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Examining Climate Change Resilient Urban Areas with Artificial Intelligence (AI)-Supported Landscape Design

Yapay Zekâ (YZ) Destekli Peyzaj Tasarımıyla İklim Değişikliğine Dirençli Kentsel Alanların İrdelenmesi

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Abstract
Climate change intensifies multidimensional environmental threats in urban areas, including flooding, drought, heatwaves, and biodiversity loss, making urban resilience a critical challenge. Developing climate-resilient cities therefore requires data-driven and integrative approaches in landscape design beyond conventional engineering solutions. In this context, artificial intelligence (AI), in combination with nature-based solutions (NBS), introduces new opportunities for the planning, implementation, and management of urban landscapes. The aim of this study is to investigate how AI-based decision support systems transform landscape design practices for climate change adaptation and ecological resilience. Using a descriptive content analysis method, selected national and international case studies focusing on plant selection, water management, green infrastructure optimization, and urban ecosystem monitoring were examined. The findings show that AI-supported plant selection models improve drought and heat tolerance while reducing irrigation demand; AI-based optimization of green infrastructure networks enhances stormwater management and significantly reduces urban flood risk; and sensor-based monitoring systems integrated with machine learning enable continuous assessment of ecosystem health and early detection of environmental stress. The study's original contribution lies in demonstrating the integrated use of digital twins, machine learning algorithms, and environmental sensors at the landscape scale, providing a structured and transferable framework for climate-responsive design decisions. Overall, the results confirm that AI-supported urban landscape approaches not only increase resilience to climate change but also support the development of more sustainable, healthy, and livable urban environment.

Öz
İklim değişikliği, kentlerde sel, kuraklık, aşırı sıcaklar ve biyolojik çeşitlilik kaybı gibi çok boyutlu çevresel tehditleri artırarak kentsel dirençliliği kritik bir mesele hâline getirmektedir. Bu nedenle iklime dirençli kentlerin geliştirilmesi, yalnızca mühendislik çözümleriyle değil, peyzaj tasarımında veri temelli ve bütüncül yaklaşımlarla mümkün olmaktadır. Bu bağlamda, yapay zekâ (YZ) teknolojilerinin doğa-temelli çözümler (NBS) ile birlikte kullanımı, kentsel peyzajın planlanması, uygulanması ve yönetiminde yeni olanaklar sunmaktadır. Bu çalışmanın amacı, YZ tabanlı karar destek sistemlerinin peyzaj tasarım süreçlerine entegrasyonunun iklim değişikliğine uyum ve ekolojik dayanıklılık üzerindeki etkilerini ortaya koymaktır. Betimsel içerik analizi yöntemiyle, bitki seçimi, su yönetimi, yeşil altyapı ağlarının optimizasyonu ve kent ekosistemlerinin izlenmesine yönelik ulusal ve uluslararası örnekler incelenmiştir. Elde edilen temel bulgular, YZ destekli bitki seçimi yaklaşımlarının kuraklık ve sıcaklık stresine dayanıklı türlerin belirlenmesini kolaylaştırarak sulama ihtiyacını azalttığını; yeşil altyapı ağlarının YZ tabanlı optimizasyonunun yağmur suyu yönetimini iyileştirerek kentsel sel riskini düşürdüğünü; sensör tabanlı çevresel izleme sistemlerinin ve makine öğrenimi algoritmalarının, kent ekosistemlerinin durumunu sürekli izlemeye ve çevresel stresin erken tespitine olanak sağladığını göstermektedir. Çalışmanın özgün katkısı, dijital ikizler, makine öğrenimi algoritmaları ve sensör tabanlı çevresel izleme sistemlerinin peyzaj ölçeğinde bütüncül biçimde ele alınarak, iklime duyarlı tasarım kararları için sistematik ve uygulanabilir bir çerçeve sunulmasıdır. Sonuç olarak, yapay zekâ destekli kentsel peyzaj yaklaşımlarının yalnızca iklim değişikliğine karşı dirençli kentler oluşturmakla kalmadığı, aynı zamanda daha sürdürülebilir, sağlıklı ve yaşanabilir kentsel çevrelerin gelişimine önemli katkılar sunduğu ortaya konulmaktadır.

INTRODUCTION

Climate change is a major environmental issue of global significance. Human activity has had an undeniable impact on this problem. As a result of climate change, air temperatures are rising, and serious problems such as drought, extreme weather events, sea level rise, heat and cold waves, water scarcity, excessive rainfall, and flooding are emerging (Pettorelli 2012, Sheppard 2012). These problems negatively affect life in cities and threaten urban life with chain reactions in every

area, from production to health. Therefore, cities, which are home to the majority of the population, infrastructure, and economic, political, cultural, and social activities, are more affected by the risks of climate change, creating vital problems for city dwellers. In this regard, cities must take long-term steps to become resilient to climate change.

Landscape architecture plays a prominent role in the sustainable management of natural and built environments. This discipline contributes to achieving ecological sustainability goals by designing resilient cities, rural areas, and ecosystems that withstand the pressures caused by climate change. The importance of landscape architecture in the context of climate change stems not only from its role as an aesthetic design tool, but also from its ability to optimize ecosystem services, promote the efficient use of water and energy resources, reduce carbon emissions, and increase biodiversity (Lenzholzer and Brown 2013). In the context of climate change, landscape architecture takes on multifaceted functions such as creating resilient green infrastructure, optimizing water management, and regulating the microclimate in cities (Stanczuk-Galwiaczek et al. 2018).

Therefore, landscape architecture has become a critical discipline in developing adaptation and resilience strategies against the climate crisis. Landscape architects should conduct studies aimed at understanding and calculating the carbon footprint within the scope of current landscape planning and design work. Similarly, architects have also developed various tools (Architecture 2030 2026) to measure the “carbon footprint” and “energy outputs” at the building scale. In this regard, targets such as “zero carbon” or “carbon neutral” have been set. In the process of combating climate change and reducing the carbon footprint, joint initiatives such as “resilient landscape design” have been launched by international landscape architecture organizations (IFLA and ASLA) (Conrad 2018). In this context, the “resilient landscape” approach can be considered an important strategic step in combating climate change. The concept of resilience refers to the capacity of a system (e.g., urban landscape) to cope with disruptive factors (e.g., global climate change, extreme heat, etc.), adapt, and maintain its function (Zhou et al. 2010, Fadeyi and Maresova 2020).

The concept was first defined in 1970 by C.S. Holling as a system's capacity to maintain its structure, functions, and existence despite the effects of external changes (Walker and Salt 2006). A resilient system does not always have to return to its original state when the disruptive factor persists; the system can absorb this impact, repair itself to return to its previous state, or evolve into a more stable structure by adapting to changing conditions (Walker et al. 2004).

At this point, artificial intelligence algorithms provide landscape designers with a more comprehensive and data-driven foundation by working on large data sets (Zhou and Wang, 2018). This contributes to accelerating resilient design processes while also enabling more conscious and knowledge-based decisions. Despite the growing body of research on climate-resilient urban design and the increasing use of artificial intelligence in spatial planning, existing studies largely focus on isolated applications such as vegetation mapping, environmental monitoring, or visualization, without providing an integrated landscape-scale evaluation of how AI can systematically support climate-resilient landscape design. Furthermore, previous research has predominantly addressed the technical performance of AI models, while their strategic role in enhancing ecological resilience, nature-based solutions (NBS), and adaptive landscape planning processes remains insufficiently conceptualized and comparatively assessed. This gap highlights the need for a comprehensive framework that connects AI technologies with climate resilience objectives within the discipline of landscape architecture.

Therefore, this study addresses this critical gap by providing a comparative and integrative landscape-scale assessment of AI-supported climate-resilient landscape design practices across multiple international and national case studies. The originality of this research lies in its systematic evaluation of how AI-based tools—including machine learning, digital twins, and sensor networks—contribute to climate-resilient landscape design through ecological performance optimization, adaptive planning strategies, and decision-support mechanisms. By linking technological capabilities with

landscape resilience outcomes, this study offers a novel conceptual and analytical perspective that advances the integration of artificial intelligence into climate-responsive landscape architecture.

The aim of this study is to examine climate-resilient urban landscape design approaches at the intersection of nature-based solutions (NBS) and artificial intelligence (AI)-based decision support systems. The study aims to evaluate design strategies that can increase the resilience of cities to climate change by revealing the data-driven, predictive, and adaptive potential offered by AI technologies in the discipline of landscape architecture. In this context, the innovative contributions offered by AI in areas such as plant selection, water management, optimization of green infrastructure networks, and monitoring of urban ecosystems are discussed. At the same time, the study seeks to answer the question: "How does AI-supported landscape design contribute to the creation of climate-resilient urban areas?"

The study employed a descriptive content analysis method. Accordingly, AI and nature-based solution-oriented landscape projects conducted at the national and international levels were examined, and a comparative assessment of existing applications was made in terms of ecological resilience, sustainability, and adaptation capacity. During the analysis process, the potential use of technologies such as digital twins, machine learning algorithms, and sensor-based environmental monitoring systems at the landscape scale was examined. The findings reveal that artificial intelligence not only supports aesthetic and functional qualities but also contributes to the design of ecologically resilient, climate-adaptive, and sustainable spaces.

The Concept of Resilient City in the Context of Climate Change

The Turkish equivalent of the term "resilience" carries meanings such as being durable, flexible, and resistant. The concept of resilience is directly related to various fields of research such as climate change, ecology, sustainability, and risk management (Folke et al. 2004). First used by Francis Bacon in 1625 (Kundak 2017), the concept of resilience is associated with many disciplines such as ecology, engineering, anthropology, psychology, sociology, and earth sciences. This concept is used intensively in disaster risk reduction, climate change adaptation, humanitarian aid, and urban planning processes. Resilience is the ability of a system, community, or society exposed to disasters to withstand, neutralize, adapt to, and recover from the effects of a disaster in a timely and efficient manner, including the protection and renewal of its basic structures and functions. However, resilience also means the ability to "bounce back" or "recover" from a shock. A community's resilience to potential hazards is determined by the extent to which it has the necessary resources and the ability to organize itself both before and during such times (UNISDR 2009).

Urban areas survive and develop through multiple processes, including economic change, migration, the functioning of natural systems, and the flow of resources such as energy and Water (Harrison 2013). In urban science, resilience encompasses approaches to which factors can make clusters called cities or settlements resilient. In the early 1970s, it was argued that an ecological system's ability to self-regulate or adapt was fundamentally dependent on its inherent resilience. In later studies, ecological systems were linked to urban systems, and urban areas were examined in terms of resilience (Harrison 2013). Today, the shocks, stresses, and pressures that cities face are increasing significantly. Natural risk factors, climate change, and the risks brought about by globalization, along with ethnic conflicts, wars, terrorist attacks, and biological weapons, create new risks (Moraci et al. 2020).

A climate-resilient city can generally be defined as a city's capacity to absorb stresses, maintain its functions, improve its condition, reorganize, and evolve in response to external pressures caused by climate change (Folke 2006). In a climate-resilient city, the objectives include creating centers within walking distance, developing a railway network connecting the entire city, and organizing green buildings and infrastructure in the most efficient way (Folke 2006).

Along with this, functions that facilitate the ecological management of the city, such as renewable energy production, water, and waste recycling; green infrastructure, the establishment of eco-villages between advanced transportation centers and corridors; and sanitation control systems and local administration are supported within the scope of resilient cities (Çiğdem and Akyol 2016).

A model that implements all these positive indicators is not yet ready. Most urban strategic plans are based on expected population growth, and sustainability plans are carried out in an environmentally sensitive manner (Newman and Jennings 2008). There are also approaches that view the transformation of small settlements into metropolitan areas as resilience. According to this approach, most cities in the world can be considered resilient. Cities possess varying degrees of resilience. They recover at different rates following disasters, including natural disasters or economic shocks (Harrison 2013).

In 1976, the United Nations Conference on Human Settlements (UN-Habitat) brought to the forefront the creation of cities resilient to the effects of climate change by providing a sustainable urban environment. These goals are addressed in the UN 2030 Sustainable Development Goals. The 17-point UN Sustainable Development Goals, prepared in 2015, converge with the Paris Climate Agreement and the Sendai Framework for Disaster Risk Reduction, drawing attention to issues such as combating climate change, access to clean water, and sustainable and resilient cities. Tuğaç (2019) quoting states that research on urban resilience examines the subject by taking into account the dimensions of ecology and sustainability, disasters and risks, economics, climate change, and all approaches together.

In climate-resilient cities, risks that may arise due to climate change are taken into account, and measures are taken to reduce these risks. Establishing greenhouse gas reduction targets and developing adaptation actions are among the key strategies for combating climate change in cities. Greenhouse gas reduction aims to prevent the increase of greenhouse gases in the atmosphere, which come from a wide range of sources, from land use to waste management, energy production to industry and transportation. Adaptation to climate change, on the other hand, aims to reduce the effects of climate change by building resilience to impacts such as floods, sea level rise, storms, and drought, and by helping cities cope with the current consequences of climate change Research on urban vulnerability and climate change adaptation in developing countries has led to the development of strategies for building resilient cities.

The following actions are recommended to overcome these challenges and make cities resilient (Galderisi 2014). Climate action plans; institutional structures and authorities to understand and address issues; coordination mechanisms established for risk reduction; personnel, budgets, and resources; risk and vulnerability assessments; early warning systems and existing emergency management capacities; ethical and participatory planning and zoning principles; critical services and infrastructure.

Artificial Intelligence Applications in Landscape Design

Artificial intelligence (AI) is defined as a set of algorithms that mimic human-like thinking, learning, and decision-making processes in computers (Alberti 2016). As today's cities are considered systems that require the management of complex data flows, AI has become an important element of transformation in urban planning. Thanks to sensor-based data collection, satellite image processing, big data analytics, and machine learning methods, environmental monitoring, transportation optimization, land use analysis, and climate adaptation strategies can be developed more effectively in cities (Forman 2014).

One of AI's most important contributions in the urban environment context is increasing the accuracy of predictive models by reducing uncertainty in spatial decision-making processes. In this respect, AI is used as a powerful tool in landscape

architecture for making ecologically based decisions (Forman 2014). In particular, AI has begun to be used frequently in urban landscape design for issues such as plant selection and biodiversity planning, water management and permeability surface analysis, ecological corridor and green network design, and urban heat island mitigation.

Plant selection processes require the evaluation of numerous variables such as climate, soil characteristics, duration of sunlight exposure, microclimate conditions, and ecological suitability. Machine learning algorithms can analyze these multidimensional data to predict the ecological suitability of species with high accuracy (Tzoulas et al. 2007). AI methods are also widely used in the early detection of invasive species, habitat suitability modeling, and species distribution predictions (Benediktsson et al. 2005). Analyzing remote sensing images with deep learning enables the rapid determination of plant health and stress conditions (Benediktsson et al. 2005).

Therefore, AI contributes to landscape architects developing more resilient and climate change-adaptive planting strategies in terms of biodiversity. Sustainable water management is a critical element in increasing the resilience of cities to climate change. Deep learning-based image classification methods enable the mapping of permeable and impermeable surfaces with high accuracy (Forman 2014). These classifications provide fundamental data for stormwater flood modeling, water routing scenarios, and drainage system optimization. Processing soil moisture, precipitation, and evaporation data with AI algorithms enables the creation of efficient water use models that reduce irrigation requirements (Hermosilla et al. 2024). In this context, AI not only analyzes existing systems but also develops predictive models for future flood risks (Hermosilla et al. 2024).

Ensuring the continuity of urban ecosystems is one of the fundamental principles of landscape planning. Artificial intelligence-supported spatial analyses identify areas that fragment habitats and hinder species mobility, and optimize ecological corridor designs based on this information (Forman 2014). Machine learning-based connectivity modeling significantly contributes to determining suitable routes for fauna mobility by increasing the accuracy of least-cost path algorithms (Forman 2014). Land cover classifications derived from remote sensing data also form an important knowledge base for the urban-scale planning of green networks (Hermosilla et al. 2024).

Ultimately, AI directly contributes to the ecological functionality of urban ecosystems by enhancing the spatial integrity of ecological networks. The urban heat island (UHI) effect is a significant urban climate issue that arises as a result of dense urban development, causing higher temperatures within cities compared to rural areas. Analyzing thermal satellite data with AI algorithms reveals temperature distributions in detail and facilitates the identification of heat-prone areas. AI-based models simulate the effects of different vegetation densities on shading and cooling, enabling the determination of optimal green infrastructure strategies (Maged et al. 2025).

Furthermore, AI-supported wind flow analyses provide critical data for the creation of cool corridors (Alberti 2016). In this context, AI enables the development of scientific, verifiable, and data-driven landscape strategies aimed at reducing the KIA effect. Various studies exist on the use of artificial intelligence systems in landscape architecture. Tebyanian's (2020) study comprehensively reviews the literature on the use of machine learning methods in urban landscape design, laying the foundation for the emerging body of knowledge in this field. The 71 academic studies selected for the research reveal how machine learning contributes to design decision-making processes, spatial analyses, the processing of environmental data, and the modeling of potential problems in urban open spaces.

This review aims to provide a methodological and conceptual basis for landscape architects to evaluate data-driven approaches. In parallel, Fernberg et al. (2021) discuss current trends in artificial intelligence technologies in the context of landscape architecture and emphasize the need to create an interdisciplinary “artificial intelligence ontology.” This ontology aims to establish a theoretical framework to ensure the circulation of design knowledge between humans and

machines in an open, interoperable, and standardized structure. Xing et. al. (2025), on the other hand, evaluate current issues in landscape design through AI-based design applications; he examines application components such as water elements, lighting arrangements, irrigation infrastructures, and ground coverings through case studies conducted on AI platforms.

The study demonstrates that artificial intelligence can be integrated into the design process not only as a formal production tool but also as an analytical support system that can be used to guide functional decisions. Nitavska and Mengots (2017) research examine the transformation undergone by digital design tools used for visual communication in landscape architecture, comparing traditional Photoshop-based production techniques with AI visualization software that works with text inputs, such as DALL·E 2 and NVIDIA GauGAN2. This comparison was analyzed by evaluation groups consisting of landscape professionals, and a comprehensive survey was conducted to determine the attitudes of professionals toward AI tools.

Finally, Sağlık and Minkara (2024) explore the relationship between urban space and emotions, discussing how emotional experiences can be transformed into spatial design. The study created conceptual spatial constructs for different emotional states and utilized AI-based visual production software to generate spatial equivalents for abstract emotional concepts. This revealed that the design process can evolve into a multi-layered structure that takes into account not only physical parameters but also the user's psychological experiences.

Technical Infrastructure of AI-Supported Landscape Systems

Sensor Networks and Remote Sensing Systems

The foundation of AI-supported landscape systems consists of sensor networks and remote sensing technologies that can collect environmental data in real time. Internet of Things (IoT)-based sensors continuously monitor variables such as soil moisture, temperature, light intensity, air quality, carbon emissions, and water levels, providing dynamic data for landscape decision-making processes (Conrad, 2018). Remote sensing systems, particularly high-resolution satellite imagery and drone-based imaging techniques, are used to assess the ecological status of large areas. AI-based image processing algorithms provide high accuracy in processes such as land cover classification, plant health determination, biomass detection, and impervious surface analysis (Benediktsson et al. 2005). In this context, the coordination of sensor networks and remote sensing technologies contributes to the early detection of changes and disturbances in landscape areas, enabling more strategic ecosystem interventions (Conrad 2018).

Integration of Big Data and Geographic Information Systems (GIS)

Landscape systems contain multi-layered spatial data such as topography, climate, soil structure, corridor connectivity, biotic elements, and user behavior. GIS-based big data infrastructures play a critical role in processing this data. While GIS systems organize spatial data, AI algorithms extract meaningful relationships from this data, helping to ground landscape decisions in an objective basis (Forman 2014). Big data analytics offers significant advantages, especially in complex urban ecosystems where the volume of data is too large to be processed using traditional methods. For example, processing raster data with millions of cells (NDVI, LST, topographic analyses) using AI classification algorithms reveals the spatial distribution of vegetation change, soil moisture, erosion risk, and heat island effects with high accuracy (Folke 2006). GIS–AI integration has become one of the fundamental components of smart city applications, green infrastructure planning, disaster management, and ecological risk mapping.

Modeling Ecosystem Services with Machine Learning

Ecosystem services—such as carbon storage, water cycle regulation, air purification, biodiversity support, shading, and recreational benefits—play a critical role in the ecological functionality of cities. Modeling these services requires complex data relationships, making machine learning methods a powerful solution. Regression models, random forests, support vector machines (SVM), and deep learning techniques can predict the spatial distribution of ecosystem services with high accuracy (Smith 2019). Services such as carbon storage and heat island effect, in particular, depend on variables such as vegetation cover density and land use, and modeling these relationships with machine learning produces critical data for landscape planning (Nitavska and Mengots 2017). Machine learning is also widely used in calculating water retention capacity, impervious surface ratios, and habitat suitability (Tzoulas et al. 2007). These methods have made it possible to develop scenarios that maximize ecosystem services in landscape design.

Digital Twin Technology and Landscape Simulations

Digital twin technology is an innovative method that enables the creation of a digital copy of a physical system, allowing it to be monitored interactively with real-time data and enabling predictive simulations. It has also been used in landscape architecture in recent years and contributes significantly to the dynamic management of urban green spaces (Alberti 2016). Landscape digital twins simulate the effects of design on ecosystem processes by integrating a wide variety of data sets, such as sensor data, GIS layers, drone images, and climate models. For example, the shading and heat reduction effects of a new tree planting design, the impact of green infrastructure arrangements on rainwater flooding risk, the carbon storage and biodiversity outcomes of plant selection scenarios, and the effects of urban form changes on wind flow can all be tested in a digital environment (Nitavska and Mengots 2017). Digital twin models reduce costs and create more reliable landscape planning processes by enabling the evaluation of design decisions before implementation.

MATERIAL AND METHODS

Material

The primary materials of this study consist of selected national and international case studies in which nature-based solutions (NBS) and artificial intelligence (AI)-based decision support systems are integrated to enhance climate resilience in urban landscapes. The cases examined include implemented or proposed projects from Europe, the Americas, and Asia, as well as examples from Türkiye. The materials analyzed in this study were obtained from the following sources:

- Articles published in peer-reviewed national and international scientific journals
- Reports released by international organizations (e.g., UN-Habitat, FAO, World Bank)
- Project documents published by municipalities, local governments, and urban planning or landscape design offices
- Technical reports related to smart cities, green infrastructure, and digital twin applications
- Case studies involving Geographic Information Systems (GIS), remote sensing, sensor-based environmental monitoring, and machine learning applications

Special emphasis was placed on urban landscape projects where AI technologies were applied to plant selection, water management, optimization of green infrastructure networks, climate risk assessment, and monitoring of urban ecosystems.

Methods

This study adopts a qualitative research approach and is conducted within the framework of descriptive content analysis. This method was selected to systematically examine existing practices and applications in order to identify common themes, strategies, and emerging trends in AI-supported landscape design for climate-resilient urban environments. Descriptive content analysis enables an in-depth interpretation of how artificial intelligence contributes to climate change adaptation and ecological resilience beyond individual or isolated cases. Within the scope of the study, a total of 10 case studies were examined, including 5 international and 5 cases from Türkiye. The inclusion of both international and national examples was intended to enable a comparative evaluation of global best practices and their contextual adaptation within the Turkish planning framework. The research process was carried out in four interrelated stages, as outlined below.

Literature Review and Development of the Analytical Framework

A comprehensive review of recent literature on climate-resilient cities, nature-based solutions (NBS), artificial intelligence, and urban landscape planning was carried out. The literature review covered publications between 2010 and 2025 and was conducted using Scopus, Web of Science, and Google Scholar databases. This time frame was selected to capture the rapid development period of AI applications in urban planning and climate adaptation. The search process was conducted using the following keywords: artificial intelligence, AI, climate resilience, urban landscape, machine learning, green infrastructure, digital twin, urban planning, GeoAI, nature-based solutions, smart city, climate adaptation, and urban heat island modeling. In addition to peer-reviewed academic studies, municipal strategy documents, EU-funded project reports, and official smart city policy documents were included to ensure the integration of research and practice. Based on this review, a thematic analytical framework was developed to guide the analysis of the case studies. The framework consists of four main themes:

- types and roles of AI technologies,
- climate risks addressed,
- landscape-based and nature-based intervention strategies, and
- spatial, ecological, and environmental outcomes.

These four themes were derived inductively from recurring conceptual and operational patterns identified in the reviewed literature and subsequently used as the primary analytical dimensions for cross-case comparison.

Case Study Selection

Case studies were selected using a purposive sampling strategy, which is appropriate for qualitative research aiming to explore specific phenomena in depth rather than to achieve statistical generalization. The selection focused on cases that represent current and emerging practices at the intersection of artificial intelligence, landscape design, and climate resilience.

The following criteria guided the case selection process:

- Explicit focus on urban climate resilience (e.g., heat mitigation, flood management, biodiversity protection);
- Use of AI-based or data-driven technologies such as machine learning, deep learning, sensor networks, or digital twin systems;
- Implementation at the urban or metropolitan landscape scale;
- Capacity to represent broader trends and widely adopted practices, rather than isolated or experimental cases.

The final sample consists of 5 international cases (including Copenhagen, Amsterdam, Singapore, Chicago, and Bengaluru) and 5 Turkish cases (including Istanbul, Mersin, Konya, Ankara, and Izmir), collectively representing contemporary tendencies in AI-supported climate-resilient landscape design. The selected cases collectively represent current global and national tendencies in AI-supported climate-resilient landscape design.

Descriptive Content Analysis and Thematic Coding

Within the scope of this study, descriptive content analysis was conducted through a structured and transparent thematic coding process. The analysis was designed to ensure consistency and comparability across all selected case studies by applying a common analytical framework derived from the literature review.

Development of Thematic Categories

Based on the synthesis of previous research on climate-resilient urban design, nature-based solutions (NBS), and AI-supported planning, four main thematic categories were identified prior to the analysis. These themes reflect the key dimensions through which artificial intelligence contributes to climate-resilient landscape design:

Theme 1-AI Technologies and Data Infrastructure: This theme focuses on the types of artificial intelligence and data-driven technologies integrated into landscape design and management processes

Theme 2-Climate Risks and Environmental Challenges Addressed: This theme captures the specific climate-related problems that AI-supported landscape interventions aim to mitigate or adapt to.

Theme 3-Landscape-Based and Nature-Based Intervention Strategies: This theme examines how AI insights are translated into spatial and ecological design decisions.

Theme 4-Spatial, Ecological, and Performance Outcomes: This theme addresses the observed or reported outcomes of AI-supported landscape interventions.

All case studies were systematically reviewed using secondary data sources such as academic publications, project reports, municipal documents, and technical studies. Relevant information was extracted and coded according to the predefined thematic categories. The coding process was conducted in three stages: (1) open coding to identify AI applications and climate-related strategies within each case; (2) axial coding to group similar practices under the four thematic categories; and (3) cross-case comparison to identify recurring patterns and contextual differences. The coding procedure was carried out by a single researcher and subsequently subjected to a secondary consistency review to enhance reliability and reduce potential subjective bias. Ambiguous classifications were re-evaluated to ensure thematic coherence. Rather than analyzing cases in isolation, the study compared how different cities addressed similar climate challenges through AI-supported landscape strategies. This approach enabled the identification of recurring patterns, dominant intervention types, and shared technological solutions, as well as context-specific adaptations.

Comparative Evaluation and Interpretation

In the final stage, the thematically organized findings were comparatively evaluated to identify recurring patterns, dominant strategies, and key contributions of AI-supported landscape design to climate resilience. The results were interpreted to assess how AI integration enhances the adaptability, performance, and long-term sustainability of urban landscapes. Overall, the analysis demonstrates that AI-supported landscape design functions not only as a tool for

improving spatial and aesthetic quality, but also as a strategic, data-driven approach that supports ecological resilience, climate adaptability, and sustainable urban development.

FINDINGS

Artificial intelligence (AI) technologies are becoming increasingly important as an innovative tool in the planning of climate-resilient cities on a global scale. Urban ecology and smart city research conducted worldwide shows that AI offers a powerful decision support mechanism, particularly in reducing the heat island effect, water management, green network planning, and modeling ecosystem services (Santamouris 2020, Batty 2024).

Similarly, AI-supported landscape design infrastructure is developing in Türkiye. Metropolitan municipalities produce heat island maps using remote sensing data and perform impervious surface analyses with AI. These data are effectively used in planning green infrastructure solutions in areas with high flood risk (Demir and Yücel 2021).

Furthermore, studies conducted at universities are adapting machine learning methods to the Turkish context for the selection of plant species compatible with climate change, the spatial modeling of ecosystem services, and digital landscape simulations (Kahraman and Avcı 2022). The findings reveal that both international and national cases apply AI technologies primarily in four functional domains: (1) climate risk prediction, (2) environmental monitoring, (3) optimization of green infrastructure, and (4) scenario-based simulation for adaptive planning. Some successful examples include:

Copenhagen, Denmark – Green Infrastructure and Climate Resilience

As the capital and largest settlement center of Denmark, Copenhagen has been systematically developing climate change adaptation policies for many years and is a pioneering city in the field of sustainability. The city's historical development process has demonstrated the necessity of both structural and planning-scale interventions to manage climate-related risks, particularly flooding and extreme rainfall. Indeed, the flood disasters caused by extreme rainfall in 2011 and 2014 resulted in millions of dollars in economic losses, necessitating a comprehensive review of the existing infrastructure approach (Batty 2024).

In this regard, the Copenhagen Climate Adaptation Plan, which came into force in 2011, envisages the integration of current data into advanced technological infrastructures and artificial intelligence (AI)-based analysis systems in order to be able to adapt quickly to unpredictable changes in climatic conditions (Figure 1).

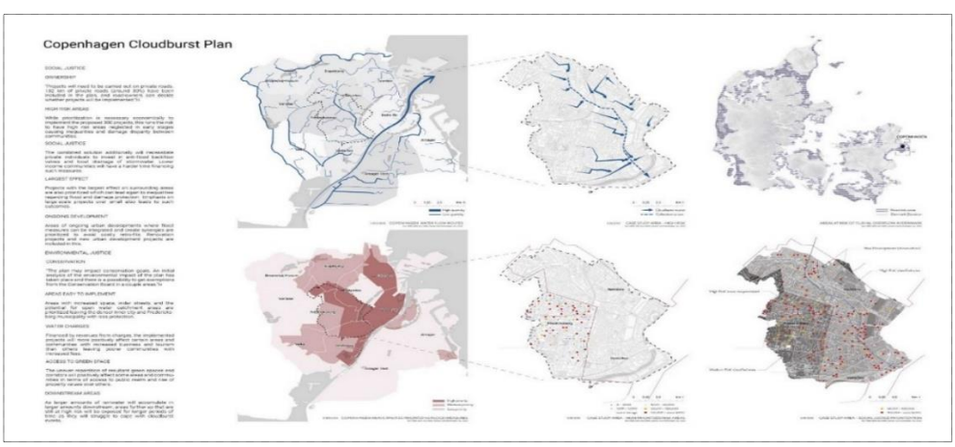


Figure 1. Copenhagen Cloudburst plan, Copenhagen, Denmark (Ziersen et al. 2017)

This approach enables the city to develop a dynamic, highly predictive, and data-driven adaptation strategy in the face of climate uncertainties (Ziersen et al. 2017). Under the plan, various applications have been developed to protect the city against climate-related threats. In this context, not only the strengthening of physical infrastructure but also the integration of machine learning, deep learning, and AI-supported simulation systems into decision-making processes has created a significant transformation. For example, machine learning models process multi-layered data sets such as historical rainfall data, topography, impermeability rates, and sewer capacity to predict the spatial and temporal distribution of sudden and intense rainfall with high accuracy, thereby optimizing planning for the separation of rainwater from the sewer network and its diversion to areas with low flood risk (Figure 2). Furthermore, deep learning-based image processing methods analyze satellite images and drone data to identify impervious surfaces where the risk of water accumulation is increased, and these data are used to guide green infrastructure planning (Miljo Metropolen 2011).

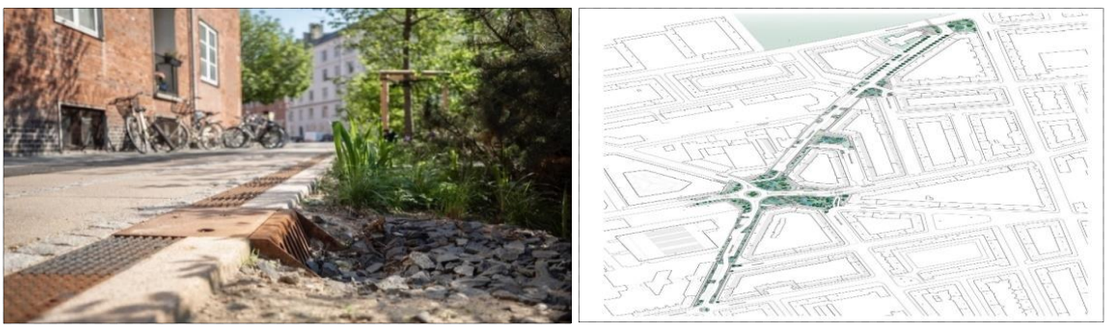


Figure 2. Sankt Kjelds square (Miljo Metropolen 2011)

In addition, AI-supported hydrodynamic modeling and scenario simulations model the flow paths of water within cities under different rainfall regimes, enabling the identification of areas at high risk of flooding. These models have served as an important reference in the redesign of asphalt surfaces, city parks, and open public spaces with climate-resilient approaches since 2011 (Balacumaresan et al. 2024). AI-based energy optimization systems applied to energy infrastructure have analyzed changes in heat demand and revealed that the new heating system could provide approximately 70% energy savings compared to traditional methods (Miljo Metropolen 2011). Furthermore, analyzing temperature, wind, and solar radiation data obtained from sensor-based environmental monitoring networks using AI algorithms to reduce the urban heat island effect provides strategic guidance for preserving existing green spaces and selecting locations for new green spaces (Balacumaresan et al. 2024) (Figure 3).



Figure 3. Masterplan and photos from Kokkedal river restoration and storm water adaptation project (Jorgensen et al. 2022)

In addition to these processes, AI-based digital twin applications encourage the widespread adoption of these applications across the city by testing the water retention capacity, energy efficiency, and flood mitigation effects of green roofs through scenarios. All these technological and design interventions contribute to Copenhagen's carbon-neutral strategy. The Copenhagen case indicates that AI-supported hydrodynamic modeling, rainfall prediction, and digital twin simulations are directly operationalized as decision-support mechanisms for flood mitigation, stormwater optimization, and urban heat island reduction.

Amsterdam, Netherlands – Biodiversity and Green Space Management

As one of Europe's early smart city implementers, Amsterdam has placed artificial intelligence technologies at the heart of its urban landscape, biodiversity, and climate resilience policies. In line with the city's comprehensive smart city strategy adopted in 2009, IoT-based sensor networks installed in large green spaces such as Vondelpark (Figure 4) and Westerpark (Figure 5) continuously monitor environmental parameters such as soil moisture, pH, microclimate data, surface temperature, and air quality, transferring this data to machine learning algorithms (Random Forest, SVM, LSTM) (Bui et al. 2021).

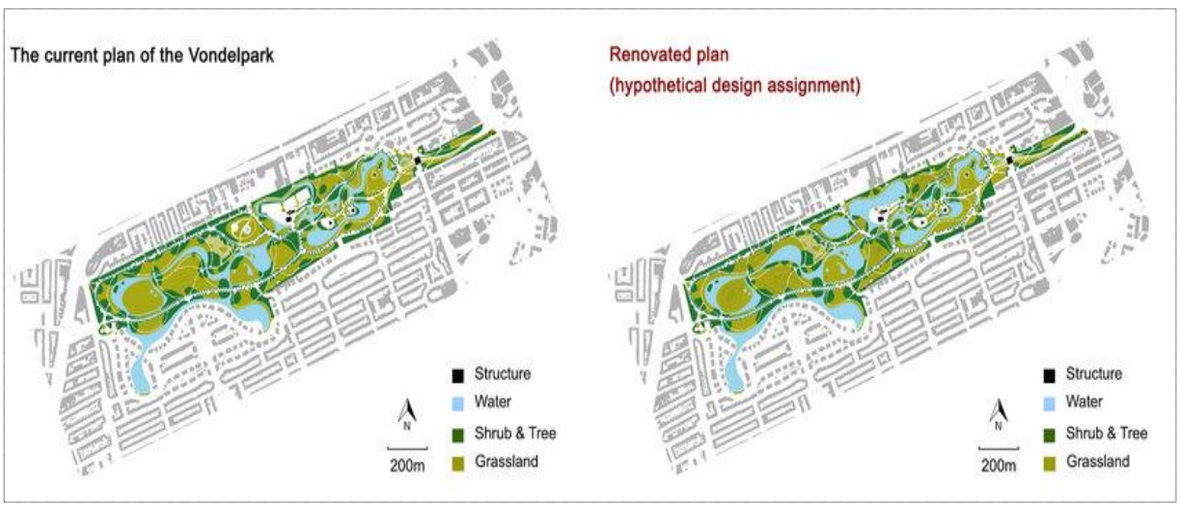


Figure 4. Vondelpark (Bui et al. 2021)

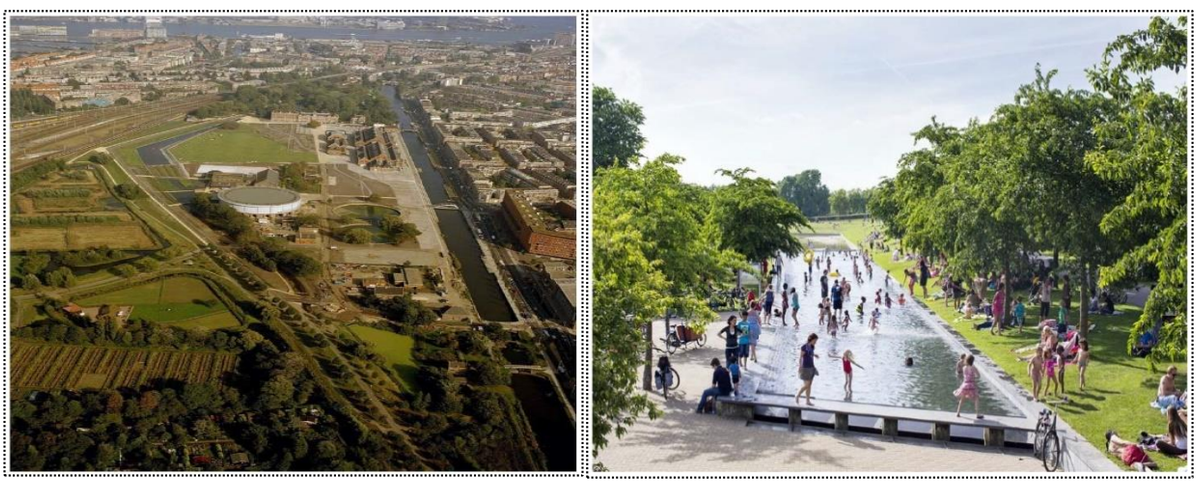


Figure 5. Aerial view of the park from the West and the Event Lake and the main access to the green central areas (Di Carlo et al. 2020)

Artificial intelligence processes this data to predict irrigation needs, optimize shading and planting strategies to reduce the heat island effect, and generate predictive maintenance models that direct water to permeable surfaces during periods of excessive rainfall. Deep learning-based image recognition systems (CNN) used by the Amsterdam Municipality and the Bosch Smart City Program detect plant stress, soil degradation, and heat accumulation by extracting spectral indices such as NDVI, EVI, and MSAVI from drone images (Sodoudi et al. 2022). These systems serve as a critical early warning mechanism, enabling decisions that enhance the cooling capacity of green infrastructure, particularly during periods of increased heat waves. The acoustic artificial intelligence systems implemented in Amsterdam's biodiversity management record bird, insect, and bat species via ultrasonic sensors and classify them through spectral analysis, thereby accurately revealing species losses or changes in migration cycles associated with climate change (Sodoudi et al. 2022).

All this data is combined with GIS + AI-based spatial planning tools to form the basis for resilience-enhancing interventions such as strengthening ecological corridors, intensifying permeable green infrastructure in flood-prone areas, and redistributing plant species with high carbon storage capacity (Sodoudi et al. 2022). Thus, Amsterdam positions artificial intelligence not only as an operational management tool, but also as a strategic sustainability component that enhances the adaptation capacity of urban ecosystems, their resilience to climate shocks, and the continuity of biodiversity. The Amsterdam case demonstrates that AI-based biodiversity monitoring, predictive irrigation, and microclimate analysis systems directly support ecosystem continuity, water efficiency, and adaptive green space management.

Singapore – Virtual City Model (Virtual Singapore)

The “Gardens by the Bay” project in Singapore is considered one of the most comprehensive examples of the decisive role played by artificial intelligence not only in landscape design but also in creating urban ecosystems that are resilient to climate change (Figure 6). Artificial intelligence algorithms simulate the effects of temperature increases, changing rainfall patterns, increased salinity, and extreme weather events on plant communities, enabling the landscape to be designed to adapt to future climate conditions (Balacumaresan et al. 2024).

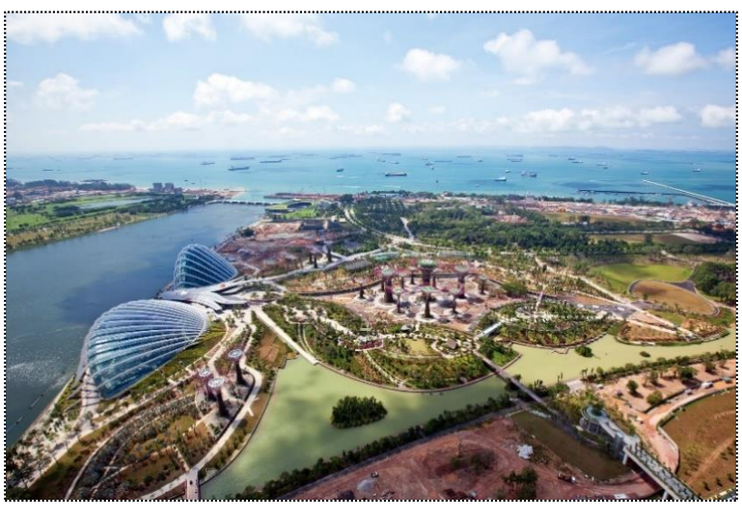


Figure 6. The Gardens by the Bay project in Singapore (Grant Associates 2012)

LoRaWAN-based sensor networks, hyperspectral imaging systems, thermal cameras, and IoT-based microclimate sensors used in the project continuously monitor areas that increase the heat island effect, regions with the highest water evaporation losses, and early signs of plant stress (Lin et al. 2025). These data are processed by artificial intelligence

models and converted into climate-adaptive design decisions, such as increasing shading intensity against heat waves, directing salt-tolerant species to specific zones, and strengthening water-absorbing plant structures in areas with high flood risk (Lee et al. 2019). Especially in high temperature and drought scenarios, AI-managed predictive irrigation systems ensure that water is applied only as needed and at the ideal time interval, thereby creating water savings and enabling the protection of plant physiology during periods of stress (Lin et al. 2025) (Figure 7).

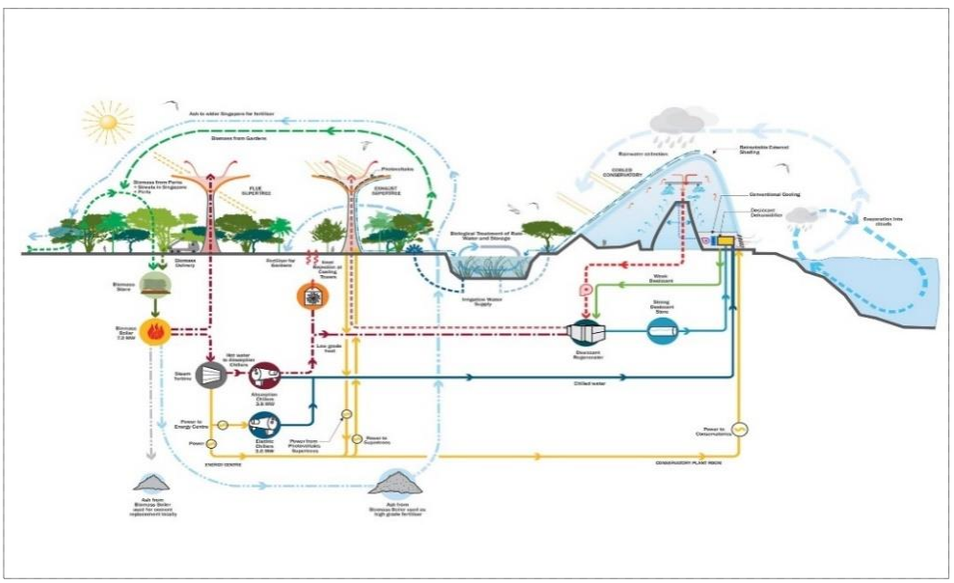


Figure 7. Continuous analysis of soil moisture and salinity data (Grant Associates 2012)

Similarly, continuous analysis of soil moisture and salinity data supports the development of plant selection models that enhance the landscape's adaptation capacity to salinity stress caused by rising sea levels in coastal areas (Conrad 2018). Furthermore, hyperspectral imaging systems detect pigment and chlorophyll changes at the leaf level at an early stage, enabling intervention before heatwave or pollution-induced stress becomes visible (Conrad 2018). Thanks to this integrated technological infrastructure, Gardens by the Bay offers an innovative climate resilience model where artificial intelligence is at the center of adaptive landscape strategies that provide protection against water management, temperature regulation, ecosystem stability, and overcoming bioclimatic thresholds. As a result, the project has evolved into a hybrid nature-technology system where the multi-layered effects of climate change on urban landscapes can be continuously monitored using AI-powered sensors and automation systems, and where the ecosystem dynamically renews itself to increase its resilience. The Singapore case indicates that AI-driven simulation, hyperspectral monitoring, and predictive irrigation systems enhance plant resilience, regulate microclimate conditions, and optimize adaptive planting strategies under extreme climate scenarios.

Chicago, USA – Array of Things (AoT) Project

The Array of Things (AoT) project implemented in Chicago offers an innovative urban data infrastructure that enhances AI-powered decision-making mechanisms through modular sensor nodes capable of continuously monitoring the urban environment, thereby radically redefining the interaction between landscape planning and climate resilience (Catlett et al. 2017). AoT sensors record numerous parameters in real time, including air quality indicators such as temperature, surface heat, relative humidity, wind speed, CO_2, and particulate matter (PM2.5/PM10), as well as light levels, traffic density, and mobility patterns (Catlett et al. 2017). These multi-layered data are processed using machine learning and data mining techniques to model the microclimate behavior of the city, the spatial distribution of urban heat islands, the

effect of impervious surfaces on surface runoff, and the contribution of vegetation to air quality with high resolution (Zhou and Wang 2018) (Figure 8).

This enables landscape architects to identify areas where the cooling effect of green spaces is most intense, develop tree planting strategies focused on shading in neighborhoods with high heat island effects, and make urban design decisions that strengthen the continuity of wind corridors. Furthermore, the microclimate data provided by AoT enables the identification of areas where surface runoff increases due to sudden and intense rainfall, providing a scientific basis for the strategic placement of nature-based solutions (NbS) such as rain gardens, bio-swales, green roofs, and permeable surface solutions in areas with high flood risk (Newman and Jennings 2008). This demonstrates that landscape infrastructure is not only an aesthetic and recreational element but also a protective climate adaptation tool against extreme weather events.

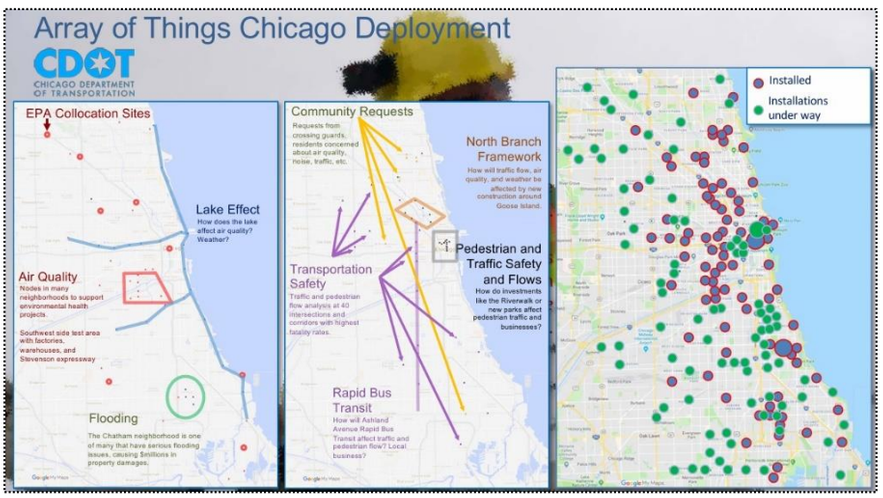


Figure 8. Array of Things (AoT) project (Catlett et al. 2017)

The AoT project's contribution to climate resilience is not limited to the production of physical data; it also has significant impacts in terms of urban governance, transparency, and participatory planning. Thanks to the project's open data approach, information sharing among researchers, local governments, community organizations, and designers is increasing, enabling the development of more integrated and evidence-based policies on climate adaptation and landscape management (Catlett et al. 2017). Furthermore, artificial intelligence models can learn from historical data to predict future temperature increases, urban mobility patterns, and pollutant dispersion pathways, enabling the development of adaptive planning frameworks that ensure the long-term sustainability of green infrastructure. These insights provided by AoT support the reintegration of Chicago's park systems with climate adaptation strategies, enhance the ecological continuity of green corridor networks, and prioritize landscape interventions that reduce climate inequalities in the city's vulnerable neighborhoods (Catlett et al. 2017). Therefore, AoT presents a pioneering model that scientifically demonstrates how AI-powered sensor technologies make the functioning of the urban landscape visible, spatially define climate risks, and establish green infrastructure as a critical urban system in the context of climate resilience.

Sensors measure surface temperatures; artificial intelligence maps this data to identify heat island hotspots. This output optimizes where landscape interventions such as shading, green roofs, and permeable surfaces should be applied (Wang et al. 2022). AoT data also enables the determination of future landscape strategies:

- Selection of rain gardens and sustainable drainage (SuDS) points to reduce flood risk: Artificial intelligence analyzes rainfall patterns to predict areas where water will accumulate.

- Plant species selection: Microclimate data (temperature, humidity, wind) determines which plant species will adapt better.
- Optimization of pedestrian and open space usage: Traffic and mobility data reveal which areas have a greater need for parks and social spaces (Zhou and Wang 2018).

Thanks to this project, artificial intelligence plays an active role in both analyzing the urban landscape and making forward-looking sustainable design decisions. The Chicago AoT case reveals that real-time sensor networks combined with machine learning enable spatial identification of heat island hotspots, flood-prone areas, and pollution zones, directly informing nature-based solution placement and green infrastructure optimization.

Bengaluru, India – Urban Forest Mapping

Artificial intelligence-supported urban forest mapping in Bengaluru stands out as a strategic tool aimed at increasing the city's resilience to climate change. Intensive urbanization, fragmentation of green spaces, and disruption of ecological integrity have made the city more vulnerable to both microclimatic changes and extreme weather events (Nagendra and Bai 2008). In this regard, the analysis of high-resolution satellite images, LiDAR scans, and unmanned aerial vehicle (UAV) recordings using machine learning algorithms reveals the spatial structure of urban forests, tree cover density, species diversity, and the connectivity level of green corridors in detail (Shastri et al. 2017) (Figure 9). These advanced datasets enable the identification of areas where the urban heat island effect is particularly intense and strengthen scientific decisions regarding the implementation of nature-based solutions such as shading, afforestation, and permeable surface applications in these areas (Nagendra and Mundoli 2019). Additionally, artificial intelligence models can analyze irregularities in rainfall patterns, surface flow dynamics, and impervious surface density, facilitating the prediction of flash floods caused by sudden rainfall and enabling the proper placement of sustainable urban drainage systems (SuDS), rain gardens, and green spaces with high water retention capacity (Ramachandra et al. 2020).

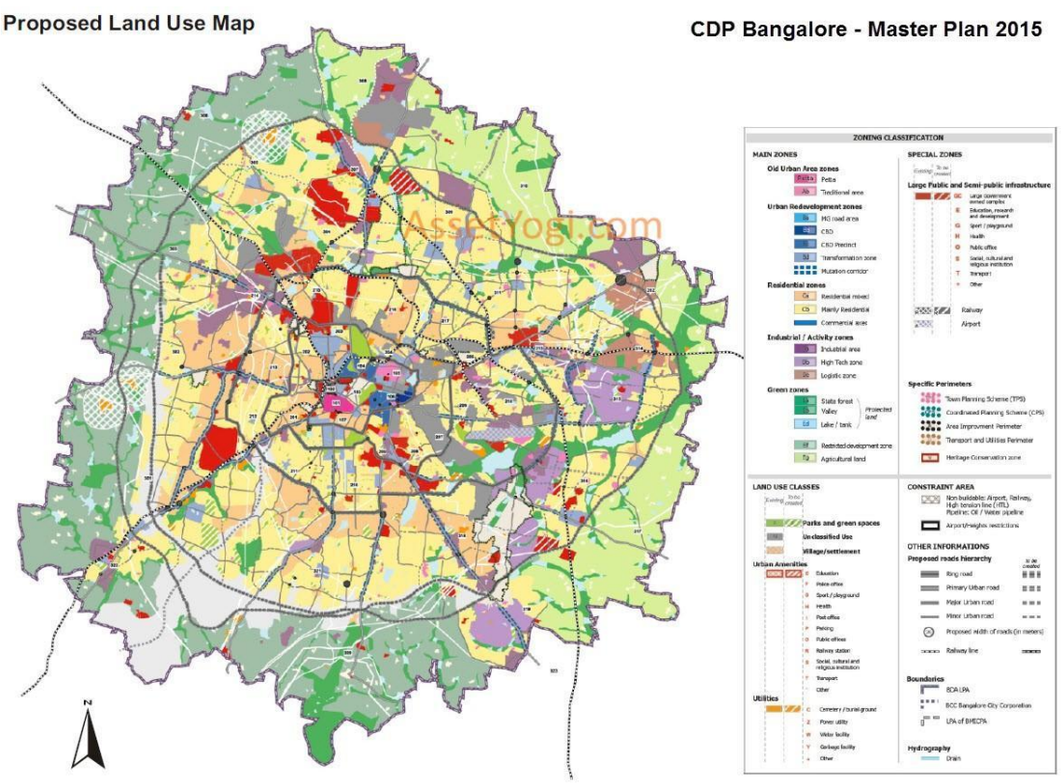


Figure 9. Urban forest mapping-Bengaluru (Nagendra and Mundoli 2019)

Climate projection-based artificial intelligence scenarios support the establishment of a flexible, adaptable, and climate-sensitive framework in landscape planning by predicting future temperature increases, deforestation trends, and how ecological risk zones will change (Mahmoud and Garcia 2019). When all these components come together, Bengaluru's AI-based urban forest management approach offers a comprehensive climate adaptation strategy that enhances the city's resilience to climate-related hazards such as extreme heat, air pollution, and flooding by strengthening the continuity of ecosystem services. The Bengaluru case indicates that AI-supported urban forest mapping strengthens ecological corridor continuity, supports flash flood prediction, and enhances ecosystem service-based landscape planning.

Istanbul – ODTÜ UP2030 Project

The UP2030 (Urban Planning and Design Ready for 2030) project, carried out by the ODTÜ Solar Energy Application and Research Center (GÜNAM), is a strategic initiative that aims to make Istanbul climate neutral and transition to sustainable energy. Artificial intelligence models developed within the scope of the project analyze the energy performance of buildings in Istanbul, predict changes in energy consumption according to different climate scenarios, and are used to maximize the energy potential that can be obtained from the sun (Erkalan 2024). Particularly in pilot areas, alternative design scenarios are rapidly tested through AI-based simulations, and the most suitable structures in terms of energy efficiency are determined. The project also uses artificial intelligence to optimize solar radiation and panel placement. The developed algorithms analyze the solar radiation falling on building roofs and the panel angle to determine the ideal placement and orientation of photovoltaic panels (Dino 2023).

This maximizes renewable energy production while aiming to improve energy efficiency and reduce carbon emissions. The project also integrates digital twin technologies to optimize energy according to Istanbul's microclimate conditions. This digital twin model provides a virtual representation of buildings and urban structures, making simulation and optimization processes more realistic (Istanbul Metropolitan Municipality 2023). The use of artificial intelligence is also prominent in transportation infrastructure. Within the scope of the project, the optimization of electric bicycle and scooter charging stations is carried out using AI algorithms, ensuring that the stations operate on solar energy and are positioned in a way that reduces carbon emissions (Erkalan 2024). This approach contributes to the creation of a climate-resilient and sustainable urban system by combining urban mobility and renewable energy integration. The UP2030 project uses artificial intelligence not merely as an analytical tool, but as a strategic component that makes urban planning decisions climate-resilient and sustainable. By improving building energy performance, maximizing solar energy potential, optimizing microclimate, and establishing carbon-neutral transportation infrastructure, the project represents a holistic approach to increasing Istanbul's climate resilience (Dino 2023, Istanbul Metropolitan Municipality 2023, Erkalan 2024). The artificial intelligence algorithms used in the UP2030 project directly support urban landscape design and climate resilience strategies. Random Forest, Gradient Boosting, and LSTM-based models predict building energy consumption, providing early warnings during periods of excessive energy demand and enabling the efficient use of energy resources (Dino 2023). This makes buildings and urban areas resilient to heat waves and energy stresses associated with climate change (Figure 10). Genetic algorithms and Particle Swarm Optimization used for solar panel placement and optimization maximize renewable energy production, supporting carbon neutrality goals and ensuring the proper integration of energy production areas into the urban landscape (Erkalan 2024).



Figure 10. PV panel integrated urban furniture prototype designed and manufactured as part of the UP 2030 project and installed in Moda İnciburnu Park (Dino 2023)

Digital twin and CNN-based geospatial machine learning models analyze the urban microclimate and optimize parameters such as shading, surface temperature, wind flow, and green space placement (Istanbul Metropolitan Municipality 2023). For example, green spaces and tree arrangements in densely built-up areas can be planned to reduce the heat island effect thanks to these AI analyses. Furthermore, mobility-focused applications such as charging station optimization encourage sustainable transportation, reducing urban carbon emissions and lowering pressure on the ecosystem. For example, Dino (2023) states, "We want to increase the usability of electric bicycles and scooters. One of the most important factors in the preference for these devices is charging (Figure 11). Users wonder how far they can travel after setting off and when the device's charge will run out. We also want to use artificial intelligence models to optimize charging stations and make these charging stations solar powered."



Figure 11. Goal to increase the use of electric bicycles and scooters (Dino 2023)

This integrated AI approach not only increases energy efficiency but also strengthens the urban landscape's capacity to adapt to climate change and plays a critical role as a decision support mechanism in sustainable urban planning (Dino 2023, Erkalan 2024, Istanbul Metropolitan Municipality 2023). The findings from the UP2030 project indicate that AI-based energy modeling, photovoltaic optimization, and digital twin simulations are integrated with urban landscape planning to address heat waves, energy stress, and carbon mitigation.

Mersin Digital Twin Project

Mersin Yenişehir Municipality's Digital Twin Project uses artificial intelligence-based advanced analytical methods to increase climate resilience (Figure 12). The Convolutional Neural Networks (CNN) and Random Forest algorithms used in the project analyze the effects of buildings and environmental elements on the microclimate in a three-dimensional digital twin model (Özyiğit 2025). CNN-based image and spatial analysis processes complex geometric information such as building morphology and roof surfaces, predicting the potential of buildings to block wind flow and surface temperature changes.



Figure 12. Mersin-Yenişehir Municipality digital twin project (Özyiğit 2025)

In this way, AI helps determine strategies that will reduce the urban heat island effect. Random Forest algorithms evaluate multivariate environmental datasets (soil moisture, vegetation density, solar radiation, air temperature) to predict which green infrastructure or afforestation arrangements will improve the city's microclimate (Yenişehir Municipality 2024) (Figure 13). The climate resilience dimension of the project is not limited to temperature and energy efficiency; it also encompasses water management, carbon sequestration, and natural shading strategies. For example, artificial intelligence simulations compare the shading, water retention, and carbon storage capacities of different species in afforestation efforts around Öksüz Stream, enabling the selection of the most suitable species. Furthermore, sensor-based simulations conducted on digital twins optimize the performance of urban drainage and irrigation systems during periods of rainfall and drought, providing early warning and intervention capabilities against extreme weather events (Özyiğit 2025).



Figure 13. Thermal comfort and surface temperature analyses (Yenişehir Municipality 2024)

Thanks to this integrated AI approach, Mersin Yenişehir is adapting its urban landscape to climate change while also increasing energy efficiency, improving microclimate conditions, and protecting biodiversity. Artificial intelligence algorithms not only analyze data but also provide urban decision-makers with strategic planning and intervention recommendations that integrate climate resilience and sustainability goals. In this respect, the project serves as an example of the integrated use of climate resilience and artificial intelligence in urban landscape management in Türkiye (Yenişehir Municipality 2024, Özyiğit 2025). The Mersin Digital Twin project demonstrates that CNN and Random Forest models are used to optimize microclimate regulation, afforestation strategies, and water retention systems, directly contributing to urban heat mitigation and ecosystem resilience.

Konya Smart City – Environmental Monitoring and Climate Platform

Konya Metropolitan Municipality has implemented an integrated smart city infrastructure that utilizes artificial intelligence (AI), IoT-based environmental sensors, and geospatial data analytics to enhance climate resilience and

environmental sustainability at the urban scale. As one of the pilot cities of Türkiye's National Smart Cities Strategy, Konya has developed a comprehensive environmental monitoring and climate management system that enables real-time observation and predictive analysis of urban climate dynamics (Republic of Türkiye Ministry of Environment, Urbanization and Climate Change 2020, Konya Metropolitan Municipality 2025). Within the scope of the Smart City Strategy and the Sustainable Energy and Climate Action Plan (SECAP), a distributed IoT-based sensor network continuously monitors key environmental parameters, including air temperature, surface temperature, humidity, air quality, and solar radiation (Konya Metropolitan Municipality 2025). These datasets are integrated into AI-supported platforms, enabling the identification of urban heat island patterns, microclimate variability, and environmentally sensitive areas. Machine learning–based predictive models analyze historical and real-time environmental data to forecast temperature increases, identify high-risk heat island zones, and support climate-responsive landscape planning (Yigitcanlar et al. 2019, Santamouris 2020). These analyses enable landscape architects and planners to identify priority areas for green infrastructure interventions, such as afforestation, green corridors, permeable surfaces, and urban parks, thereby enhancing ecosystem resilience and improving microclimate regulation. In addition, geospatial AI and remote sensing technologies enable high-resolution mapping of vegetation density, impervious surfaces, and land surface temperature, providing critical decision support for optimizing green infrastructure networks and mitigating climate-related risks, including extreme heat and drought (Konya Metropolitan Municipality 2025).

Beyond environmental monitoring, Konya's smart city platform supports adaptive urban planning through AI-based decision support systems that enable scenario simulations and data-driven evaluation of landscape and climate adaptation strategies. This integrated digital infrastructure strengthens ecosystem management, improves resource efficiency, and enhances the long-term resilience of urban landscape systems. Furthermore, Konya Metropolitan Municipality is implementing innovative low-carbon urban development projects that complement its AI-supported climate resilience framework. One prominent example is the Konya City Library, designed as Türkiye's first zero-carbon public building (Türkiye Today 2025). The project integrates climate-responsive architectural design with environmental sustainability principles, minimizing carbon emissions while preserving existing vegetation and incorporating green spaces into the urban fabric. This approach demonstrates how climate-neutral infrastructure can function as part of a broader climate-resilient landscape system by supporting ecological continuity, improving microclimate regulation, and reducing urban heat accumulation (Konya Metropolitan Municipality 2025) (Figure 14).



Figure 14. Konya City Library, Türkiye's first zero-carbon public building, integrated with green infrastructure and climate-responsive design strategies (Konya Metropolitan Municipality 2025)

The integration of zero-carbon infrastructure with AI-supported environmental monitoring strengthens Konya's capacity to implement data-driven climate adaptation and mitigation strategies. Environmental data analyzed through AI can

inform landscape interventions such as tree placement, shading strategies, and green infrastructure planning, enhancing ecological performance and urban climate Resilience (Türkiye Today 2025). Through the integration of AI, IoT, and geospatial analysis, Konya presents a scalable model in which artificial intelligence functions as a critical decision-support tool for climate-responsive landscape planning and sustainable urban development (Konya Metropolitan Municipality 2025; Santamouris 2020; Yigitcanlar et al. 2019). The Konya case indicates that AI-supported environmental monitoring and geospatial analytics are operationalized to identify heat island zones, prioritize green infrastructure interventions, and integrate zero-carbon public architecture into climate-responsive landscape systems.

Ankara Smart City – Environmental Data and Climate Monitoring Systems

Ankara has emerged as one of Türkiye's leading metropolitan areas implementing artificial intelligence (AI)-supported smart city technologies to improve climate resilience, environmental monitoring, and sustainable landscape planning. Within the framework of the Ankara Smart City Strategy and climate adaptation policies, the municipality has developed integrated digital infrastructures that combine IoT-based environmental sensors, geospatial analysis, and AI-driven decision support systems to monitor and manage urban climate risks (Ankara Metropolitan Municipality 2023). AI-supported environmental monitoring systems deployed across Ankara continuously collect high-resolution spatial and temporal data, including air temperature, land surface temperature, humidity, solar radiation, air quality indicators, and urban heat island intensity. These datasets are integrated into machine learning models that identify spatial climate risk patterns and enable predictive analysis of urban microclimate dynamics (Yigitcanlar et al. 2019, Batty 2024). This predictive capability allows landscape architects and urban planners to determine priority intervention areas where green infrastructure can most effectively reduce heat stress and enhance ecosystem services. In addition, Ankara has implemented advanced geospatial smart city platforms such as the AnkaGeo Smart City Management System, which integrates geographic information systems (GIS), real-time urban data streams, and AI-supported spatial analytics into a unified digital interface. This platform enables the visualization and analysis of critical environmental parameters, including vegetation distribution, land surface temperature, impervious surfaces, and environmental risk zones (AnkaGeo 2020). By providing a comprehensive geospatial decision-support environment, the system allows planners and landscape architects to identify priority areas for afforestation, green infrastructure expansion, and climate-sensitive landscape interventions, thereby enhancing the ecological performance and climate resilience of the urban landscape (Figure 15).

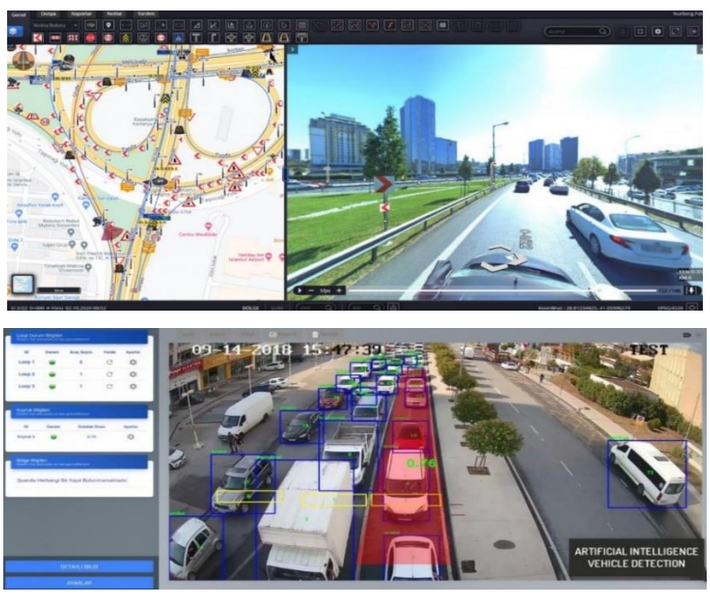


Figure 15. AnkaGeo Smart City Management Platform showing AI-supported geospatial monitoring, environmental data visualization, and spatial decision-support functions for climate-responsive landscape planning in Ankara (AnkaGeo 2020)

Beyond AI-supported monitoring and geospatial analytics, renewable energy infrastructures in the Ankara metropolitan region also illustrate how energy systems influence spatial planning decisions. A notable example is the ground-mounted solar power plant implemented in the Polatlı district of Ankara Province. Although primarily developed as a renewable energy production facility, such utility-scale photovoltaic installations significantly affect land allocation, surface characteristics, and landscape morphology at the urban–rural interface. The spatial footprint and site-selection process of large-scale solar infrastructure require integration with geospatial planning tools and environmental assessment systems, thereby linking energy transition strategies with territorial planning frameworks. In this context, renewable energy systems function not only as technical utilities but also as spatial determinants that shape land-use patterns and contribute to climate mitigation and resilience objectives. Remote sensing technologies combined with convolutional neural networks (CNN) and geospatial machine learning algorithms enable detailed mapping of vegetation cover, impervious surfaces, and thermal distribution patterns across Ankara's urban landscape. These AI-based spatial analyses provide scientific guidance for optimizing urban afforestation strategies, strengthening ecological corridors, and improving the spatial configuration of parks and green infrastructure networks to enhance climate adaptation capacity (Yigitcanlar et al. 2019).

In particular, identifying urban heat island hotspots enables targeted landscape interventions such as increasing tree canopy cover, implementing nature-based cooling solutions, and improving thermal comfort in densely built urban districts. Furthermore, Ankara has integrated digital twin and smart urban management systems into its planning framework, enabling scenario-based simulations of climate adaptation strategies. These digital models allow planners to evaluate the potential impacts of alternative landscape design interventions on temperature regulation, water management, and ecosystem performance before physical implementation (Batty 2024).

AI-supported simulation environments enable the optimization of landscape configurations by predicting how different vegetation patterns, shading structures, and permeable surfaces will influence urban microclimate regulation and heat mitigation. AI-based environmental analytics also contribute to sustainable water management and drought adaptation strategies, which are particularly critical for Ankara due to its semi-arid climatic conditions. Machine learning models analyze long-term climate projections, precipitation variability, and evapotranspiration patterns to support efficient irrigation planning, drought-resistant plant selection, and sustainable landscape maintenance practices (Santamouris 2020). This predictive landscape management approach improves the long-term sustainability and adaptive capacity of urban green infrastructure systems. Moreover, Ankara's smart city infrastructure supports integrated climate governance by enabling real-time monitoring, open data access, and evidence-based urban planning processes. The integration of AI, geospatial technologies, and environmental sensor networks transforms urban landscape systems into adaptive and responsive ecological infrastructures capable of dynamically responding to climate stressors (Batty 2024). Through these AI-supported decision support mechanisms, Ankara demonstrates how digital technologies can enhance landscape performance, strengthen ecological resilience, and support the development of climate-resilient urban environments. The Ankara case reveals that AI-based geospatial monitoring platforms (AnkaGeo), digital twins, and environmental sensor systems function as spatial decision-support tools for afforestation planning, heat island mitigation, and solar land-use integration.

İzmir – AI-Supported Smart City and Climate-Resilient Landscape Planning

Izmir Metropolitan Municipality has implemented a comprehensive smart city and climate adaptation strategy that integrates artificial intelligence (AI), geographic information systems (GIS), remote sensing, and environmental sensor networks to enhance climate-resilient urban landscape planning. As part of Izmir's Sustainable Energy and Climate Action Plan (SECAP) and Smart City Strategy, AI-supported environmental monitoring and spatial analysis systems are used to

assess climate risks, including urban heat island effects, drought, and ecosystem degradation (Izmir Metropolitan Municipality 2020, European Commission 2020).

IoT-based environmental sensors distributed across urban green spaces continuously collect real-time data on temperature, humidity, soil moisture, solar radiation, and air quality. These datasets are analyzed using machine learning algorithms to identify spatial patterns of heat accumulation, water stress, and vegetation performance. AI-based predictive models enable landscape planners to identify priority areas for green infrastructure interventions, optimize plant selection based on climate suitability, and improve irrigation efficiency in response to drought conditions. Remote sensing and deep learning techniques are also used to analyze satellite imagery and generate high-resolution land surface temperature (LST), normalized difference vegetation index (NDVI), and impervious surface maps. These spatial analyses enable the identification of climate-vulnerable zones and support the strategic placement of nature-based solutions such as urban forests, green corridors, permeable surfaces, and shaded public spaces (European Commission 2020). In this context, the AIPH Green City Case Study (Peynircioglu Stream Ecological Restoration Project) on Izmir highlights the municipality's integrated urban greening programs as a leading example of nature-based climate adaptation. The case study emphasizes multifunctional green infrastructure interventions — including urban forests, ecological corridors, community gardens, and shaded public spaces — that enhance biodiversity, increase urban shade coverage, and mitigate localized heat stress through coordinated planning strategies (Alper 2022) (Figure 16).

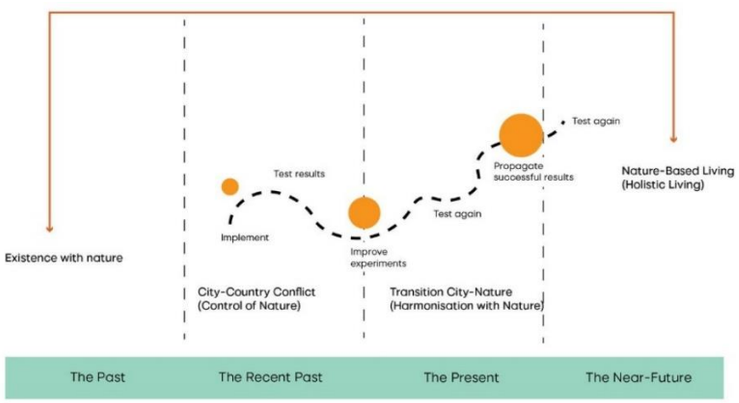


Figure 16. The development of the principles of a nature-based lifestyle (Alper 2022)

These initiatives demonstrate how large-scale greening programs, supported by spatial analysis and planning frameworks, contribute to measurable improvements in thermal comfort, ecosystem services, and community engagement in climate adaptation processes (Figure 17).



Figure 17.Nature-based urban greening initiatives in Izmir highlighted in the AIPH Green City Case Study, İzmir (Alper 2022)

In addition, digital twin and AI-supported simulation tools are increasingly integrated into Izmir's urban planning processes, enabling scenario-based evaluation of landscape design interventions under different climate projections. These systems allow planners to simulate the cooling effects of vegetation, evaluate ecosystem service performance, and optimize green infrastructure configurations to enhance thermal comfort and ecological resilience (Batty 2024). Through this integrated AI-supported decision-support framework, Izmir enhances its capacity to develop climate-responsive landscape strategies, improve microclimate regulation, strengthen ecosystem services, and support sustainable urban adaptation. The Izmir case demonstrates how artificial intelligence can function as a critical planning tool that bridges environmental monitoring, spatial analysis, and adaptive landscape design to increase urban climate resilience, while nature-based urban greening programs reinforce these digital systems through tangible spatial interventions. The Izmir case indicates that AI-supported environmental monitoring, remote sensing, and digital twin simulations are directly linked to the strategic implementation of urban greening programs, ecological corridors, and adaptive planting strategies to mitigate heat stress and drought risks.

DISCUSSION

The findings of this study indicate that AI-supported landscape design is increasingly integrated into urban climate resilience strategies. This aligns with prior literature highlighting the potential of data-driven, adaptive, and predictive approaches in urban planning (Sodoudi et al. 2022, Batty 2024, Lin 2025). Comparative analysis of international cases such as Copenhagen, Amsterdam, and Singapore demonstrates that AI technologies—including machine learning, digital twins, and sensor networks—significantly contribute to optimizing water management, reducing urban heat islands, monitoring biodiversity, and implementing nature-based solutions (NBS).

These cases validate prior findings that AI can enhance both ecological performance and spatial aesthetics, strengthening the adaptability and sustainability of urban ecosystems (Mahmoud and Garcia 2019). Local examples from Türkiye, including the Istanbul UP2030 and Mersin Digital Twin projects, illustrate how AI applications can be adapted to specific urban contexts, supporting energy optimization, microclimate regulation, and green infrastructure planning. This demonstrates that lessons from international best practices can be localized effectively. However, several limitations and potential risks must be considered.

Firstly, AI models require high-quality, up-to-date data; incomplete or low-resolution datasets can reduce predictive accuracy, as observed in urban forest mapping and energy simulation applications. Secondly, the successful implementation of AI-based strategies demands strong governance, interdisciplinary expertise, and institutional capacity, limiting scalability in municipalities with weaker administrative frameworks. Thirdly, technological and financial costs associated with digital twins, sensor networks, and continuous monitoring systems may hinder widespread adoption. Finally, ethical and social concerns—including data privacy, equitable access, and over-reliance on automation—highlight the necessity of hybrid approaches that integrate AI with local knowledge and human decision-making processes. Beyond these operational limitations, it is also important to critically consider the inherent technological and epistemological constraints of artificial intelligence itself. AI models rely heavily on historical and real-time datasets to generate predictive outputs; however, climate change is characterized by non-linear dynamics, extreme variability, and unprecedented environmental conditions that may not be fully represented in existing training data (Batty 2024). This creates uncertainty in model predictions and may reduce reliability when applied to future climate scenarios that exceed historical baselines. Furthermore, many advanced AI models—particularly deep learning algorithms—operate as "black box" systems, where the internal decision-making processes are not easily interpretable by human users (Toderas 2025). This lack of transparency may limit trust, reduce accountability, and complicate the integration of AI outputs into planning and design decisions.

In addition, AI-driven optimization processes tend to prioritize quantifiable environmental parameters such as temperature reduction, vegetation density, or hydrological efficiency, while qualitative spatial dimensions—including cultural landscape values, user perception, and place identity—remain difficult to integrate into algorithmic frameworks. This limitation is particularly significant in landscape architecture, where spatial meaning, cultural context, and human experience play a central role in design outcomes. Therefore, AI should be understood not as a fully autonomous decision-making mechanism but as an advanced decision-support tool that complements professional expertise, interdisciplinary knowledge, and context-sensitive planning approaches. Integrating AI with human-centered design, participatory planning processes, and local ecological knowledge remains essential to ensure that technologically optimized landscapes also achieve socially inclusive, culturally responsive, and ecologically resilient outcomes (Batty 2024, Toderas 2025). To provide a structured synthesis of the case studies discussed above, Table 1 presents a comparative overview of AI technologies, climate risks, landscape strategies, and spatial–ecological outcomes.

Table 1. Comparative analysis of case studies based on four thematic dimensions of AI-supported landscape design for climate resilience

Case Study	AI Technologies & Roles	Climate Risks Addressed	Landscape/NBS Strategies	Spatial, Environmental, & Ecological Outcomes
Copenhagen	ML, digital twins, deep learning, sensors	Flooding, extreme rainfall, heat islands	Rainwater separation, green infrastructure, hydrodynamic modeling	Reduced flood risk, optimized stormwater management, heat island mitigation
Amsterdam	ML (Random Forest, SVM, LSTM), CNN, IoT sensors	Heat islands, drought, biodiversity loss	Predictive irrigation, shading optimization, species monitoring, ecological corridors	Enhanced biodiversity, water use efficiency, improved microclimate
Singapore	AI simulations, LoRaWAN sensors, hyperspectral imaging	Temperature rise, rainfall variability, salinity, drought	Adaptive planting, predictive irrigation, shading, water retention strategies	Climate-resilient plant communities, reduced water stress, adaptive urban ecosystems
Chicago (AoT)	ML, data mining, sensor networks	Heat islands, flooding, pollution	Green space optimization, rain gardens, SuDS	Improved microclimate, flood risk mitigation, evidence-based planning
Bengaluru	ML, UAVs, LiDAR, satellite imagery	Heat islands, flash floods	Urban forest mapping, green corridor planning, permeable surfaces	Strengthened ecosystem services, enhanced climate resilience
Istanbul (UP2030)	ML (Random Forest, Gradient Boosting, LSTM), digital twins	Heat waves, energy demand, carbon emissions	PV panel optimization, green spaces, sustainable mobility	Reduced energy consumption, optimized microclimate, climate-resilient infrastructure
Mersin	CNN, Random Forest, digital twins, sensors	Heat islands, flood risk	Green infrastructure, afforestation, water retention optimization	Improved urban microclimate, energy efficiency, biodiversity protection
Konya	ML, IoT-based environmental sensors, geospatial analytics	Heat islands, drought, air quality stress	Environmental monitoring, green infrastructure planning, zero-carbon public building integration	Enhanced microclimate regulation, improved environmental governance, strengthened climate adaptation capacity
Ankara	ML, GIS-based smart city platform (AnkaGeo), digital twins, solar infrastructure	Heat islands, drought, energy stress	Geospatial climate monitoring, afforestation planning, solar land-use integration	Improved spatial decision-support, optimized green infrastructure placement, reduced climate vulnerability
Izmir	ML, GIS, remote sensing, digital twins	Heat islands, drought, ecosystem degradation	Urban greening programs, ecological corridors, permeable surfaces, adaptive planting	Enhanced ecosystem services, improved thermal comfort, integrated nature-based climate adaptation

Table 1 demonstrates that while AI technologies are applied across diverse climatic and geographical contexts, the functional emphasis of each case varies according to dominant risk factors and institutional priorities. While some cases foreground flood mitigation and hydrological modeling, others prioritize biodiversity monitoring, renewable energy optimization, or urban heat reduction through adaptive planting and green infrastructure systems. To further clarify the

degree of thematic correspondence across these cases, Table 2 evaluates the intensity of integration within the same four analytical dimensions introduced in Table 1.

Table 2. Thematic intensity matrix based on four core analytical dimensions

Case Study	AI Technologies & Roles	Climate Risks Addressed	Landscape / NBS Strategies	Spatial, Environmental & Ecological Outcomes
Copenhagen	●●●	●●●	●●●	●●●
Amsterdam	●●●	●●	●●●	●●●
Singapore	●●●	●●●	●●●	●●●
Chicago (AoT)	●●●	●●●	●●	●●
Bengaluru	●●	●●●	●●●	●●●
Istanbul (UP2030)	●●●	●●	●●	●●
Mersin	●●●	●●	●●●	●●●
Konya	●●	●●	●●	●●
Ankara	●●●	●●	●●	●●
Izmir	●●	●●	●●●	●●●

●●● = Strong structural integration; ●● = Moderate integration; ● = Limited integration

The thematic intensity matrix reveals differentiated structural patterns. Copenhagen and Singapore demonstrate balanced and high-intensity integration across all four analytical dimensions, indicating comprehensive AI–landscape coupling. Amsterdam and Bengaluru show strong ecological and NBS-oriented integration, while Istanbul and Ankara display higher technological intensity relative to spatial transformation outcomes. Konya appears comparatively monitoring-oriented, with moderate integration across spatial and ecological dimensions. These variations confirm that AI-supported landscape resilience operates through diverse structural configurations rather than a uniform implementation model.

Beyond the comparative findings presented above, the significance of this study lies in its conceptual and methodological contribution to the emerging field of AI-supported landscape resilience. First, the study moves beyond purely technological discussions by explicitly linking AI applications to spatial design strategies and ecological outcomes. Second, by structuring the analysis around four integrated dimensions—AI technologies, climate risks, landscape/NBS strategies, and spatial–ecological outcomes—it provides a systematic framework for evaluating the depth and intensity of AI integration in landscape architecture. Third, the inclusion of both international and Turkish cases demonstrates how global technological paradigms can be adapted to diverse governance and climatic contexts. This multi-scalar and comparative perspective contributes to bridging the gap between smart city discourse and landscape architectural practice, offering a structured model for assessing AI as a design-support tool rather than a purely technical infrastructure. AI-supported landscape design offers substantial opportunities for creating climate-resilient, ecologically sustainable, and adaptive urban spaces. However, it should not be implemented without consideration of its limitations and contextual factors. Future research and applications should focus on integrating AI with local knowledge, increasing institutional capacity, ensuring equitable access, and continuously evaluating ecological and social outcomes to fully harness AI's potential in enhancing urban landscape resilience and sustainability.

CONCLUSIONS AND RECOMMENDATIONS

Artificial intelligence (AI) has emerged as a strategic tool for enhancing urban resilience to climate change by enabling predictive, data-driven, and adaptive planning processes. This study demonstrates that AI-supported landscape design does not merely function as a technical optimization tool, but operates as an integrative decision-support framework linking climate risk analysis, spatial planning, and ecological performance. Systematic literature reviews indicate that AI plays critical roles in risk prediction, resource optimization, and decision support mechanisms in both infrastructure management and adaptation planning (Toderas 2025). Machine learning and geographic AI (GeoAI) methods are

employed for pre-scheduling infrastructure maintenance, regulating energy consumption, and developing early warnings for climate-related hazards such as floods, heat waves, and droughts (Kumar et al. 2025). However, beyond these established functions, the comparative analysis conducted in this study reveals that the effectiveness of AI in landscape architecture depends on the depth of its integration across technological, climatic, spatial, and ecological dimensions. This allows cities to adopt proactive, data-driven strategies rather than reactive responses to climate risks.

In urban landscape design, AI's potential is particularly evident in optimizing green infrastructure. AI-supported models enhance the accuracy of design decisions by integrating thermal analyses, microclimatic conditions, and terrain morphology for the placement of trees, parks, and urban green corridors (Shaamala et al. 2025). These approaches contribute to mitigating urban heat island effects and strengthening thermal comfort management. Furthermore, analyzing urban canopy cover through drones and satellite data enables more accurate modeling of carbon sequestration potential, maximizing the effectiveness of nature-based solutions for both climate adaptation and carbon storage strategies (Shaamala et al. 2025). This study contributes a structured analytical framework—based on four interconnected dimensions (AI technologies, climate risks, landscape strategies, and spatial–ecological outcomes)—that enables systematic evaluation of how deeply AI is embedded within landscape resilience practices. By applying this framework to both international and Turkish cases, the research demonstrates that AI-supported resilience operates through differentiated structural intensities rather than uniform implementation models.

For future research, it is crucial to conduct detailed analyses of carbon sinks and greenhouse gas balances using AI. AI-based digital twins and machine learning models should be applied to monitor and simulate the long-term performance of landscape components with carbon storage capacity, such as tree species, grasslands, and soils (Columbia Climate School 2024). In addition, multimodal deep learning models that integrate satellite imagery, topography, and meteorological data can generate high-resolution and realistic predictions of urban heat stress and thermal risk (Yi et al. 2025). These analyses would provide strategic decision support systems for urban planners and landscape architects, allowing scenario-based evaluation and optimization of green infrastructure under projected climate conditions. Overall, the primary outcome of this research is the proposition that AI should be conceptualized as a spatially embedded and ecologically oriented planning instrument, rather than as an isolated technological layer within smart city infrastructures. By positioning AI within landscape architectural logic, the study offers a bridging perspective between digital urbanism and climate-responsive spatial design. Close collaboration among landscape architects, data scientists, and urban planners is essential to ensure that AI's analytical capabilities align with aesthetic, social, and ecological objectives (Ghorbanifar 2025). Such interdisciplinary approaches are key to creating innovative and resilient urban futures that are simultaneously climate-resilient and livable.

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