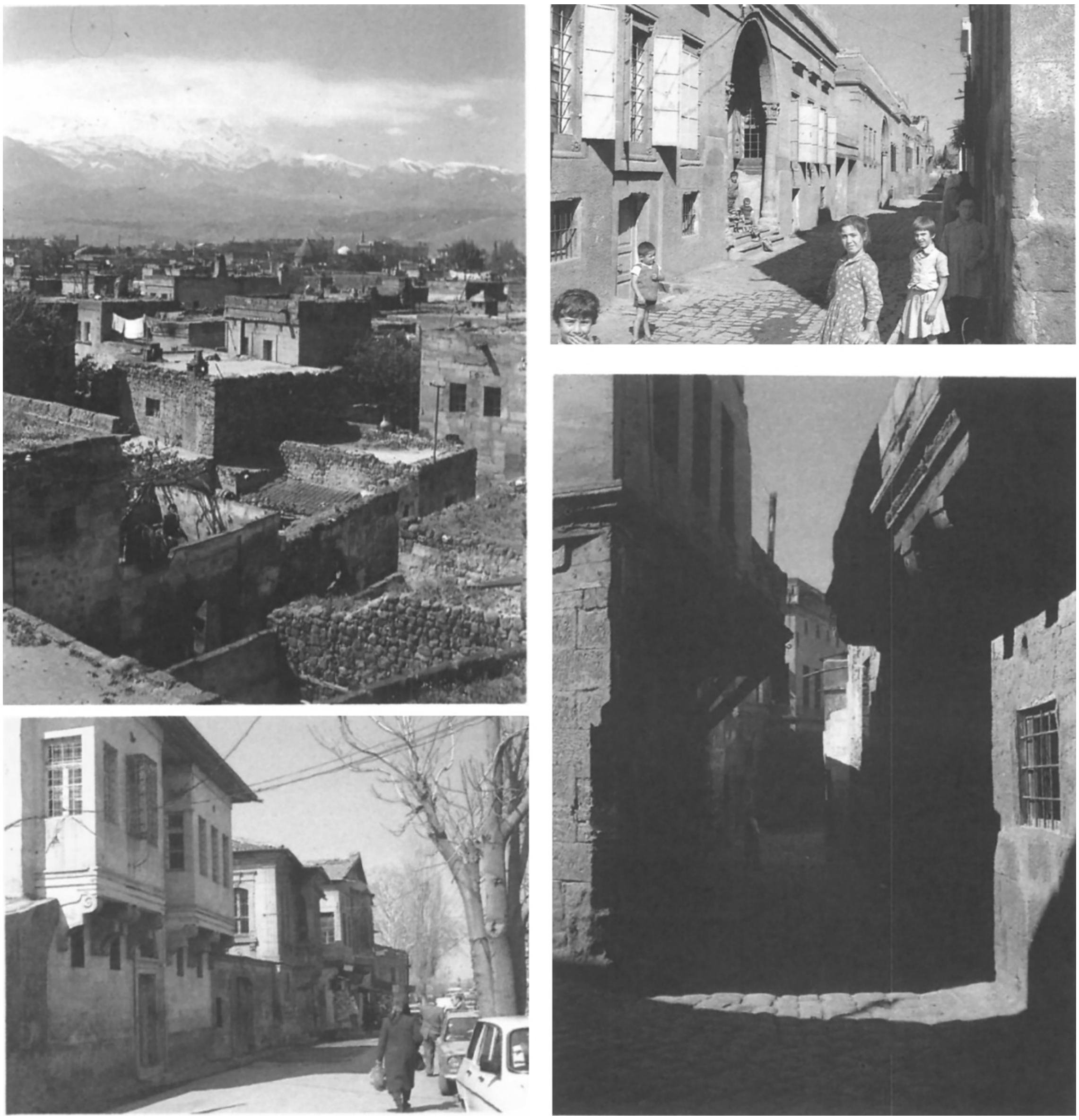

Figure 2 Traditional streets of Kayseri in the 1950s, 1970, 1989 (Source: İmamoğlu, 2006)

Traditional Turkish houses reflect a harmony with nature and cultural values, a quality emphasized by Bektaş (2013). In the case of Kayseri, this harmony was shaped by the region's cold winters, the presence of Mount Erciyes, and the need for sunlight. These climatic and environmental factors, along with cultural notions of privacy, influenced the form of the house. The inward-facing houses were organized around a central courtyard (*hayat*), used year-round by extended families and enclosed to ensure privacy (*mahram*) (Figure 3). Rooms (*harem*) opened onto the courtyard. At the same time, the *sofa* functioned as a multi-purpose space for daily life and hospitality—tiered levels (*seki* and *sekialtı*) marked transitions between clean and unclean zones. Also, it differentiated between areas of use and circulation (Figure 4).

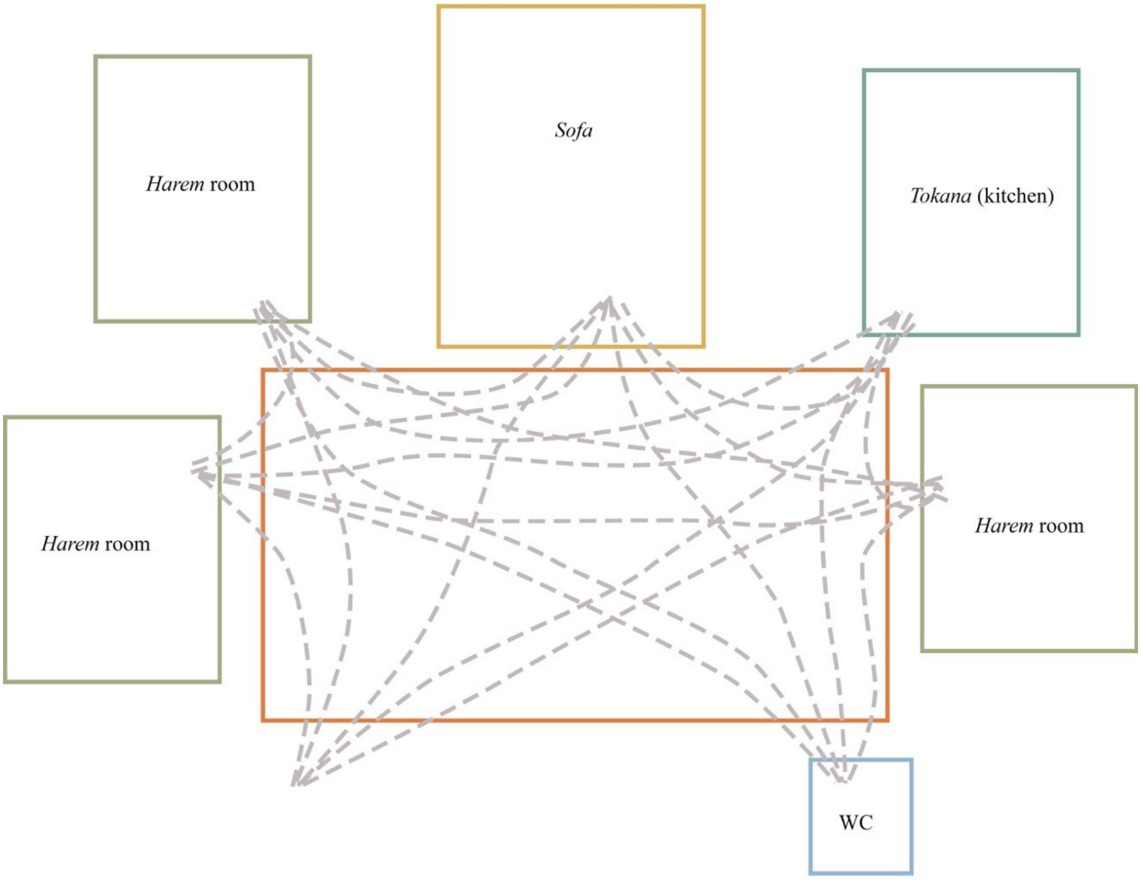

Figure 3 Movement map in Hayat

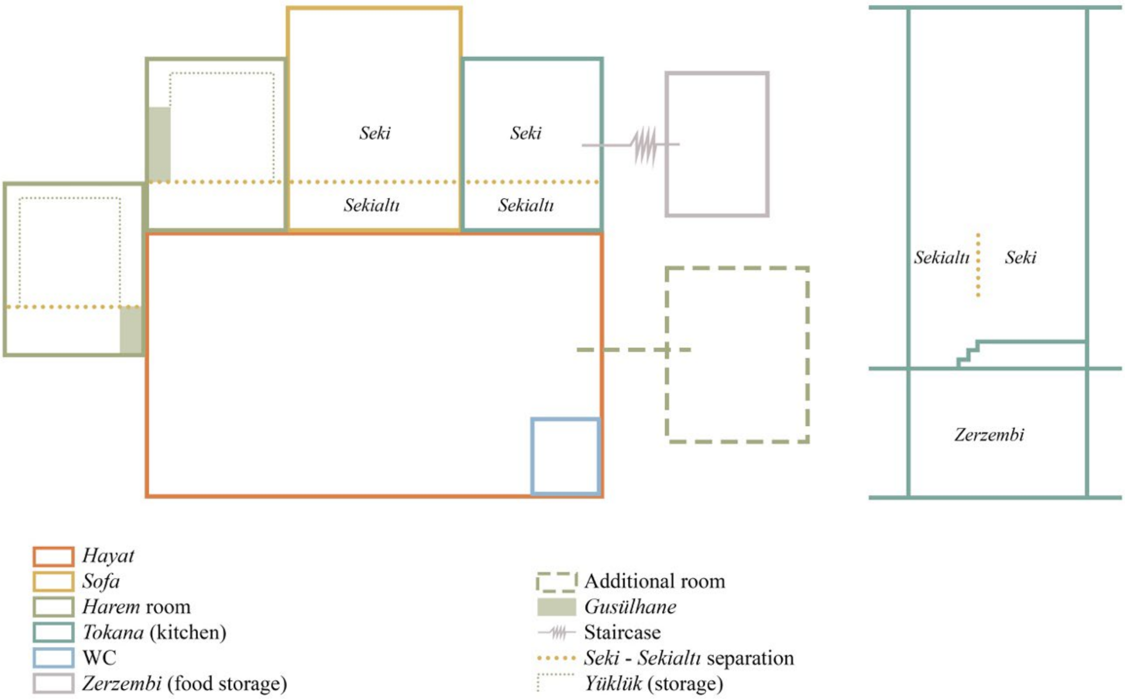

Figure 4 Graphical representation of the traditional Kayseri house

As families expanded, additional spaces were incorporated into the household, and rooms served multiple functions—including eating, sleeping, and prayer—facilitated by built-in storage units and portable belongings (İmamoğlu, 2006). In the absence of plumbing infrastructure, bathing was conducted in designated *gusülhane* spaces, while toilets were typically located in the corners of the courtyard (Figure 5, Figure 6). Houses were modest, prism-shaped, flat-roofed, and constructed from locally sourced materials— architectural characteristics common to both the Middle East and Mediterranean region (İmamoğlu, 2006). Thick stone walls and wooden linings provided thermal insulation and building orientation often prioritized climatic conditions over street alignment (Çakıroğlu, 1952; Özkeçeci, 2004).

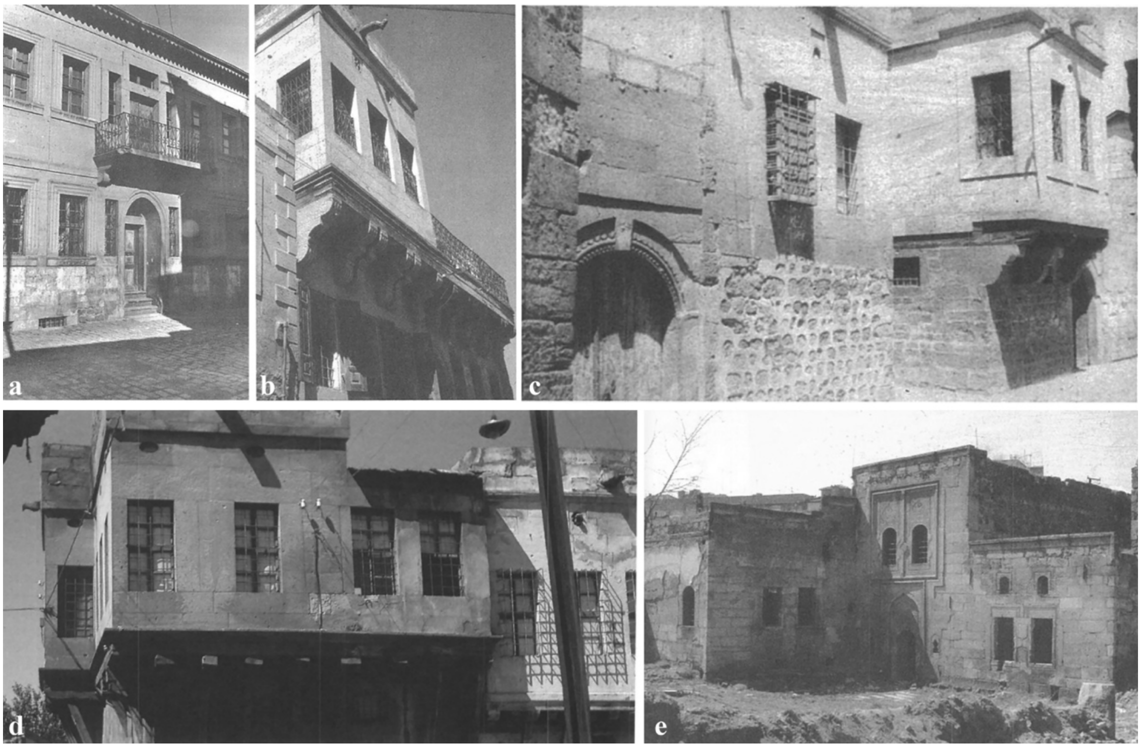

Figure 5 Traditional Kayseri house (a.Nedim Bey house, b.Kadir Bey house, c.No-name, d.Hacı Ahmet Ağa house, e.Mollaoğulları house, Sources: İmamoğlu, 2006; 2014)

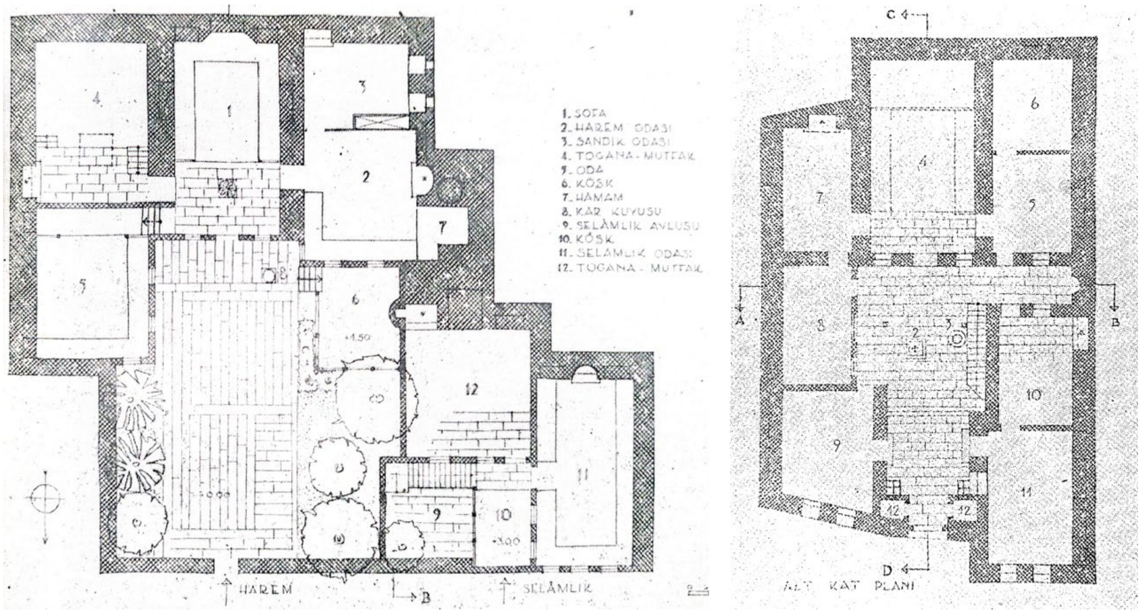

Figure 6 Plan examples of traditional Kayseri houses (Left: Aslandağ evi, Right: No name, Source: Çakıroğlu, 1952)

Interior spaces such as the *sofa*, *tokana* (kitchen), and *harem* reflected prevailing norms of privacy and social organization. Courtyards often included kiosks (*köşk*) and designated service areas (İmamoğlu, 2006). In larger houses, separate *selamlık* (guest) sections and gardens were incorporated and evolved in response to changing family needs (Ateş, 1997). Basements (*zerzembi*) were typically used for storage, livestock, or servant quarters, while lofts (*tahtalı*) accommodated coachmen (Çakıroğlu, 1952; Çetin, 2021; İmamoğlu, 2006; Şahin, 2010) (Figure 7). Furnishings were minimalist and flexible: bedding (*yüklük*), floor tables (*yer sofrası*), and prayer rugs were brought out as needed. Western-style furniture appeared in wealthier households by the late 19th century (İmamoğlu, 2006).

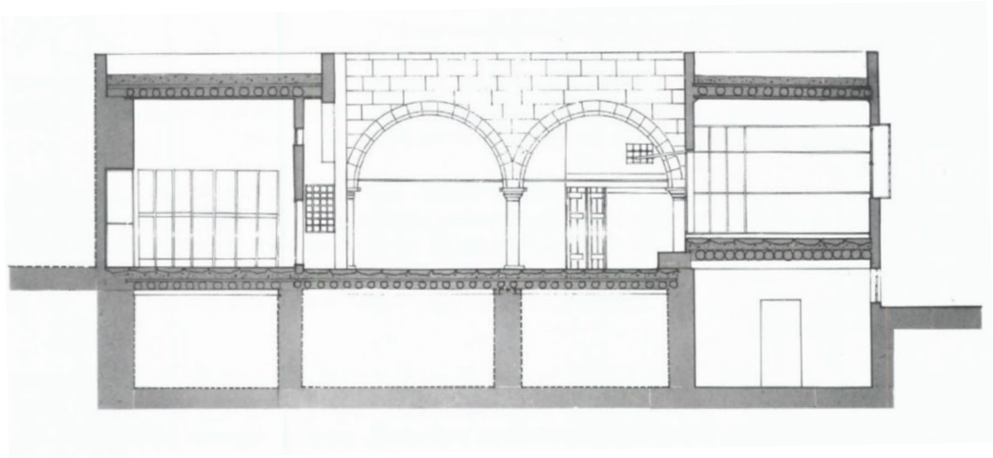

Figure 7 Section example of traditional Kayseri house, Çayırağası house (Source: İmamoğlu, 2006)

With the modernization that accompanied the establishment of the Republic, the lifestyle associated with traditional Kayseri houses—shaped by long-standing cultural norms—underwent a significant transformation. Following the War of Independence—marked by significant population movements such as deportations and the population exchange, which deeply altered the city's social composition—urban growth entered a period of stagnation. It was not until the 1930s, with the establishment of a new socio-political order and the onset of industrialization, that this growth was reactivated. Rapid development intensified after World War II. From the 1950s onward, traditional neighborhoods—particularly those located south of the Inner Castle—were systematically demolished and replaced with grid-planned business districts and apartment blocks, in line with the modernization objectives set out in the 1945 Oelsner-Aru Plan, turning Kayseri into a large-scale construction site (İmamoğlu, 2006).

Beginning in the 1930s, state investments began to reshape urban life by promoting modern lifestyles by constructing housing near factories, cinemas, schools, and other public amenities (Çelik, 2017a). The Sümerbank Textile Factory housing project significantly departed from traditional residential forms. New developments emerged along key axes such as Sivas Avenue and Atatürk Boulevard, characterized by geometric site plans and the use of modern construction materials. Neighborhoods such as Sahabiye and Örnekevler came to embody this emerging urban identity, replacing stone courtyard houses with outward-facing brick and concrete apartment buildings (Kocatürk & Yücel, 2012).

Under the 1945 Oelsner-Aru Plan, the Sahabiye neighborhood was organized according to grid planning and garden city principles, featuring two- to three-story residential buildings (Alemdar, 2010; Asiliskender & Özsoy, 2010). Influenced by Westernization, the period from the late 19th to the mid-20th century functioned as a transitional phase, preparing the ground for apartment-style living. Traditional courtyard houses gradually led to symmetrical, outward-oriented buildings with smaller gardens, central halls, and increased verticality. Beginning in the 1950s, the use of reinforced concrete replaced stone masonry, facilitating the widespread construction of three- to four-story apartment buildings mainly in the traditional center of Kayseri (Oral, 2006; Kocatürk, 2009; Kocatürk & Yücel, 2012; Yücel et al., 2020).

In the 1970s, although traditional houses remained prevalent, increasing migration and the rise of informal settlements prompted the introduction of the 1975 Taşçı Plan, which promoted wider streets and high-rise construction (Tekinsoy, 2011; Yücel et al., 2020). Cooperative housing models, municipal support, and the pursuit of economic efficiency drove the growth of high-rise buildings along major boulevards. Shared construction costs and higher-density development made apartment living more accessible to residents and profitable for developers.

From the 1970s onward, municipal planning prioritized wide roads and vibrant boulevards as desirable residential corridors, attracting middle- and upper-income groups. While detached houses—particularly in neighborhoods like Hürriyet—continued to exist, apartment blocks expanded significantly in both size and number. Following the 1986 development plan, architectural unity began to decline, and high-rise buildings increasingly occupied large parcels with minimal garden space. By the 1990s, residential buildings had reached up to 15 stories (Kocatürk & Yücel, 2012; Yücel et al., 2020).

During the 1990s, high-rise development extended beyond major boulevards, gradually altering the city's spatial character. The cooperative housing model declined, giving way to profit-oriented build-and-sell practices. As landowners acquired greater bargaining power, housing production increasingly reflected short-term, user-unfriendly strategies. Construction, supported by political and economic interests, emerged as a central driver of urban growth.

Rapid urbanization has resulted in significant cultural and architectural losses. While modern apartments replaced older, difficult-to-maintain houses, destroying historic neighborhoods led to the erasure of urban memory (Çelik, 2017c). Today, wide boulevards and luxury buildings coexist with 12th-century structures, creating spatial juxtapositions that disrupt historical continuity (Korat, 2009). Like many ancient cities in Turkey, Kayseri has experienced a substantial loss of cultural heritage.

Older generations often perceived modern apartments as symbols of progress, a view that contributed to the abandonment of historic neighborhoods (Figure 8). Formerly prestigious areas were left to newcomers, leading to the neglect of buildings and the gradual erosion of long-standing traditions (Özkeçeci, 2004).

Figure 8 Change in street scale (Sources: İmamoğlu, 2006; Oral, 2006; Erciyes 38; Kaya, 2011)

The morphology of housing in Kayseri has undergone significant transformation over time. As the traditional house evolved into modern housing forms, substantial changes occurred in both floor plans and structural organization. As previously noted, traditional houses were organized around the *hayat* (courtyard), which functioned as the central hub linking all domestic activities. Shaped by local living practices, the traditional house was highly responsive to user needs, exemplified by the flexible addition of new rooms when necessary. With the onset of modernization, residents encountered new construction materials, technologies, and apartment-based housing models. The municipality supported this transition by promoting the use of contemporary building technologies in newly planned areas of the city. Residents rapidly embraced these developments. Following the 1945 urban plan, the Sahabiye neighborhood became a central site for family-oriented apartment living. While some residents were allocated plots in exchange for expropriated properties, others relocated to Sahabiye in response to emerging housing trends (Figure 9).

Figure 9 Examples of traditional Kayseri houses, family apartments, row houses, and apartment blocks (Sources: Özdin, 2009; Oral, 2006)

These family apartments were primarily initiated and financed by affluent families. Although many were initially unfamiliar with the construction processes associated with these new building types, they actively participated in their development. According to interviewees, the planning and design of these apartments often drew inspiration from examples in Istanbul. Engineers—either family members or professionals based in Kayseri—were familiar with such precedents and frequently led the planning and coordination of the projects.

Although the apartment building typology introduced by modernization was initially unfamiliar, residents adapted it to align with their established ways of living. Unlike traditional houses, which evolved through spatial additions, modern apartments have fixed plans. Nevertheless, residents actively intervened during the construction process to create centrally planned layouts that echoed the courtyard-centered (*hayat*) organization of traditional houses. In this adaptation, the central hall replaced the *hayat* as the core space of domestic life, linking all rooms and accommodating a range of everyday activities. Like the *hayat*, the hall also served multiple functions— occasionally used as a sleeping area, much like the harem rooms, as noted by interviewees.

A comparison between the traditional house and the family apartment reveals several key spatial and material differences. Traditional houses were constructed using stone and followed an organic layout that allowed for spatial expansion over time. In contrast, family apartments are built with reinforced concrete and adhere to fixed floor plans. The central space in traditional houses—the open-air *hayat*—is replaced in family apartments by an enclosed central hall that serves a similar connective function. In the traditional house, the largest space was the *sofa*, typically elevated above adjacent rooms and used for both everyday life and receiving guests. In the family apartment, this role is assumed by the *salon* (guest room), though its scale is more restrained due to standardized ceiling heights. One notable shift is the relocation of the toilet from exterior areas, such as the courtyard, to the interior of the house. Likewise, while traditional houses featured private *gusülhane* units within individual rooms, family apartments introduced a shared bathroom. The addition of the balcony—absent in traditional housing—represents another architectural innovation that distinguishes the apartment typology.

The family apartment aligns closely with modern housing typologies when considering its general characteristics. For example, some floor plans include a small anteroom adjoining the parents' bedroom to enhance privacy. However, this architectural model—originally adopted from Western design conventions—has been shaped by traditional housing culture. Consequently, features such as a central hall, overhead storage areas above bathrooms or kitchens, and built-in cupboards (*yüklük*) in certain units distinguish the family apartment from standard modern housing prototypes.

The spatial organization of cooperative houses—also referred to as row houses in some sources—particularly those located along Sivas Street, reflects a closer alignment with contemporary housing concepts compared to family apartments. In these houses, the central hallway characteristic of family apartments is replaced by a small entry vestibule, which serves solely as a greeting space. A key distinction in these houses is the introduction of a bedroom hall:

similar to layouts in Western modern housing, a more private corridor branches off from the main living area, providing access to the bedrooms. Incorporating this bedroom hall and the more precise articulation of spatial boundaries contributes to a layout more consistent with standardized modern housing models (Figure 10).

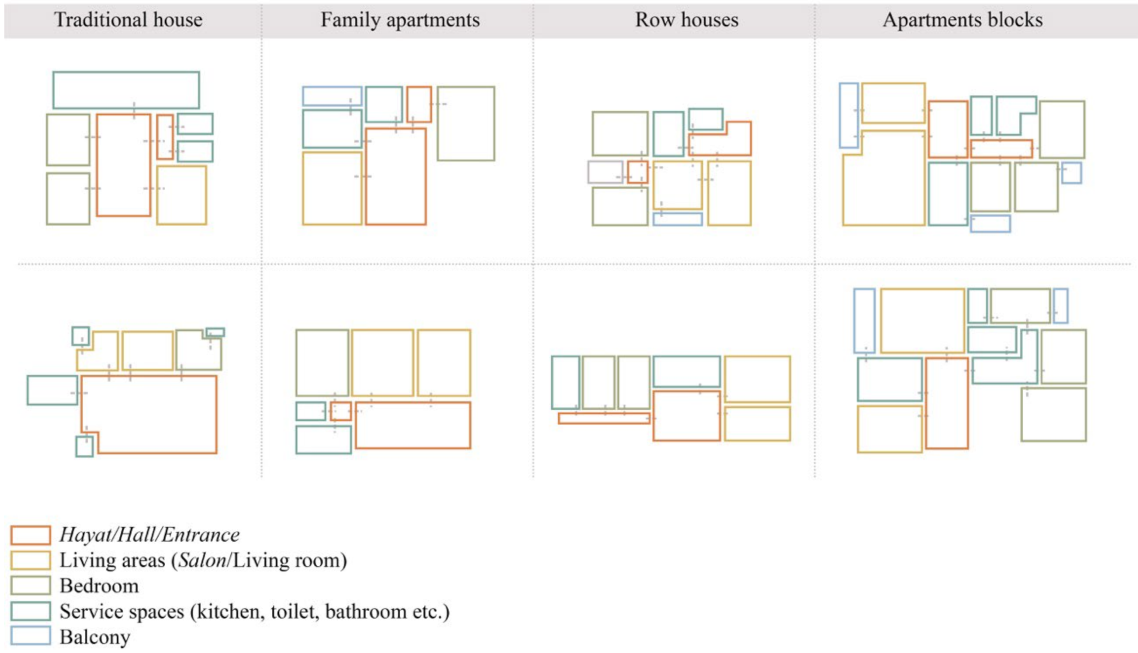

Figure 10 Morphological differentiation from traditional houses to apartment blocks

Traditional lifestyles and housing designs in Kayseri were inherently conducive to collective living. Extended families commonly gathered in the central space—the *hayat*—to socialize and reinforce intergenerational bonds. Interviewees who had lived in traditional houses frequently recalled, with affection, evenings spent around the *iskembi* (a type of hearth), sharing warmth and conversation. In stove-heated houses, particularly in early family apartment buildings, the central hall functioned as the main heated area, with adjacent rooms warmed indirectly. This spatial and thermal configuration encouraged co-presence in shared areas. In contrast, several middle-aged interviewees described the contemporary trend—where family members spend time in separate rooms—as “unfortunate” or “negative.” While such individualization was seldom mentioned in relation to stove-heated houses, it was more commonly associated with radiator-heated houses, where each room is independently heated.

Another notable aspect of life in family apartment buildings was the tendency toward collective living not only among family members but also among neighbors. Many individuals accustomed to the “inward-facing” spatial and social logic of traditional houses continued similar patterns of interaction after relocating to family apartments, often sharing space with extended family or familiar neighbors. As a result, a sense of shared domesticity and communal life persisted despite the shift in architectural form. Several interviewees recalled that doors were frequently left open in these buildings, and residents moved freely between one another’s houses.

However, this sense of collective living gradually diminished with the advent of cooperative housing, which fostered more formalized and individual-oriented lifestyles. Many former residents of family apartments, who had previously lived alongside relatives and acquaintances, now found themselves sharing buildings with unfamiliar neighbors, particularly in the new cooperative housing developments along Sivas Street. These modern houses, more closely aligned with contemporary housing standards, encouraged inward-oriented, nuclear-family-based domestic life. Several interviewees described this transition as being marked by greater social distance, symbolically and spatially, as front doors remained closed and inter-household interaction declined.

In cooperative houses, where domestic life tends to be more inward-oriented than family apartments, the house layout typically features a dual living area between the entrance hall and the bedroom corridor. The larger of these spaces is situated closer to the main entrance, while the smaller one is accessed via the bedroom hall and connects directly to the private areas of the house. This spatial configuration reflects and reinforces a more segmented and privacy-oriented mode of domestic life. The main living area, which links to the kitchen and toilet through the entrance hall and to the bedrooms and bathroom via the bedroom corridor, also opens onto the street through a front balcony, functioning as the central node of household activity. A door separating the two living spaces further enhances this segmentation, assigning the larger room the role of a formal *salon* used primarily for receiving guests.

Compared to the layout of a family apartment, where the front door opens directly into a central hall, the living space in cooperative housing is positioned deeper within the interior of the house. This configuration results in a more secluded living area, which may be described as an inner-*hayat*: a contemporary reinterpretation of the traditional *hayat*, offering increased spatial privacy in settings where buildings are shared with non-kin. Furthermore, this space is separated from the *salon*—typically used to receive male guests—by an interior door, thereby situating it in alignment with cultural norms surrounding *mahram* and gendered spatial practices.

The cooperative housing predominantly constructed along Sivas Street strongly aligns with contemporary housing typologies. In the contemporary context, the inward-facing structure characteristic of traditional domestic life has evolved into a spatial organization that accommodates a more open daytime life and a more private nighttime routine (Ateş, 1997). This transformation has produced two distinct functional zones, separated by transitional spaces such as the entrance hall and the bedroom corridor—a layout reflects the spatial segmentation typical of modern housing design. Technological advancements, including the introduction of plumbing and household appliances such as refrigerators, have brought new conveniences and contributed to the reorganization of domestic interiors around specific functions, reinforcing a more individualized and compartmentalized mode of living.

These houses—particularly in their spatial organization around what is described in this study as the inner-*hayat*—exemplify a hybrid typology. While the overall apartment structure was shaped by Western models of modernization, cooperative housing units differ from family apartments in that residents had little direct influence over the layout. Nevertheless, it appears that the architects or engineers responsible for their design, sharing common cultural codes, incorporated spatial configurations that remained compatible with local living practices. Alternatively, the space originally conceived as a *salon-salomanje* (En. dining room, Fr. *salle à manger*), characteristic of Western housing and frequently depicted in Yeşilçam cinema, did not align with a formal dining culture in Kayseri. Instead, residents reinterpreted this space and gradually transformed it into an *inner-hayat*. Although these modern houses were initially designed according to Western standards, they became hybridized through everyday practices and localized reinterpretations, in this way (Figure 11).

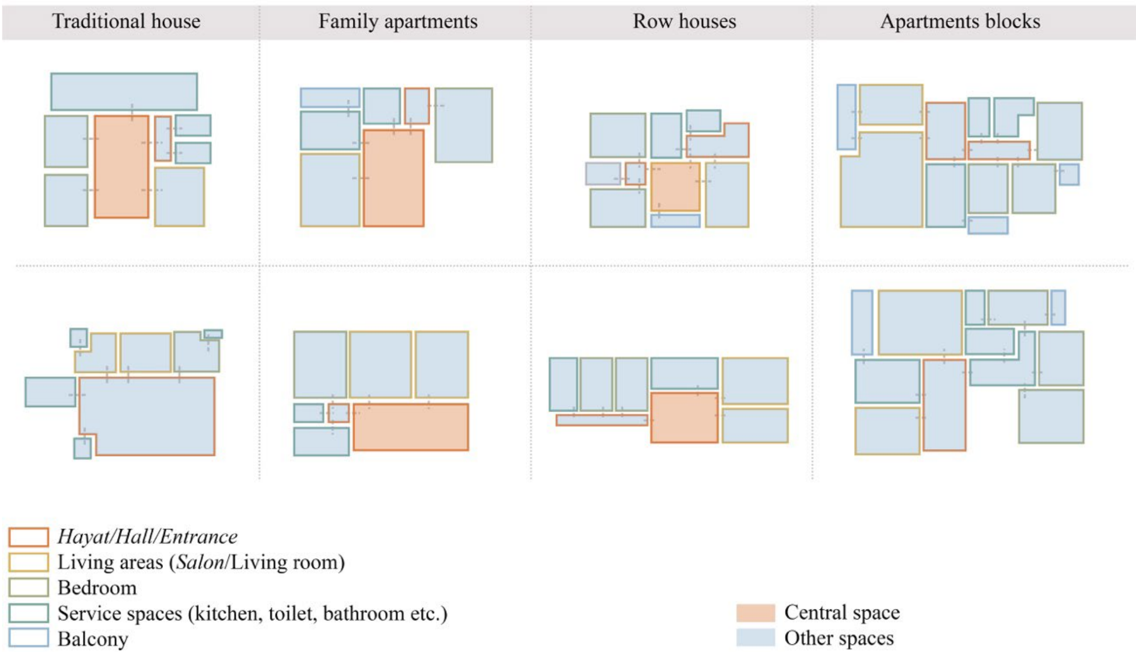

Figure 11 The disappearance of the central space

The apartment blocks constructed along Sivas Street represent a residential typology consistent with the modern housing model, in which each space is defined by a specific function. These units, ranging from 200 to 300 square meters, feature floor plans that distinctly separate daytime and nighttime zones. The daytime zone comprises the entrance hall, which provides access to the kitchen, living room, *salon*, and a restroom. From the same entrance hall, a bedroom corridor leads to the private areas of the house, including bedrooms, a bathroom, and, in some cases, additional spaces such as a laundry room. All functional areas are organized around two transitional spaces: the entrance hall and the bedroom corridor, which together structure the spatial hierarchy of the unit.

In family apartment buildings, the central hall functioned as both a living space and a reception area. In contrast, cooperative housing introduced a specialized entrance hall, designed exclusively for reception. Although the entrance hall remains a feature in contemporary apartment blocks, its scale has expanded to approximate a living area. As part of the daytime zone, it now serves as the primary spatial node for daytime circulation. However, despite its increased size, it continues to function predominantly as a transitional space and point of entry, rather than as a site of everyday activity and social interaction, as the central hall once did.

The use of corridors in apartment buildings first appeared in the early 1930s in housing structures constructed in neighborhoods such as Şişli, Taksim, and Nişantaşı. In these early examples, the front section of the house typically consisted of one or more *salon* units. In contrast, the rear section accommodated the bedrooms and a bathroom, arranged along a corridor. The kitchen was positioned between these two zones. The front part of the house was designed as a semi-public space accessible to guests, whereas the rear part was reserved as a private, inward-facing area, disconnected from external visibility (Pulat Gökmen, 2011). Within this spatial hierarchy, the bedroom hall —or “night hall”—plays a key role in maintaining privacy and reinforcing the functional segmentation of domestic space (Figure 12).

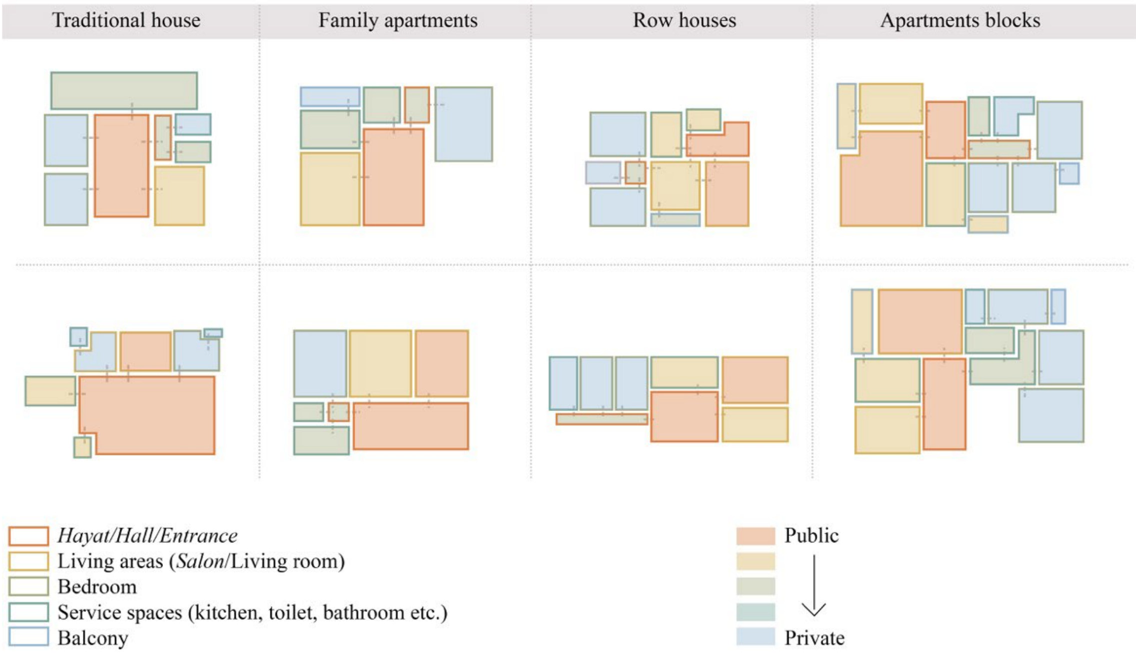

Figure 12 Changes in domestic privacy

In contemporary housing—particularly in many urban settings—floor plans are typically organized into two primary zones. The first comprises the entrance hall and the connected spaces, such as the living room, *salon*, kitchen, and a toilet. The second zone, accessible through the entrance hall, includes the bedroom hall and the private spaces it connects to, primarily the bedrooms and a shared bathroom. This clear functional segregation and increased house sizes have contributed to the prevalence of 4+1 layouts (three bedrooms, one living room, and one *salon*) or larger. In such configurations, it is common for each household member to occupy a separate, individualized room.

In the houses along Sivas Street, the bedroom hall is typically small and serves primarily as a transitional space, separated from the daily living area by a door to ensure privacy. In contrast, in larger houses that emerged in later periods, the bedroom hall constitutes part of a more distinct, separate spatial domain. In some examples, the corridor extends and changes direction within itself, creating deeper layers of privacy and further reinforcing spatial segmentation and hierarchy. These elongated and reoriented corridors function as buffers between rooms, enhancing acoustic and visual separation and thereby contributing to the individualization of intra-household relationships (Kurt, 2021).

As individuals move through these spaces—from public to private through a series of thresholds—the communal relationships once fostered in the *hayat* of traditional houses, or the central hall of family apartments have increasingly given way to individualized living patterns. This transformation becomes more pronounced as children grow up and leave the house, often resulting in the remaining spouses spending time in separate rooms of their preference (Figure 13).

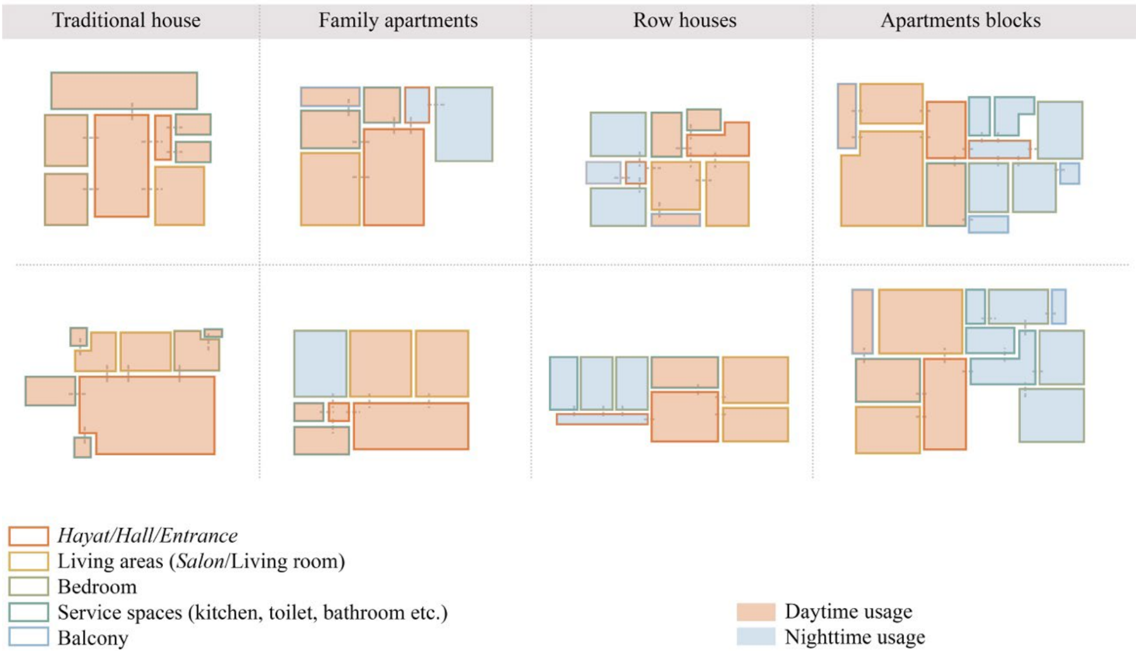

Figure 13 Changes in space usage across daytime and nighttime

From traditional to modern houses, the spatial section of the house has undergone a significant transformation. While the overall structural form has shifted from horizontal layouts to vertical constructions, the internal spatial organization has moved in the opposite direction—from vertical to horizontal. Traditional houses were typically one- or two-story structures with basements, where spatial relationships were articulated vertically. Architectural elements such as *seki* (raised platforms) and *sekialtı* (spaces beneath these platforms) created vertical stratifications within individual rooms, reinforcing a layered sense of spatial hierarchy. However, with the introduction of family apartments, residences became confined to single-floor units within multi-story buildings, resulting in the loss of these internal vertical relationships and the flattening of domestic space (Figure 14).

One of the most notable features of family apartments is their ability to accommodate the traditional extended family lifestyle within a new architectural form. In traditional houses, spatial expansion typically occurred horizontally by adding new rooms to meet the evolving needs of a growing family. In family apartments, this logic was reinterpreted vertically by adding extra floors. As one interviewee recounted, in the family apartment his father had built in Sahabiye, his grandfather lived on one floor, his nuclear family resided on another, and the top floor had been pre-constructed for him to occupy after marriage. In this way, the spatial logic of the traditional house—characterized by incremental horizontal expansion—was reimagined through vertically stacked units. This transformation illustrates how modern housing forms were adapted to retain the multi-generational living arrangements embedded in local cultural practices.

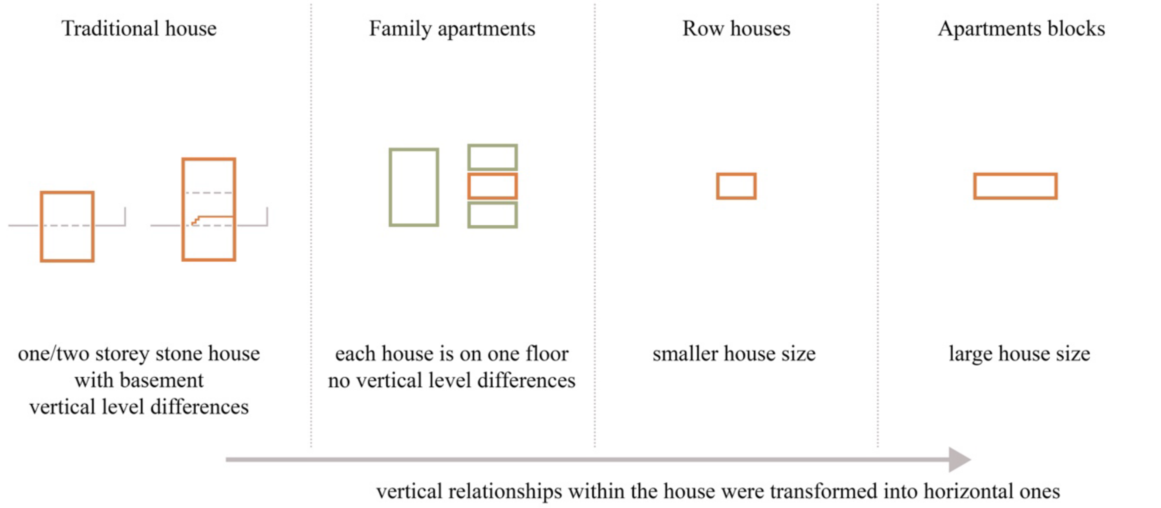

Figure 14 Change of house section

In the traditional house, people were accustomed to immediate access to a private open space or gardens outside their doors. Despite this, the transition to apartment living occurred relatively smoothly. A key factor in this adaptation was the rationalizing logic introduced by modernization. Although the new housing typology did not entirely correspond to existing cultural practices and spatial habits, it was readily embraced due to its comfort, convenience, and modern amenities (Figure 15, Figure 16).

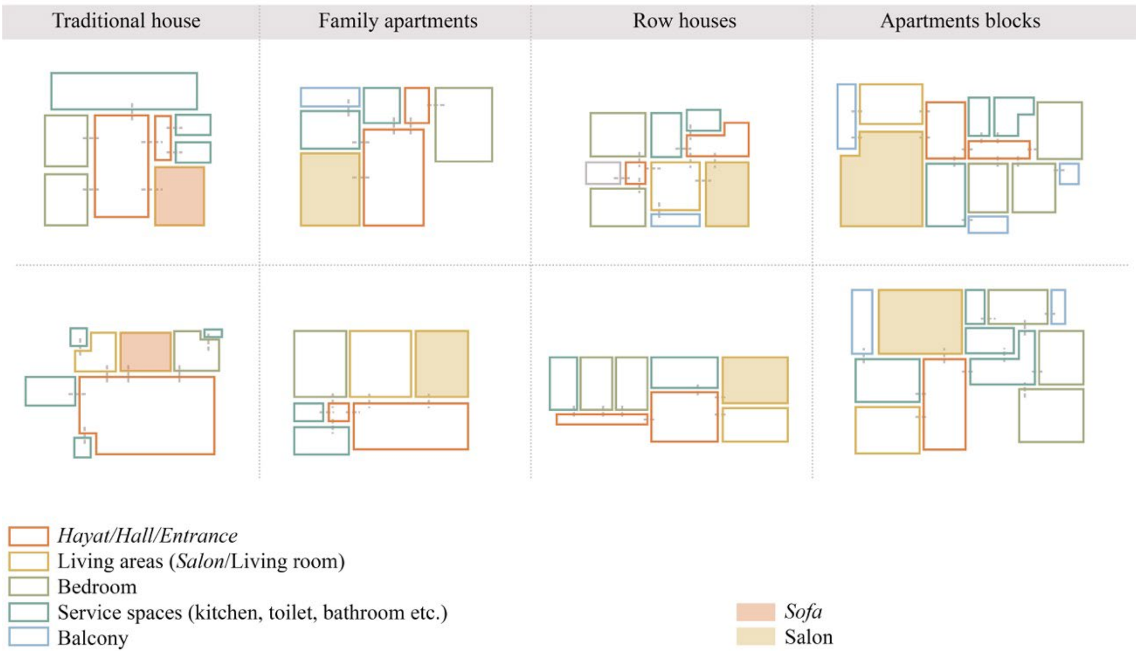

Figure 15 The transformation of the sofa into the salon in apartment layouts

Figure 16 The relocation of the bathroom: the WC was moved inside the house; the gusülhane was first lost, then reinterpreted as an en-suite bathroom

Although the people of Kayseri quickly adapted to apartment living due to its comfort and convenience, they have not fully adjusted to the social dynamics of the modern housing system despite having lived in such settings for over fifty years. In contemporary apartment life, interpersonal relationships tend to be more distant, and people adopting a more individualistic lifestyle are often less engaged in neighborly interactions than in the past. While each new housing typology was initially embraced as a symbol of modernity and social mobility, everyday life within apartments has increasingly become more introverted. Nonetheless, once interpersonal connections are established, residents often revive modes of solidarity reminiscent of the extended family structure. Under favorable conditions, these habitual social practices resurface, illustrating the persistence and adaptability of traditional forms of sociality within modern residential environments.

Human behavior often operates through habituated patterns that facilitate quick decision-making. The mind can be likened to a mechanism that triggers context-dependent responses, shaped by prior experiences. For instance, individuals accustomed to an individualistic lifestyle may initially retreat into personal space when confronted with unfamiliar social settings. However, as trust and familiarity develop, ingrained social habits—rooted in earlier communal modes of interaction—may reemerge.

The shift from individualism to communal interaction often unfolds gradually in apartment living. Initially marked by social distance, neighborly relations tend to evolve, echoing older forms of neighborhood solidarity. Residents begin to reoccupy shared spaces informally, placing items on balconies, entrusting children to neighbors, or storing belongings in communal areas such as rooftops. These seemingly minor practices signal a return to collective habits embedded in earlier modes of living. As spatial boundaries become more porous, prior social codes resurface. In this process, individualization—fueled by the forgetting of communal life—is countered by acts of remembering that reinstate routines of solidarity and shared domesticity.

Some individuals approach the apartment setting as if it were a private home with a garden, overlooking the collective nature of shared spaces and the norms of equal participation they entail. This attitude reflects spatial perceptions and embodied habits inherited from earlier housing typologies. How residents engage with their neighbors in apartment buildings often illustrates this continuity. Though seemingly minor, practices such as placing chairs in stairwells or corridors reveal how shared spaces are reimagined as semi-private extensions of the domestic sphere.

During a visit to one of the interviewees, two other residents of the same building were observed sitting in front of their doors, cracking sunflower seeds around a small table and chairs placed in the shared corridor. Although they explained their behavior as a response to the heat inside their house, this use of communal space as an extension of the private domestic sphere illustrates how prior spatial habits continue to inform practices in modern housing environments.

Such practices transform apartment living into a configuration reminiscent of family apartment arrangements. In these settings, where doors are often left open and shared spaces are used collectively, residents recreate, at the apartment scale, the neighborhood culture they once inhabited. It reflects a continuation of earlier social habits, manifesting as a form of communal living within modern housing structures.

Subtle expressions of this spatial perception frequently surface in everyday practices. For instance, placing a trash bin at the apartment entrance or leaving shoes outside the door reflects habits grounded in a traditional mindset. The implicit logic is: “The shoes remain outside because this is not the house proper—it is an extension of the garden.” However, the apartment corridor is meant to be a shared space. Yet, the individual does not fully internalize this and continues to act based on past habits. These behaviors indicate that the person’s perception of space has not fully adapted. They still view the corridor as a separate living area, struggling to accept it as a space for communal use.

This mindset offers valuable insights into how an individual’s perception of space is shaped and how they instinctively interact with shared areas. In traditional rural life, the boundaries of the house were clearly defined, whereas gardens and outdoor spaces were perceived as more flexible and communal. These spatial habits have endured through the transition to urban living, reemerging in modified forms within apartment settings.

For instance, practices such as perceiving the corridor beyond the doorstep as a garden, leaving trash outside the door, or hanging laundry on the building’s façade reflect the persistence of traditional spatial logics. These behaviors are not simply individual habits but represent inherited spatial practices transmitted across generations. People subconsciously organize and use shared apartment spaces in accordance with prior dwelling experiences, treating them as extensions of their private domain.

While the balcony is formally part of the house, it is often perceived not as an interior space but as an extension of the garden. However, this perception has shifted among individuals who have adopted more Westernized lifestyles, as evidenced by practices such as drying laundry on the balcony or using indoor drying racks.

5. Conclusion

The transformation of housing in Kayseri reflects the city’s unique position at the intersection of enduring cultural traditions and successive waves of modernization. This study has demonstrated that national policies and ideological shifts, local dynamics, spatial practices, and socio-economic structures have continually redefined domestic architecture in Kayseri. Rather than serving as a passive recipient of top-down planning decisions, Kayseri has actively negotiated the terms of its urban development, producing a distinct trajectory of housing transformation, locally rooted and shaped by broader structural forces.

While many typological shifts identified in this study—such as the transition from courtyard houses to apartment blocks or the rise of nuclear family-oriented layouts—mirror national patterns observed across Turkey, Kayseri’s experience offers a particularly nuanced interpretive frame. Its transformation has been shaped not only by national planning regimes but also by the city’s embedded cultural codes, historical layering, and the persistent influence of local memory on spatial adaptation.

The traditional Kayseri house—with its courtyard-centered organization, multifunctional spaces, and environmentally responsive design—embodied a mode of living rooted in kinship networks, religious norms, and neighborhood solidarity. These houses functioned as shelters and material expressions of social relations and everyday practices. The Republican era, however, marked the onset of spatial standardization and architectural modernization. The increasing adoption of apartment buildings—particularly the post-1980 high-rise typologies—signaled a broader shift toward compartmentalized spatial arrangements and nuclear family-oriented lifestyles.

Drawing on oral histories, archival materials, spatial analysis, and field observations, this study has traced how transformations in housing have reshaped not only the morphology of the houses but also daily routines, interpersonal dynamics, and notions of privacy and belonging. Crucially, this transition was neither linear nor uniform. Instead, it unfolded through ongoing negotiations as residents adapted modern housing forms to traditional spatial and social logics—transforming, for instance, central halls into symbolic “inner hayat” spaces or repurposing corridors and balconies as semi-private communal zones. This hybridity underscores the resilience of cultural memory and the persistence of traditional spatial practices within contemporary housing frameworks.

Kayseri’s housing transformation illustrates that modernization is neither simply imported nor uniformly applied, but rather reinterpreted and reconfigured through local agency. It highlights the importance of place-based and culturally sensitive perspectives in urban research and planning. Effective future strategies must account for economic and spatial considerations and the enduring influence of social norms, historical memory, and everyday spatial practices that shape domestic life.

Ultimately, Kayseri’s housing culture provides a critical perspective for understanding the entanglements of identity, memory, and urban form. It demonstrates that cities like Kayseri—where tradition and modernity are deeply interwoven—invite us to reconsider urban transformation not as a binary rupture but as a layered and negotiated process that continues to unfold over time.

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Nihan Muş Özmen: Writing – Original draft, Methodology, Analysis, Writing – review & editing. Burak Asiliskender: Writing – review & editing

Declaration of Competing Interest

The authors declare that they have no known competing financial interest or personal relationships that could have appeared to influence the work reported in this paper.

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Data Availability

Data will be made available on request.

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Resume

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Assessing the vulnerability of cities to climate change: A new index proposal for Türkiye cities

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Abstract

On a global scale, as cities continue to grow and climate change brings increasing hazards, the vulnerability and risk levels for cities are also rising. Assessing the risk and vulnerability of urban areas has become more vital now than in previous decades. In this context, the climate–adaptive city approach is gaining importance alongside sustainable development. Türkiye's geographical location is considered one of the most vulnerable regions in terms of climate change, due to decreasing precipitation and rising temperatures. In the literature, some studies primarily evaluate the full range of risks associated with climate change, while others develop a climate–adaptive city approach that focuses on a single risk. However, the consequences of climate change vary across regions and countries. In this study, the vulnerability of cities to climate change is discussed separately for each risk. Vulnerability criteria are considered separately for drought, sea-level rise, heavy rainfall, and extreme heat. For each risk, indicators of the impact, pressure, vulnerability, resistance, and adaptive capacity that contribute to the risk are identified. Methodologically, relevant studies in the literature were compiled, previous studies were utilized in determining the indicator, and new indicators were developed. As a result, a holistic approach has been developed to assess the vulnerability of cities to climate change across all risks. This makes it possible to identify both how cities remain unprepared for the consequences and risks of climate change and, on the other hand, the climate–adaptive aspects of cities. This study is intended to contribute to researchers working on urban resilience as well as to urban municipalities. In conclusion, a guiding index has been put forward to inform planning and decision-making processes for the creation of a climate–adaptive city.

Keywords: climate–adaptive city, climate change, resilient city, vulnerability assessment index, Türkiye

1. Introduction

UNDESA (2012) projected that 75 percent of an estimated global population of 9 billion will live in urban areas in 2050. Urban areas (with at least 50,000 residents) account for 71% of carbon emissions, even though they cover less than 3% of the Earth's surface (IPCC, 2007). Therefore, cities play a critical role in making the world a more sustainable place. On the other hand, environmental changes such as unpreventable global warming affect cities more severely than rural areas. Urban resilience has become a prominent concept as cities continue to grow (Carmin et al., 2012; Leichenko, 2011). Most reports (UNEP, 2012; Franklin & Andrews, 2012) highlight the challenges facing cities in this century. The need for adaptation is evident across cities of all sizes and climates, particularly in the rapidly growing cities of developing countries (Greenwalt et al., 2018). According to the Regional Climate Change Index (RCCI), the Mediterranean Region, along with the Northeastern European regions, is considered a 'primary hot-spot region'. Türkiye, located in the Eastern Mediterranean Basin, is recognized as one of the regions most threatened by climate change (IPCC, 2007; Giorgi, 2006). The vulnerability of the Mediterranean Region stems from its position in the transition zone between the North African Climate and that of Central Europe. Consequently, it is influenced by interactions between these two zones, hence even minor changes

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in air circulation can result in significant changes of the Mediterranean Climate (Giorgi & Lionello, 2008).

Vulnerability is defined as the degree of susceptibility of a city or community to the consequences of hazards or stress (Turner et al., 2003). Stress develops gradually but with steadily increasing pressure (e.g., climate change, drought). Pelling (2003) points out the system of weakness as the inability to avoid or absorb potential harm. Hazards are classified as natural (e.g., earthquake, volcanic eruption, hurricane), social (e.g., civil riot, terrorist attack), or technological (e.g., spill, explosion, release of toxic chemical). In recent decades, a new class of hazard has emerged, known as socio-natural, which results from human action, such as climate change. Vulnerability increases in direct proportion to exposure and susceptibility and is inversely related to coping capacity (Villagrán de León, 2006). Chambers (1989) submitted the external and internal sides of vulnerability:

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- External: related to exposure to external shocks and stresses; and
- Internal: associated with defencelessness, incapacity to cope without damaging losses.

Vulnerability can be defined as a combination of damage potential, resilience, and resistance. Bogardi (2006) clarified resistance as related to the capacity of the system to remain unchanged for an interval of time following a disruptive event. In contrast to resistance, resilience refers to the system's capacity to return to its pre-disaster state. Coping capacity is defined as a combination of resistance and resilience (Villagrán de León, 2006).

Resilience denotes the natural, built, social, and economic capacities of an urban system to manage change and to respond after experiencing disaster, stress, or shock (Newton & Doherty, 2014). Urban resilience includes strengthening the resistance of cities to natural disasters such as earthquakes or floods, as well as to risks such as human-induced global warming or terrorist attacks. Moreover, the focus of resilience is not only reducing losses in the face of a risk, but rather on improving the overall performance of a system when confronted with threats. Cities should have key attributes that enable them to be reactive, adaptable, recoverable, regenerative, and transformable in the face of risks and hazards (Dincer & Yalçıner Ercoşkun, 2024). Urban planning is critical to achieving resilient cities by incorporating climate change into urban planning, analyzing high-risk areas, preventing urban areas, developing climate adaptation plans, and determining building codes related to climate change. Vulnerability assessments can be regarded as the first step in achieving adaptation-planning integration (Sılaydın Aydın, 2021). Climate adaptation is defined as the adjustment of natural or human systems to potential climate stimuli or their effects, which involves mitigating damages, taking advantage of opportunities, and ultimately preventing or reducing vulnerability to climate change. Climate-adaptive cities' characteristics are: effective resource management, stakeholder participation, a low-carbon economy, decentralized climate change management, innovation in governance and industry, utilizing knowledge, education-focused, and foresight in planning (Yari et al., 2024).

There are many studies in the literature on assessing urban vulnerability to global warming. Xie and Zheng (2017) examined the evaluation indicator system for climate-adaptive cities. Balica et al. (2012) developed a Coastal City Flood Vulnerability Index based on exposure, susceptibility, and resilience to coastal flooding. This study demonstrated the most vulnerable cities through an analysis of nine coastal cities around the world. Binita et al. (2015) conducted vulnerability analyses by combining climatic, social, land cover, and hydrological components into a unified vulnerability assessment. Kim et al. (2016) assessed the vulnerability of Korea and identified key municipalities at risk to support the national adaptation plan. Zanetti et al. (2016) developed the socio-environmental vulnerability index for coastal areas in the context of climate change and applied it to the city of Santos, Brazil. Jubeh and Mimi (2012) developed the Governance and Climate Vulnerability Index, which measures the vulnerability of five countries (Israel, Jordan, Lebanon, Palestine, and Syria) to water-related issues, taking into account governance and climatic indicators. Menezes et al. (2018) developed a Municipal Vulnerability Index and evaluated the factors that make the municipalities in the state of Amazonas, Brazil, vulnerable to climate change in the context of the world's largest tropical forest, as well as regions of the State are the most susceptible. Feindouno et al. (2020) proposed an index of exogenous vulnerability that can be used to identify countries that are more susceptible in terms of structural and physical reasons.

Studies conducted for Turkish cities: Sılaydın Aydın et al. (2017) identified the primary spatial factors that increase vulnerability to excessive precipitation and sea-level rise and determined the zones at risk in İzmir (Türkiye) based on building characteristics and development. Sılaydın Aydın (2021) sought to develop a framework on how vulnerability analysis should be handled at different scales. Akbulut Başar (2023) proposed a spatial multi-criteria analysis of the physical environment. This study aims to analyze the vulnerability of the Niğde city center. Salata et al. (2022) studied the sponge district concept in İzmir (Türkiye), one of Europe's most vulnerable areas to pluvial flooding. They employed a composite index to determine potential areas of intervention for nature-based solutions. Toy and Eren (2023), proposed suggestions for Türkiye concerning the classification and parameterization of urban characteristics that affect climate elements, the conversion of these parameters into data, and the monitoring and evaluation of meteorological parameters alongside these data. Gülpınar Sekban and Acar (2024) aimed to illustrate how spatial solutions can be developed by integrating climate change adaptation strategies into the redesign of urban open green areas, thereby enhancing ecosystem services and reducing the carbon footprint of the designs by embedding these strategies into the design process.

There are two theses in the YÖK Theses database on global warming and cities: Hajibayov (2017) prepared a thesis entitled: 'Evaluating the impact of floods on planning in Edirne city in terms of global climate change'; and Çimen (2023) completed a thesis entitled: 'The relationship between megacities and global warming: a comparison between Kocaeli and Şanlıurfa'. In addition to these valuable studies, there is no comprehensive research addressing all the risks of climate change in Türkiye, nor is there any study analyzing urban vulnerability separately for all risks.

1.1. Aim and Objectives

1.1.1. Aim

The study aims to develop an index to measure the vulnerability of cities in Türkiye, not to a single consequence of climate change, but to all possible consequences.

1.1.2. Objectives

The following objectives have been outlined to develop the index:

a. To identify criteria for assessing the vulnerability of cities to climate change in terms of drought, sea-level rise, extreme heat, and extreme heavy rainfall
b. To develop new criteria
c. To identify cities that are more vulnerable to different risks and to contribute to the necessary policies and preparations

1.2. Research Questions

a. Which cities are at risk and have more vulnerability to the various consequences of climate change?

2. Literature Review

2.1. Climate Change

The cause of climate change is the significant increase in greenhouse gas emissions on a global scale. This also leads to changes in exposure to climate hazards, with the impacts depending to a certain degree on social, economic, and governance factors that determine both sensitivities and their capacities (Leary et al., 2008). Climate change causes unpredictable weather events, an increased incidence of both extreme heat and cold, rainfall instability, rising sea levels, and the melting of land-based ice masses. Other concerns include the impacts of food production and low-lying human settlements. While impacts of climate change will vary regionally, they can be summarized as follows (Change, I. P. O. C., 2001):

Freshwater resources: By mid-century, annual average river runoff and water availability are projected to decrease by 10-30% in some dry regions at mid-latitudes; however, they are expected to rise by 10-40% at high latitudes and in some wet tropical areas. Water supplies stored in glaciers and snow cover are projected to decline, which is expected to increase drought-affected areas. Heavy precipitation events will heighten flood risk.

Ecosystems: Many ecosystems are likely to be affected by land-use change, overconsumption of resources, flooding, drought, wildfire, insect outbreaks, and ocean acidification. If the global average temperature exceeds 1.5-2.5°C, the functions and structures of ecosystems, ecological interactions, and the geographic ranges of species are expected to change. The increasing atmospheric carbon dioxide causes ocean acidification and affects marine shell-forming organisms, such as corals and other species that depend on them.

Food and forest products: At lower latitudes, especially in tropical and seasonally dry regions, crop productivity is expected to decrease. In addition, fish species are projected to experience regional shifts in production.

Coastal systems and low-lying areas: Coasts may be among the highest-risk areas due to sea-level rise. Dense urbanization in low-lying areas will face challenges such as tropical storms or local coastal subsidence. If the global average temperature increases by 1-4°C, partial deglaciation of the Greenland and West Antarctic ice sheets could cause sea levels to rise by 4-6 m or more. If the Greenland and West Antarctic ice sheets melt completely, sea-level rise will reach 7 m and about 5 m, respectively.

Industry, settlement and society: Economies are closely linked to climate-sensitive resources, and industries and settlements experiencing rapid urbanisation in areas prone to extreme weather events or located in coastal and river floodplains are among the most vulnerable. Extreme weather events are expected to cause economic and social losses. Moreover, climate change and its associated exposures are likely to impact human health.

Both rural and urban areas are confronted with climate change through a complex feedback mechanism that affects entire systems. To set an example, while extreme precipitation increases flood risks, it can also facilitate the spread of vector-borne microbes. Urban areas are at greater risk of floods because most changes in the hydrology and geomorphology of rivers and drainage basins occur in these areas. The most vulnerable social group consists of poor households that lack insurance coverage to recover and rebuild their homes. In addition, the urban heat island (UHI) effect makes urban areas more vulnerable to the heat-related manifestations of climate change. UHI, together with heat waves, has particularly detrimental effects on low-income populations, as these residents are less likely to afford health insurance or air conditioning. Moreover, resource-based industries, which are highly sensitive to changes in temperature and precipitation, can lead to a 'socio-economic drought'. Elderly populations will also be affected by heat waves and extreme weather conditions (Binita et al., 2015). Consequently, elderly and lower-income populations are more vulnerable to the consequences of climate change.

Solutions vary by country, region, and city. In high-income countries, improving urban spaces is critical for reducing greenhouse gas emissions. In developing countries, different solutions should be implemented (Greenwalt et al., 2018). Cities around the world need to implement planning and practices that will increase urban resilience against climate change (Balica et al., 2012). The World Bank (2021) suggests that nature-based solutions beneficial for urban resilience include wetlands, salt marshes, river floodplains, sandy shores, forests, river and stream renaturation, open green spaces, urban agriculture, and building solutions. These solutions make important contributions, such as mitigating heat stress, reducing flood risk, and storing carbon.

As a preliminary step, vulnerability analysis is essential for assessing the resilience and vulnerability of cities. Only after this step is it possible to determine adaptation policies. In addition, the vulnerability levels of cities vary according to many factors, such as their physical, geographical, infrastructural, and building conditions. In addition, many social and economic factors, such as the level of development, unemployment rates, the proportion of the population living alone, the proportion of children, the elderly, women, and disabled people, increase the vulnerability of the city (Sılaydın Aydın, 2021; Dincer & Yalçıner Ercoşkun, 2024).

As cities continue to grow and become more complex, poor urban design and management have unintended consequences (Pickett et al., 1997). Because the dynamics of cities are non-linear, we have to change traditional linear planning methodologies. Urban ecosystem services need to be sustainable, and new means of planning have to deal with the complexity of urban areas (Wilkinson, 2011). Evidently, we need to integrate governance systems with stakeholder participation for improving adaptive and transformative capacities of cities (Barthel et al., 2010).

3. Methods and Materials

Different methods are used to assess vulnerability on different scales. At the national scale, various tools are used to assess the vulnerability of countries, including the disaster-risk index (BCDR-UNDP), the hot-spots model (World Bank), the composite vulnerability index, natural disaster vulnerability indicators, the social vulnerability index, and disaster-risk indices (IADB-ECLAC-IES) (Villagrán de León, 2006). These models typically draw on data from past disasters and related losses, make predictions for the future, and identify the most vulnerable countries.

Munich Re Group (2003) developed a method to assess the vulnerability of megacities around the world, using three parameters: structural vulnerability, standard of preparedness/safeguards, and overall quality of construction and building density. The index is built on a foundation of information on the current status of the cities, rather than on the historical outcomes of previous disasters. Many studies assessing vulnerability at the local level have developed methods within the framework of various criteria according to the type of disaster (Villagrán de León, 2006). Most indices are based on metrics, mainly the arithmetic or weighted mean of factors.

In addition to physical and structural vulnerability, social and economic vulnerability is equally important. A combination of biophysical and social processes generates vulnerability (Tonmoy et al., 2014). In the literature, various criteria such as age, personal wealth, single-sector economic dependence, poverty, unemployment, renter population, immigrants, race, income, gender, inmate population, female-headed household, and occupation are used to measure social vulnerability (Zanetti et al., 2016; Binita et al., 2015). In this study, social and economic vulnerabilities are assumed to remain constant across all risks and are therefore not included in the criteria set.

The method is based on the information about the current status rather than previous disasters. The first reason for this is that the effects of climate change on the atmosphere and ecosystems are only beginning to be observed. The second reason is the view that the effects of climate change will manifest very rapidly over the next century. The impacts of climate change are discussed under four headings: Drought, Sea-Level Rise, Heavy Rainfall, and Extreme Heat. For these headings, factors were determined according to the criteria of effect, pressure, vulnerability, resistance, and adaptive capacity. All factors are presented without weighting. The first type of indicator, *effect*, describes the criteria that reveal the risk. The second criterion, *pressure*, includes indicators that increase the vulnerability of the city and have a negative impact. The third indicator, *vulnerability*, shows the dimensions of the city's existing structural, natural, economic, and geographical characteristics that have the potential to increase risk. The *resistance* criterion has a positive effect. It includes indicators that the city has and that increase its resilience. Finally, the *adaptive capacity* criterion shows the indicators that have the potential to be developed for the city.

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Extreme weather events, as one of the consequences of climate change, are not analyzed under a distinct heading. This is because extreme heat and extreme precipitation were addressed separately, while hurricane risk was not considered. The first reason for this is that, in the studies in the literature, the methodologies for determining the storm risk are largely predicated on whether a settlement has previously experienced a storm disaster. However, hurricane risk may apply to all settlements, not only to those with a history of hurricanes. It was excluded from the scope as it was a disaster that developed outside the physical, structural, and spatial characteristics of the city. The second reason is that Türkiye has never experienced a hurricane disaster to date.

One of the difficult aspects of identifying risk is that it requires a large amount of local data, which is often unavailable for extended areas (Zanetti et al., 2016). In many studies, the choice of method depends on the objectives of the study and the availability of data (Feindouno et al., 2020). In this study, factors were formed on the basis of the available data.

4. Results and Findings

4.1. Indicators Determining Urban Vulnerability to Climate Change

Studies show that the consequences of climate change differ for each region and city. While some regions will face drought, some regions will face sudden heavy rainfall or extreme heat (Figure 1). In order to create climate-adaptive cities, it is initially necessary to determine the vulnerability of each city.

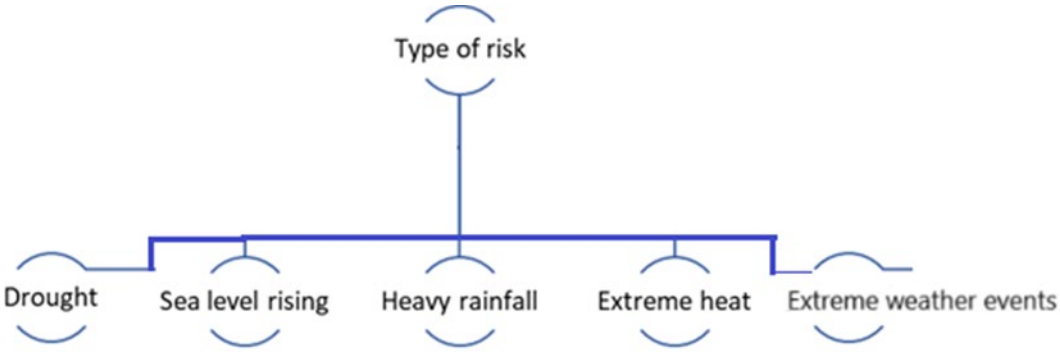

Figure 1 Type of risk due to climate change (Prepared by the author)

In this study, an index has been developed to assess urban vulnerability to climate change across different dimensions. In this way, it will be possible to more effectively manage the resources allocated to countries' resilience. Through this comprehensive method, both the vulnerability of cities and their resilience can be determined. In addition, it will help reveal the deficient dimensions in order to increase adaptation in a city. Thus, an assessment template will be established to measure the vulnerability of cities. The necessity of such a method arises from the fact that no country has sufficient resources to make all cities climate-adapted to all risks simultaneously. Therefore, countries need to implement a climate-adaptive approach in stages, beginning with high-risk cities. The identification of risk types and indicator types is as follows:

Table 1 Drought Risk Indicators and Impact

Risk	Indicator types	Effect	Indicators	Impact	References
DROUGHT	Effect	Negative	Temperature level	Average annual air temperature affects the amount of precipitation. Studies accepted a lower limit of -4,7 and an upper limit of 28.4.	Adapted from Feindouno et al., 2020
			Rainfall level	Drought risk increases if annual rainfall is low. Studies accepted a lower limit of 33.5 and an upper limit of 3792.4.	Adapted from Feindouno et al., 2020
	Pressure		Trend in temperature instability	As air temperature increases and humidity decreases, precipitation may decline. Studies accepted a lower limit	Adapted from Feindouno et al., 2020

				of -0.07 and an upper limit of 0.02 for annual average temperature change.	
			Trend in rainfall instability	Decreases in the rainfall regime increase the risk of drought. Studies accepted a lower limit of -287 and an upper limit of 202 for changes in rainfall instability.	Adapted from Feindouno et al., 2020
			Consecutive dry days	The climate parameter that indicates a greater propensity for dry periods. The higher the average CDD, vulnerability increases.	Adapted from Menezes et al., 2018
			Records of water supply decrease due to drought	Vulnerability is considered very high if the annual reduction in water resources is over 50%.	Adapted from Kim et al., 2016
			Urban population	As the population grows, vulnerability increases because of rising water and food demand.	Adapted from Sılaydın Aydın, 2021; Villagrán de León, 2006
			Rate of population growth	Vulnerability increases in cities with annual population growth rates above 4%.	Adapted from Sılaydın Aydın, 2021
			Distance to the water supplies (km)	Distant water sources contribute to increased vulnerability.	Adapted from Jubeh and Mimi, 2012
			The presence of forest areas near settlements due to forest fires	The risk of forest fires increases, especially in summer, in areas where rainfall decreases and temperatures rise.	Elaborated by the author
			Proportion of urban population living from agriculture	Vulnerability rises as the proportion of the population dependent solely on agriculture increases.	Elaborated by the author
			Water consumption per capita	Pressure increases as per capita water consumption rises.	Adapted from Xie and Zheng, 2017
	Vulnerability		Amount of agricultural area	Vulnerability increases as the amount of agricultural land and the share of the agriculture sector in the city's economy.	Elaborated by the author
	Resistance	Positive	Water potential	Resistance increases when the annual per capita availability of water resources is high.	Adapted from Sılaydın Aydın, 2021
			Greywater recycling systems	The reuse of treated wastewater and the rate of wastewater recycling reduce water demand.	Adapted from Jubeh and Mimi, 2012; Xie and Zheng, 2017
			Dry farming practices	Dry farming practices reduce water demand in the agricultural sector (the sector with the highest water consumption).	Elaborated by the author
			Rainwater harvesting systems	The collection rate of rainwater falling on building roofs and asphalt surfaces, the presence of rainwater collection systems in buildings, and the incentives applied reduce water demand.	Adapted from Freni and Liuzzo, 2019
			Drought-resistant planting and green areas	Drought-tolerant landscaping in yards and parks increases the resilience of urban greenery.	Elaborated by the author
			Efficient household water use strategies	Efficient household water use strategies reduce water demand.	Adapted by Leary et al., 2008
			Drought-resistant agricultural practices	Drought-resistant crop varieties and efficient irrigation systems reduce water demand.	Rezvani et al., 2023
	Adaptive capacity		Forest cover, reforestation and afforestation	The amount of forest land and trees to reduce greenhouse gas emissions and fight drought by increasing atmospheric humidity. On the other hand, drought can also lead to forest fires. Therefore, precautions can be taken for forest areas close to settlements.	Rezvani et al., 2023 and Sılaydın Aydın, 2021

The drought risk depends on the current levels of temperature and rainfall, as well as on the trends over time. Green spaces play a key role in stormwater management, and raingardens are shallow vegetated areas that help to collect and treat the stormwater runoff from the surrounding impermeable surfaces (Croce & Vettorato, 2021). Greywater recycling helps to reduce freshwater demand (Rezvani et al., 2023). The indicators of drought risk are presented in Table 1.

Table 2 Sea Level Rise, Risk Indicators, and Impact

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Risk	Indicator types	Effect	Indicators	Impact	References
SEA LEVEL RISE	Effect	Negative	Sea level rise	Vulnerability increases as the sea level rises. Studies reported sea level rise values from the most vulnerable to the most resilient: 0.9 m, 0.7 m, 0.5 m, 0.3 m, 0 m.	Adapted from Zanetti et al., 2016 and Tallis et al., 2011
	Pressure		Altitude	Positive effect if the altitude of the city is high.	Adapted from Sılaydın Aydın et al., 2017
			Distance to the coast	Should be evaluated together with altitude: If the altitude of the area between the settlement and the coast lies at or below sea level, being far from the coast has less positive impact. However, if the settlement itself is located at sea level or below, and there are high-altitude areas between it and the coast, it can be considered more resilient. In addition, cities situated on cliffed shores and at high altitudes have high resistance, even when they are close to the coast.	Adapted from Zanetti et al., 2016 and Anazawa et al., 2013
			The ratio of built-up area at low altitude	The risk increases as the proportion of built-up areas in low-altitude coastal areas increases.	Adapted by Ercanlı, 2024, Balica et al., 2012, Kahraman and Aydın, 2016
			The length of the coastline	The risk increases as the length of the built-up area along the coast increases.	Adapted by Ercanlı, 2024, Balica et al., 2012, Kahraman and Aydın, 2016
			Population at risk	The percentage of the total population living in areas of high and very high risk for landslides and hydrological events of the total population.	Adapted from Menezes et al., 2018
			Rate of population growth	Cities with positive annual population growth rates are more vulnerable.	Elaborated by the author
			Irrigation and freshwater systems close to the sea	The risk increases if such systems are located both close to the coast and at low altitude due to the salinization risk.	Adapted by Leary et al., 2008; Balica et al., 2012
			Costs of coastal protection versus the costs of land use relocation	Coastal uses with high relocation costs, such as industrial and technology centers, increase vulnerability.	Adapted from IPCC, 2007

			Urban densities on the coast	Ratio of neighborhood population size to neighborhood area in the coast.	Elaborated by the author
			Share of territory 1 m below sea level	The risk may increase if the altitude in some areas of the settlement reaches sea level or falls below it. In some studies, the lower limit is defined as 0 and the upper limit as -93.5 cm.	Adapted from Feindouno et al., 2020 and Sılaydın Aydın, 2021
	Vulnerability		Loss of tourism-related income	Proportion of the population living in the tourism zone if tourism areas are on the coast.	Adapted from Leary et al., 2008
	Resistance	Positive	High altitude	The risk decreases as the altitude increases	Adapted from Ercanlı, 2024
			Open space ratio of coastal and low-altitude areas	The risk decreases as the open space distance between the coast and the building areas increases.	Adapted from Ercanlı, 2024, Balica et al., 2012, Cowell et. al, 2003
	Adaptive capacity		Implementation of trench and seawall	Topographic redesign of the space between the coastline and building blocks according to risk (e.g., slope) will decrease risk	Adapted from Ercanlı, 2024, Rezvani et al., 2023
			Implementation of new architectural systems	Flexible living spaces with floating architectural systems, designing structural systems that can rise with the water level, will decrease risk.	Adapted from Ercanlı, 2024

Due to climate change, coastal communities are expected to be increasingly affected by floods and sea-level rise. 21% of the world's population lives within coastal zones, and under current conditions, 46 million people experience storm-surge flooding per year. Moreover, the potential impacts of sea-level rise pose a risk for the broader coastal ecosystem and urban areas (Balica et al., 2012). According to modelling studies of thermal expansion, glaciers, and ice-sheets, the estimated rate of sea-level rise from 1910 to 1990 ranges from 0.3 to 0.8 mm per year (Church et al., 2001). After the 1990s, the rate of global mean sea-level rise has reached 3.3 mm per year, nearly twice that of the previous decades (Cazenave & Cozannet, 2014). It has been suggested that sea-level rise could exceed 1 m during this century (Feindouno et al., 2020). Climate change is expected to impact tourism by accelerating beach erosion, inundating and degrading coral reefs, threatening hotels, damaging other tourism-related infrastructure, and discouraging tourists from visiting the affected areas (Leary, 2008). Indicators of sea-level rise risk are presented in Table 2.

Another consequence of global climate change is sudden rainfall, which increases the risk of flooding. The impermeable surfaces in urban areas increase the risk of flooding. In addition, technological developments contribute to the creation of climate-adapted cities. Indicators of heavy rainfall risk are presented in Table 3.

Table 3 Heavy Rainfall, Risk Indicators and Impact

Risk	Indicator types	Effect	Indicators	Impact	References
HEAVY RAINFALL	Effect	Negative	Rainfall level	High precipitation level increases the risk. The accepted rainfall range is 3792,4 mm (upper limit) and 33,5 mm (lower limit)	Adapted from Feindouno et al., 2020
	Pressure		Trend in rainfall instability	Flood risk increases as changes in precipitation trends go to up levels, negative levels, and drought risk increases as they go to negative levels. The accepted	Adapted from Feindouno et al., 2020

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				range is -287 (lower limit) to 202 (upper limit).	
			Urban population	As the population increases, the risk increases as the urban area expands and the proportion of impermeable surface increases.	Elaborated by the author
			Rate of population growth	Vulnerability increases for cities with annual population growth rates above 4%.	Adapted from Sılaydın Aydın, 2021
			Size of built-up area	As urban areas expand, vulnerability rises due to increased impermeable surfaces and a higher population exposed to potential disasters.	Adapted from Sılaydın Aydın, 2021; Villagrán de León, 2006
			Footprint ratio	As the footprint ratio (floor area of the building on the parcel) increases, the proportion of impermeable surface and flood risk increases.	Adapted from Sılaydın Aydın, 2021
			Slope	In flat areas, the risk of flooding increases, while in areas with high slopes, severe runoff situations are experienced (with slopes above 80% and below 20% most risky)	Adapted from Sılaydın Aydın et al., 2017 and Zanetti et al., 2016
			Water body proximity (WBP)	Flood risk increases in settlements close to water bodies such as lakes and dams.	Adapted from Anazawa et al., 2013
			The rate of impermeable surface	Impermeable surfaces such as roads, highways, building footprints, and parking lots increase flood risk.	Elaborated by the author
	Vulnerability		Geotechnical classification of soil (GCS)	From the most vulnerable to the most resilient: 1. Colluvium and talus body, expansive soils 2. Alluvial, fractured rock with clean raptures filled with clays 3. Laterite soils, sandy soil 4. Tertiary non-expansive soil, fractured rock with rugose surface 5. Bedrock	Zanetti et al., 2016
			Urbanization close by rivers and natural drainage areas	Drainage areas in and near the city increase vulnerability.	Adapted from Sılaydın Aydın et al., 2017
	Resistance	Positive	Flood barriers, trenches and levees in flood-prone areas	Topographic redesign according to risk (slope, etc.) will decrease risk.	Adapted by Ercanlı, 2024, Rezvani et al., 2023
			High open space ratio, natural and green areas	Increasing the proportion of permeable surfaces that allow rainwater to reach the soil increases urban resilience.	Adapted from Sılaydın Aydın et al., 2017, Xie

					and Zheng, 2017
			Implementation of floating or stilted structures	Initiatives and regulations for the development of floating or stilted structures increase resilience.	Adapted from Huebner, 2025
			Subbasement	Proportion of buildings with subbasement strengthened resistance.	Adapted from Sılaydın Aydın, 2021
			Rainwater and sewage systems	The installation of rainwater harvesting tanks with a capacity higher than 5 m³ will reduce risk.	Adapted from Freni and Liuzzo, 2019
			Green roofs and walls	For moderate rainfall events, if at least 50% of the surrounding area has green roofs, and for strong rainfall events 60% to 95% of green roofs could prevent flooding.	Adapted from Mora-Melià et al., 2018
			River basin management, restoration of natural water bodies and wetland restoration	River and wetland restoration will reduce flood risk.	Adapted from Wharton and Gilvear, 2007
			Permeable pavements	Technological applications such as porous asphalt and the use of pervious concrete in the landscape structures, such as parking areas, bicycle roads, and walkways, allow rainwater to be delivered to the underground effectively	Adapted from Tokgöz et. al., 2022
	Adaptive capacity		Presence of unused land	Planning urban gaps as open and green spaces can reduce flood risk.	Adapted from Sılaydın Aydın, 2021

It is to be expected that heat waves due to global climate change will pose a greater problem closer to the equator. However, studies indicate that the impacts will also be significant at higher latitudes. Because of albedo feedback and ocean current heat transport, surface temperature will strongly alter by about 5-12 °C in polar regions, while it is expected to be 2-3 °C in the low and mid-latitudes. High latitudes will be more vulnerable to alteration by changes in climate, through changes in sea ice, permafrost, river flow, or weather conditions (Roots, 1989), whereas heat waves are expected to pose a more severe problem at low latitudes. The World Meteorological Organization (WMO) defines a heat wave as five or more consecutive days of prolonged heat during which the daily maximum temperature exceeds the average maximum temperature by at least 5 °C (9 °F). Heat waves exacerbate air pollution, increase fire risk, cause heat- and drought-induced crop failures, and pose a significant risk to human health (Zeder & Fischer, 2023). Total urban warming refers to the combined increase of extreme heat in urban settlements from both the UHI effect and anthropogenic climate change. Studies indicate that at latitudes closer to the equator, the increase in the annual number of days with temperatures above 30°C is more pronounced (Tuholske et al., 2021). Some studies also suggest that wind speeds can decrease up to 22% under extremely high temperatures and severe drought conditions (Jiménez et al., 2011). But dense high-rise buildings in urban areas weakened wind speeds, and rapid urbanization has intensified the UHI effect and increased the frequency of urban heat wave events (Zong et al., 2021). On the other hand, strong winds can have detrimental effects on infrastructure, forests, and fires (Gliksman et al., 2023).

Urban design and urban surfaces play a key role in fostering the consequences of climate change. Urban surfaces can be divided into two main categories: ground and building surfaces. Ground surfaces include road networks and urban open spaces, while building surfaces comprise façades and rooftops. Cool materials can help maintain lower surface temperatures and mitigate the UHI effect. Green spaces improve thermal comfort, while green building elements ensure indoor and outdoor climatic comfort and energy efficiency. Building roofs account for approximately 20-25% of the total urban surface (Croce & Vettorato, 2021). Therefore, green roof applications are of considerable importance. In addition, urban tree planting provides localized cooling effects (Rezvani et al., 2023). Extreme heat risk indicators are presented in Table 4.

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Table 4 Extreme Heat, Risk Indicators, and Impact

Risk	Indicator types	Effect	Indicators	Impact	References
EXTREME HEAT	Effect	Negative	Latitude	Vulnerability increases for cities located closer to the equator. Cities located at latitudes lower than 45 degrees North and South are more vulnerable.	Elaborated by the author
			Wind velocity and impact	Impact calculation based on the annual average number of windy days and wind intensity (Very low and very high wind impacts are negative, average values are positive). It positively affects thermal comfort at high temperatures, as the wind reduces the sensation of heat The number of days with a daily maximum wind speed exceeding 14 m/s is considered risky. Winds up to 10.8 m/s are considered "normal". Above 10.8 (10.8 * 3.6 = 38.8 km/h) is strong wind. Winds above 17.1 m/s (61.2 km/h) are storms.	Kim et al., 2016
	Pressure		Temperature	The number of days with over 33 °C of daily maximum temperature is considered risky.	Kim et al., 2016
			Urban density and urban area	Risk increases as urban densities rise, especially in megacities with a population density exceeding 3000 p/km², and urban areas reach 1000 p/km² or more.	Elaborated by the author
			Urban population	Although population growth does not have a direct impact, the urban heat island effect increases due to the demand for construction and the density required for the population. Megacities with populations in the millions are the most vulnerable cities.	Elaborated by the author
			Rate of population growth	Cities with positive annual population growth rates are more vulnerable.	Elaborated by the author
			Proportion of reflecting surface	The ratio of reflective surfaces, such as reinforced concrete, glass, and steel, in the city. Scoring of all surfaces should be recommended according to the albedo effect.	Elaborated by the author
			Road widths	As road widths increase, the urban heat island effect increases as the proportion of reflective surface increases.	Elaborated by the author
			Presence of forest areas near settlements due to forest fires	Forest areas near or within cities increase the risk of fire, especially in areas with drought and arid regions.	Elaborated by the author
	Vulnerability		Urban heat island effect	Urban heat island effect has a multiplier effect with global warming.	Elaborated by the author
			Proportion of elderly and child population	The percentage of the population that is elderly (60 years or older) and the projection of children aged 0 to 4 years for the coming or planned years constitute the vulnerable population.	Adapted from Menezes et al., 2018
	Resistance		Amount and proportion of absorbent surfaces that do not reflect sunlight and reduce local temperature	The proportion of surfaces such as forests, wooded areas, grass, green roofs, water bodies, and soil in and around the city reduces temperature (Maximum positive impact in forest areas, minimum positive impact in soil areas)	Croce and Vettorato, 2021
			Fire-resistant materials	The proportion of heat-resistant pavement materials and initiatives/regulations for the	Rezvani et al., 2023

				development of fire-resistant buildings encourages resilience.	
			Highly reflective and emissive materials	White or light-colored reflective materials, super-cool materials, and retroreflective materials increase resilience.	Croce and Vettorato, 2021
			Shading status of public areas	Ensuring climatic comfort, closed public space ratio, air-conditioned public space ratio, underground public space ratio, tree ratio in streets and pedestrian areas, shade-casting urban furniture, pavement shaded by buildings, etc.	Rezvani et al., 2023
			Cooling centers	Safe and air-conditioned environments protect from heat stress, and the number and size of air-conditioned buildings.	Rezvani et al., 2023
			Thermal comfort transportation	Air-conditioned public transport: vehicle ratio, metro line length, walkable green corridors	Elaborated by the author
			Green roofs and facade systems	Designing and building roofs and facades as absorbent surfaces instead of reflective surfaces has positive effects both in terms of the urban heat island effect and indoor thermal comfort.	Croce and Vettorato, 2021
			Building insulation	Proportion of buildings with insulation, and mandatory insulation requirements for new buildings.	Rezvani et al., 2023
			Hospital and health services	Health workers and health facilities per capita, enhanced emergency services, and infrastructure.	Rezvani et al., 2023
			Rescue and firefighting manpower	Strong firefighting manpower and infrastructure increase resilience against fire risk.	Adapted from Villagrán de León, 2006
			Existence of clean water resources	Increased water demand: Water consumption is expected to rise due to hot weather, affecting clean water resources.	Adapted from Change, I. P. O. C. (2001)
	Adaptive capacity		Presence of unused land	Mitigating the urban heat island effect by designating urban gaps in and around the city as green spaces.	Elaborated by the author

5. Conclusion

It is now well established that the effects of global climate change have different consequences for each region and city. In some regions, the risk of flooding increases due to irregular and excessive rainfall, whereas in others, the risk of drought increases. In addition, a climate-adaptive city approach is becoming increasingly important for protecting cities from potential future climate-related disasters. At this point, vulnerability assessments are among the first steps to be taken in order to identify the disasters that cities may face. In this study, all risks are considered separately in the vulnerability assessment of cities. Considering the limited resources of countries and urban municipalities, it is evident that taking precautions against all risks will be difficult. This study aims to provide a guiding index for both researchers working on urban resilience and city administrations. Thus, it seeks to contribute to the literature.

In addition, the incorporation of climate change into urban planning, zoning laws to prevent building in high-risk areas, the development of climate adaptation plans, and the development and enforcement of building codes related to climate change are key steps of the urban planning process for climate-adaptive cities. In future studies, a score-based index should be created by developing and weighting new criteria for vulnerability assessments.

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Declaration of Competing Interest

The author declare that they have no known competing financial interest or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

Ethics Committee Approval

Ethics committee decision is not necessary for this study.

Resume

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Analysis of wooden pillar and wooden ceiling mosques of the Seljuk and principalities period

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Özlem Sağıroğlu Demirci**

Abstract

Mosques, as structures meticulously designed and constructed, represent the pinnacle of architectural and aesthetic solutions within Islamic civilizations. The desire for proximity to the mihrab in mosque design has necessitated the development of original and rational structural solutions, leading to significant advancements in architectural technology and technique. Mosque architecture, predominantly masonry, reflects both local architectural influences and the availability of materials, often shaped by regional traditions and construction methods specific to certain periods. A notable example of this is the wooden columned and wooden-ceilinged mosques, extensively constructed in Anatolia during the Seljuk and Principalities periods, where all elements, except for the masonry walls, were crafted from wood. This article presents a typological analysis of mosques with flat timber beams, wooden columns, and wooden ceilings, offering a comprehensive examination of their distinctive architectural features. The structural analysis encompasses all aspects from the foundation to the roof, with detailed documentation of their construction techniques. The aim of this study is to contribute to the conservation and restoration efforts of these mosques, a group of which only a few original, high-quality examples remain. Furthermore, this research is of particular significance as it represents one of the first studies to document the ceiling solutions of wooden hypostyle mosques, some of which are listed on the UNESCO World Heritage List. For the typological studies, both on-site examinations were conducted and data from previous sources were evaluated. The ceiling analysis was carried out using application photographs of a restored mosque, employing a three-dimensional modeling method.

Keywords: conservation, cultural heritage, hypostyle mosques, straight beam, wooden masjid

1. Introduction

Based on evidence gathered from scientific excavations, it is plausible to assert that wood has been employed as a construction material since the earliest stages of human civilization. Its widespread use can be attributed to its accessibility, ease of processing, and high load-bearing capacity relative to its lightness, particularly in regions where climatic conditions favor its utilization. In Anatolia, wood has been a preferred material in both civil and monumental architecture up until the mid-20th century, predominantly utilized in flooring systems, roofing structures, and as a key element in walls and architectural features, serving both structural and aesthetic functions.

The architectural evolution of mosques in Anatolia underwent significant diversification with the arrival of the Turks, who had embraced Islam, following the Battle of Manzikert in 1071. The Great Mosques constructed in the newly conquered cities and regions stand as some of the most valuable examples of Anatolian Seljuk architecture, both in terms of construction techniques and aesthetic qualities. Material selection for mosque construction typically reflects the significance of the structure itself, with wood being employed in smaller mosques, particularly in walls using timber furring or timber frame systems. In rare instances, wooden struts were used to support the roof

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structure. Mosques featuring wooden ceilings and columns represent unique examples of how wood was employed both structurally and decoratively.

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The architectural evolution of mosques in Anatolia underwent significant diversification with the arrival of the Turks, who had embraced Islam, following the Battle of Manzikert in 1071. The Great Mosques constructed in the newly conquered cities and regions stand as some of the most valuable examples of Anatolian Seljuk architecture, both in terms of construction techniques and aesthetic qualities. Material selection for mosque construction typically reflects the significance of the structure itself, with wood being employed in smaller mosques, particularly in walls using timber furring or timber frame systems. In rare instances, wooden struts were used to support the roof structure. Mosques featuring wooden ceilings and columns represent unique examples of how wood was employed both structurally and decoratively.

The earliest examples of mosques with wooden ceilings and columns are found in the cities of Kufa and Basra, located on the Arabian Peninsula (Öney, 2007). Consequently, such structures are often referred to in the literature as "Kufa-type mosques" in addition to terms like "wooden columned mosques" or "multi-columned mosques." The first such mosques in Anatolia date back to the late 12th and early 13th centuries. Kuran (2012) offers two hypotheses regarding the origins of these mosques in Anatolia. The first posits a connection to earlier examples of Greek temples with wooden columns and Phrygian megarons, which were characterized by their wooden columns and have a significant place in the architectural history of Anatolia. The second hypothesis suggests that the Turks, upon settling in Anatolia in the 11th century, may have brought knowledge of this building type from Central Asia, as they did not encounter similar structures in eastern and southeastern Anatolia.

Kuran further traces the origins of this architectural form to the 7th century, pointing to the canopy constructed from date palm trunks in the courtyard of the Prophet Muhammad's house in Medina as an early prototype. While mosques with wooden ceilings and columns, such as the one built by Amr Ibn al-As in Fustat, existed during this period, the influence of regional architecture, which often utilized stone and marble columns, became dominant as Islam spread into Asia. This interaction may have led to the development of wooden columned mosques, which the Turks could have introduced to Anatolia (Kuran, 2012). Aslanapa (1990) concurs with this view, suggesting that this architectural style reached Anatolia through structures like the Arus-ül Felek Mosque, built by Sultan Mahmud of Ghazni, as well as through mosques constructed by the Karakhanids in cities such as Samarkand, Bukhara, and Khiva (Aslanapa, 1990).

A second hypothesis, also advanced by Kuran (2012), emphasizes the continuous and deliberate use of wooden columns by the Turks, drawing parallels to their traditional use of wooden poles in tent structures. According to this theory, the Turkish tribes who adopted Islam in Central Asia may have worshiped in multi-columned mobile mosques, which in turn influenced the aesthetic development of mosques in settled areas (Kuran, 2012). Akok (1976), on the other hand, stresses that the use of wooden roofing systems has a long-standing tradition in Anatolian civil architecture, predating the arrival of the Seljuks. He notes that the combination of masonry walls, wooden pillars, and wooden roofs constitutes a distinct, local construction technique in Anatolia, remarking, "Masonry and wood pillars, wood, and earth roof coverings, with all their building nuances, represent an indigenous architectural style (Akok, 1976).

During the Seljuk and Principalities periods, mosques with wooden columns and ceilings continued to be constructed, especially in central Anatolia, with several high-quality examples emerging. Although their construction decreased with the rise of the Ottoman Empire, they remained a part of mosque architecture, albeit in limited numbers. Numerous studies have been conducted on the architectural, structural, and decorative aspects of these mosques. For example, the structural behavior of the Ahi Elvan (Er Akan, 2010) and Aslanhane Mosques (Çakıcı et al., 2009) has been analyzed using finite element modeling, while the material composition of mosques such as the Mahmut Bey Mosque (Akyol et al., 2006), Sivrihisar Great Mosque (Akyol, 2019), and Beyşehir Eşrefoğlu Mosque (İçel, 2020) has been examined through archaeometric analysis. In addition, mosques such as the Ayaş Great Mosque (Karaçağ, 2010), Afyon Great Mosque (Akkanat, 2010), Mahmud Bey Mosque (Akok, 1946; Yaylacıoğlu, 2010; Aydın & Perker, 2017), Eşrefoğlu Mosque (Akok, 1976; Koçu, 2014) and Arslanhane Mosque (Karaseki, 2007) have been analyzed for their architectural features, material types, and decorative elements, while Çilek (2020) focused specifically on the ornamental features of the Eşrefoğlu Mosque.

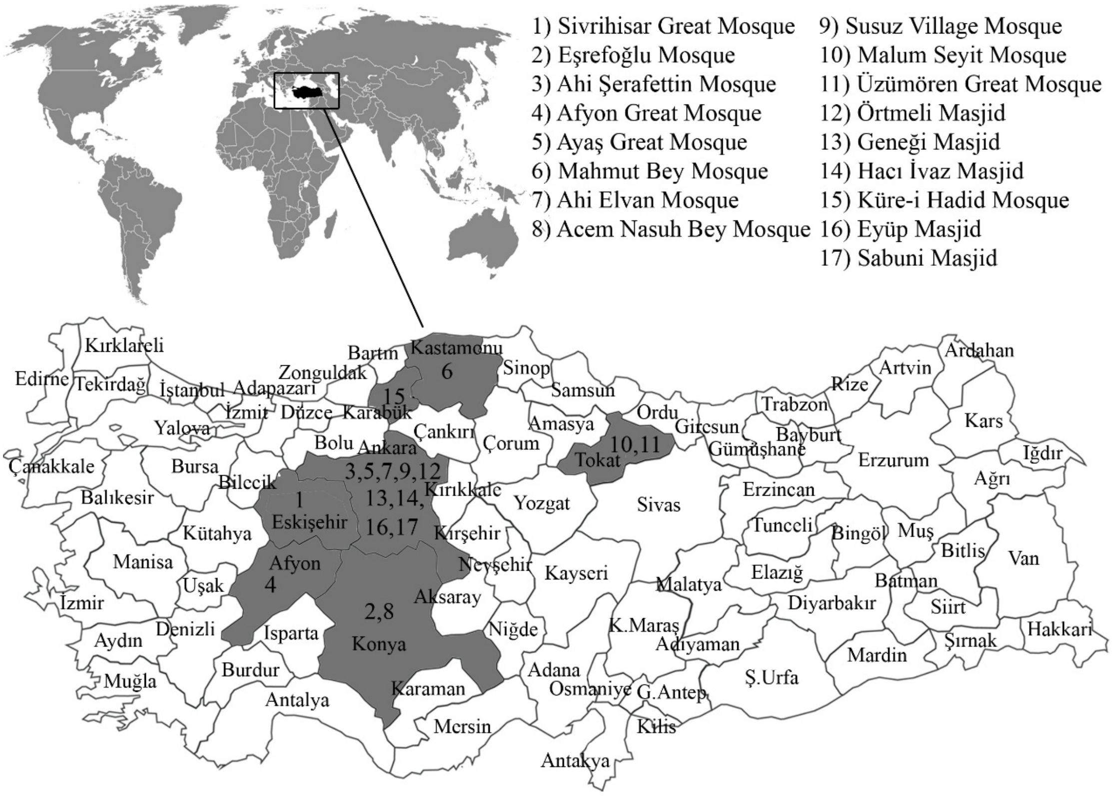


Figure 1 Location of mosques (The provinces where the structures are located are indicated by numbers)

The present study examines mosques constructed with straight beams, wooden pillars, and wooden ceilings during the Seljuk and Principalities periods (Figure 1), forming a typology with specific shared characteristics. Their structural systems have been meticulously analyzed through typological studies, with the aim of increasing awareness of their architectural composition to aid in conservation and restoration efforts. Given the limited number of surviving examples, understanding the structural configurations of these mosques is critical to ensuring their preservation. The unique contribution of this study lies in its detailed analysis of the construction systems, including the roofing structures, and the presentation of this information to the academic community for the first time. The significance of this research is further heightened by the recent inclusion of five such mosques—Eşrefoğlu Mosque, Mahmut Bey Mosque, Sivrihisar Great Mosque, Afyon Great Mosque, and Aslanhane-Ahi Şerafettin Mosque—on the UNESCO World Heritage List in 2023 under the designation "Wooden Hypostyle Mosques of Anatolia from the Medieval Pe.. Accordingly, Structure No. 1 is in Eskişehir; Structures No. 2–8 are in Konya; Structures No. 3–5–7–

9–12–13–14–16–17 are in Ankara; Structure No. 4 is in Afyon; Structure No. 6 is in Kastamonu; Structures No. 10–11 are in Tokat; and Structure No. 15 is in Karabük (Figure 1).

2. Methodology

In the scope of this study, an investigation was undertaken into the flat-roofed wooden mosques from the Seljuk and Beylik periods. A typological analysis was constructed by examining their qualitative attributes. The identification of the mosques' characteristics was informed by field observations as well as a review of prior scholarly research. In the examination of the ceiling systems, photographs from the restoration of the Aslanhane Mosque and on-site measurements of the Mahmut Bey Mosque in Kasaba Köy were synthesized and rigorously analyzed. Although photographic documentation was available for the Aslanhane Mosque, particular emphasis was placed on detailing the ceiling of the Mahmut Bey Mosque due to the distinctive nature of its ceiling system, which is characterized by unique ornamental elements.

The primary limitation of this research arises from the absence of photographic documentation regarding the ceiling repairs of the Mahmut Bey Mosque, which has hindered the comprehensive analysis of its ceiling system. Although the mosque underwent restoration, the intricate handcrafted embellishments of its ceiling and the structural relationship between the roof and ceiling could not be thoroughly examined due to the lack of repair photographs. Consequently, detailed structural data specific to this mosque were unattainable, necessitating reliance on the ceiling repair photographs of the Aslanhane Mosque.

The classification and typological delineation of culturally significant structures, particularly those designated for preservation, are critical for future academic studies. Accordingly, the proposed categorization and identification of similarities and differences among wooden-ceilinged mosques are expected to inform and guide subsequent restoration efforts. Moreover, the detailed exposition of unique construction systems will offer valuable support for restoration practices involving comparable structures in future projects.

3. The Research Findings

In the scope of this study, an investigation was undertaken into the flat-roofed wooden mosques from the Seljuk.

3.1. Typological Classification of the Mosques

Publications concerning mosques from the Seljuk-Principalities period, particularly those featuring wooden pillars and ceilings, remain scarce. These structures are typically classified typologically and detailed according to the construction techniques of their support systems and ceilings. Öney (2007) identifies both monumental examples and smaller masjids, which she likens to tiny houses, within this group of mosques. She further notes that these structures exhibit various features depending on the number of naves, the presence of narthexes, and courtyards. However, Öney refrains from presenting a typological classification in her study (Öney, 2007).

Akok (1976) contributes to this discourse by categorizing the grand mosque types that emerged in 13th-century Anatolia into three primary groups based on their structural characteristics. The first group consists of mosques whose surrounding walls, vaults, and arches serve as load-bearing elements, without the inclusion of wooden materials in their roofs or supports. In contrast, the second and third groups, while sharing similar masonry techniques for their surrounding walls, incorporate wooden roofs. In the second group, the roof is supported by rows of stone pillars or arches, whereas in the third group, wooden pillars are employed as structural supports (Akok, 1976).

Akok's classification focuses on the use of masonry and wooden elements in roofs and supports. Meanwhile, Tuncer (1979) offers a similar typological study specifically addressing wooden roofs. He classifies wooden roofing systems of the Seljuk period into three groups: the first group includes structures where wooden trusses are employed, with the underside either exposed (as seen in the Great Mosque of Diyarbakır) or covered with wood (such as in the Ağaçayak, Hacı İlyas, and Hacı Musa Mosques). In the second group, the wooden beams of the roof rest on rows of masonry arches. The third group features structures where stone and wooden pillars replace the series of arches supporting the roof (Tuncer, 1979).

Önge (1975) undertakes a broader typological study of wooden ceiling formations across various structures from the Seljuk and Principalities periods. Although his research encompasses all building types from this era, the typology can also be applied to mosques, as relevant examples exist for each subcategory. Önge examines examples dating from the 11th to 15th centuries of the flat beam system, commonly referred to as the 'soil roof (karadam),' which is considered the simplest form of wooden ceiling and involves a covering of earth. He identifies two types of beaming systems: straight and inclined wooden beams. Furthermore, Önge notes that flat wooden beams can be left exposed, overlapped, or used as part of vaulted or domed wooden ceilings, with three variations of coverage: uncoated, top-coated, or bottom-coated (Önge, 1975).

3.2. Architectural Elements and Scissor-Truss Wooden Ceiling Typology in Mosques

The structural pillars supporting the ceiling and forming the naves in mosques with wooden ceilings are utilized in two distinct typologies. The first method involves the use of roughly-hewn timber, wherein the tree trunk is employed after its bark has been stripped and the branches and knots have been cleaned, without further shaping or chipping of the wood (Figure 2).

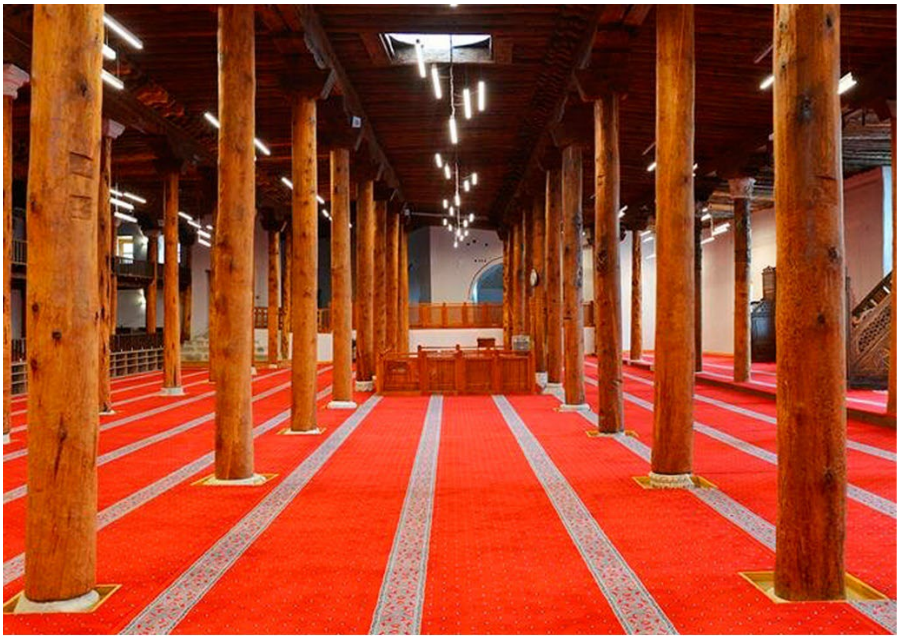


Figure 2 Sivrihisar Great Mosque wooden columns

While trees with smooth surfaces were generally selected for these circular cross-section pillars, in some instances, knotty trees with irregular surfaces were also employed, as seen in the Sivrihisar Great Mosque—though subsequent interventions over time have also contributed to this condition. Circular cross-section, unchiseled pillars are more prevalently used in mosques. Another method involves shaping the log into square, rectangular, or polygonal prisms. Notable examples of this include the polygonal prism-shaped supports surrounding the pool in the Beyşehir Eşrefoğlu Mosque (Figure 3).

Figure 3 Sivrihisar Great Mosque column capital

The art of carving and relief is observed in only a limited number of examples, such as the wooden pillars situated in front of the mihrab in the Sivrihisar Great Mosque. Similarly, hand-carved ornamental elements for aesthetic purposes can be seen in select instances, such as in the Kastamonu Mahmut Bey Mosque (Figure 4). The number and dimensions of the pillars are typically proportional to the overall size of the structure. However, it is also possible to find pillars of varying lengths and diameters within the same building. For example, in the Sivrihisar Great Mosque, pillar diameters range from 34 to 52 cm.

Figure 4 Kastamonu Mahmutbey Mosque wooden columns

Pedestals were typically employed beneath the pillars at their junction with the ground. These pedestals primarily served to prevent deterioration by protecting the pillars from moisture absorption from the ground, while also facilitating the even distribution of the roof’s load across a broader surface area. Additionally, pedestals were used to bridge the gap between the ground and pillars of varying heights, thus equalizing the upper elevations. The use of pedestals of different heights within the same structure, as seen in the Sivrihisar Great Mosque and Ankara Hacı İvaz Masjid, supports this functional intent. These pedestals could be crafted from smoothed stone blocks, intricately worked stone blocks, or spolia from ancient civilizations (Figure 5). Pedestals were positioned either above or beneath the floor slab. In many existing examples, the pedestal remains visible on the ground. Önge (1975) cites the Great Mosque of Afyon as an example of pedestals located beneath the floor slab. However, during restoration work in 1952-53, the original spolia pedestals were removed and replaced with the plain stone pedestals seen today (Önge, 1975). Additional examples of sub-floor pedestals include the pillars in the Hacı İvaz Masjid and those situated in front of the mihrab in the Mahmut Bey Mosque in Kastamonu.

Figure 5 Sivrihisar Great Mosque pedestals

Column capitals are generally employed to connect the pillars to the ceiling. In addition to their aesthetic function, these capitals facilitate the smooth transfer of the load from the main ceiling beam to the column and help align the struts to the appropriate height with surrounding elements. Capitals were crafted from either wood or stone. Önge (1975) classifies wooden column capitals into three types: wooden beams with profiles at both ends, and wooden pieces shaped as inverted truncated cones or pyramids (Önge, 1975). Önge interprets these capitals as 'beam headers with wooden profiles at both ends,' which function more as cushions to prevent the struts from exerting excessive pressure on the beam, rather than acting as traditional capital heads. These components are often found atop other wooden capitals, serving as sleeper beams (Figure 6). As these parts are referred to as sleeper beams in other literature (Akok, 1976; Tuncer, 1979), this article classifies them as 'pillars without capitals' and organizes them accordingly in the typology. Examples of pillared mosques without capitals include the Beyşehir Çavuş Village Mosque and the Karaman Hoca Mahmud Mosque. Mosques with inverted truncated cone or pyramid-shaped capitals, such as the Sivrihisar and Ayaş Great Mosques (Figure 6), exemplify this architectural feature. Among pyramid-shaped capitals, those with muqarnas (stalactite) decoration stand out for their aesthetic and technical qualities. Önge (1968) identifies two types of muqarnas capitals. The first type, carved from solid wood, is rare today, with one of the finest examples found in the Mahmud Bey Mosque in Kasabaköy, where these capitals were intricately carved and embellished with decorative patterns (Önge, 1968).

Figure 6 Beyşehir Çavuş Village Mosque column capital

Another technique for creating this type of capital involves manufacturing the components separately and affixing them to the pillar by nailing. Examples of this technique, referred to in the literature as 'nailed stalactite wooden capitals,' include the Genegi Masjid, Eşrefoğlu Mosque, and Afyon Great Mosque (Önge, 1968). These capitals are non-structural, serving purely decorative purposes. According to Önge (1968), these capitals are typically arranged in octagonal or polygonal compositions on wooden pillars with circular, octagonal, or polygonal cross-sections. After the first 4-5 rows, the top of the capital generally takes the form of a star, polygon, or square and fits securely beneath the ceiling beam. A flat wooden platform, composed of boards placed side by side, supports the beam on top of the capital. Önge also notes a distinctive tapering at the end of the inverted cone or pyramid-shaped struts near the head, referring to these shorter, thinner sections as the 'neck' (Figure 3), with the Beyşehir Eşrefoğlu Mosque cited as a prime example (Önge, 1968; Önge, 1975). Additionally, some of these wooden capitals feature hand-drawn ornaments, created using madder dye. In some instances, such as the Beyşehir Çavuş Village Mosque, Beyşehir Eşrefoğlu Mosque (Figure 7), or Kastamonu Mahmut Bey Mosque, these ornamental designs extend to the ceiling, while in others, they are confined to specific areas.

Figure 7 Beyşehir Çavuş Village Mosque column capital

Non-wooden capitals, in contrast, were often repurposed from the architectural remnants of earlier civilizations, such as spolia, and incorporated into mosque structures. These spolia capitals can be found in simple linear forms (Figure 8) or adorned with floral motifs (Figure 9), typically following the Corinthian order with acanthus leaf decorations (Table 1).

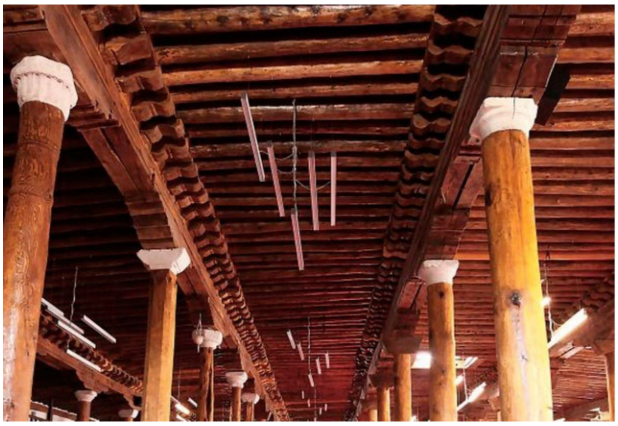


Figure 8 Sivrihisar Great Mosque column capital

Figure 9 Ahi Şerafeddin Mosque column capital

Table 1 The Features of Pillars, Pedestals and Column Caps in Mosques with Wooden Ceilings

Mosques with wooden pillars and wooden ceilings	Pillars					Pedestal			Capitals					
	Section		Ornament			Available		Non. Ava.	Spolia		Not spolia			Hand-drawn
	Circular	Angular	Carving	Relief	Hand-drawn	Simple	Ornamental		Simple	Ornamental	Without capital	Muqarnas	Conical	
Sivrihisar Great Mosque	●		●	●		●	●		●	●			●	
Eşrefoğlu Mosque	●	●			●	●						●		●
Ahi Şerafettin Mosque	●					●			●	●	●			
Afyon Great Mosque	●					●						●		
Ayaş Great Mosque	●					●						●	●	
Mahmut Bey Mosque		●			●			●			●	●		●
Ahi Elvan Mosque	●	●				●			●	●	●			
Acem Nasuh Bey Mosque	●					●						●		●
Susuz Village Mosque	●	●						●			●			
Malum Seyit Mosque	●	●	●			●							●	
Üzümören Great Mosque	●							●			●		●	
Örtmeli Masjid	●							●		●				
Geneği Masjid	●					●						●		●
Hacı İvaz Masjid	●							●	●					
Küre-i Hadid Mosque	●				●			●			●			●
Eyüp Masjid	●					●					●			
Sabuni Masjid		●				●			●					

Profiled wooden sleepers, aligned parallel to the pillars, are positioned beneath them at the junctions where the primary load-bearing beams connect to the pillar capitals. These sleepers are composed of one or two sections, depending on the thickness of the main upper carrier beam. By distributing the point pressure exerted by the pillars across a broader surface, the sleepers help to prevent damage to the beams. These wooden sleepers are typically employed in either a flat form (uncarved), with minimal carving (Figure 10), or with intricate carvings (Figure 11), depending on the design profile.

Figure 10 Üzümören Great Mosque wooden sleepers and wooden column capitals

Figure 11 Malum Seyit Mosque wooden sleepers and wooden column capitals

Some of these elements, utilized in various mosques with differing profiles, have been transformed into aesthetic features through the addition of hand-drawn ornamental decorations (Figure 12), similar to those found in other parts of the mosque.

Figure 12 Eşrefoğlu Mosque wooden sleepers and wooden column capitals

3.3. Ceiling System

The pillars supporting the main beams, positioned on wooden sleepers, are carved into square or rectangular prisms. This design ensures that the upper (intermediate) beams make full contact with the pillar heads or sleepers, allowing the load to be evenly distributed across the entire surface. These beams extend continuously across the pillars, with the joints between beam sections aligned with the central axis of the pillars. The main load-bearing beams, spanning between the pillars and the masonry walls, create long, rectangular naves (Figure 13). In mosques with this architectural layout, the width of the naves can reach up to 4.5 to 5 meters in the axial arrangement formed by the wooden posts. The number of naves, determined by the spacing between the pillar axes, is a defining characteristic of this type of mosque (Table 2, Table 3). Typically, the central nave is higher than the lateral naves in this architectural form. The increased height of the central nave is achieved through a stepped construction of wooden elements extending from the console. In some buildings, the lateral naves are sloped to provide the necessary gradient for the upper cover, while in others, the slope is achieved by progressively raising the height of each nave towards the center. Depending on the size of the structure, mosques are typically designed with an odd number of naves—3, 5, 7, or 9. The central nave is often wider and/or higher than the others, contributing to the distinctive sanctuary space created by this layout.

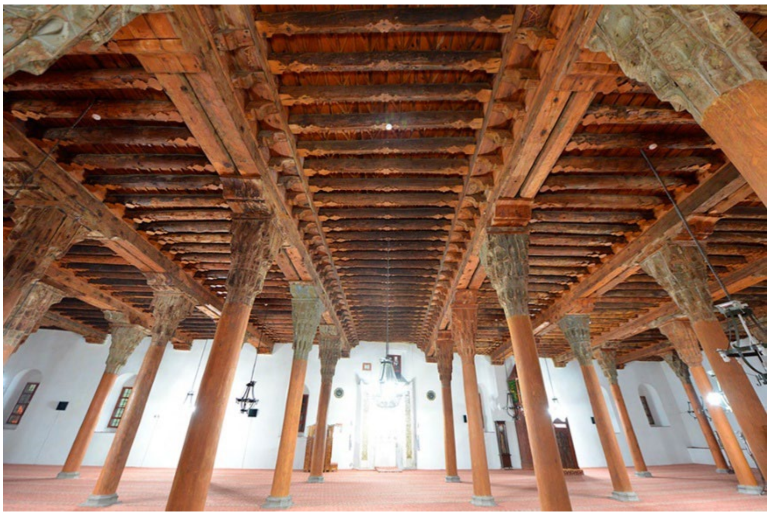


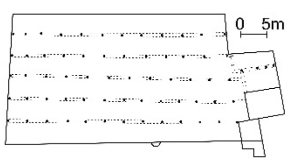
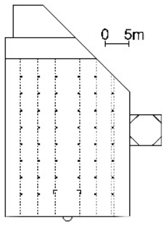
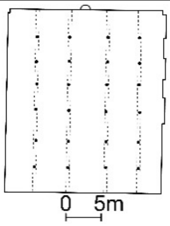
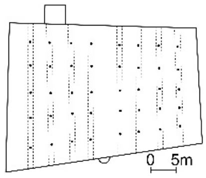
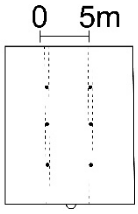
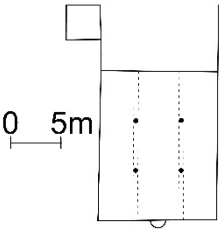
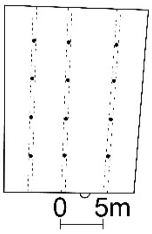
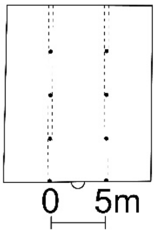
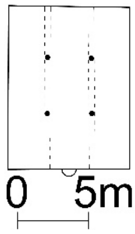
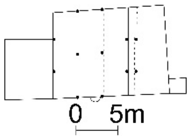
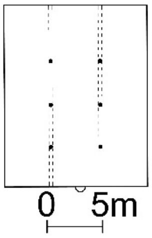
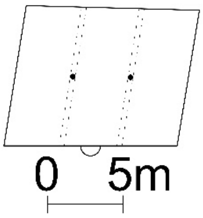
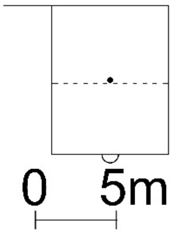
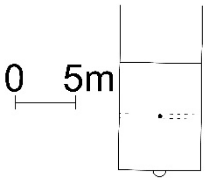
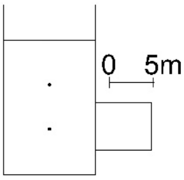
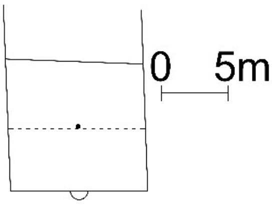
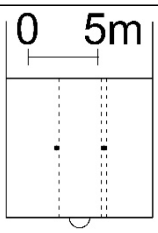
Figure 13 The naves in Afyon Great Mosque

The main beams that define the naves are extended along the pillars, positioned to form the long sides of the naves. When upper (intermediate) beams of the same or occasionally varying heights are placed on these beams from both directions, two main carrier beams are positioned side by side on each pillar without any gaps (Figure 13). Tuncer (1979) notes that the decision to use single or double beams depends on the span and cross-sectional dimensions, as double main beams provide a more secure fit for the upper (intermediate) beams and are more suitable for muqarnas capitals. Additionally, it is known that beams parallel to the walls are integrated into the masonry walls, corresponding to the wooden beams supported by rows of pillars. These wall-mounted beams align with the main beams in the structure, taking on the role of primary load-bearing elements along the walls.

Table 2 Wooden Beams, Nave and Roof Elements in Wooden Ceiling Mosques

Mosques with wooden pillars and wooden ceilings	Wooden Beams		Nave Setup											Roof Elements			
	Side naves		Axis direction		Height		Number of naves							Snow well		Lighting lantern	
	Straight	Sloping	Mihrab axle	Parallel to the mihrab axis	Rising towards the center	All naves are equal	2	3	4	5	6	7	9	Available	Nope	Available	Nope
Sivrihisar Great Mosque		●		●	●						●				●	●	
Eşrefoğlu Mosque		●	●		●							●		●		●	
Ahi Şerafettin Mosque	●		●		●					●					●		●
Afyon Great Mosque	●		●		●								●		●		●
Ayaş Great Mosque	●		●		●			●							●		●
Mahmut Bey Mosque	●		●		●			●							●		●
Ahi Elvan Mosque	●		●		●				●						●		●
Acem Nasuh Bey Mosque	●		●		●			●							●		●
Susuz Village Mosque	●		●		●			●							●		●
Malum Seyit Mosque	●		●		●			●							●		●
Üzümören Great Mosque	●		●		●			●							●		●
Örtmeli Masjid	●		●		●			●							●		●
Geneği Masjid	●			●	●		●								●		●
Hacı İvaz Masjid	●			●	●		●								●		●
Küre-i Hadid Mosque	●		●			●	●								●		●
Eyüp Masjid	●			●		●	●								●		●
Sabuni Masjid	●		●		●			●							●		●

Table 3 Plans of Wooden Ceiling Mosques

Plans				
Sivrihisar Great Mosque	Eşrefoğlu Mosque	Ahi Şerafettin Mosque	Afyon Great Mosque	Ayaş Great Mosque
				
Mahmut Bey Mosque	Ahi Elvan Mosque	Acem Nasuh Bey Mosque	Susuz Village Mosque	Malum Seyit Mosque
				
Üzümören Great Mosque	Örtmeli Masjid	Geneği Masjid	Hacı İvaz Masjid	Küre-i Hadid Mosque
				
Eyüp Masjid	Sabuni Masjid			
				

The naves are covered by upper (intermediate) beams placed parallel to the shorter sides of the structure. The spacing between these beams is approximately 1 to 1.5 times the width of the beam, and they are secured to the masonry walls either by resting on the main beams extended over the pillars or by being embedded within the wall itself. Önge (1975) notes that these beams typically penetrate 20-30 cm into the masonry wall. Consoles are created by extending the upper (intermediate) beams into the nave, forming profiled consoles. The ends of these consoles are profiled and support a secondary beam placed above them. The upper (intermediate) beams resting on this secondary beam are used to cover the elevated central nave (Figure 14). This method, which involves the use of multiple rows of consoles to raise the central nave, is exemplified in structures such as the Sivas Grand Mosque, Beyşehir Eşrefoğlu Mosque, Kastamonu Mahmut Bey Mosque, and Aslanhane Mosque. This elevation not only resolves the issue of roof slope but also enhances the aesthetic value of the interior.

The openings at the points where the upper (intermediate) beams rest on the main beams are covered with flat wooden boards, approximately 1 cm thick. These boards are inserted into specially carved grooves along the side faces of the beams by sliding them from above (Figure 15). Typically, the boards are inclined toward the ceiling. In some instances, moldings have been observed, particularly on the upper sections of these boards. Additionally, decorative wooden boards are incorporated into the ceiling system for aesthetic purposes. These boards are affixed either beneath both ends of the beams or above the joints where paired main beams are used, and they are often carved with motifs and embellished with hand-drawn decorations. These decorative boards are referred to as 'sayvan' (Önge, 1975) or 'lambriken' (Tuncer, 1979) (Figure 14).

Figure 14 The canopy/lambricanes in Afyon Great Mosque

Figure 15 Photos taken during the restoration of the Arslanhane Mosque

To prevent soil from falling into the mosque, an insulating layer is placed on top of the upper (intermediate) beams (Figure 16). Tuncer (1979) explains that this insulating layer consists of wooden plates, upon which a mixture of barren clay (with added salt) and straw or tow is applied to prevent cracking. Önge (1975), on the other hand, suggests that this layer may be composed of reed, mat, or plate-shaped boards. He further notes that after this layer is plastered with mud, it is covered with 30-40 cm of salty soil, a traditional covering known among the people as 'karadam' or 'soil roof'.

Tuncer (1979) notes that while the ceilings of mosques can be ventilated from below, the presence of a top soil covering prevents ventilation from above. To address the risk of decay, a secondary ceiling was introduced in the restoration of the Konya Doğanhisar Grand Mosque, built in 1548, and the Konya Ilgın Yukarı Çiğil Village Mosque, which dates back to before the first quarter of the 18th century. This secondary ceiling was created by placing an additional main beam over the original beams. However, no such secondary ceiling was found in the Ankara Aslanhane Mosque (Directorate General of Foundations, 2023) (Figure 17).

Figure 16 Photos taken during the restoration of the Aslanhane Mosque

Figure 17 Photos taken during the restoration of the Aslanhane Mosque.

The 'Karadam' soil roof covering was a common feature in rural Anatolian architecture. This covering was created by laying a layer of stones, reeds, wicker mats, or thin branches to prevent soil from falling onto the wooden beams, followed by a 10-30 cm thick layer of soil. Research has also been conducted on the composition of the soil used in this covering. Bulut Karaca (2021) indicates that the soil consists of two layers: a 3-4 cm layer of impermeable clay and a high-salt-content soil referred to as 'barren' or 'trim' (Bulut Karaca, 2021). In contrast, İner and Çağlarer (2013) describe the second layer of mud, called 'bişirik,' as being composed of clay-rich soil mixed with straw.

In subsequent years, the roofs of many mosques from this period were restored or altered to feature fitted roofs covered with tiles. However, various researchers assert that these roofs were originally covered with soil. For instance, Akok (1976) notes that, despite the Beyşehir Eşrefoğlu Mosque's new wooden roof with copper plates, it was originally covered with soil, like other structures from this period. Similarly, Tükel Yavuz (2002) suggests that most buildings of this era, excluding conical tombs and baths, originally had flat roofs, many of which were earthen, though this is not always certain. She identifies cut stone slabs as the roofing material for some structures, such as the Karatay Inn. Kuran (1995) also observes that the flat earthen roof of the Niksar Great Mosque was later protected with a tiled, sloped roof.

During this period, smooth, knot-free trees with minimal branching and cracks were selected for construction. Tuncer (1979) states that these woods were kiln-dried and treated with insect repellent. While tree species varied, juniper and yellow pine were used for the construction of the Sivrihisar Great Mosque (Sivrihisar Municipality, 2024), and it is known that all the timber elements of the Beyşehir Eşrefoğlu Mosque were made from pine (Akok, 1976). Tuncer (1979) also notes the use of fine-fiber spruce, cedar, and fir in such mosques. Notably, nails were not used in the assembly of the timber structures. Instead, joints were crafted by inserting wedges between the wooden elements, using various techniques to fit the pieces together.

3.4. Analysis of Scissor-Truss Ceiling System in the Context of Kasabaköy Mahmut Bey Mosque

Although mosques with scissor-trussed ceiling systems exhibit various typologies, they are fundamentally constructed using the same structural principles. In this regard, the ceiling system of the Kasabaköy Mahmut Bey Mosque has been analyzed, with restoration images from the Aslanhane Mosque providing further support, leading to conclusive insights. As a result, the restoration of structures employing similar systems can be effectively undertaken by understanding these ceiling formations.

Following the construction of the stone walls, the first step in the ceiling assembly involves the placement of vertical posts. In the Mahmut Bey Mosque, the columns are octagonal, measuring 35 cm at the base and 26 cm at the top. The detailed column under examination features a muqarnas-style capital, with the widest section having a diameter of 58 cm. To evenly distribute the load between the column and the main beams, a simple, flat cushion is placed parallel to and 3.5 cm beneath the main beam. The main beam is then positioned atop this cushion, extending in the same direction. To elevate the ceiling system, profiled small beams, approximately 1 meter long and 17 cm wide, are vertically placed on the main beam at 40 cm intervals. These beams are adorned with decorative penwork on both the lower and side surfaces.

The connection between these beams is achieved by inserting approximately 2 cm thick boards into grooves cut into the beams. The rigidity of the structure is further reinforced by the placement of long beams vertically over the upper part. The final support beams for the side aisles are placed vertically on top of these two beams, with one end embedded in the stone wall and the other extending outward by approximately 28 cm. Three grooves are carved into this beam to close gaps and ensure the connection of beams, with two grooves accommodating boards for the side aisles and one for the main aisle.

Additionally, to reinforce the connection between the beams and prevent any slippage, a vertically oriented beam is placed over the profiled sections. The area between this beam and the wall is covered with wood, enclosing the side aisles. The ceiling of the main aisle is formed by positioning beams vertically and in alignment with the final beam, with evenly spaced intervals. The final layer of beams also features grooves at both ends, into which boards are inserted to close the gaps between them.

In this section, decorative elements are introduced by vertically mounting star-shaped carved boards between the beams, over which flat, uncarved wooden boards are placed. To stabilize both the wood and the ceiling structure, the entire ceiling is filled with soil. While the original design involved a soil-filled roof, subsequent interventions replaced this with a pitched roof. Roof beams were placed on top of the soil layer, completing the roof system (Figure 18).

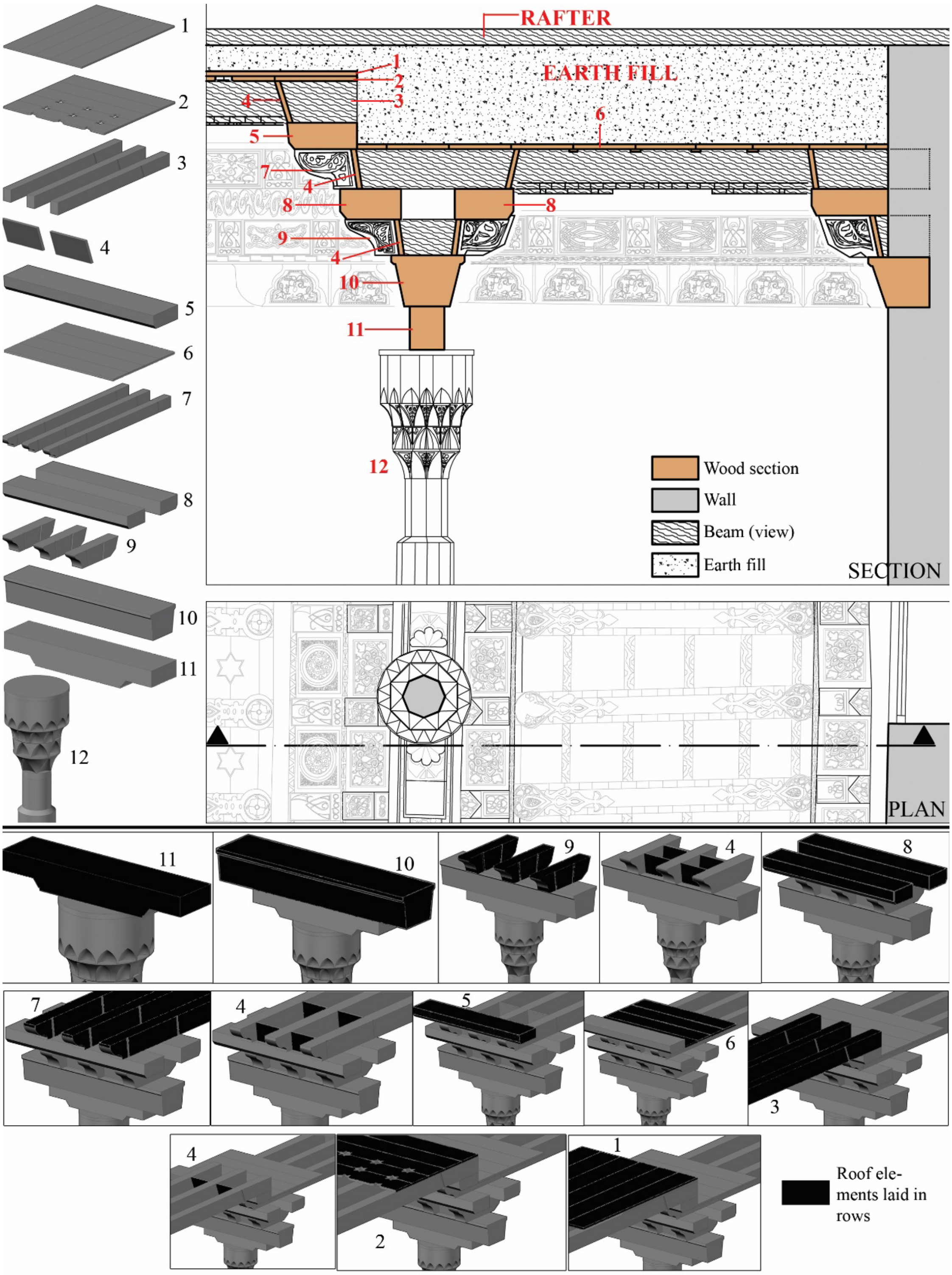


Figure 18 Carrier system analysis of Kasabaköy Mahmud Bey Mosque

4. Results and Discussion

Scholarly opinions differ regarding the origins and development of mosques with wooden pillars and ceilings. These structures, which were built during the Anatolian Seljuk and Principalities periods, continued to be constructed gradually over time. However, the mosques featuring superior wood craftsmanship and aesthetic sensibilities—characterized by wooden pillars, ceilings, and flat weft-beam roof systems—represent a distinct architectural typology. These mosques are differentiated from those with domes, overlapping ceilings, or vaulted systems. Within the scope of this study, these structures were examined within the context of the Seljuk and Principalities periods. Nevertheless, many mosques, particularly those in regions where timber is abundant, were constructed using wood as a primary or sole material, often in conjunction with masonry structures.

Many mosques, particularly those in regions abundant with timber, were constructed using wood either as the primary or a significant building material, often alongside masonry. The mosques analyzed in this study are characterized by masonry walls, while all other elements, including the roof, are made entirely of wood. In these buildings, wooden pillars, arranged in rows, support the ceiling. These pillars rest on original or repurposed stone plinths or foundations, which may be visible either above or below ground. Most of the pillars feature capitals made of either spolia or wood. Above these capitals, wooden sleepers were placed to distribute the load, supporting the primary beams, which run continuously across the structure and define the naves. The naves are covered by beams laid perpendicular to the main beam. Restoration data and surviving original examples indicate that the roofs of these buildings were originally flat. A key structural detail is the arrangement of the naves at progressively lower levels relative to one another, which facilitates water drainage from the roof. In this typological study, system details such as the number of naves, their height and orientation, as well as key elements like column capitals, pedestals, and pillars, were identified and analyzed. The analysis was further supported by restoration photographs from the Aslanhane Mosque, providing, for the first time in the literature, comprehensive and detailed information on the structural characteristics of these buildings (Figure 18).

In addition to the qualitative assessments provided in the discussion, the tabulated data further illuminate the structural and stylistic diversity among the examined mosques. Table 1 reveals that approximately two-thirds of the surveyed examples incorporate circular-section pillars, while the remaining third employ angular or polygonal forms. The presence of hand-carved ornamentation on pillars is relatively rare, observed in fewer than 20% of the cases, which underscores the functional priority of these elements over decorative concerns. However, in certain examples such as the Mahmut Bey Mosque and Eşrefoğlu Mosque, ornamentation extends beyond the pillars to encompass capitals, pedestals, and even sleeper beams, reflecting a more elaborate artistic program.

A comparative reading of Table 1 also indicates that spolia usage in capitals remains a significant feature: nearly half of the mosques examined reuse stone capitals from earlier civilizations, frequently of Corinthian inspiration with acanthus leaf motifs. This practice not only reflects the pragmatic reuse of available materials but also the aesthetic integration of pre-Islamic architectural vocabulary into Seljuk and Beylik period religious structures. Wooden muqarnas capitals, by contrast, occur in roughly one-quarter of the cases, often in the most architecturally refined examples. Their concentration in prominent mosques—such as those of Sivrihisar, Beyşehir, and Kasabaköy—suggests an intentional association between this decorative form and high-status commissions.

The analysis of Table 2 demonstrates that the majority of mosques employ a three- or five-nave arrangement, accounting for almost 70% of the dataset. Wider central naves, either elevated or flanked by lower side naves, appear in over half of the examples, highlighting a spatial hierarchy directed towards the mihrab axis. Snow wells and lighting lanterns are comparatively scarce—present in less than one-third of the mosques—which may relate to regional climatic variations and construction traditions. The data also reveal that straight-beam configurations dominate, while sloping side naves are less common, suggesting a persistence of flat-roof construction methods consistent with the traditional “karadam” soil roof typology.

From a typological standpoint, as summarized in Tables 1–3, the co-occurrence of certain features points to regionally influenced design patterns. For example, the combination of circular-section pillars with stone spolia capitals and flat beam ceilings predominates in central Anatolia, whereas polygonal pillars with elaborately carved wooden muqarnas capitals are more frequent in the western examples. Quantitatively, these stylistic combinations account for nearly 80% of the surveyed corpus, reinforcing the notion that while individual mosques exhibit unique craftsmanship, they remain anchored within well-defined architectural traditions of the Seljuk and Principalities periods.

5. Conclusions

The present study represents the first comprehensive analysis of the ceilings and detailed architectural drawings of the 'Wooden Hypostyle Mosques of Anatolia from the Medieval Period,' which are listed on the UNESCO World Heritage List. The construction details of the wooden ceiling analyzed in this study are based on the Kasabaköy Mahmutbey Mosque, selected for its highly authentic ceiling, preserved with intricate pen work decorations.

The findings from this research are crucial for identifying and anticipating potential issues in similar structures, particularly in the context of conservation and restoration efforts. These insights will inform decision-making processes in conservation applications. As additional fine details are identified and incorporated over time, the data generated from this study will further contribute to the advancement of preservation practices.

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CRediT Authorship Contribution Statement

Ercan Aksoy: Writing – review &editing, Writing – original draft, Methodology, Investigation, Data curation, Conceptualization, Resource, Writing – original draft. Özlem Sağıroğlu Demirci: Writing – review &editing, Methodology, Data curation, Conceptualization, Resource.

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No conflict of interest was declared by the author.

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Resume

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A new paradigm in parking management: From quantitative models to stakeholder participation

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Abstract

This study investigates the selection process of "Parking Management" strategies, a critical component of parking facility planning. An integrated approach is developed, combining quantitative assessment models with those based on expert and user opinions, to select effective "Parking Management" strategies. Additionally, parking strategies for the Trabzon-Ortahisar district were determined by analyzing observed on-site parking behaviors. The study hypothesized that conventional approaches would be insufficient for selecting parking management strategies and would fail to adequately adapt to user profiles and parking usage patterns. At this stage, car parking strategies selected through traditional methods—such as car parking capacities, usage rates, projection studies, and data obtained from user and car parking surveys—were compared. The AHP (Analytical Hierarchy Process) method was used as the selection criterion. As an outcome, the study proposes a method that incorporates user opinions to determine optimal strategies for addressing parking problems caused by the imbalance between parking spaces and parking demand.

Keywords: parking management, analytical hierarchy process, Trabzon, transportation planning

1. Introduction

There has been a steady increase in private car ownership due to accelerated industrialization, leading to higher urban economic growth, increased incomes, improved living standards for urban residents, and significant population growth (Shen, 1997). The rapidly growing economy, along with policies and subsidies, and the rising use of private vehicles in urban areas, have made car parking a major concern for urban transport planning and traffic management worldwide (Parmar et al., 2020). The surge in private vehicle ownership continually heightens the need for parking spaces (Open Government Data (OGD) platform India, 2018). This growth rate has not allowed for adequate off-street parking capacity, especially in city centers and central business districts, leading vehicle owners to park on the roadside. Consequently, enhancing parking spaces through effective parking management strategies is recognized as a key solution to alleviating urban congestion (Shen et al., 2020).

In recent years, the evolving understanding of car park management has shifted towards the rational allocation of existing resources rather than creating new supply. Previously, strategies focused on maximizing supply and minimizing prices, which proved ineffective. Currently, the primary objective is optimizing parking supply (Moeinaddini et al., 2013). Initial parking policies aimed to solve these problems by increasing supply to meet demand, based on minimum parking requirements (Dave et al., 2019). However, supply-oriented approaches have inadvertently increased car ownership and reduced public spaces available for physical activities, public transport, and other essential recreational, social, cultural, and economic activities.

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Today, parking demand management is the most prevalent approach to addressing these issues by designing policies that reduce demand and encourage modal shifts (Yan et al., 2019). Users can adapt to parking policies by altering their parking behavior, mode of transport, destination, schedule, or activities. Additionally, parking policies serve as a revenue source for local governments while balancing the need to manage transport demand and discouraging long-term use of parking spaces to protect urban vitality (Coombe et al., 1997). Within car parking strategies, the focus should be on enforcing maximum parking requirements rather than encouraging minimum parking requirements.

In the past, parking problems were addressed by increasing the supply of car parks, a paradigm that prioritized drivers within the transport system (Weinberger et al., 2010). Consequently, the demand for car parking spaces has also risen. Urban areas face significant challenges such as traffic congestion, air pollution, and environmental degradation, all of which complicate the functioning of transportation systems (Tafidis et al., 2017).

Initially, the management of parking focused on safety and the regulation of traffic flow on streets (Marsden, 2006). This led to the development of policies aimed at managing on-street parking, considering parking standards in new developments, and providing off-street public off-street parking facilities (Shoup, 1999; 2005). Parking Management (PM) emerged as a system offering various solutions to parking demand beyond merely creating new parking spaces. PM includes plans, policies, programs, and strategies to address potential parking issues (Litman, 2024). It also supports land use planning efforts, enhances pedestrian accessibility, and identifies transit priorities and flows (Delaware Valley Regional Planning Commission, 2004). PM refers to strategies and practices that enhance the efficiency of parking facility usage (Barhani, 2007). It identifies current or potential parking problems, estimates the costs and possible revenues from parking areas, and clarifies car park management strategies and their implementation (Okubay, 2008). Proper implementation of PM provides socio-economic and environmental benefits by maximizing the efficiency of parking spaces. Given the current challenges with parking areas, the selection of appropriate management and strategy choices is critical. Effective parking management significantly contributes to the sustainability of urban transport development (Thanh, 2017).

Several international studies analyze user parking behavior. Research indicates that well-designed parking regulation frameworks contribute to more efficient use of the transport network, lower emissions, higher densities, and better urban design (IHT, 2005; Shoup, 2005; Stubbs, 2002; Valleley et al., 1997). Conversely, poorly designed policies can have detrimental effects. For instance, Shoup (2006) reviewed 16 surveys in 11 international cities and found that, on average, 30% of cars in traffic are searching for a parking space, with an average search time of 8.1 minutes. In a survey on illegal parking, 48% of respondents admitted to parking illegally (RAC Foundation, 2004). The choice of a parking space is influenced by social, economic, and environmental factors such as age, income, number of available parking spaces, parking costs, accessibility, and search time. The time spent searching for a parking space significantly impacts total travel time, making the time factor crucial in drivers' parking space selection behavior (Polak & Axhausen, 1990).

Chien et al. (2020) analyzed people's on-street parking selection behavior by considering a fuzzy multi-attribute decision-making process for optimal parking space selection. Inspired by such multi-criteria decision-making models, this study applies the Analytic Hierarchy Process (AHP) to incorporate both user and expert inputs into a coherent decision framework. The study emphasized factors affecting driver behavior, showing that distance to the parking space, walking distance, lane condition, and the condition of available parking spaces significantly influence drivers' choices. Han et al. (2018) proposed a parking space selection model for mixed land use, considering common parking policies for visitor parking. This model incorporated variables such as age, gender, parking duration, search time, number of available free spaces, total number of parking spaces, and conditions in other car parks, and was validated using TransCAD software.

Asakura and Kashiwadani (1994) investigated the effect of a parking information system on drivers' parking space selection behavior. They developed a multinomial logit (MNL)-based disaggregated choice model, considering factors like parking fee, walking distance, and availability information. The study found that drivers with incomplete information prioritized parking fees over walking distance and safety.

Waraich and Axhausen (2012) presented a model focusing on parking space choice to analyze individual behavior. They developed a utility function for a parking space by evaluating each attribute's preference weight score that influences a person's choice from a given set of options. This model predicted user behavior using the multi-agent transportation simulation toolkit (MATSim) framework, integrating an evolutionary algorithm to include parking features impacting decision-making.

Demir (2019) analyzed changes in roadside parking user behaviors in Istanbul using approximately eight years of parking data. The study examined the effects of fee increases and short-term free parking practices, evaluating occupancy rates based on user preferences data. Seasonal average parking time was analyzed with time series, and the parking tariff model in the transportation master plan was assessed using regression analysis, identifying inconsistencies.

Additionally, several studies, including those by Sattayhatewa and Smith Jr. (2003), Hess and Polak (2009), and Chaniotakis and Pel (2015), have developed discrete choice models to predict user behavior. These models consider variables such as parking fees, length of stay, proximity to the final destination, and the availability of public transport. Kelly and Clinch (2006) expanded on this work by incorporating variables like parking frequency, trip purpose, and monthly income.

There are numerous studies in the literature focused on car park planning and strategy development. These studies encompass car park management, strategy evaluation and planning, car park operation, pricing policy, cost-benefit analysis, site selection of car parks, and sustainable innovative parking solutions. However, these studies predominantly capture the rational aspect of parking behavior, often neglecting the individual psychological characteristics of drivers. They do not adequately consider usage habits, traffic cultures, transport purposes, mobility trends, or car park users' opinions about the current situation.

While numerous studies have focused on parking pricing (Shoup, 2006; Kelly & Clinch, 2006), facility location (Chien et al., 2020), and user behavior modeling (Han et al., 2018; Waraich & Axhausen, 2012), relatively few have developed an integrated approach that combines user preferences, expert opinions, and traditional demand-based models. Furthermore, there is limited research on participatory strategy selection methods tailored to mid-sized cities like Trabzon, where topographical constraints and user habits strongly influence parking behavior. This study aims to address these gaps by offering a hybrid methodological framework for the selection of parking management strategies. This aim directly responds to the deficiencies identified in previous studies that either rely solely on demand estimation or focus exclusively on user behavior modeling, as outlined in the literature.

Analysis has shown that there is a lack of studies where users are directly involved in the process, the selected strategies are tested in the field, and multiple methods are employed simultaneously. This study aims to address these gaps by providing a healthier and more realistic approach to the applicability of parking strategies. By increasing the detectability of potential short- to medium-term problems before implementation and incorporating expert opinions alongside demand-capacity calculations and heuristic decisions, the scientific rigor of the study will be enhanced. Unlike conventional studies that rely solely on demand projections or user behavior models, this study adopts a holistic approach by integrating traditional quantitative methods, user profiles, and expert evaluations within a participatory planning framework. This integration provides a more realistic and inclusive basis for the selection of parking management strategies.

This study contributes to the literature by integrating demand-based modeling, user preferences, and expert judgment through an AHP-based participatory framework. Unlike conventional parking studies that rely solely on quantitative forecasting, this approach introduces a multidimensional decision-making model tailored for urban parking strategy formulation.

2. Study Area and Method

2.1. Study Area

This study contributes to the literature by integrating demand-based modeling, user preferences, and expert judgment through an AHP-based participatory framework. Unlike conventional parking studies that rely solely on quantitative forecasting, this approach introduces a multidimensional decision-making model tailored for urban parking strategy formulation.

Trabzon is a city situated directly along the coast, continuing to evolve and expand. Historically, Trabzon developed in a linear corridor oriented parallel to the sea, extending along the east-west axis up until the 2000s. Following this period, the city began to experience more compact growth in the southern settlement areas, reflecting a shift in urban expansion patterns.

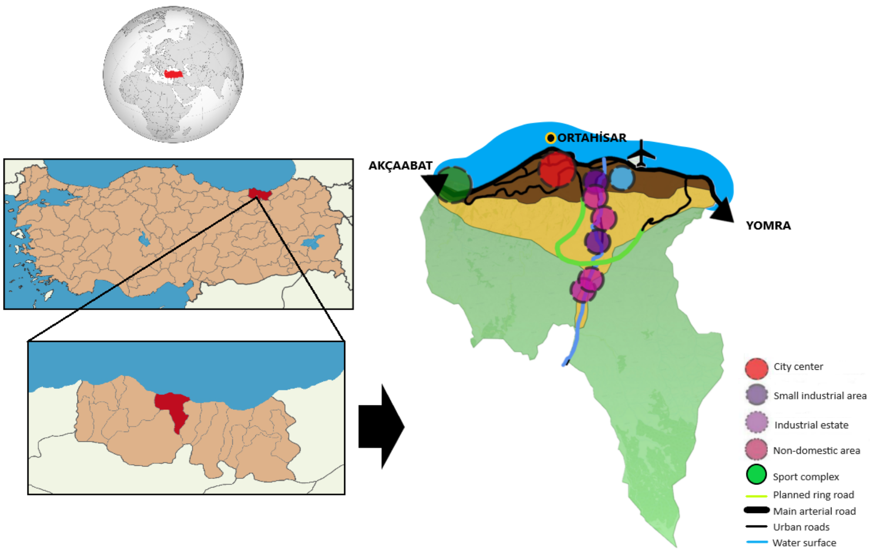

Figure 1 Location and land use structure of Ortahisar district

The transport network in Ortahisar district primarily extends along the east-west axis, parallel to the city's coastline, facilitating connections with coastal districts. Another critical transportation corridor is the E-97 motorway, which runs linearly from north to south, linking Ortahisar with Gümüşhane. This motorway is significant as it provides direct access to Trabzon International Airport and Trabzon Port, intersecting with the city's main axis. This intersection plays a pivotal role in bolstering the city's economic activity, investment prospects, and tourism potential by enhancing logistics and passenger transport. The city center is situated in the northern part of Ortahisar and is closely integrated with the historical bazaar. The north-south axis, stretching from Ortahisar to Maçka, includes non-residential urban service areas, commercial establishments, and higher education institutions.

The Ortahisar district was selected based on multiple criteria. As Trabzon's historic and administrative center, it hosts the city's highest concentration of commercial, touristic, and public institutions. It contains the most congested road segments and the most frequently used curbside and facility-based parking zones. Data availability from the municipal parking operator (TRABİTAŞ), the diversity of parking types, and the observed mismatch between parking demand and supply further justified its selection. In addition, Ortahisar's physical structure—marked by narrow streets, steep terrain, and pedestrian-heavy zones—provides a representative setting to analyze the city's broader parking challenges.

Among the city's most frequented streets are Devlet Sahil Yolu Street, Cumhuriyet Street, Tanjant Street, Kahramanmaraş Street, Gazipaşa Street, Uzun Street, Semerciler 52 Street, and Kunduracılar Street. Kahramanmaraş Street, notably one of the most heavily trafficked streets, extends from Trabzon Meydan Park—renowned for its historical significance—towards the Hagia Sophia. This street is a focal point of the city due to its commercial areas, financial institutions, and accommodation services. It is also well-served by public transport, features accessible pedestrian pathways, and offers ample parking opportunities. The locations mentioned above are visually presented in Figure 1 and Figure 4-5, providing spatial clarity regarding the distribution of parking-intensive road segments and user movement patterns.

In terms of parking infrastructure, Trabzon predominantly relies on roadside parking, which is prevalent on streets and avenues adjacent to or near major traffic routes. Off-street parking facilities are strategically located near busy streets and are concentrated in the city center, providing additional parking options.

The Ortahisar district was selected as the study area at the district level, as it constitutes the historical and functional core of Trabzon. This area hosts the city's most intense parking problems due to its role as the primary commercial, administrative, and transportation hub. The spatial concentration of public institutions, historical zones, and pedestrian-dominated streets results in a critical mismatch between parking supply and demand. Therefore, Ortahisar offers a representative urban context to examine integrated parking management strategies.

In the Ortahisar district of Trabzon, a total of 57 parking facilities were identified and classified as either on-street or off-street. Among these, 45 are off-street parking lots, including open-air and structured facilities. However, it was observed that 8 of these off-street lots were out of service, and 1 was allocated for exclusive use by a hospital. The remaining 12 parking facilities consist of on-street parking areas, which are concentrated along central urban axes—particularly around Meydan Square and Hagia Sophia Square—and are primarily designed for parallel parking. In addition, 8 major roadside corridors were identified as key parking axes, reflecting the circulation-dependent character of on-street parking in the area.

2.2. Methodology

2.2.1. Research Questions

In line with the aim of this study, the following research questions were formulated:

What are the most appropriate and applicable policy alternatives for the city center of Trabzon (Ortahisar), considering local demand characteristics, user behavior, and expert evaluations?

Sub-Questions:

- How do users' parking preferences and behaviors influence the prioritization of strategy alternatives?
    - This question is grounded in behavioral parking models that account for user decision-making in mixed-use contexts, as demonstrated by Han et al. (2018) in Transportation Research Part C
- To what extent can traditional parking demand calculations be reconciled with user expectations and expert opinion?
    - Previous studies (e.g., Q. Han et al., 2018; Shen et al., 2020) highlight that standard projection models often omit qualitative perspectives, underscoring the need for integrative approaches—though empirical integration remains limited. One analogous study combining GIS and AHP for decision criteria integration is Aydınoğlu and Iqbal (2021) in ISAG-2019 proceedings
- How can the Analytic Hierarchy Process (AHP) be used to synthesize multiple inputs (user surveys, parking data, expert assessments) into a robust strategy selection model?

- The effectiveness of AHP in participatory transportation planning has been demonstrated in studies such as de Luca (2014) in Transport Policy, which emphasizes public engagement integration in transport decision-making using calibrated AHP frameworks

2.2.2. Technical Flow

The study employs a hierarchical framework where each stage influences subsequent stages. The initial phase involves the preparation of the Analytic Hierarchy Process (AHP) method, which is informed by results from the "Car Parking Survey" and the "User Survey." The strategies derived from these surveys were then adapted to account for the city's physical structure, parking usage patterns, and urban mobility, and were subsequently presented to experts for evaluation.

The first stage of the study, strategy determination through traditional methods, forms the foundation of the approach. The strategies developed from census studies, demand forecasts, and projections will influence the formulation of questions for users and the AHP study, thereby shaping expert opinions and, consequently, the study's outcomes. Following the initiation by the decision-maker, strategy options were refined using professional expertise, field studies, and urban knowledge.

A key aspect of this study, distinguishing it from others, is the inclusion of car park users in the strategy selection process. This inclusion aims to assess the practical applicability of the proposed strategies within the city context. Scientific results often diverge from practical applications, which underscores the importance of incorporating user perspectives. At this stage, the strategies, based on traditional methods and projections, were communicated to users, and their feedback was collected. This feedback, alongside insights into user parking habits, informed the development of a methodology. The outcome of this dual approach produced strategies with potential solutions to the city's parking issues. Following the study, it is essential to rank these strategies based on their importance. Flowchart of the methodology is given in Figure 2.

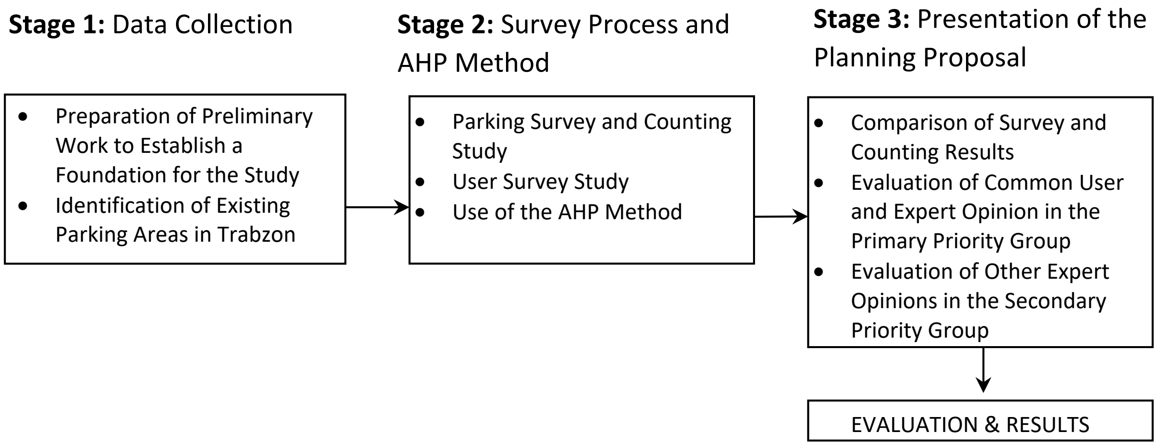

Figure 2 Flowchart of the methodology

STEP 1: In the study, the initial step involved analyzing the car parking inventory data provided by Trabzon Metropolitan Municipality. Using this data, the locations of roadside and off-street parking areas managed by municipal and private enterprises within Ortahisar district were identified through on-site inspection and observational studies.

STEP 2: The study began by analyzing the car parking inventory data obtained from Trabzon Metropolitan Municipality. Based on this data, the locations of both roadside and off-street parking areas managed by municipal and private entities within Ortahisar district were identified through on-site detection and observational studies. Field studies were conducted to assess the data from Trabzon Metropolitan Municipality and associated units. These studies highlighted deficiencies in parking areas and identified problematic regions within the city. Subsequently, a "Car Parking Survey" was executed within these identified areas. This survey involved collecting data from parking operators to determine various physical characteristics of the parking facilities, including types, capacities, ground features, fee tariffs, and construction dates. Additionally, a census study was performed to assess capacity usage and occupancy rates, which are crucial for the study. The car park survey form is detailed in Table 1.

Table 1 Car Parking Survey Form

GENERAL INFORMATION	
Parking Code and Name:	
District:	
Neighborhood:	
Street-Number:	
Location:	
Phone:	o o No Phone
Type:	o Parking lot o Covered o Multi-story o Roadside o Parking meter
Ownership:	o Private o Municipality o Association o Foundation o Other: ....
Operation:	o Private o Municipality o District Municipality o Association o Foundation o Other:..........
Number of Staff:	
Year Opened for Service:	
PHYSICAL CONDITION	
Capacity (Vehicles)	
Structure Type:	o Reinforced Concrete o Steel
Number of Floors:	
Area (m²):	
Above Ground:	o Yes o No
Surface Type:	o Soil o Concrete o Asphalt o Paving Stone o Gravel o Other........
Entrance/Exit:	o Single o Double
Barrier:	o Single o Double
Information System:	o Single o Double
Horizontal Marking:	o Single o Double
Vertical Marking:	o Single o Double
Fire Control:	o Single o Double
Elevator:	o Single o Double
Security Camera:	o Single o Double
Average Number of Tickets (Daily):	
Working Days:	o Weekdays o Every Day o Specific Days (................ ....)
Working Hours:	o 8 AM - 6 PM o 24/7 o Other (....................)
Busiest Days:	o Monday o Tuesday o Wednesday o Thursday o Friday o Saturday o Sunday
Busiest Hours:	
FEE (TL) (Automobile)	
Paid Parking?	o Yes, Paid o No, Free
Fee Schedule:	
Payment Types:	o Cash o Credit Card o Special Card o Trabzon Card
Subscription:	o Available o Not Available
Number of Subscribers:	
Automatic Entry System:	o Available o Not Available
ISSUES	
o Infrastructure Issues (Ground Coating, Lighting, Security, Unit Vehicle Parking Space, etc. Specify ......) o High Demand o Low Demand o High Fee o Low Fee o Traffic	

Field studies are completed by photographing the areas, recording the GPS coordinates of the surveyed locations, and updating the parking area data using digital processing. This process also involved identifying physical inadequacies within the car parking areas. Additionally, car park counting procedures were conducted. These counts were performed in areas with high traffic density and associated parking issues. Car park counting sheets were utilized to document daily capacity usage, fill out roadside parking sheets, and create roadside parking observation charts. Parking counts were systematically conducted across three distinct time periods throughout the day: morning hours (approximately 09:00), midday (around 12:00), and late afternoon to early evening (around 17:00). These specific intervals were purposefully selected to capture the dynamic fluctuations in parking demand associated with typical urban mobility patterns. The morning and evening periods coincide with peak commuting hours, reflecting residential-to-workplace and return flows, whereas the midday period was intended to observe the relative stasis of parked vehicles and parking turnover influenced by commercial, administrative, and recreational activities in the city center. This temporal stratification enabled a more representative and nuanced understanding of diurnal parking behaviors in the study area. Observations and counts were made for both roadside and facility parking areas. An example of a count sheet is provided in Table 2.

Table 2 Car Park Census Sheet

	Park Area Name	Street Name	Capacity	Parking Angle	Number of Vehicles		
					09:00	12:00	17:00
1							
2							
3							
4							
5							

The data obtained from the questionnaire study were processed using the QGIS 3.10 software, incorporating the attributes of each car park. The processed data were then transferred to Excel, where statistical distributions of responses were analyzed. Demand, projection, and capacity calculations were performed based on the occupancy information collected. Annual statistics on usage, occupancy rates, future population, and vehicle usage rates for the city were utilized, along with projection calculations for Ortahisar district using traditional methods, to develop car park management strategies. These strategies were subsequently evaluated through the "User Surveys" study. User feedback was sought to assess their perspectives on these strategies and to refine the strategies based on their suggestions and opinions. This approach aimed to evaluate the practicality of the proposed strategies in real-world conditions and gauge public acceptance and engagement with the system. Car park user surveys were conducted in Ortahisar city center, with participation from 442 residents. User survey study points and the Car Park User Questionnaire Form are presented sequentially in Figure 3 and Table 3.

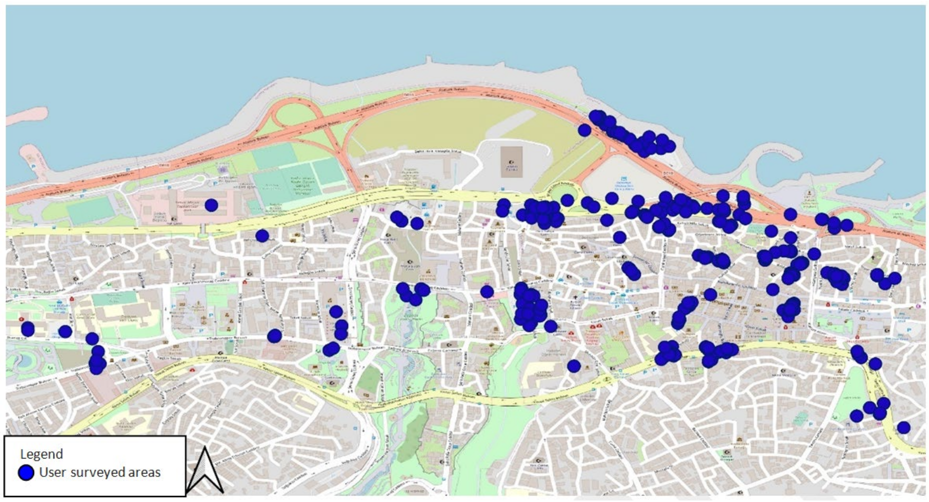

Figure 3 User survey study points

Table 3 Car Park User Questionnaire Form

GENERAL INFORMATION

District:	
Neighborhood Name / Neighborhood Code:	
Street-Number:	
Location:	
Phone:	
USER DEMOGRAPHIC DATA	
Age:	
Gender:	o Female o Male
Place of Birth:	
Reason for Being in the Area:	o Home o Work o Education o Shopping o Other
TRANSPORTATION DATA	
From Which Neighborhood Did You Come to the Parking Lot?	............................../ o Home o Work o Other
Do You Own a Private Vehicle?	o Yes o No
What Mode of Transportation Do You Use for Home-Work Purposes?	o Own Vehicle o Shuttle o Bus o Minibus o Company Vehicle
How Long Will Your Vehicle Typically Remain Parked?	
How Long Has Your Vehicle Been Parked So Far?	
What Are Your Usual Parking Hours?	o 08:00-10:00 o 10:00-12:00 o 12:00-14:00 o 14:00- 16:00 o 16:00- 18:00 o 18:00 -
Do You Have Difficulty Finding a Parking Space?	o Yes o No
Are You Satisfied with the Parking Fees?	o Yes, I Am Satisfied o No, I Am Not
Where Do You Typically Park Your Vehicle During the Day?	o Roadside o Side Street o Open Parking Lot o Covered Parking Lot
How Many Hours Do You Park Your Vehicle During the Day?	o 0-2 Hours o 2-4 Hours o 4-6 Hours o All Day
Have You Ever Paid a Parking Fine for Your Vehicle?	o Yes o No
How Do You Reach Your Destination After Parking Your Vehicle?	o On Foot o By Bus o By Minibus o By Bicycle o By Shuttle
STRATEGY DETERMINATION	
What Is Most Important to You in Parking Areas?	
o Proximity to the target o Security o Fee o Roadside Parking o Nearby Parking	
What Is the Maximum Distance You Prefer to Park Your Vehicle?	
o 0-50 Meters o 51-100 Meters o 101-150 Meters o 151-250 Meters o 251 Meters and Above	
Would You Like to Reserve a Parking Space in Advance?	
o Yes o No	
Would You Use Shared Parking Areas?	
o Yes o No	
Would You Use an App to Check Parking Availability on Your Phone?	
o Yes o No	
Are You Satisfied with the Parking Fees? If Not, What Is Your Suggestion?	
o Yes, I Am Satisfied o No, I Am Not	
Should Parking Fees Be the Same Everywhere or Vary Based on Location, Type, and Duration?	
o Yes, They Should Vary o No, They Should Be the Same	
Would You Consider Using Another Mode of Transportation After Parking Your Vehicle? If Yes, What Is Your Preference?	
o Yes, I Would Consider (..........................) o No, I Would Not	
Would You Prefer a Nearby High-Fee Parking Lot or a Distant Low-Fee Parking Lot?	
o Nearby and High-Fee o Distant and Low-Fee	
If You Could Benefit from Public Transportation at a Discount by Using It Frequently, Would Your Usage Increase?	
o Yes, It Would Increase o No, It Would Not	
If Infrastructure and Routes for Bicycle Transportation Were Strengthened Across the City, Would You Use a Bicycle as a Means of Transportation? If Your Answer Is No, What Is the Reason and Which Mode of Transportation Do You Prefer?	
o Yes, I Would Use It o No, I Would Not Use It, Because .... Transportation Preference	

If Pedestrian Paths Were Strengthened Across the City, Would You Use Walking as a Means of Transportation? If Your Answer Is No, What Is the Reason and Which Mode of Transportation Do You Prefer?
o Yes, I Would Walk o No, I Would Not, Because .... Transportation Preference ....
YOUR COMMENTS AND SUGGESTIONS

The aim of the study is to incorporate user input into strategy selection through survey studies. Initially, parking strategy selection was conducted using traditional methods, where parking lot occupancy and usage rates were determined, and strategy choices were made based on these results, without considering user preferences or usage habits. In the subsequent stage, user involvement was integrated into the strategy selection process through survey questions. The strategies identified from occupancy and usage data were presented to parking users via the "User Survey" study to observe their responses and attitudes. This phase aimed to refine the strategies by incorporating user feedback and addressing their suggestions and complaints. The goal was to evaluate the applicability of the proposed strategies in real-world conditions and assess public engagement with the system. Car park user surveys were conducted in Ortahisar city center, involving 442 participants.

The Analytic Hierarchy Process (AHP) is employed as the primary multi-criteria decision-making (MCDM) method to prioritize parking management strategies. While AHP constitutes the methodological framework, the criteria evaluated within this framework—such as demand level, land-use compatibility, accessibility, implementation cost, and user satisfaction—represent the evaluative dimensions informed by literature review and expert opinions. This distinction is critical: AHP is the decision-making tool, whereas the listed items are criteria structured and weighted within that tool. The Analytic Hierarchy Process (AHP) study, conducted with 13 experts in transportation, further advanced this process. The study began by defining the decision-making problem and setting strategy selection as the objective. Necessary decision criteria were identified through the "User Survey," and possible decision alternatives were outlined. A hierarchical structure was established to organize these alternatives. Importance levels for each criterion were determined using pairwise comparisons, and the prioritization of alternatives was based on these comparisons. The agreement rate was calculated from the expert prioritization data. Alternatives were ranked according to their priority values, and sensitivity analysis was performed to finalize the study.

The AHP method, a well-established Multi-Criteria Decision-Making (MCDM) technique, was utilized in this study. AHP, as defined by Zionts (1979), is a decision analysis method used to address complex decision problems across various fields. It involves analyzing complex situations and making informed decisions (Darko et al., 2018). The technique is known for its pairwise comparison approach and is widely applied in decision support systems (Podvezko, 2009). AHP integrates both qualitative and quantitative factors, allowing for a comprehensive evaluation of criteria (Sáenz-Royo et al., 2024). Multi-criteria decision-making focuses on modeling and analyzing decisions based on multiple criteria (Dağdeviren & Eren, 2001; Kocamustafaoğulları, 2007). AHP's ability to incorporate subjective and objective considerations makes it a robust tool for decision-making (Canhasi, 2010).

In the AHP approach, criteria were compared using a matrix format with values ranging from 1 to 9. A value of 1 was placed along the diagonal of the matrix, representing the comparison of each criterion with itself. The criteria compared in this study included:

- P1: Safety
- P2: Proximity to the target
- P3: Reserved parking space
- P4: Shared parking space
- P5: Predisposition to mobile applications

- P6: Wage sensitivity
- P7: Sensitivity to pedestrian transportation

Table 4 provides a sample expert evaluation.

Table 4 Questionnaire Study Where Comparison Values are Obtained

Criteria	Preferred																	Criteria
Safety	9	8	7	6	5	4	3	2	1	**2**	3	4	5	6	7	8	9	Proximity to the target
Safety	9	8	7	**6**	5	4	3	2	1	2	3	4	5	6	7	8	9	Reserved parking space
Safety	9	8	7	6	5	4	3	2	1	2	3	**4**	5	6	7	8	9	Shared parking space
Safety	9	8	7	6	5	4	3	2	1	2	3	4	**5**	6	7	8	9	Predisposition to mobile applications
Safety	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Wage sensitivity
Safety	9	8	7	6	5	4	**3**	2	1	2	3	4	5	6	7	8	9	Sensitivity to pedestrian transportation
Proximity to the target	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Reserved parking space
Proximity to the target	9	8	7	6	5	4	3	2	1	**2**	3	4	5	6	7	8	9	Shared parking space
Proximity to the target	9	8	7	6	5	**4**	3	2	1	2	3	4	5	6	7	8	9	Predisposition to mobile applications
Proximity to the target	9	8	7	6	5	4	3	2	1	2	3	4	5	**6**	7	8	9	Wage sensitivity
Proximity to the target	9	8	7	6	5	4	3	2	1	2	3	4	**5**	6	7	8	9	Sensitivity to pedestrian transportation
Reserved parking space	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	**8**	9	Shared parking space
Reserved parking space	9	8	**7**	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Predisposition to mobile applications
Reserved parking space	9	8	7	6	5	4	3	2	1	2	3	**4**	5	6	7	8	9	Wage sensitivity
Reserved parking space	9	8	7	6	5	4	3	2	1	**2**	3	4	5	6	7	8	9	Sensitivity to pedestrian transportation
Shared parking space	9	8	7	6	5	4	3	2	1	2	3	4	5	6	**7**	8	9	Predisposition to mobile applications
Shared parking space	9	8	7	6	5	4	**3**	2	1	2	3	4	5	6	7	8	9	Wage sensitivity
Shared parking space	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Sensitivity to pedestrian transportation
Predisposition to mobile applications	9	8	7	6	5	**4**	3	2	1	2	3	4	5	6	7	8	9	Wage sensitivity
Predisposition to mobile applications	9	8	7	6	5	4	3	2	1	**2**	3	4	5	6	7	8	9	Sensitivity to pedestrian transportation
Wage sensitivity	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	**9**	Sensitivity to pedestrian transportation

STEP 3: Based on the survey studies and expert consultations conducted for strategy selection, a prioritization of the strategies deemed suitable for the city was necessary. The results from the survey and the Analytic Hierarchy Process (AHP) study led to the categorization of strategies into two main groups:

First Priority Group: This group comprises strategies that were consistently identified as top priorities based on both user feedback and expert opinions. These strategies are considered the most critical for addressing the city's parking and traffic issues.

Second Priority Group: This group includes strategies where there was a discrepancy between user and expert opinions. Although these strategies may not align fully with user preferences, experts believe they could significantly enhance traffic flow and overall quality if implemented.

This prioritization helps in focusing efforts on strategies with the greatest consensus and potential impact while also considering expert recommendations for additional improvements.

2.3. Integration of Data Sources

In this study, a multi-layered methodological approach was employed to ensure a comprehensive assessment of parking management strategies in Ortahisar. Firstly, field-based parking inventories and temporal occupancy counts provided empirical data on the actual spatial and temporal demand for parking. These were conducted at multiple time intervals during a typical weekday to reflect peak and off-peak usage patterns.

Secondly, a user survey was designed to capture individual-level perceptions, preferences, and behavioral tendencies regarding parking availability, accessibility, pricing, and enforcement mechanisms. These user insights allowed the study to incorporate demand-side sensitivities into the strategy selection process.

Thirdly, expert opinions were collected from 13 professionals including transportation planners, municipal officers, and academic experts involved in the city’s transportation planning. These inputs were structured into pairwise comparisons using the Analytic Hierarchy Process (AHP), and consistency ratios were applied to filter reliable responses. Seven expert responses passed the $CR<0.1$ threshold and were used to construct the final decision matrix.

The integration of these data sources followed a tiered logic: parking inventory and counts identified physical constraints and baseline conditions; user surveys provided behavioral and perceptual dimensions; and expert evaluations offered strategic prioritization using quantitative weighting. The final outcome was a harmonized framework wherein empirically observed conditions, user-side feedback, and expert-driven weights were triangulated to propose context-sensitive parking strategies.

3. Analysis and Findings

This section provides an analysis of the results derived from field studies and survey data. Strategy selection was informed by the findings from the parking lot survey, user survey, and Analytic Hierarchy Process (AHP) study. The choices were made based on a comprehensive evaluation of these studies and analyses.

The term parking survey refers to the field-based inventory and occupancy count of on- and off-street parking lots, while the term user survey denotes a questionnaire conducted with individual users to gather opinions, preferences, and behavioral patterns regarding parking practices.

3.1. Parking Survey Results

An examination of the parking infrastructure in Trabzon reveals a diverse array of parking facilities. It has been identified that both licensed parking businesses, regulated by the Zabıta Directorate, and unlicensed operators are present in the city. Municipal parking operations are managed by TRABİTAŞ, a municipal company, which oversees both off-street and roadside parking lots. TRABİTAŞ operates 13 off-street and 6 roadside parking facilities. Among the 13 off-street parking lots managed by the municipality, 2 are enclosed and 11 are open-air facilities. The total capacity of these off-street parking lots is 1,025 vehicles, and all are currently in active operation.

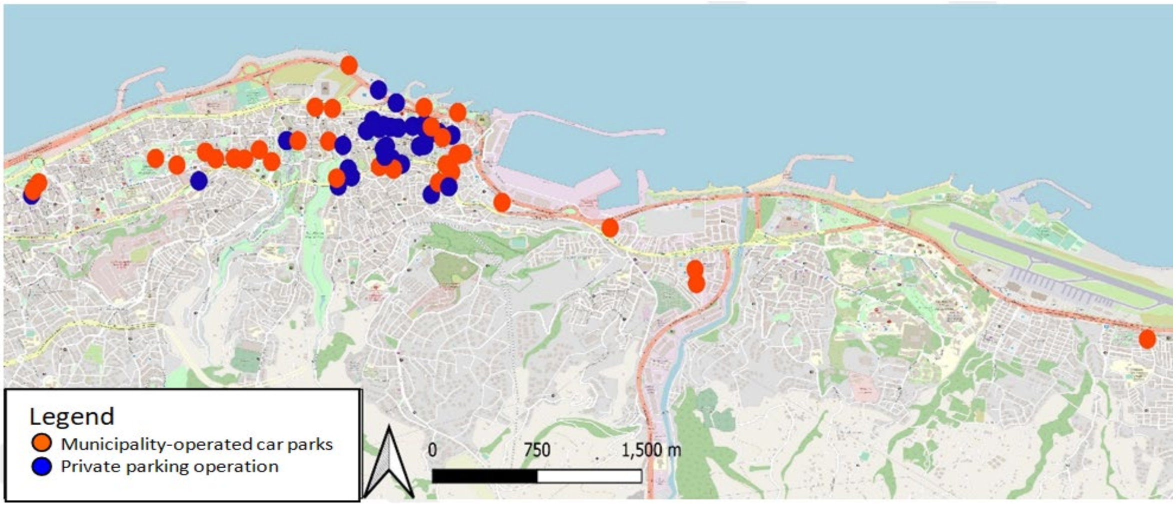

Figure 4 Location of parking lots in Ortahisar district (Source: Produced within the scope of the study)

As part of the study, 57 parking lots in Ortahisar were inspected. Of these, 12 are roadside parking facilities and 45 are off-street parking lots. During the on-site observation and identification studies, it was noted that 8 of the off-street parking lots were out of service, and 1 was designated as a hospital parking lot serving patients and their families. Roadside parking areas, which are concentrated in the city center and around Hagia Sophia Square—a prominent and dynamic area—are primarily designed for parallel parking.

A comprehensive parking lot inventory survey was conducted across 69 parking lots, with a detailed "Parking Lot Survey" carried out in 32 of these facilities. The surveys aimed to assess various aspects of the parking lots, including types, capacities, ground features, fee structures, and construction dates. In addition to evaluating these physical characteristics, a census was performed to determine capacity utilization and occupancy rates. This analysis highlighted parking areas facing capacity issues. Location of off-street and roadside parking lots with capacity problems are given in Figure 6.

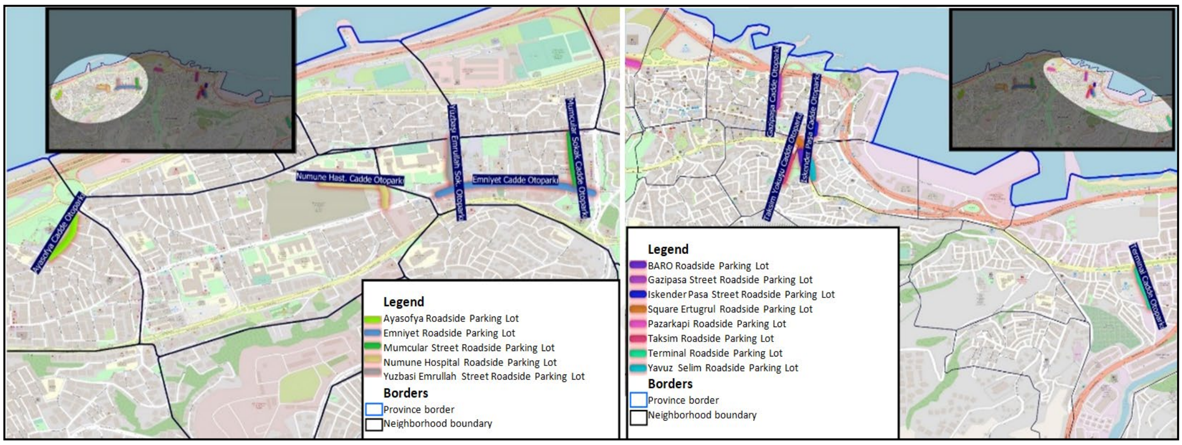

Figure 5 Roadside parking areas

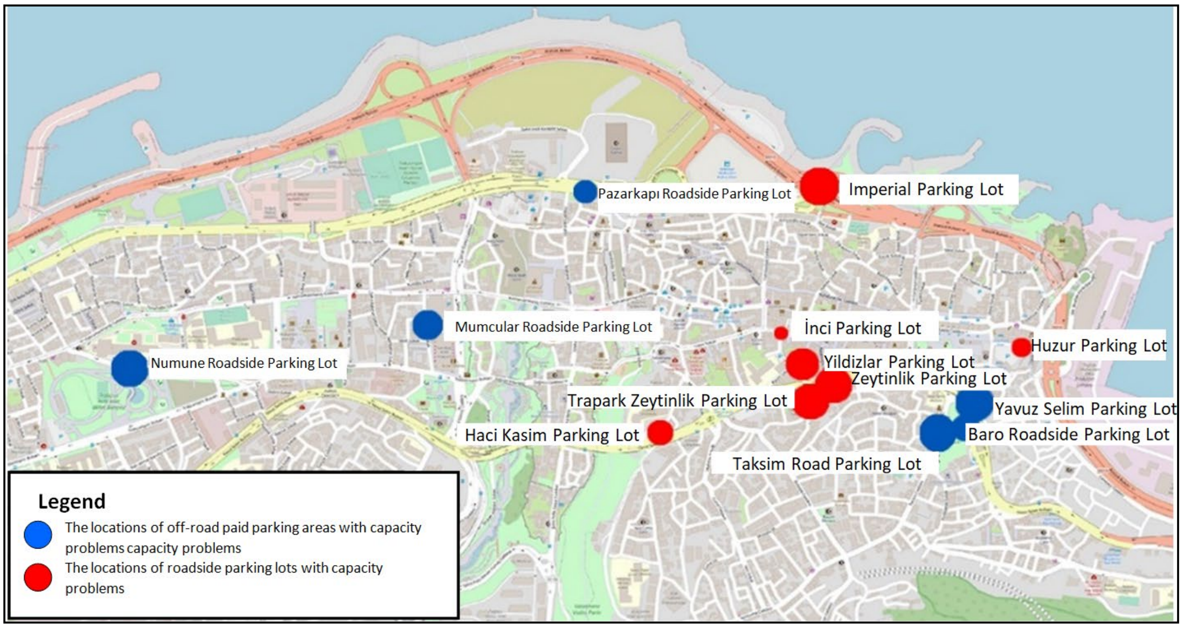

Figure 6 Location of off-street and roadside parking lots with capacity problems

Ortahisar district serves as the central hub of Trabzon province in terms of social, economic, and spatial aspects. This centrality leads to the concentration of various issues, including transportation, accessibility, and parking challenges, within the district. The current population of Ortahisar and projected population figures for the year 2040, based on the development areas outlined in the master development plans, are provided below. Current and 2040 Population Projections for Ortahisar District are given in Table 5.

Table 5 Current and 2040 Population Projections for Ortahisar District

Current Population	328.509
Additional Population Expected in 2040	322.899
Total Population in 2040	651.408

In 2021, the population of Ortahisar district was recorded at 328,509. By 2040, the population is projected to increase by an additional 322,809, resulting in a total estimated population of 651,408. Several approaches for calculating parking demand based on vehicle numbers are outlined below (Özdirim, 1994):

West German Criteria: This method, considered applicable to Turkish cities, suggests that one parking space should be provided for every 5-8 cars in the city center.

U.S. City Standards: In large cities across the United States, it is estimated that 12% of all vehicles will be parked in the city center during peak hours. In smaller cities, this percentage increases to 18%. To estimate parking demand, the total number of vehicles is calculated using coefficients of 5 and 8, based on the West German criteria, for both the current year and the year 2040. Ortahisar District City Center Parking Demand According to the First Method (According to 5-8 coefficients) and Parking Demand for the City Center of Ortahisar District According to the Second Method (According to 12% and 18% rates) are given in Table 6 and 7.

Table 6 Ortahisar District City Center Parking Demand According to the First Method (According to 5-8 coefficients)

Coefficient	Current Situation (Vehicle)	Year 2040 (Vehicle)
5	12.746	32.570
8	7.966	20.356

According to the second method, the large city coefficient is 12% and the small city coefficient is 18%. Parking demand according to these approaches is given in Table.

Table 7 Parking Demand for the City Center of Ortahisar District According to the Second Method (According to 12% and 18% rates)

Percentage (%)	Current Situation (Vehicle)	Year 2040 (Vehicle)
12	7.647	19.542
18	11.471	29.313

Given that Ortahisar does not exhibit metropolitan characteristics at the national or global level, and considering the relatively high projection values for 2040, it is deemed appropriate to apply the criterion of one vehicle per eight vehicles in the city center. According to this approach, the current parking demand is calculated at 7,966 vehicles, while the projected demand for 2040 is 20,356 vehicles. In response to these projections, traditional calculation methods suggest that strategies aimed at enhancing the efficiency of existing parking spaces will be optimal, especially considering the anticipated population growth and the resulting increase in parking space requirements. Therefore, the following strategies are proposed for the city:

Strategies to Increase Parking Lot Effectiveness:

- Sharing of Reserved Areas

- Strategies for Shared Parking Spaces between Locations

Given the challenges associated with creating new parking areas due to the city's morphological constraints or relocating existing parking facilities, these strategies aim to optimize the use of current resources and address the high demand for parking in the city center.

Setting Parking Maximums (Upper Limits of Standards):

This strategy aims to set maximum parking limits to manage demand effectively. The primary goal is to encourage users to adopt alternative modes of transportation, such as public transit, walking, cycling, or shuttle services.

Parking Pricing Strategies:

This approach seeks to alleviate parking issues and reduce urban transportation problems by influencing demand through pricing mechanisms.

Improving Pricing Methods and Providing Financial Incentives:

These strategies focus on developing a comprehensive pricing policy for parking areas and reducing demand by offering affordable transportation alternatives, thus encouraging users to switch to public transport. Based on demand and projection calculations, the implementation of these strategies is expected to alleviate future congestion and address bottlenecks in parking facilities effectively.

3.2. User Survey Results

The survey results indicate that the primary purpose for participants traveling to the region is business-related, followed by shopping and other activities. Notably, 97% of the participants use their own private vehicles for these trips to the city center. When parking, users typically prefer to park for a duration of 0-15 minutes. It has been observed that off-street open parking areas are generally favored by users. Figure 7 illustrates the preferences regarding travel and parking among the users.

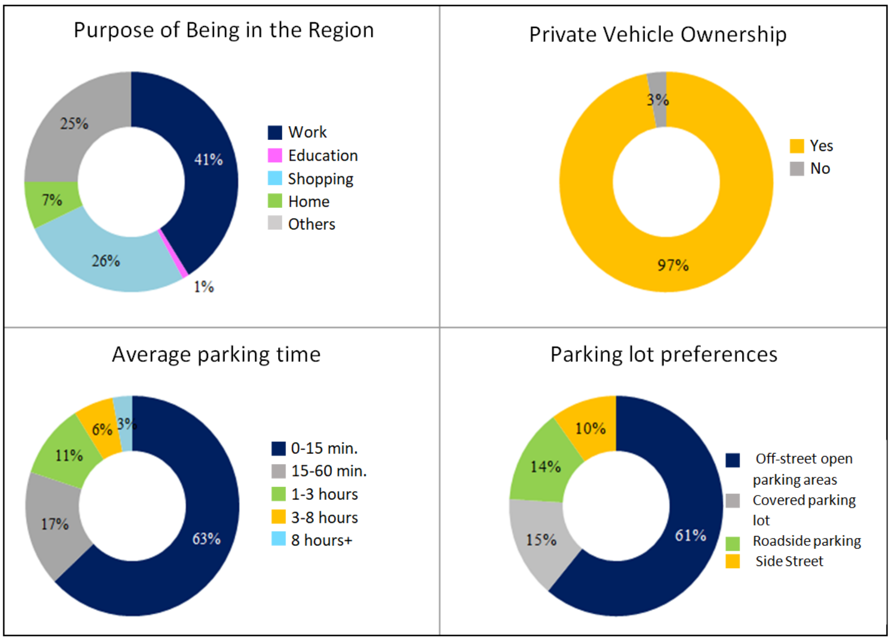

Figure 7 Users' travel and parking trends

The primary concern for users when selecting parking facilities is security, followed by proximity to their destination and the fee structure. An analysis of user preferences regarding the distance between parking areas and destinations reveals a relatively even distribution. Specifically, 23% of users consider distances ranging from 0-50 meters to be acceptable, 25% prefer distances of 51-100 meters, and 24% are comfortable with distances of 250 meters or more. However, the 51-100 meter range is the most frequently reported preference for walking distance. Figure 8 illustrates the distribution of these responses.

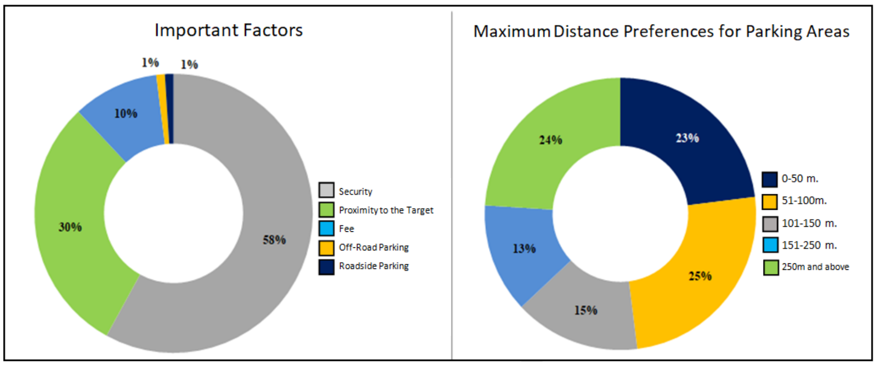

Figure 8 Issues of importance for participants in parking lots

In addition to socio-demographic and transportation data, the survey participants were queried on specific aspects to identify parking strategies that could enhance the efficiency and utilization of parking facilities in Trabzon. The survey addressed several key management strategies, including the use of reserved parking spaces, the implementation of shared parking arrangements, the potential for modal shifts in transportation, and preferences regarding possible changes in transportation modes. Users' attitudes and preferences towards strategies are given in Figure 9.

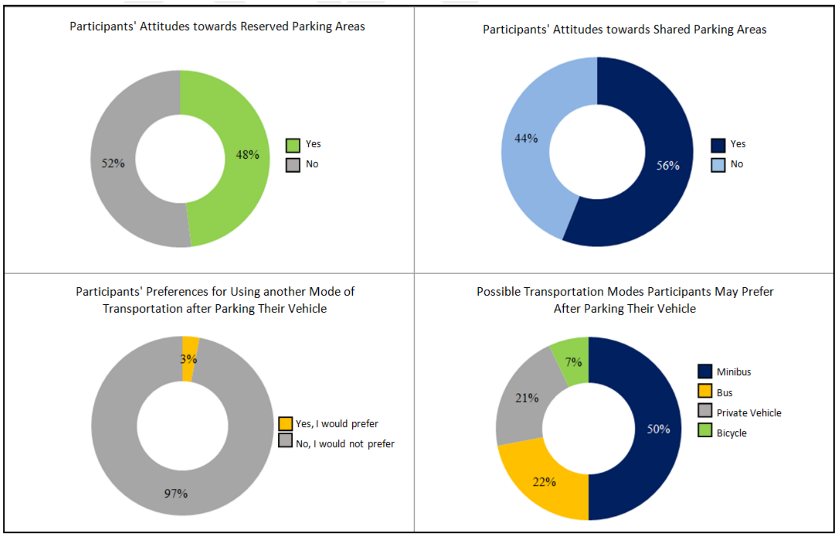

Figure 9 Users' attitudes and preferences towards strategies

Parking strategies play a crucial role in managing demand and promoting the use of alternative transportation modes such as public transit, cycling, and walking to alleviate urban traffic congestion. This section of the survey explored users' attitudes toward cycling and pedestrian transportation. Findings indicate that 60% of participants do not favor cycling, whereas 40% expressed an interest in using bicycles. Additionally, 19% of users indicated a reluctance to engage in pedestrian travel, while 81% reported a willingness to walk. Those who do not prefer walking or cycling cited factors such as challenging terrain, age, long distances, and safety concerns, preferring automobiles over these alternative modes. The Figure 10 illustrates the survey participants' responses.

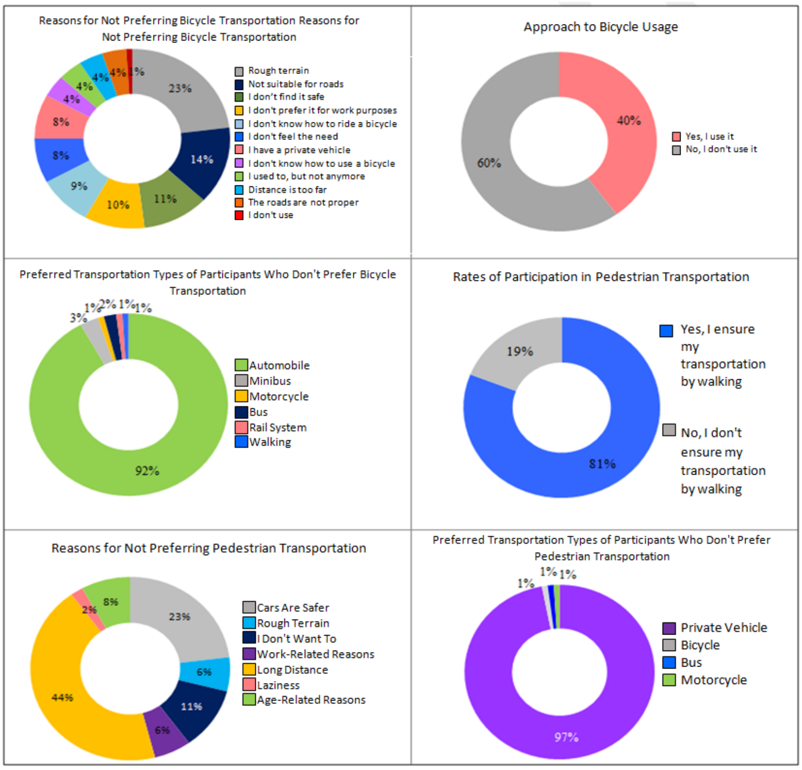

Figure 10 Users' attitudes towards pedestrian and bicycle transportation

The survey also assessed users' attitudes toward parking fees and fee policies. Of the respondents, 60% expressed satisfaction with the current fee structure, while 40% advocated for changes. The most notable suggestion was to adjust pricing policies, followed by requests for tariff reorganization, expansion of parking areas, and promotional campaigns. In the event that a distance-based pricing system were implemented, 66% of users indicated a preference for parking in areas closer to their travel destinations, even if this meant incurring higher fees.

The survey results reveal that parking lot users predominantly utilize parking for business and shopping purposes. A significant majority, 97%, own private vehicles. Due to the city's hilly terrain, transportation between residential areas and commercial centers is facilitated by inclined roads, challenging climatic conditions, and the linear layout of the city along the coast. These factors contribute to a high reliance on private vehicles. Consequently, users prefer parking facilities in proximity to their travel destinations. Despite the strong preference for private vehicles, improvements in pedestrian and bicycle infrastructure could lead to increased use of these modes. Additionally, policies that encourage public transportation may gradually reduce dependence on private vehicles, positively impacting urban traffic.

Based on the analysis of parking lot surveys, census studies, and user feedback, seven criteria have been identified as ideal for parking areas, considering their applicability and manageability for both the city and its users. These criteria are:

- Sensitivity to pedestrian transportation
- Fee sensitivity
- Reserved parking spaces
- Shared parking spaces
- Integration with mobile applications
- Proximity to destinations
- Security

These criteria will be prioritized using the Analytical Hierarchy Process (AHP) in the following section, after which short- and long-term parking strategies will be developed in alignment with the ranking results.

3.3. AHP Analysis Results

Based on the analysis of parking demand, user feedback, and operational deficiencies, a set of seven criteria was identified for evaluating and selecting parking management strategies. Following the methodology described in Section 2.2, the expert-based AHP process was conducted using criteria derived from both the user survey and demand analysis. These criteria were used in the Analytic Hierarchy Process (AHP) to structure expert decision-making:

- Security
- Proximity to Destinations
- Reserved Parking Spaces
- Shared Parking Spaces
- Integration with Mobile Applications
- Fee Sensitivity
- Sensitivity to Pedestrian Transportation

These criteria are consistent with common decision-making factors identified in previous AHP-based parking studies (Chien et al., 2020; Han et al., 2018; Waraich & Axhausen, 2012), ensuring both contextual relevance and methodological rigor.

As a result of the study, safety ranked first, followed by proximity to the destination and sensitivity to pedestrian transportation strategies. In the final phase of the study, expert opinions were collected to establish the priority weights among the evaluation criteria used in the Analytic Hierarchy Process (AHP). The expert group consisted of 13 professionals including academics in transportation planning and industrial engineering, as well as practitioners involved in the Trabzon Transportation Master Plan and municipal experts from relevant departments. Pairwise comparison forms were distributed, and the responses were analyzed to generate a combined criteria matrix. Among the 13 expert responses collected, consistency ratios (CR) were calculated for each pairwise comparison matrix in accordance with the standard AHP procedure. Based on Saaty's acceptable threshold of 0.1, 7 responses were found to be consistent (CR < 0.1) and thus were included in the final aggregation process. The geometric means of these consistent responses were used to construct the final pairwise comparison matrix, as shown in Table 8.

Table 8 Criteria Selection in Expert Study

	C1	C2	C3	C4	C5	C6	C7
Criteria	Security	Proximity to destinations	Reserved parking spaces	Shared parking spaces	Integration with mobile applications	Fee sensitivity	Sensitivity to pedestrian transportation
Expert 1	0.05620	0.246620	0.09861	0.117010	0.05068	0.07543	0.21577
Expert 4	0.20427	0.151990	0.14565	0.061157	0.03711	0.1528	0.219327
Expert 6	0.08725	0.156939	0.12909	0.059869	0.10857	0.1606	0.18244
Expert 8	0.31216	0.042956	0.06340	0.054122	0.04367	0.06836	0.19365
Expert 9	0.31073	0.145863	0.03804	0.048047	0.03124	0.21659	0.04659
Expert 12	0.22698	0.183322	0.06517	0.021029	0.05179	0.14038	0.03799
Expert 13	0.27864	0.156290	0.05580	0.060165	0.03525	0.12189	0.23213
Geometric Average	0.21089	0.15485	0.08511	0.060200	0.05119	0.13372	0.16113

A pairwise comparison matrix has been given based on the final priority weights presented in Table 9. This matrix reflects the relative dominance of each criterion over the others, consistent with the logic of the Analytic Hierarchy Process (AHP). The values were calculated using Saaty's fundamental scale, where each element of the matrix is obtained by dividing the relative weight of one criterion by another. The resulting matrix ensures reciprocal consistency and forms the basis for the prioritization results provided in Table 9.

Table 9 Criteria-to-Criteria Pairwise Comparison Matrix

Criteria	Security	Proximity	Reserved	Shared	Mobile	Fee	Pedestrian
Security	1.000	1.362	2.477	3.504	4.120	1.577	1.309
Proximity	0.734	1.000	1.815	2.571	3.026	1.151	0.960
Reserved	0.404	0.551	1.000	1.416	1.664	0.636	0.528
Shared	0.285	0.389	0.706	1.000	1.175	0.449	0.373
Mobile	0.243	0.330	0.601	0.851	1.000	0.382	0.318
Fee	0.634	0.869	1.572	2.228	2.619	1.000	0.828
Pedestrian	0.764	1.042	1.893	2.682	3.143	1.207	1.000

To ensure the internal consistency of expert judgments in the pairwise comparison process, the consistency index (CI) and maximum eigenvalue (λ_{max}) were calculated according to the standard AHP methodology (Saaty, 1980). The calculated λ_{max} value is 7.716, and the resulting consistency index (CI) is 0.119. Since the number of criteria is 7, the corresponding Random Index (RI) is 1.32, and the consistency ratio (CR = CI / RI) is approximately 0.090. This value is below the commonly accepted threshold of 0.1, indicating an acceptable level of consistency in the aggregated matrix. Consistency Index and Maximum Eigenvalue (λ_{max}) are given in Table 10.

Table 10 Consistency Index and Maximum Eigenvalue (λ_{max})

λ_{maks}	7.716179314
CI	0.119363219

To enhance methodological transparency, detailed normalization tables of the consistent pairwise comparison matrices used in the aggregation process are presented. The standard normalization step in AHP, in which each element is divided by the column sum to ensure comparability across criteria, is given in the Table 11.

Table 11 Normalization Stages

NORMALIZATION / 1st Stage								**NORMALIZATION / 3th Stage**							
	K1	K2	K3	K4	K5	K6	K7		K1	K2	K3	K4	K5	K6	K7
K1	1	0.17	0.13	1	1	1	1	K1	0.032	0.062	0.047	0.037	0.04	0.034	0.028
K2	6	1	1	6	6	5	5	K2	0.194	0.365	0.364	0.222	0.24	0.172	0.139
K3	8	1	1	6	6	8	6	K3	0.258	0.365	0.364	0.222	0.24	0.276	0.167
K4	1	0.125	0.167	1	4	9	6	K4	0.032	0.046	0.061	0.037	0.16	0.31	0.167
K5	1	0.167	0.143	1	1	4	8	K5	0.032	0.061	0.052	0.037	0.04	0.138	0.222
K6	6	0.167	0.111	6	5	1	9	K6	0.194	0.061	0.04	0.222	0.2	0.034	0.25
K7	8	0.111	0.2	6	2	1	1	K7	0.258	0.041	0.073	0.222	0.08	0.034	0.028

NORMALIZATION / 2nd Stage								**NORMALIZATION / 4th Stage**	**NORMALIZATION / 5th Stage**
	K1	K2	K3	K4	K5	K6	K7	0.564	14.053
K1	0.032	0.062	0.047	0.037	0.04	0.034	0.028	3.19	13.167
K2	0.194	0.365	0.364	0.222	0.24	0.172	0.139	3.804	14.079
K3	0.258	0.365	0.364	0.222	0.24	0.276	0.167	2.483	21.387
K4	0.032	0.046	0.061	0.037	0.16	0.31	0.167	1.732	20.818
K5	0.032	0.061	0.052	0.037	0.04	0.138	0.222	2.513	17.562
K6	0.194	0.061	0.04	0.222	0.2	0.034	0.25	1.513	14.393
K7	0.258	0.041	0.073	0.222	0.08	0.034	0.028	**AVERAGE (λmax.): 16.494**	

To determine the prioritization degrees shown in Table 11, the standard Analytic Hierarchy Process (AHP) procedure was followed. In this process, the pairwise comparison values provided by the experts are first normalized. This normalization ensures that each column in the comparison matrix sums to one, making the values comparable across criteria. After normalization, the priority weight of each criterion is obtained by calculating the average of its normalized values across all comparisons. These average values represent the relative importance of each criterion and are referred to as the prioritization degrees. This method is widely recognized in the AHP literature (e.g., Saaty, 1980; Forman & Gass, 2001; Ishizaka & Labib, 2011) as a standard approach for deriving weights from consistent comparison matrices.

The results of the geometrically averaged criteria were ranked from largest to smallest and the "Safety" criterion with the highest value of 0.210895 was the most preferred criterion by the experts in the study, followed by the "Proximity to Target" criterion with 0.154846. The order of preference of the criteria, where the expert opinions are analyzed and the criteria are calculated with the AHP method, is given in the Table 12.

Table 12 Prioritization of Criteria

Criteria	Selection	Preference order of criteria
Security	0.210895	1
Sensitivity to pedestrian transportation	0.161126	2
Proximity to destinations	0.154846	3
Fee sensitivity	0.133717	4
Reserved parking spaces	0.085109	5
Shared parking spaces	0.060199	6
Integration with mobile applications	0.051689	7

The expert study identified "Safety" as the highest priority criterion. Similarly, the user survey revealed that safety is the most significant factor for users when choosing parking facilities. This criterion is crucial in influencing users' preferences for parking location or type. According to the expert study, the second priority is "Sensitivity to Pedestrian Transportation, followed by "Proximity to Destination" as the third priority. These two criteria are interrelated and can be addressed through effective implementation and optimal strategies. Enhancing the pedestrian transportation system can encourage users to utilize parking facilities at various distances, as indicated by the balanced distribution of preferred distances in the user survey. Strategies that support and emphasize pedestrian transportation can revitalize urban mobility.

"Proximity to Destination" is the next priority criterion where pedestrian transportation cannot be sufficiently improved. Field observations and surveys reveal that the city's topographical challenges, such as sloping terrain, make pedestrian travel difficult, leading users to favor parking areas closer to their destinations. The survey data suggest that users predominantly rely on private vehicles due to the slope, distance, and climatic conditions. However, improving pedestrian infrastructure could increase users' willingness to use alternative modes of transportation.

The "Wage Sensitivity" criterion, derived from the survey, reflects a mixed response. While 60% of respondents are satisfied with the current tariff structure, 40% believe that prices should be more affordable. Nonetheless, when given a choice between safety, proximity to the destination, fare, and parking locations, fare was the most preferred issue after safety and proximity, aligning with the findings of the expert study.

4. Setting Properties in Strategy Selection

As previously outlined, three distinct methods were employed to develop the parking strategy: demand estimation, user surveys, and the Analytical Hierarchy Process (AHP). To ensure these methods collectively represent a coherent and meaningful framework, the results were integrated and applied to the Ortahisar city center. Each method supports and complements the others.

- The strategies identified through demand forecasting include:
- Sharing Reserved Areas
- Strategies for Shared Parking Spaces across Locations
- Parking Pricing Strategies
- Enhancing Pricing Methods and Providing Financial Incentives
- Park & Ride Strategy

While these strategies address the parking issues in the city, their practical applicability was questioned in relation to the city’s physical structure and established transportation patterns. Consequently, these strategies were presented to parking lot users through a survey to gauge their reactions and preferences. The strategies identified from the user survey include:

- Safe Urban Mobility
- Parking Pricing Strategies
- Sharing of Reserved Areas
- Strategies for Shared Parking Spaces between Locations
- Improving Pricing Methods and Providing Financial Incentives
- Enhancing Walking and Cycling Facilities

Based on the data obtained from both the demand forecasting and user survey, these strategies were used as criteria for the AHP study. The goal was to integrate demand results and user preferences with expert opinions to assess the suitability of the strategies for the city.

The criteria established for the AHP study are:

- Sensitivity to Pedestrian Transportation
- Fee Sensitivity
- Reserved Parking Spaces
- Security

- Shared Parking Spaces
- Integration with Mobile Applications
- Proximity to Destinations

Through these three studies, a prioritization hierarchy for strategy selection was developed. The prioritization is as follows:

- First Priority: Strategies where there is consensus between expert opinions and user preferences. These strategies should be prioritized in the decision-making process.
- Second Priority: Strategies favored solely by experts. These strategies are given secondary priority based on the city's structure, traffic culture, supply-demand balance, and expert knowledge and experience.

Figure 11 illustrates the prioritization exercise in strategy selection.

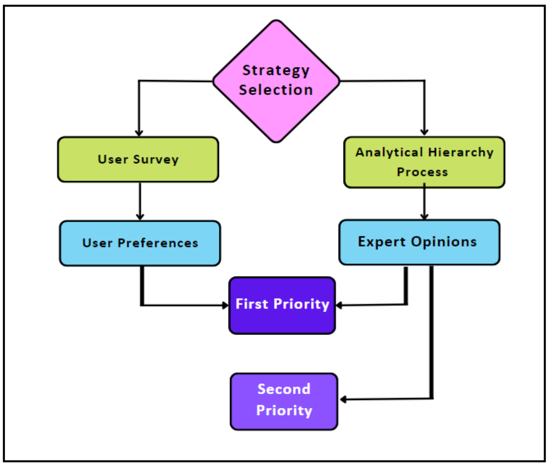

Figure 11 Prioritization study in strategy selection

First Priority Strategies are those where there is a consensus between user preferences and the AHP study results. These strategies are prioritized in the selection process. The most frequently preferred strategies include:

- Security
- Sensitivity to Pedestrian Transportation
- Proximity to Destination
- Integration with Mobile Applications

Among these, security emerges as the highest priority. Both users and experts agree that the safety of life and property in parking areas is paramount.

Second Priority Strategies consist of recommendations from experts that users have not favored but are proposed to maintain traffic flow and address parking issues in Trabzon Ortahisar city center. While these strategies are derived from data and expert evaluation, their applicability is context-sensitive and may vary depending on implementation capacity and behavioral adaptation. These strategies include:

- Positional Pricing
- Park & Ride System
- Expansion of Cycling Infrastructure

Positional Pricing aims to manage parking supply and demand by spatially varying parking fees, with the goal of reducing central area parking, especially roadside parking. Higher fees in a designated geographical area are intended to discourage parking in the city center, addressing traffic disruptions caused by high vehicle density and inadequate pedestrian routes.

Park & Ride (P&R) is another recommended strategy. Although users may not currently favor P&R, expert evaluations suggest it could support urban mobility improvements in the context of Ortahisar's morphological and traffic characteristics. The strategy is not prescriptive but proposed as a planning tool subject to contextual assessment. The P&R system is intended to provide an alternative to central city parking and improve overall traffic conditions.

Expanding Cycling Infrastructure is the final expert recommendation. Bicycles offer a modern transportation option for urban travel, either as a standalone mode or as a feeder to public transport. To increase cycling adoption, improvements should be made to the bicycle network, including the establishment of maintenance stations and rest areas. While current user preferences for cycling are limited, infrastructure enhancements—such as network continuity and support facilities—are expected to create enabling conditions, as supported by expert assessments. These do not represent forecasts, but context-informed recommendations.

All these studies and recommendations are grounded in demand calculation. While these models incorporate user preferences and expert inputs, the resulting strategies are indicative rather than predictive. They are intended to inform decision-makers within current constraints, not to prescribe long-term outcomes.

5. Results and Consideration

The key contribution of this research lies in its multi-layered integration of traditional demand-based models, real-time user preferences, and expert-based prioritization using AHP. This hybrid structure sets the study apart from existing literature by offering a more grounded and participatory approach to parking strategy selection. Parking management strategies represent an advanced approach in the contemporary planning paradigm, offering solutions to various parking-related issues such as capacity, volume, utilization, type, and operation. This approach aims to enhance the capacity of parking facilities through more efficient use, avoiding the need for additional infrastructure. It is particularly effective in regions with challenging geographical features and limited land use, such as Trabzon.

Survey data indicates that there are parking management strategies that the community will readily adopt due to their alignment with cultural habits and daily routines. The selected strategies are designed to formulate policies and programs that promote more efficient use of parking spaces, yielding economic, social, and environmental benefits. While these strategies typically provide a 5%-10% improvement in the short term, they can achieve 20%-40% efficiency gains in the long term through various combinations and effective practices. Implementing these strategies without constructing new facilities is both cost-effective and feasible.

The integration of field data, user preferences, and expert judgments enabled a multi-dimensional understanding of parking dynamics in Ortahisar. These findings validate the hybrid methodological approach outlined earlier, demonstrating how traditional data, user insights, and expert analysis can converge into implementable parking strategies. This comprehensive perspective facilitated the identification of context-specific strategies that are not only technically sound but also behaviorally and administratively feasible. The prioritization of strategies through expert-driven AHP analysis reflected both on-ground realities and stakeholder expectations, thus enhancing the operational applicability of the final recommendations.

Parking management enhances user service quality and choice, fosters flexibility, and contributes to the creation of more functional communities. It also adapts to new demands and uses. Essential criteria for successful parking management include providing convenient parking options and effectively informing users about the parking system.

This study integrates traditional methods with user opinions and demand calculations to propose parking strategies for Trabzon Ortahisar. Traditional approaches alone were insufficient for strategy selection, as they did not adequately address user profiles and habits. Consequently, traditional methods, such as calculations of parking capacities and utilization rates, were compared with user and parking surveys. The AHP method was employed to refine the strategy selection and provide optimal recommendations for the city. Population growth projections indicate that Ortahisar's population will rise from 328,509 in 2021 to approximately 651,408 by 2040. Demand calculations using both West German and U.S. city criteria led to a preference for the German approach, given Ortahisar's non-metropolitan status. This approach estimated a parking demand of 7,966 vehicles currently, rising to 20,356 by 2040. This demand is addressed by both paid parking and free roadside options.

Traditional methods suggest that strategies aimed at increasing parking space efficiency, such as shared parking strategies and setting parking maximums, are ideal for the city. Other strategies include parking pricing and improving pricing methods to encourage alternative modes of transport. User survey data was collected to assess preferences and demands for various strategies, including:

- Strategies to Increase Parking Space Efficiency
- Setting Parking Maximums
- Parking Pricing Strategies
- Improving Pricing Methods and Providing Financial Incentives

The survey provided insights into vehicle ownership, trip purposes, and transportation mode preferences. Based on the results, seven criteria were identified as ideal for parking management:

- Sensitivity to Pedestrian Transportation
- Fee Sensitivity
- Reserved Parking Spaces
- Shared Parking Spaces
- Integration with Mobile Applications
- Proximity to Destinations
- Security

These criteria were prioritized using the AHP method, with input from 12 experts. The final prioritization was as follows:

- Security
- Proximity to Destinations
- Sensitivity to Pedestrian Transportation
- Fee Sensitivity
- Reserved Parking Spaces
- Shared Parking Spaces
- Integration with Mobile Applications

The study demonstrates a hybrid approach, combining traditional methods with user feedback to inform strategy selection. This approach is expected to provide more realistic and actionable solutions for parking management. Future research should explore the impacts of these strategies on urban planning scenarios and investigate their roles in shaping urban mobility and accessibility plans. This thesis, with its hybrid approach, is anticipated to serve as a foundational contribution to future studies.

5.1. Compatibility of Ortahisar's Central District Characteristics with Parking Data

Ortahisar, as the central business and administrative district of Trabzon, is characterized by narrow street layouts, insufficient off-street parking capacity, and high daily visitor traffic. The parking inventory revealed that 8 of the 45 off-street parking lots are out of service and only 12 roadside parking zones exist, which are inadequate to meet the local demand. These findings clearly reflect a mismatch between parking supply and demand in this high-density central area.

5.2. Discrepancy Between User-Prioritized Strategies and the Existing Parking System

Strategies such as time limitation and pricing were strongly favored by users; however, they are either minimally implemented or entirely absent in the current parking system. Especially in the city center, uncontrolled long-term parking reduces turnover and impairs access for other potential users. This highlights a significant gap between user expectations and the current operational framework.

5.3. Balance and Tension Between Expert and User Opinions in the Local Context

The AHP analysis indicated that while users prioritize practical benefits (e.g., time and fee control), experts emphasize system-oriented solutions (e.g., access management and technological integration). Nonetheless, commonly supported strategies such as time restrictions suggest not a contradiction but rather differing hierarchies of importance. This implies that the integration of both perspectives is feasible and meaningful.

5.4. Applicability of the Ranked Strategies in the Context of Ortahisar

Most of the proposed strategies—such as time restrictions, dynamic pricing, and user prioritization—are applicable in Ortahisar's compact and historically constrained urban fabric without requiring significant physical infrastructure changes. However, strategies involving technological systems demand both adequate municipal digital capacity and a cultural adaptation by users. Therefore, in the short term, low-cost and regulation-based strategies appear to be the most viable.

5.5. Practical Implications for the Ortahisar Case

The findings of the study highlight several practical implications that can guide parking policy development in Ortahisar. As the central district of Trabzon, Ortahisar experiences significant pressure on its limited parking infrastructure, especially around commercial and historical centers such as Atatürk Square and Hagia Sophia Square. The integration of user preferences, expert evaluations, and parking inventory analysis led to a prioritized strategy list that emphasizes time-restricted parking and dynamic pricing as feasible and impactful interventions. These strategies directly respond to the short-term, high-turnover demand structure typical of the district. Moreover, the participatory approach adopted in the study provides a replicable model for other urban areas in Turkey where user behaviors and institutional expertise must be aligned to enhance the efficiency of parking management. The consistency observed between expert priorities and user demands in the final strategy hierarchy further supports the legitimacy and implement ability of the proposed solutions within the unique spatial, social, and economic context of Ortahisar.

In doing so, the study fulfills its initial objective of bridging methodological gaps in parking strategy selection for mid-sized urban areas like Trabzon.

Beyond identifying context-specific parking strategies, the study demonstrates the applicability of an AHP-based participatory planning model in urban mobility decision-making. By combining demand estimation, user surveys, and expert evaluations, this model offers a replicable and scalable framework for integrated parking management, particularly in complex urban settings.

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CRediT Authorship Contribution Statement

Ecenur Sarıca Karakulak: Writing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. Görkem Gülhan: Writing – review & editing, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data Availability

The data that support the findings of this study are not publicly available because they are not solely owned by the authors. Access to the data may be subject to restrictions imposed by third parties.

Ethics Committee Approval

No ethics committee approval was required for this study since all datasets and survey instruments used are already published and properly cited in the references.

Resume

Ecenur Sarıca Karakulak is an urban and regional planner with a strong academic and professional background in sustainable urban mobility and parking management. She earned her undergraduate degree in Urban and Regional Planning from Pamukkale University-Faculty of Architecture and Design, Denizli, Turkey, where she also completed her master's degree in the same department. Her thesis focused on parking management strategies and integrated both quantitative modeling and stakeholder-based approaches, highlighting her expertise in contemporary urban transportation challenges. Currently, she works as a Urban Planner at the Denizli Metropolitan Municipality, where she contributes to urban planning initiatives with an emphasis on mobility, accessibility, and sustainable development. Her professional interests include transport planning, public space design, and the integration of smart solutions into urban policy.

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Multidimensional analysis of teaching techniques used in higher education: The case of a landscape architecture department

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Abstract

This study provides a multidimensional analysis of teaching techniques in a landscape architecture department. The study aims to identify the most effective among different learning methods and analyze the effectiveness of the training offered by lecturers through student feedback and lecture notes. It is imperative to acknowledge the significance of student feedback as a crucial source of data for the evaluation of teaching methodologies and curriculum design. The study indicates that, beyond the extent of student learning of the course material, it is also imperative for teaching methodologies to align with the students' perceptions and personalities. To this end, a questionnaire was administered to students enrolled in four distinct courses (Computer Aided Design, Planting Design, Landscape Engineering, and Project-I) at the beginning and end of the semester. The objective of the questionnaires is to assess the students' level of knowledge regarding the topics included in the curriculum of the relevant courses. The study used a quantitative research method, a 5-point Likert-type scale, and a one-group pretest-posttest design. The data obtained were analyzed using reliability, frequency, independent, and dependent sample t-tests. In addition, the consistency between student feedback and end-of-semester course scores was also examined. The results of the study show that, in general, there is a statistically significant increase in the knowledge level of students in all courses toward the end of the semester. However, the effectiveness levels of the teaching techniques vary by course and subject. For instance, it was determined that teaching techniques were more successful in the Computer-Aided Design course (89.2% effective), while this rate was lower in the Project-I course (66.6% effective). In addition, students' perceptions of their knowledge levels (post-test results) were found to be higher than their end-of-semester scores. In the student feedback, issues such as insufficient class hours, lack of visual examples, and the importance of practical applications were also mentioned. In conclusion, the study shows that the evaluation of the questionnaire data and student scores together can be an effective tool in determining the level of teaching effectiveness and identifying issues that require revision in the curriculum.

Keywords: educational effectiveness, higher education, landscape architecture, student feedback, university

1. Introduction

In modern societies, which have a remarkable variety of opportunities to access information, the need to find the most effective techniques among different learning methods is becoming more and more prominent. In this regard, the effectiveness of the education provided by individuals in the position of instructors needs to be well analyzed. Education is a process that supports individuals' social, cultural, and intellectual development. Education in schools, on the other hand, focuses more on the transfer of course content to students. Although the level of effectiveness of the education provided in educational institutions is questioned through assessment/evaluation methods such as homework and exams, additional assessment/analysis methods need to be developed and implemented. At this point, feedback from students in the learner position is of great importance. Because, unlike teaching, learning is a non-explicit (hidden) activity. In this context, the two most important factors are the content of the curriculum and the teaching

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methods applied by the course instructors. Therefore, further evaluation and analysis of the collection of student feedback should focus on these two factors. An examination of the relevant literature reveals that there are various studies on this subject. Mortimore (1993) suggested that in addition to focusing on presentation skills, it is crucial to understand how students learn and how subject knowledge can be transformed to be appropriate for students of different ages. Feng (2007) noted that in order to develop effective strategies, it is necessary to have a full understanding of the students' situation based on the information obtained from the results of psychological tests, questionnaires, and surveys. Scheerens et al. (2013), concluded that among the indicators examined in their study on the effectiveness of schools, curriculum-related factors showed the greatest effects. In order to identify students' learning styles and match teaching patterns to them, Khaleghimoghaddam (2023) proposed to test students' learning styles in the early stages of studies to find appropriate solutions. As Erdoğan et al. (2021) have noted, the necessity of updating the education process and curriculum is a matter of discussion. Law (2022) noted that an effective curriculum has become a critical component of higher education due to changes in the techno-socio-economic environment and digital revolutions in Industry 4.0. Similar studies in literature have addressed the complexity of curriculum effectiveness and emphasized the need for a multidimensional approach to curriculum evaluation and improvement. Cheong Cheng (1994) emphasized the importance of coherence between curriculum change and teacher development and the need for a comprehensive framework to manage these processes. Vasilev et al. (2024), found that teaching methods are the most significant subgroup of factors affecting the quality and effectiveness of the educational process. In the point of selection of the right teaching methods, it should not be forgotten that the most important data source in meeting this need is the feedback received from students. As stated by Artkan and Kaya (2021), the necessity of developing teaching methods that align with students' perceptions and personalities, contingent on their developmental stage, becomes evident. Schweinberger et al. (2017) stated that effective feedback is crucial for knowledge acquisition and subsequent school improvement activities. In a study conducted by Shafique et al. (2018), students recognized the importance of feedback for academic performance, highlighting the need for structured feedback mechanisms and improved faculty engagement. Student questionnaires can help instructors create effective teaching programs (Fuchs et al., 1990). A review of the literature shows that many studies emphasize the value of student questionnaires in the assessment of curriculum effectiveness and the need for continuous improvement. Marsh and Roche (1997) stated that under appropriate conditions, students' evaluations of teaching are multidimensional, reliable, and stable. Amua-Sekyi (2016) noted that assessment by students has an impact on how teachers teach and therefore on how students learn. Lanning et al. (2012) emphasized the importance of continuous evaluation and adaptation of the curriculum based on student feedback. Tagulwa et al. (2023) concluded that curriculum assessment has a strong, positive and significant impact on students' employability. Stobaugh et al. (2020) stated that student opinions are a valid source of data for measuring teacher effectiveness. It should not be ignored that these data have the potential to be useful not only in measuring teacher effectiveness but also in various aspects. Heritage and Heritage (2013) stated that the data obtained as a result of the feedback received is an important resource in revealing the current learning status of students and making decisions about the next steps in education. The questionnaire results in Mart (2017)'s study also show that student evaluations are useful and have an impact on the quality of teaching methods of instructors. In addition, it was concluded that student participation is essential in the evaluation of teaching methods in higher education institutions. Kuhn and Rundle-Thiele (2009) also reported that students' perceptions of measures of learning success are relevant for educators in higher education. Through self-initiated feedback generation, students not only gain a deeper understanding of their strengths and areas for improvement but also develop essential metacognitive skills that support lifelong learning and academic success (Lipnevich & Smith, 2022; Nicol & Kushwah, 2024).

The needs of all stakeholders need to be considered to create an effective curriculum and consequently improve the quality of education. Accordingly, systematic evaluations of curriculum and teaching techniques in educational institutions are essential to ensure sustainability in effective education. In this context, to determine the quality of education, students at Selçuk University Department of Landscape Architecture were asked to fill out questionnaire forms at the beginning and end of the semester in four different courses (two for each course). By analyzing the data obtained from the questionnaires, findings related to the effectiveness of the education provided in these courses and the opinions/expectations of the students about the curriculum were discussed. In the light of the findings, the techniques used in instructing the relevant courses were evaluated and outputs were obtained for the revisions needed in the curriculum. Although there are many studies in the related literature that have conducted questionnaires about the curriculum, most of them have only used student feedback as a data set and determined the study outputs accordingly. This study differs from other studies in that it uses not only student feedback but also students' course scores at the end of the semester as the two main factors of the data set. The study outputs were prepared by questioning whether there is consistency between these factors. In this framework, answers to the following questions were sought within the scope of this research:

- How is the level of effectiveness of the education provided to the students?
- Is there consistency between student feedback and students' performance levels (course scores)?
- Is it possible to obtain data to guide the instructor as a result of the questionnaires conducted to determine the students' level of knowledge about the curriculum?

It is expected that the multidimensional evaluation process carried out within the scope of this study and the findings obtained would contribute to the increase in the level of effectiveness in education in other higher education institutions.

2. Methods and Materials

The flow chart summarizing the process carried out within the scope of the study is given in Figure 1. In the first stage, the literature review on the subject was completed and the questions to be answered were determined. The next step was to decide on which courses the study would be conducted on. Following the determination of the courses, the design of the questionnaires to be applied was completed and the questionnaires were finalized by finalizing the revisions needed as a result of the preliminary questionnaire studies.

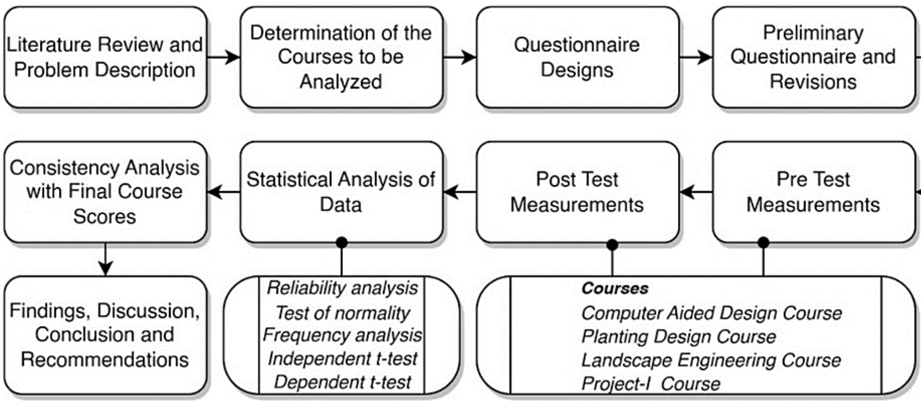


Figure 1 Flow chart of the study

In the next stage, pre-test measurements were performed at the beginning of the academic year for the students taking the determined courses. At the end of the semester, post-test measurements were performed on the same participants after the completion of the education provided within the scope of the curriculum. The data obtained from the pre, and post-test measurements were digitized. Following this stage, various statistical analyses were performed on the data obtained and research findings were prepared. The findings of the study were evaluated, the conclusions and recommendations section were prepared, and the process was completed.

2.1. Questionnaire Designs and Samplings

The method to be used in the study is based on questionnaire measurements. In the determination of the courses to be questioned, it was ensured that there was categorical diversity in the course subjects, and the information obtained in face-to-face interviews with the students was taken into consideration. In this respect, the courses to be questioned through questionnaire measurements are Computer Aided Design, Planting Design, Landscape Engineering, and Project-I courses. The questionnaire designs were based on the relevant course curriculum. The aim was to determine the level of knowledge of the students about the subjects in the curriculum before and after taking the course. The content of the questionnaire consists of statements that measure students' level of knowledge about the subjects in the curriculum of the relevant courses. The questionnaire prepared for the Computer Aided Design course consists of 5 sub-sections. These sections consist of statements that measure the level of knowledge about 5 software (Autodesk AutoCAD, Adobe Photoshop, Trimble Sketch Up, Act-3D Lumion, and Adobe Illustrator) taught in the course. Similarly, the Planting Design course questionnaires consist of 5 sub-sections. These sections consist of statements that measure the level of knowledge of the students about planting design elements, planting design principles, functions of plants, dendrological characteristics of plants, and planting types. The design of the questionnaire for the Landscape Engineering course, which consists of three sub-sections, was based on the topics of land forming, circulation (transportation) systems/parking lots, and irrigation/drainage. The questionnaire form prepared for the Project-I course consists of three sub-sections based on the three basic stages of the landscape design process: research/analysis, design, and development. The questionnaire forms were designed to be conducted both at the beginning and at the end of the semester. The sample of the study consists of the students (4 courses, 51+37+46+47 students) of the Department of Landscape Architecture at Selçuk University who will take the courses in the relevant academic year.

2.2. Measurement Methods and Data Collection

In this study, a 5-point Likert-type scale model was applied as one of the quantitative measurement methods. Single Group Pre-Test - Post-Test Design was applied. A single-group pretest-posttest procedure (Figure 2) refers to a design used to evaluate the effect of an intervention on a group of participants. In this type of design, participants are initially given a pre-test, followed by the intervention, and then a post-test to assess changes. The pretest and posttest are the same tests conducted at different times.

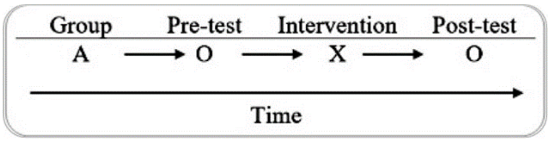


Figure 2 Single group pre-test - post-test design

The questionnaire forms were conducted face-to-face with the students twice, once at the beginning and once at the end of the semester, and the effectiveness level of the education provided was questioned. A data set was prepared as a result of digitizing the data obtained from the questionnaire forms.

2.3. Data Analysis

The data obtained as a result of the questionnaire process was subjected to statistical analysis with IBM SPSS 27.0 software. The statistical analysis methods applied were reliability, frequency, t-test for independent groups, and dependent sample t-test to find out whether there was a statistically significant difference between the results of the questionnaire at the beginning and end of the semester. The dependent sample t-test is used to assess the difference between two measurements in the same group. Subsequently, the data were analyzed comparatively to investigate whether there was consistency between the student feedback obtained from the questionnaires and the final exam scores. This analysis is an appropriate method to assess whether there is a consistent relationship between students' post-test feedback and exam scores. Finally, the data obtained from the pre-test and post-test were analyzed on the basis of each statement (curriculum topics) in the questionnaires.

3. Results and Discussion

3.1. Findings Related to the Analysis of Pre-Test Data

Reliability analysis, test of normality, frequency analysis, and independent sample t-test analyses were applied to the data sets obtained from the questionnaires conducted at the beginning of the semester for each course. The results of the analysis are given below.

3.1.1. Reliability Analysis Results

As a result of the reliability analysis applied to the pre-test data of the Computer Aided Design, Planting Design, Landscape Engineering, and Project-I course questionnaires, Cronbach's Alpha values were found to be ,913-,925-,691-,868 respectively (Table 1) and it was confirmed that the statements in the questionnaires were reliable.

Table 1 Reliability Analysis Results for Pre-Test Data

Course	Cronbach's Alpha	Evaluation
Computer Aided Design	,913	Strong
Planting Design	,925	Strong
Landscape Engineering	,691	Reasonable
Project-I	,868	Reliable

After testing the reliability of the data, the next stage is to analyze whether the data is normally distributed. As a result of this analysis, it is decided whether the statistical analysis to be performed will be parametric or non-parametric tests.

3.1.2. Test of Normality Results

Skewness and Kurtosis values were analyzed for the test of normality to determine whether the groups were normally distributed or not. It was observed that the Skewness value ranged between ,313 and 1,273 and the Kurtosis value ranged between -,803 and 1,127 (Table 2). A normal distribution is accepted when Kurtosis and Skewness values are between -1,5 and +1,5 (Tabachnick et al., 2013). As a result of the tests of normality, it was determined that the groups were normally distributed for all courses, and it was determined that it was appropriate to use parametric tests in the analysis of the data.

Table 2 Test of Normality Results for Pre-Test Data

	Skewness		Kurtosis		Shapiro-Wilk	
Course Data Set	Statistic	Std. Error	Statistic	Std. Error	df	Sig.
Computer Aided Design	1,273	,333	1,127	,656	51	,000
Planting Design	,313	,388	-,803	,759	37	,266
Landscape Engineering	,892	,350	,117	,688	46	,001
Project-I	,880	,347	,539	,681	47	,007

3.1.3. Frequency Analysis Results

It was found that most of the students who participated in the questionnaires (between 90.2% and 100%) took the relevant course for the first time and the majority of them (between 78.7% and 97.8%) had never attended any training apart from the relevant course (Table 3).

Table 3 Students' Course-Taking Status and Level of Off-Course Education

Course	Taking for the First Time	No off-course Education
Computer Aided Design	90,20%	88,20%
Planting Design	97,30%	97,30%
Landscape Engineering	100,00%	97,80%
Project-I	100,00%	78,70%

Frequency analyses were performed to determine the distribution rates of the groups and the knowledge levels of the students according to the courses and subjects. The data obtained as a result of the analysis were shown in Figure 3.

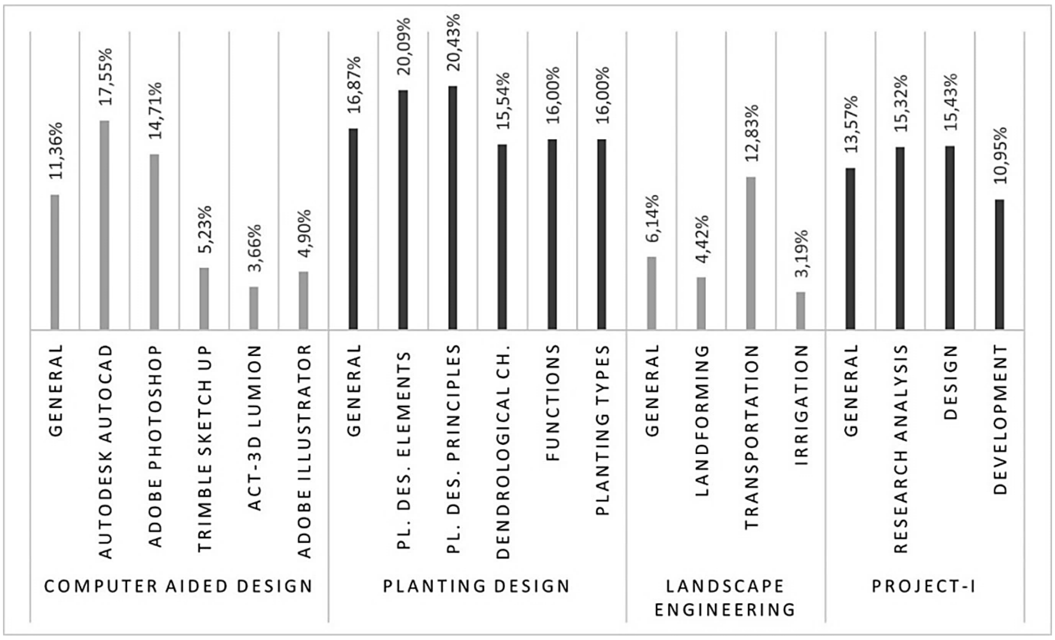


Figure 3 The knowledge levels of the students based on the courses and subjects at the beginning of the semester

An analysis of the students' level of knowledge about the curriculum before taking the course shows that the highest level of knowledge (16,87%) was in the Planting Design course and the lowest level of knowledge (6,14%) was in the Landscape Engineering course. It was determined that the highest level of knowledge (17,55%) was in “Autodesk AutoCAD” software and the lowest level of knowledge (3,66%) was in “Act-3D Lumion” software. It was found that the level of knowledge about "planting design elements" and "planting design principles", which are among the topics of the Planting Design course, was above 20%. Examining the data of the Landscape Engineering course, where the lowest level of knowledge is determined, it is seen that only "transportation systems/parking lot" is above 10% and "irrigation and drainage" is at the level of 3,19%. In the Project-I course, it is observed that the level of knowledge about all sub-sections is above 10%.

3.1.4. Independent t-Test Results

Based on the results of the independent t-test applied at 95% confidence interval (Table 4), it was seen that the level of knowledge about the curriculum of the Computer Aided Design course differed significantly between those who took the course for the first time and those who had taken the course before ($p=,011$), while it did not differ according to gender ($p=,272$). As seen in the table, the mean knowledge level of the students who took the Computer Aided Design course for the first time ($\bar{X}=18,83$, ss=18,48) is significantly lower ($t(-2,630)=49$, $p<0,05$) than the mean knowledge level of the students who took the course before ($\bar{X}=41,2$, ss=12,58). It was found that the level of knowledge about the curriculum of the Planting Design course did not differ significantly between those who took the course for the first time and those who had taken the course before ($p=,280$), while it differed significantly according to gender (p=,028). The mean knowledge level of female students taking the Planting Design course ($\bar{X}$=31,89, ss=17,79) is significantly higher (t(2,292)=35, p<0,05) than the mean knowledge level of male students taking the course ($\bar{X}$=18,27, ss=12,74).

Table 4 Independent t-Test Results for Pre-Test Data

Variable	Sub-Group	N	$\bar{X}$ (ss)	t	df	p	Course
Gender	Female	37	18,73 (15,78)	-1,136	16,85	,272	Computer Aided Design
	Male	14	27,07 (25,69)				
Course Taking Status	First time	46	18,83 (18,48)	-2,630	49	,011*	
	Taken before	5	41,2 (12,58)				
Gender	Female	26	31,89 (17,79)	2,292	35	,028*	Planting Design
	Male	11	18,27 (12,74)				
Course Taking Status	First time	36	28,36 (17,41)	1,097	35	,280	
	Taken before	1	9,00				
Gender	Female	29	4,45 (4,16)	-,979	44	,333	Lands. Eng.
	Male	17	5,71 (4,28)				
Gender	Female	30	13,43 (9,42)	1,230	45	,225	Project-I
	Male	17	10,06 (8,30)				

** p<,05 statistically significant*

Considering the course-taking status in Landscape Engineering and Project-I courses, it was noted that all of the students participating in the questionnaire took the relevant courses for the first time. For this reason, an independent t-test was applied only for gender status for these courses. For both courses, it was determined that the level of knowledge about the curriculum did not differ according to gender (p=,333; p=,225).

3.2. Findings Related to the Analysis of Post-Test Data

Reliability analysis, test of normality, frequency analysis, and independent sample t-test analyses were applied to the data sets obtained from the questionnaires conducted to the students at the end of the semester for each course. The results of the analysis are given below.

3.2.1. Independent t-Test Results

As a result of the reliability analysis applied to the pre-test data of the Computer Aided Design, Planting Design, Landscape Engineering, and Project-I course questionnaires, Cronbach's Alpha values were found to be ,932-,956-,891-,924 respectively (Table 5) and it was confirmed that the statements in the questionnaires were reliable.

Table 5 Reliability Analysis Results for Post-Test Data

Course	Cronbach's Alpha	Evaluation
Computer Aided Design	,932	Strong
Planting Design	,956	Strong
Landscape Engineering	,891	Reasonable
Project-I	,924	Reliable

3.2.2. Independent t-Test Results

Skewness and Kurtosis values were analyzed for the test of normality to determine whether the groups were normally distributed or not. It was observed that the Skewness value ranged between -,686 and ,388 and the Kurtosis value ranged between -,876 and ,759 (Table 6). As a result of the tests of normality, it was determined that the groups were normally distributed for all courses, and it was determined that it was appropriate to use parametric tests in the analysis of the data.

Table 6 Test of Normality Results for Post-Test Data

Course Data Set	Skewness		Kurtosis		Shapiro-Wilk	
	Statistic	Std. Error	Statistic	Std. Error	df	Sig.
Computer Aided Design	-425	,333	-,876	,656	51	,018
Planting Design	-,686	,388	-,435	,759	37	,010
Landscape Engineering	-,145	,350	-,288	,688	46	,604
Project-I	-,036	,347	-,554	,681	47	,350

3.2.3. Frequency Analysis Results

Frequency analyses were performed to determine the distribution rates of the groups and the knowledge levels of the students according to the courses and subjects. The data obtained as a result of the analysis were shown in Figure 4.

Analyzing the students' level of knowledge about the curriculum after taking the course, it is seen that the highest level of knowledge (85,74%) is in the Computer Aided Design course and the lowest level of knowledge (75,87%) is in the Landscape Engineering course. It was determined that the highest level of knowledge (90,78%) was in 'Autodesk AutoCAD' software and the lowest level of knowledge (78,37%) was in 'Adobe Illustrator' software. It was found that the level of knowledge was above 84% in all subjects except the subject of 'functions of plants' among the subjects of the Planting Design course. Examining the data of the Landscape Engineering course, which is determined to have the lowest level of knowledge in general, it is seen that the level of knowledge is above 80% in the subjects of 'land forming' and 'transportation systems/parking', while other subjects are below this value. In the Project-I course, the highest value (82,13%) was in the 'design phase' and the lowest value (75,74%) was in the 'development phase'.

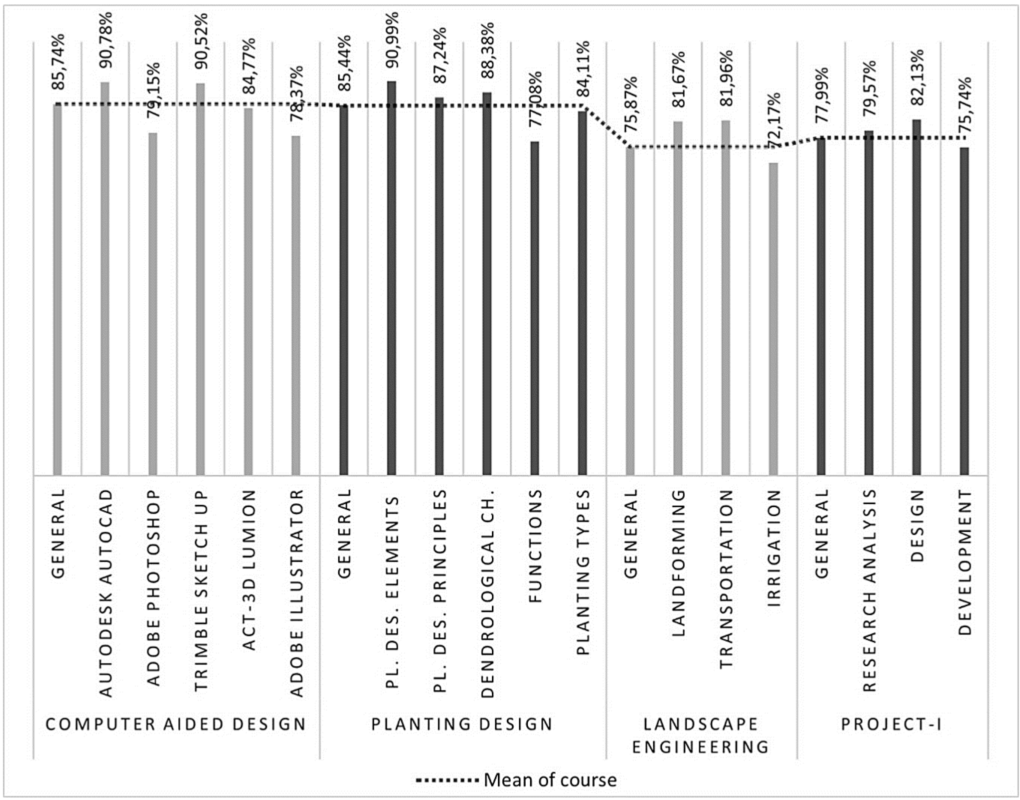


Figure 4 The knowledge levels according to the courses and subjects at the end of the semester (post-tests)

3.2.4. Independent t-Test Results

According to the results of the independent t-test applied at 95% confidence interval (Table 7), it was determined that the level of knowledge about the curriculum of Computer Aided Design and

Planting Design courses did not show a significant difference between those who took the course for the first time and those who had taken the course before. Examining whether there is a difference according to gender, it is observed that only the level of knowledge for the Planting Design course differs significantly between male and female students (p=,012). The mean knowledge level of female students taking the Planting Design course ($\bar{X}$=145,65, ss=16,23) is significantly higher (t(2,292)=35, p=,028) than the mean knowledge level of male students taking the course ($\bar{X}$=129,91, ss=17,07).

Table 7 Independent t-Test Results for Post-Test Data

Variable	Sub-Group	N	$\bar{X}$ (ss)	t	df	p	Course
Gender	Female	37	158,14 (16,40)	-,339	49	,736	Computer Aided Design
	Male	14	159,93 (18,07)				
Course Taking Status	First time	46	158,46 (17,08)	-,219	49	,827	
	Taken before	5	160,2 (14,24)				
Gender	Female	26	145,65 (16,23)	2,657	35	,012*	Planting Design
	Male	11	129,91 (17,07)				
Course Taking Status	First time	36	140,86 (18,05)	-,226	35	,822	
	Taken before	1	145,00				
Gender	Female	29	62,41 (7,42)	1,747	44	,080	Lands. Eng.
	Male	17	57,77 (10,60)				
Gender	Female	30	73,07 (9,85)	2,762	45	,080	Project-I

** p<,05 statistically significant*

3.3. Findings Related to the Dependent Sample t-Test

A dependent sample t-test was applied to the data sets obtained as a result of the pre-test and post-tests conducted to determine the effectiveness level of the education provided for the courses during the semester (Table 8). Regarding the effectiveness level of the education provided, it was detected that there was a statistically significant difference between the mean knowledge level before and the mean knowledge level after all courses (p=,000). Computer Aided Design course mean increased from 21,02 to 158,63; the Planting Design course mean increased from 27,84 to 140,97; the Landscape Engineering course mean increased from 4,91 to 60,7 and the Project-I course means increased from 12,21 to 70,19.

As expected, a significant increase was observed in the general averages of students' knowledge levels before and after taking the course for all courses. The main purpose here is to observe this change specifically for sub-topics rather than the general average increase. At this point, it is possible to understand which subjects have been learned more effectively, or which ones have deficiencies by looking at the t values. It can be understood that the larger the t value, the greater the increase in the student's knowledge level.

In order to analyze the statements given in the course questionnaires according to the sub-sections, a dependent sample t-test was applied to the data related to these statements. Based on the results of the test applied to the data, it was determined that there was a statistically significant difference between the means of before and after knowledge level for all of the subjects taught within the scope of the relevant curriculum in all courses. It was found that post-test means were higher than pre-test means in all courses. This can be interpreted as a statistically significant effect of the education provided on a subject basis.

Table 8 Dependent Sample t-Test Results for Pre-Test and Post-Test Data

Course	Subject		N	$\bar{X}$ (ss)	t	df	p
Computer Aided Design	General	Pre-Test	51	21,02 (19,11)	-43,468	50	,000
		Post-Test	51	158,63 (16,71)			
	Autodesk AutoCAD	Pre-Test	51	10,53 (10,85)	-27,892	50	,000
		Post-Test	51	54,47 (4,57)			
	Adobe Photoshop	Pre-Test	51	4,41 (6,47)	-16,228	50	,000
		Post-Test	51	23,75 (5,42)			
	Trimble Sketch Up	Pre-Test	51	1,57 (2,5)	-49,539	50	,000
		Post-Test	51	27,16 (3,16)			
	Act-3d Lumion	Pre-Test	51	1,1 (1,92)	-41,675	50	,000
		Post-Test	51	25,43 (3,81)			
	Adobe Illustrator	Pre-Test	51	1,47 (4,06)	-25,360	50	,000
		Post-Test	51	23,51 (5,2)			
Planting Design	General	Pre-Test	37	27,84 (17,46)	-28,071	36	,000
		Post-Test	37	140,97 (17,81)			
	Planting Design Elements	Pre-Test	37	6,03 (5,14)	-22,323	36	,000
		Post-Test	37	27,3 (3,44)			
	Planting Design Principles	Pre-Test	37	10,22 (8,57)	-19,870	36	,000
		Post-Test	37	43,62 (5,34)			
	Dendrological Character	Pre-Test	37	3,11 (3,42)	-20,647	36	,000
		Post-Test	37	17,68 (2,45)			
	Functions of the Plants	Pre-Test	37	4 (3,35)	-19,447	36	,000
		Post-Test	37	19,27 (3,51)			
	Planting Type	Pre-Test	37	4 (3,65)	-19,564	36	,000
		Post-Test	37	21,03 (4,62)			
Landscape Engineering	General	Pre-Test	46	4,91 (4,20)	-36,602	45	,000
		Post-Test	46	60,7 (8,91)			
	Land forming	Pre-Test	46	1,33 (1,93)	-36,716	45	,000
		Post-Test	46	24,5 (3,69)			
	Transportation/Parking	Pre-Test	46	1,28 (1,39)	-21,932	45	,000
		Post-Test	46	8,2 (1,38)			
	Irrigation/Drainage	Pre-Test	46	0,48 (1,07)	-32,927	45	,000
		Post-Test	46	10,83 (1,97)			
Project-I	General	Pre-Test	47	12,21 (9,09)	-26,381	46	,000
		Post-Test	47	70,19 (10,14)			
	Research/Analysis	Pre-Test	47	1,53 (1,76)	-18,000	46	,000
		Post-Test	47	7,96 (1,52)			
	Design	Pre-Test	47	3,09 (2,69)	-23,402	46	,000
		Post-Test	47	16,43 (2,38)			
	Development	Pre-Test	47	6,02 (5,27)	-26,383	46	,000
		Post-Test	47	41,66 (6,53)			

3.4. Findings Related to the Comparison of Test Results with End-of-Semester Course Scores

The data obtained from the pre-test and post-test were analyzed in order to determine the effectiveness level of the training and the change between these tests, in other words, the amount of increase in students' knowledge level was calculated on the basis of course subjects (Figure 5). The highest increase (85.29%) among the five software programs taught in the curriculum for the Computer Aided Design course was in the "Trimble Sketch Up" software, while the lowest increase (64.44%) was in the "Adobe Photoshop" software. It is seen that the highest increase (72,84%) is in "Dendrological Characteristics of Plants" and the lowest increase (61,08%) is in "Functions of Plants" in the Planting Design course. Of the courses whose curriculum consists of 3 basic subjects each, the highest increase (77.25%) in the Landscape Engineering course was in the subject of "Land Forming", and the highest increase (66.70%) in the Project-I course was in the subject of "Design Phase".

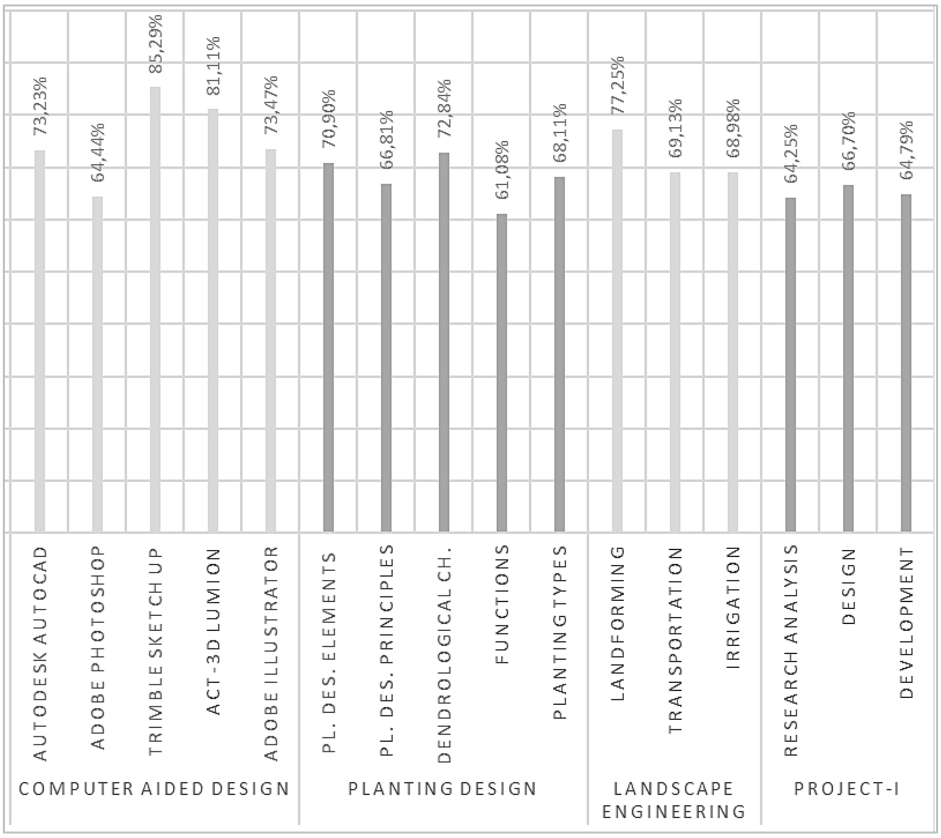
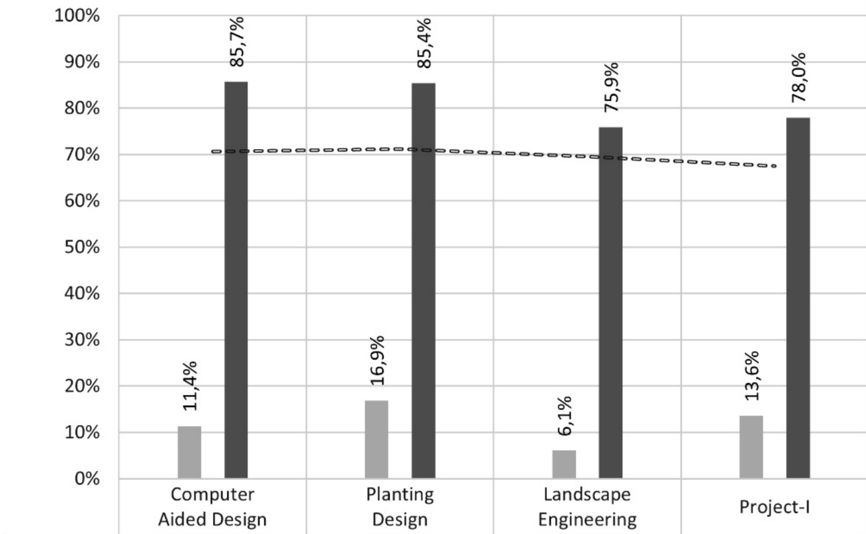


Figure 5 Differences between means according to subjects in pre-tests and post-tests (%)

The differences between the post-test and end-of-semester course scores were analyzed to determine the consistency between the students' responses to the post-tests conducted at the end of the semester and their end-of-semester scores in the courses (Figure 6).

A comparison of the pre-test averages shows that the lowest level of knowledge (6.1%) was in the Landscape Engineering course and the highest level of knowledge (16.9%) was in the Planting Design course. Analyzing the data on post-test and end-of-semester course score means, it is recognized that the end-of-semester course score means for all courses are lower than the post-test mean scores. It is clear that the post-test mean (85.7%) in the Computer Aided Design course was higher than the final score means (70.7%) of the related course. It was understood from the related graph that the same situation was also valid for other courses. This means that the level of knowledge that students think they have is higher than the level of knowledge they actually have. Consequently, checking the consistency of the post-test survey data with the end-of-semester course scores is very important in terms of the validity of the findings.



	Computer Aided Design	Planting Design	Landscape Engineering	Project-I
Pre-Test	11,4%	16,9%	6,1%	13,6%
Post-Test	85,7%	85,4%	75,9%	78,0%
Final Course Score	70,7%	71,2%	69,5%	67,5%

Figure 6 Pre-test, post-test, and end-of-semester course score means

3.5. Findings Related to the Comparison of Test Results with End-of-Semester Course Scores

The situation has been examined until this stage of the study, both in terms of the relevant courses and the sub-sections that constitute the curriculum. It is possible to determine which of the sub-sections in the curriculum are in the category of "open to improvement" in terms of teaching techniques as a result of these analyses, but it is foreseen that it would be useful to go into more detail about the statements that constitute the sub-sections in order to reach more precise results. In this context, a situation analysis was conducted separately for each of the statements in the questionnaires. The analyses were performed by calculating the differences between the students' knowledge levels at the beginning and end of the semester about a subject. The difference, which explains the level of development in the student, indicates the level of effectiveness of the education provided. The higher the difference, the higher the effectiveness of the teaching methods. While the level of effectiveness of the education provided was categorized according to the subjects in the curriculum if the difference between the student's level of knowledge on a subject at the beginning and end of the semester was in the range of;

0%-20%, it was evaluated as *'very low'*,

20,1%-40%, it was evaluated as *'low',*

40,1%-60%, it was evaluated as *'medium',*

60,1%-80%, it was evaluated as *'high'*,

80,1%-100%, it was evaluated as *'very high'.*

The data obtained as a result of these analyses are given in Figure 7 (the graphs show the range between 40% and 100% as no development below 40% was calculated).

Based on the data of the 37-statement Computer Aided Design course questionnaire, it is understood that the teaching techniques of the subjects in the statements numbered 1,2,3, and 14 need revision. A development in the range of 40%-60% was found between the knowledge levels of the students at the beginning and end of the semester on the subjects in question. In this context, the level of effectiveness of the education provided on the relevant subjects was evaluated in the 'medium' category. It was reported that the effectiveness levels of education in the remaining 33 subjects were in the 'high' and 'very high' categories. As a result, it can be stated that the education provided in this course, in which 33 out of 37 statements were in the 'high' and 'very high' categories, was 89.2% (33/37) effective.

As per the 33-statement Plant Design course questionnaire data, the level of effectiveness of the education provided for statements 1, 14, 21, 22, and 23 is in the 'medium' category. The education provided for statement number 32 is in the 'very high' category, while for the remaining 27 statements is in the 'high' category. It can be concluded that 84.9% (28/33) effective training was provided for this course in which 28 of the 33 statements were in the 'high' and 'very high' categories.

As a result of the analyses performed to determine the level of effectiveness of the education provided in the Landscape Engineering course curriculum consisting of 16 statements, it is recognized that statements numbered 7 and 8 are in the 'very high' category, statements numbered 15 and 16 are in the 'medium' category, and all of the remaining 12 statements are in the 'high' category. It is possible to state that 75% (12/16) effective education was provided in this course, in which the effectiveness level of the education given for 12 of the 16 statements was in the 'high' and 'very high' categories.

Regarding the data of the Project-I course consisting of 18 statements, it is demonstrated that the effectiveness level of the education provided for the statements numbered 1, 6, 15, 16, 17, and 18 is in the 'medium' category, whereas the remaining 12 statements are in the 'high' category. Within the scope of this course, it was determined that the level of effectiveness of the education provided for any statement was not in the 'very high' category. In this course, where 12 out of 18 statements were in the 'high' category, it can be concluded that a 66.6% (12/18) level of effectiveness was achieved.

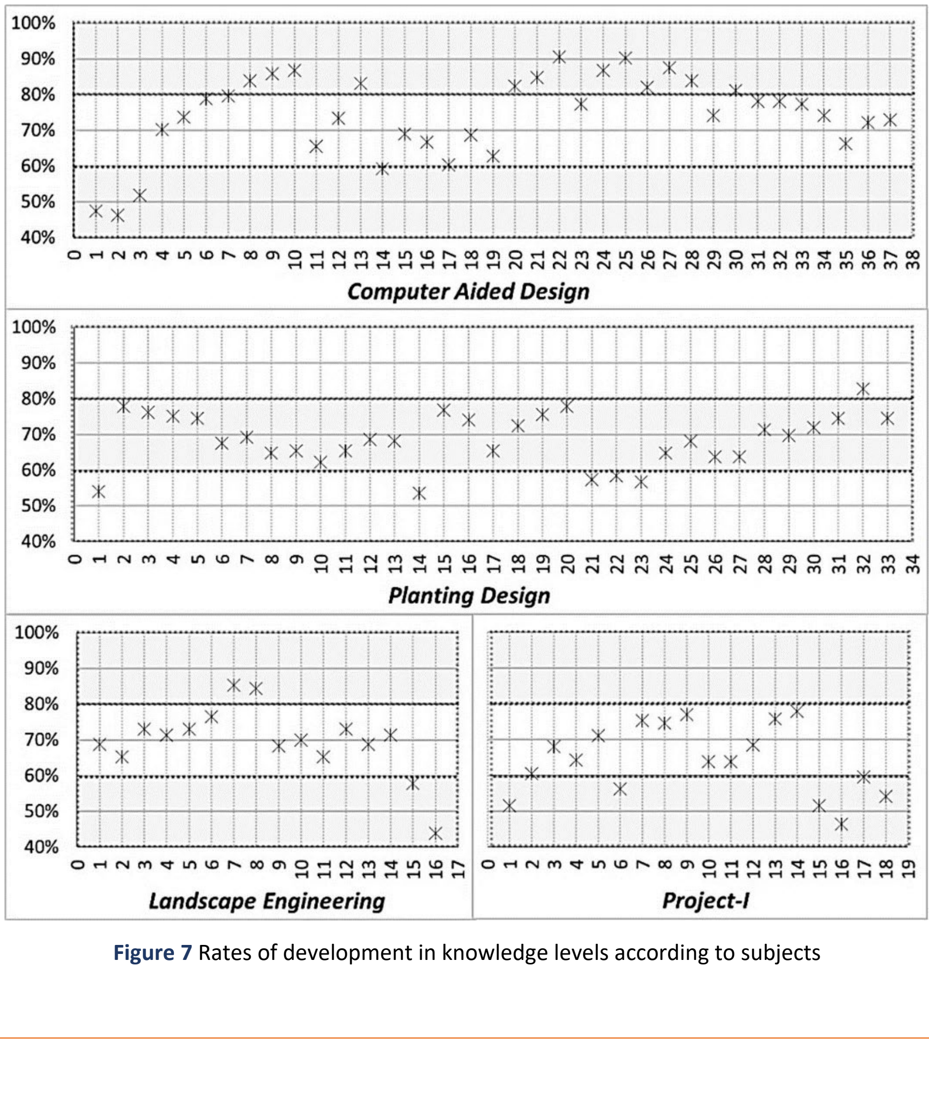


Figure 7 Rates of development in knowledge levels according to subjects

As a result of all analyses, it was determined that the most successful course in terms of the effectiveness level of the education provided was Computer Aided Design (89.2%), followed by Planting Design (84.9%), Landscape Engineering (75%) and Project-I (66.6%). In light of these data, it can be concluded that the teaching techniques applied in the Project-I course should be re-evaluated and the required revisions should be performed.

4. Conclusion and Recommendations

In this study, in order to determine the level of effectiveness of the education provided to higher education students, a questionnaire was conducted twice, once at the beginning and once at the end of the semester for various courses. The data obtained by questionnaires and the end-of-semester course scores of the students were analyzed by various methods and the strong and weak aspects of the education provided were identified. A detailed current situation analysis of the course curriculum was carried out with the method used in the study. The level of effectiveness of the education provided on all the subjects taught during the semester was clearly determined. As a result of the findings, it was determined which subjects needed revision in order to provide a more effective education to the students. In addition, other opinions and demands of the students were obtained with the open-ended questions in the last section of the questionnaire forms. As a result of analyzing the negative responses received in this section, other issues that need to be improved for each course were identified in line with the students' opinions. For the Computer Aided Design course, which is carried out for a total of 4 hours per week, 2 theoretical and 2 practical, the comments were noted that the course hours were insufficient and should be increased. In addition to the fact that the sourcebook used in the course for the Planting Design Course was found insufficient in terms of visual examples, it was reported that it would be more beneficial to practice on-site rather than the education given in the classroom. Regarding the Landscape Engineering course, it was reported that the practice hours were too long and strenuous; more concentration should be given to the presentation of the subject and more sample questions should be solved. Especially the subject of irrigation was reported to be inadequately explained in the sourcebook used and there were complaints that more time should be planned for this subject. For this course, similar to the comments for Computer Aided Design, participants also stated that the course hours should be increased and that the curriculum subjects could not be taught in a single course. Furthermore, similar to the comments made for the Planting Design course, it was also stated that some of the topics for this course could be better learned through on-site practices. Concerning the Project-I course, the disadvantages of online education provided during the Covid-19 pandemic were mentioned intensively. Students reported that they had difficulties in the course because they did not have sufficient proficiency in the computer software they needed to use within the scope of this course. It was also stated that more sample projects should be shown in the course. On the other hand, positive feedback was received from students regarding the questionnaires conducted for all courses. It was stated that the questionnaires were very useful, that it was very valuable to pay attention to the opinions of the students about the courses, and that this practice should be done for other courses in the department. Similarly, the main findings in Steadman's (1998) study were that both instructors and students had positive attitudes towards Classroom Assessment techniques, instructors used it to improve teaching and help students learn, and students found it a valuable learning tool. Charalambous et al. (2021) also stated that better linking teaching quality to student learning processes can create effective changes in education. Student interactions are critical in this context.

The process conducted in the study demonstrated that it can be an important tool not only for increasing the effectiveness of the education provided but also for the self-improvement of the instructors. Various studies in relevant literature emphasize the importance of this issue. Fauth et al. (2019) found that there is a strong relationship between teacher efficacy and student achievement. In another study conducted with 924 students, it was determined that teacher behaviors affected students' cognitive and metacognitive skills (Kyriakides et al., 2020). The methodology used in the study provided the instructors with the opportunity to learn which subjects were successfully taught and which subjects were deficient in the curriculum of the course. This situation shows the issues that need to be revised in the teaching techniques used by the instructors. Therefore, it should not be neglected that the process conducted within the scope of the study has the potential to be very useful not only for the students but also for the instructors.

As mentioned in the introduction section of the study, this research differs from other studies in that it uses not only student feedback but also students' course scores at the end of the semester as the two main factors of the data set.

As a result of the evaluation of the research questions, in this study,

the effectiveness levels of the education provided in the related courses were identified,

it was stated that whether there is consistency between student feedback and students' achievement levels (course scores),

and as a result of the data obtained, it has been proved that outputs that will guide the instructors can be gathered.

As a result, it is foreseen that the implementation of the process carried out within the scope of this study in other higher education institutions will contribute to increasing the level of effectiveness in education and the development of academic staff.

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All contributions to this article, including conceptualization, methodology, data collection, analysis, writing, visualization, and review, were performed solely by the author, Ahmet Akay.

Declaration of Competing Interest

The author declare that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data Availability

Data will be made available on request.

Ethics Committee Approval

This research was approved by the decision of Selçuk University Faculty of Architecture and Design Scientific Ethics Committee dated 15/10/2021 and numbered 06.

Resume

Ahmet Akay is currently employed at the Department of Landscape Architecture at Selçuk University. His research focuses on landscape design, walkability, urban studies, and, notably, the enhancement of visual quality in urban areas. Akay integrates innovative approaches at the intersection of urban design and environmental acoustics, aiming to elevate both the aesthetic and functional values of urban landscapes. His recent publication, "An Acoustical Landscaping Study: The Impact of Distance Between the Sound Source and Landscape Plants on Traffic Noise Reduction," examines the role of landscape configurations in mitigating urban traffic noise. Moreover, his most cited work, "Relationships between the Visual Preferences of Urban Recreation Area Users and Various Landscape Design Elements," provides a detailed analysis of the nexus between visual quality and user preferences in urban recreational spaces.