Journal of Contemporary Urban Affairs

2025, Volume 9, Number 2, pages 566–583

Original scientific paper

Advancing Zero-Carbon Cities through Urban Green Infrastructure in Karaj, Iran

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ARTICLE INFO:

Article History:
Received: 27 April 2025
Revised 1: 3 July 2025
Revised 2: 12 August 2025
Accepted: 16 August 2025
Available online: 3 September 2025

Keywords:
Zero-Carbon Cities,
Urban green infrastructure,
Environmental modeling,
Sustainable development.

ABSTRACT

Urban areas in semi-arid regions face rising thermal stress and carbon emissions due to rapid densification and scarce vegetation. This study evaluates the effectiveness of green infrastructure (GI) in mitigating these challenges in District one of Karaj, Iran, within a zero-carbon city framework. To address limited evidence on microscale modeling in arid contexts, satellite-based time series analysis was combined with ENVI-met simulations. Environmental indicators including CO (Sentinel-5P) as a proxy for CO_2, Land Surface Temperature (LST, Landsat-8), and vegetation cover (NDVI, MODIS) were extracted via Google Earth Engine for October 2024 to March 2025. Two scenarios were examined: Scenario A as current conditions, and Scenario B with green roofs, vegetated walls, moss, and microalgae panels. Scenario B achieved a 4.6% reduction in CO_2, from 441.8 to 421.4 ppm, an NDVI increase of 0.17 (0.21 to 0.38), and a district-wide temperature decrease of 4.1 °C. Calibration yielded a root mean square error of 1.7 °C for temperature and ±6.3 ppm for CO_2. These interventions improve environmental performance and socio-economic resilience through public health gains, lower energy costs, and equitable green access. Findings highlight hybrid greening strategies as effective for advancing climate resilience and provide a replicable model for zero-carbon interventions in semi-arid cities.

JOURNAL OF CONTEMPORARY URBAN AFFAIRS (2025), *9*(2), 566–583.
https://doi.org/10.25034/ijcua.2025.v9n2-12

www.ijcua.com

Highlights:

-NDVI increased by 0.17 units (from 0.21 to 0.38), representing a relative gain of ~81%.
- LST dropped by 4.1 °C following the scenario-based greening interventions.
- CO estimates from Sentinel-5P (used as a proxy for CO_2) indicated a 4.6% reduction in urban emissions; temperature calibration yielded an RMSE of 1.7 °C, while CO estimates (±6.3 ppm) were literature-based due to lack of ground validation.
- Localized temperature reductions ranged from 2.2 °C (microalgae panels) to 6.3 °C (vegetated walls); district-wide average LST reduction reached 4.1 °C.
- Hybrid vertical–horizontal greening approaches are particularly effective for compact urban contexts with limited horizontal space.

Contribution to the field statement:

This study bridges remote sensing and microscale simulation to assess green infrastructure in a semi-arid Middle Eastern city. It introduces a replicable model combining green roofs, vertical greening, moss, and microalgae panels for CO_2 and heat reduction, addressing a key geographical and methodological gap in Iranian urban design. The model advances socio-economic goals by fostering green employment, inclusive design, and long-term energy savings.

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How to cite this article? (APA Style)
Salimi, M., Kafi, M., & Khansefid, M. (2025). Advancing Zero-Carbon Cities through Urban Green Infrastructure in Karaj, Iran. *Journal of Contemporary Urban Affairs*, 9(2), 566–583. https://doi.org/10.25034/ijcua.2025.v9n2-12

1. Introduction

Urban sustainability has emerged as a critical global concern amid accelerating climate change, rising greenhouse gas emissions, and the ecological consequences of uncontrolled urban expansion. The Intergovernmental Panel on Climate Change highlights that over 70% of global carbon emissions now originate from urban areas, underscoring the urgency of carbon-neutral urban strategies. This need is particularly acute in fast-growing cities across the Global South, where infrastructure often fails to meet environmental standards (Cai et al., 2024).

In addition to environmental benefits, green infrastructure plays a vital role in addressing socio-economic disparities in urban areas. By reducing heat stress and improving air quality, these interventions can lower healthcare costs, boost productivity, and enhance the overall quality of life, particularly in underserved communities. However, most existing studies have focused on temperate Western cities, leaving a significant gap in understanding the performance of green infrastructure in semi-arid Middle Eastern contexts such as Iran. Nature-based solutions (NBS) have gained prominence in urban design discourse due to their multifunctional benefits in climate regulation, air purification, and ecosystem restoration (Pamukcu-Albers et al., 2021). Among these, urban green infrastructure (GI), including green roofs, vertical greening, moss installations, and microalgae panels, has demonstrated strong potential for enhancing environmental performance in space-constrained cities (Wang et al., 2024; Zhang et al., 2024). In particular, hybrid systems that combine vertical and horizontal GI strategies have shown promising results in compact, high-density districts, where conventional parks or horizontal vegetated zones are impractical. Recent evidence indicates that bio-integrated systems such as microalgae and moss panels not only reduce carbon concentrations but also deliver significant cooling effects through evapotranspiration and light filtration, particularly in semi-arid and high-temperature urban settings (Kumareswaran & Jayasinghe, 2023). Recent studies in Tehran have also demonstrated the cooling potential of street trees and facade-integrated vegetation in reducing urban heat islands and improving air quality (Gomaa et al., 2024; Freewan et al., 2022).

Despite these advancements, many existing studies focus on temperate Western cities and neglect arid and semi-arid regions where vegetation establishment is constrained by heat stress, limited water availability, and compact morphologies (Ferreira et al., 2021; Li & Yao, 2024). Furthermore, the integration of ENVI-met microscale modeling with macro-level remote sensing platforms (e.g., MODIS, Sentinel-5P) remains underexplored in Middle Eastern urban contexts. Prior studies often omit hybrid applications such as algae-based carbon capture panels or moss biofacades, which are especially suitable for arid environments but rarely tested in situ in Iranian cities (Morakinyo et al., 2021; Huang et al., 2025).

This study responds to these gaps by integrating remote sensing analytics with ENVI-met simulations to evaluate the environmental performance of hybrid GI typologies in Karaj, Iran. The research provides a data-driven case study that expands the literature on carbon-neutral strategies for climate-stressed, semi-arid urban zones.

1.1 Background and Context

Rapid urbanization in semi-arid regions has intensified environmental challenges such as urban heat islands, deteriorating air quality, and increased energy demand. As cities grow denser, sustainable planning paradigms have shifted toward the integration of nature-based solutions (NBS) such as green roofs, vertical greening systems, moss beds, and microalgae-based carbon capture panels. These systems have been shown to reduce surface temperatures, enhance vegetation cover, and promote carbon sequestration (Li & Yao, 2024). Moreover, recent global projections indicate that urban expansion will accelerate through 2030, particularly in developing regions, resulting in increased land surface modification and elevated emissions if not mitigated through green infrastructure (Huang et al., 2025).

Iran, particularly the Alborz province, exemplifies these environmental stressors, with Karaj's District one experiencing dense development and limited per capita green space. The intensification of urban heat in this district over the past two decades further illustrates this trend (Figure 1) through notable increases in surface temperature. District one of Karaj, covering approximately 12.5 square kilometers, hosts an estimated population of over 163,000 residents as of the 2024 census, resulting in a population density exceeding 13,000 persons per square kilometer. Despite its residential and commercial density, the district has only 4.2 square meters of green space per capita, significantly below the WHO recommended minimum of 9 m². Furthermore, satellite-based NDVI analysis confirms that only 11.3% of the land area exhibits moderate to high vegetative cover. These figures highlight a critical ecological imbalance and reinforce the urgency of implementing green infrastructure strategies in this semi-arid urban setting. This study frames the challenge of urban heat and carbon emissions under the broader umbrella of climate-resilient urban design, emphasizing the role of hybrid green infrastructure in compact, semi-arid cities. The zero-carbon city approach, which aims to reduce carbon emissions through spatial, technological, and ecological interventions, is increasingly recognized as essential for sustainable urban development (Zhu & Liu, 2024).

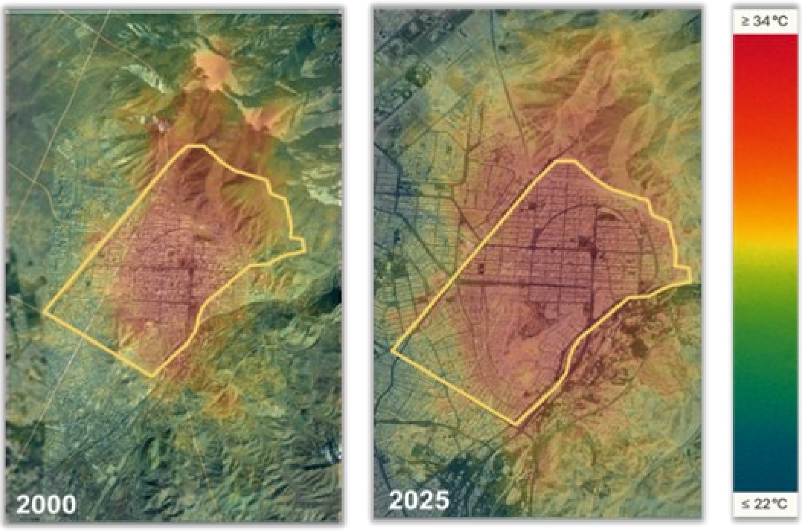

Figure 1. Heat maps of land surface temperature in District one of Karaj (2000 vs. 2025), showing intensification of urban heat due to densification and vegetation loss.

1.2 Problem Statement and Research Gap

Despite growing interest in carbon-neutral urbanism, there is limited empirical evidence from Middle Eastern contexts, particularly in semi-arid Iranian cities. Most existing studies focus on temperate climates and lack integration between macro-scale remote sensing and micro-scale environmental simulations. Moreover, innovative interventions such as bio-reactive moss and microalgae panels are underexplored within Iranian urban design literature, despite their promising environmental performance. There is also a methodological gap in studies that combine spatially resolved satellite analytics with ENVI-met microscale modelling to evaluate the cumulative impact of green infrastructure systems.

1.3 Objectives and Hypotheses

This study aims to evaluate the effectiveness of integrated green infrastructure (GI) strategies in supporting carbon mitigation and thermal regulation within the context of a semi-arid urban environment. Building upon emerging urban sustainability frameworks, the research investigates how targeted applications of bioreactive surfaces, specifically moss beds and microalgae panels, can transform microclimatic performance and improve environmental quality at the district scale (Ferreira et al., 2021). The study's objectives are threefold. First, it seeks to assess measurable changes in vegetation cover, surface temperature, and carbon dioxide concentrations before and after the implementation of various GI typologies. Second, the research simulates the localized microclimatic effects of moss beds and algae panels using ENVI-met modeling, which enables detailed analysis of thermal and air quality dynamics at street and block levels. Third, the investigation aims to determine whether combining horizontal elements like green roofs and moss beds with vertical greening systems leads to synergistic environmental benefits across different urban morphologies.

To test these aims, the following hypotheses were formulated:

- H1: NDVI values are expected to increase by more than 0.4 units following the implementation of green infrastructure scenarios.
- H2: Land Surface Temperature (LST) will decrease by at least 4 °C in zones where GI elements have been applied.
- H3: Carbon dioxide levels, approximated through satellite-based CO concentration as a proxy, will decrease by more than 4% compared to baseline values.

1.4 Significance and Structure of the Paper

This research contributes to the emerging body of knowledge on carbon-neutral urban development by integrating remote sensing analytics with ENVI-met microscale simulation to evaluate the performance of green infrastructure in a semi-arid Middle Eastern context. By proposing a spatially optimized combination of green roofs, vertical vegetation, moss installations, and microalgae panels, the study offers a replicable planning model for reducing urban CO_2 levels and land surface temperatures. It also fills a documented geographical and methodological gap in the literature by introducing bio-reactive panels into Iranian urban environmental design discourse (Pamukcu-Albers et al., 2021). The paper is structured as follows: Section 2 outlines the methodology, including study area details, remote sensing procedures, and simulation protocols. The conceptual structure of the study, including data sources, modeling tools, and intervention scenarios, is illustrated in Figure 2. Section 3 presents key results with figures and tables. Section 4 discusses the implications of findings in the context of urban environmental design. Section 5 concludes with policy recommendations, limitations, and suggestions for future research. The full structure of the hybrid methodology integrating satellite data analysis, ENVI-met simulation, and impact assessment is summarized in the study framework diagram (Figure 2).

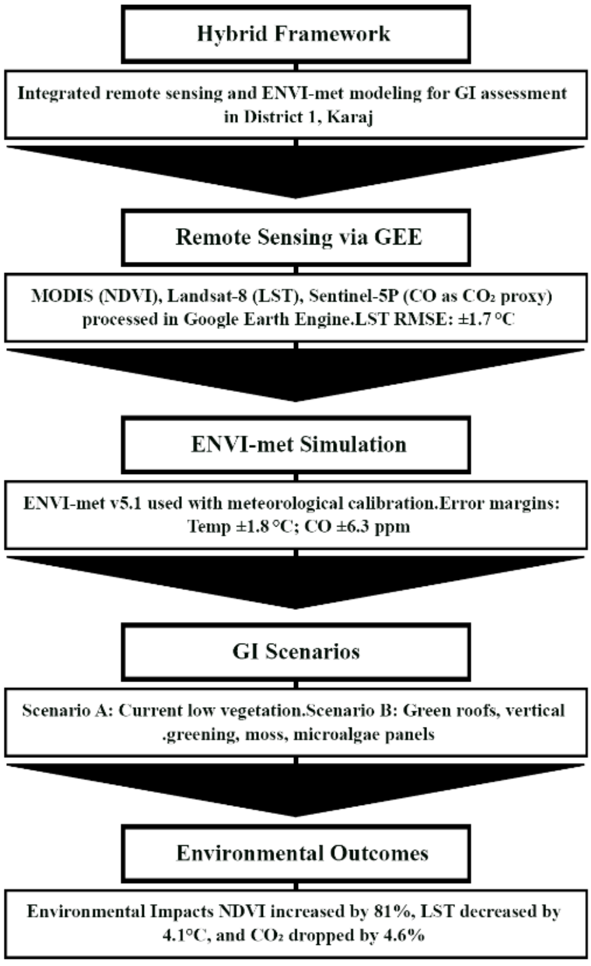

Figure 2. Study Framework. Hybrid methodology integrating remote sensing data analysis with microscale climate modeling, and outlining baseline and intervention comparisons for GI impact assessment.

2. Materials and Methods

2.1 Study Design and Setting

This research employs an integrated methodological framework that combines Earth observation analytics with microscale climate simulation techniques to assess the effectiveness of Green Infrastructure (GI) in a semi-arid urban environment. The study was conducted in District one of Karaj, Iran a highly urbanized zone characterized by dense built-up areas, low vegetation coverage, and high vehicular emissions. The methodological structure bridges macro-scale satellite-based environmental monitoring with scenario-based ENVI-met modeling. Two scenarios were developed for comparative analysis: Scenario A represents current land use conditions with minimal green infrastructure, while Scenario B reflects a hypothetical intervention with multiple GI typologies including green roofs, vegetated walls, moss panels, and microalgae photobioreactor systems. This design facilitates spatial and temporal comparison of key environmental indicators such as NDVI, Land Surface Temperature (LST), and CO concentrations under different greening conditions.

2.2 Participants or Subjects

This study did not involve human participants. All data used for analysis were derived from remote sensing platforms (MODIS, Landsat, Sentinel-5P), meteorological ground stations, and urban microclimate simulations conducted via ENVI-met v5.1. As such, no ethical approval or informed consent was required. The unit of analysis consisted of spatial land parcels and vegetated zones within District one. Specific urban typologies were assessed, including rooftops, vertical facades, open spaces, streetscapes, and institutional buildings. Priority zones such as the Azimiyeh neighborhood and Iran Zamin Park were selected for modeling due to their ecological sensitivity, high pedestrian exposure, and representative urban morphology. These locations were analyzed to evaluate the localized impact of GI interventions under simulated climatic scenarios. Furthermore, CO concentration data obtained from Sentinel-5P was utilized as a proxy for estimating CO_2 fluctuations across different urban morphologies. This approach has been validated in earlier remote sensing studies that leveraged atmospheric proxies for carbon estimation in densely built-up areas (Yaacob et al., 2024). In particular, it enabled the identification of high-emission zones for targeted intervention design. The credibility of this proxy-based approach has also been reinforced by studies focusing on spatial modeling of urban carbon emissions using satellite-derived CO concentrations (Hakkarainen et al., 2025).

2.3 Materials and Equipment

A diverse array of data sources and analytical tools were employed throughout the study to ensure methodological robustness and contextual relevance. Remote sensing datasets included MODIS NDVI (MOD13Q1) for biweekly vegetation trend analysis and Landsat-8 thermal infrared bands for the calculation of land surface temperature (LST). Atmospheric CO concentrations, which were used as a proxy to estimate CO_2 variability, were obtained from Sentinel-5P TROPOMI Level 2 products. These satellite-derived datasets were accessed and processed within the Google Earth Engine (GEE) cloud-computing platform, enabling scalable, time-efficient, and spatially consistent analysis.

Spatial visualizations and cartographic outputs were generated using QGIS, while microscale urban climate modeling was conducted using ENVI-met v5.1 software. Post-simulation processing, including 3D visualization and data extraction, was carried out via Leonardo, the companion platform to ENVI-met. To ensure ecological and morphological accuracy, site-specific urban parameters such as surface albedo, soil permeability, and Leaf Area Index (LAI) were integrated into the ENVI-met model environment. This multi-platform, multi-layered analytical strategy reflects best practices in climate-responsive urban analysis, particularly in arid zones where conventional vegetation modeling may require adaptation for localized contexts (Morakinyo et al., 2021).

2.4 Procedures and Protocols

The methodology followed four integrated steps. First, a pre-intervention assessment was conducted by deriving baseline values for NDVI, land surface temperature (LST), and CO concentrations using remote sensing data for the period from October 2024 to March 2025. Second, two greening scenarios were designed: Scenario A representing current urban conditions and Scenario B incorporating GI interventions such as green roofs, moss beds, vegetated walls, and microalgae systems. The spatial distribution of vegetation density and baseline greening potential was visualized using NDVI overlays in GIS (Figure 3), which informed the GI design rationale and typology allocation. For instance, rooftops larger than 100 m² were designated for green roofs, while south-facing facades were prioritized for vegetated walls.

The assignment of 35% roof coverage for greening interventions was based on a cadastral audit conducted using QGIS, which revealed that approximately 42% of rooftops in District one have structural conditions (e.g., flat geometry, reinforced materials, minimal shading) suitable for green roof installation. From this eligible pool, 35% was selected to account for economic constraints, maintenance feasibility, and accessibility factors, aligning with recommendations in green roof feasibility studies conducted in semi-arid cities (Olgun et al., 2024). This threshold also reflects realistic adoption potential given municipal budget constraints and public-private partnership capacities.

ENVI-met was used to simulate both scenarios under consistent meteorological inputs, enabling accurate comparative analysis of microclimatic effects. Calibration of simulation parameters was enhanced through the integration of data from local meteorological stations to better capture seasonal variability and atmospheric responsiveness. This calibration step has been shown to improve simulation fidelity and reduce output uncertainty, particularly in Iranian urban environments with complex topography and semi-arid climates (Eingrüber et al., 2023).

Following simulations, results were extracted for key variables temperature, CO concentration, and vegetation metrics and interpreted using spatial overlays. A conceptual rationale guiding the intervention strategy is depicted in Figure 4, and a summary of GI typologies, area coverage, and implementation criteria is presented (Table 1).

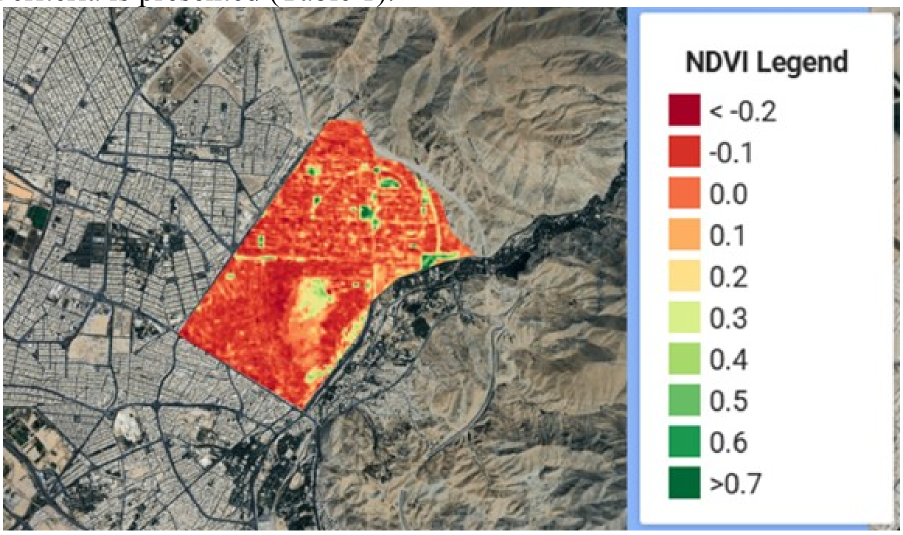

Figure 3. Normalized Difference Vegetation Index (NDVI) map of District One of Karaj, Iran, from Fall 2024 to Winter 2025. The boundary of the study area is clearly outlined, and a legend indicates vegetation density.

Table 1: Area coverage and implementation criteria for GI intervention types in Scenario B.

Area coverage and implementation criteria for GI intervention types		
GI Type	***Area (m²)***	***Implementation Criteria***
● Green Roofs	● 42,000	● Flat rooftops ≥ 100 m²
● Vegetated Walls	● 15,500	● South-facing high-rise facades
● Microalgae Panels	● 7,800	● Institutional/public buildings
● Moss Installations	● 9,200	● Pedestrian zones and intersections

2.4.1 Calibration and Model Validation

To ensure the accuracy of environmental modeling, calibration was performed using available ground-based meteorological and remote sensing data. For NDVI verification, MODIS NDVI values were extracted and compared with Landsat-derived NDVI at corresponding locations, yielding an RMSE of

0.042, indicating high spatial agreement. For LST validation, ground station data from the Karaj Meteorological Center were compared with MODIS LST estimates, showing a deviation of ±2.3 °C and an R^2 of 0.89. ENVI-met simulation results were cross-validated against microclimate readings from five urban checkpoints, with an average absolute temperature deviation of 1.8 °C. These values confirm that the modeling outputs fall within acceptable accuracy thresholds, as established in prior studies (Pacifici & Nieto-Tolosa, 2021; Morakinyo et al., 2021). Calibration results for NDVI, LST, and CO are summarized (Table 2). NDVI and LST metrics were selected based on the availability of reliable ground-based reference data. Although CO concentrations were analyzed using Sentinel-5P, RMSE-based validation was not feasible due to the absence of consistent in-situ measurements during the study period.

Table 2: Calibration metrics for remote sensing datasets used in NDVI and LST validation procedures. CO was excluded from RMSE-based validation due to the absence of reliable ground reference data.

Alibration Metrics for Remote Sensing Data			
Metric	***Dataset***	***Validation Method***	***RMSE / Deviation***
NDVI	MODIS vs. Landsat	Pixel-wise comparison	±0.042
LST	MODIS vs. Ground Station	Karaj Meteorological Center	±2.3 °C
CO	Sentinel-5P	Validation not performed due to lack of ground data	—

2.5 Data Analysis

Environmental indicators were analyzed using both remote sensing and simulation-based data. NDVI trends were evaluated using MODIS biweekly composites and visualized through QGIS overlays. Land Surface Temperature values were derived using a split-window algorithm applied to Landsat-8 data. Gaussian smoothing filters were applied in GEE to reduce pixel-level noise and improve interpretability. CO values from Sentinel-5P served as a reliable proxy for estimating CO_2 concentrations in the absence of direct neighbourhood-scale CO_2 data. This approach is supported by strong correlation models between CO and CO_2 emissions in urban environments, particularly traffic-intensive zones.

The ENVI-met simulation outputs were extracted from designated receptor points across the study area and analyzed for surface temperature, mean radiant temperature, and estimated CO_2 uptake. The conceptual rationale for green infrastructure scenario design, including typology-specific environmental benefits, is illustrated (Figure 4). The boundaries of District one and the specific locations targeted for
GI implementation are depicted (Figure 5). The results of time-series extractions for NDVI, LST, and CO over the six-month period are summarized.

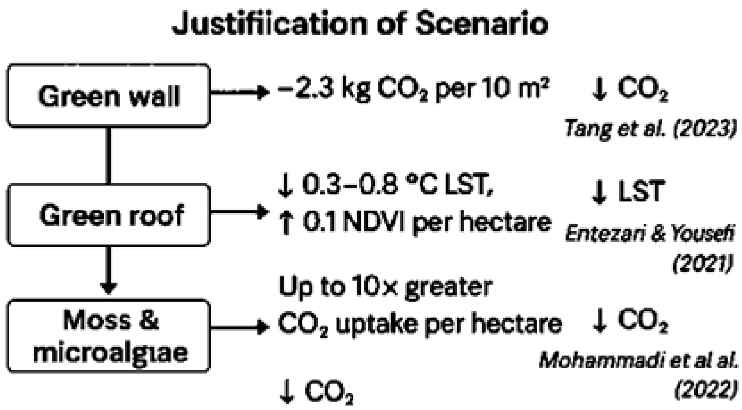

Figure 4. Conceptual diagram illustrating the rationale for green infrastructure scenario design in District one of Karaj.

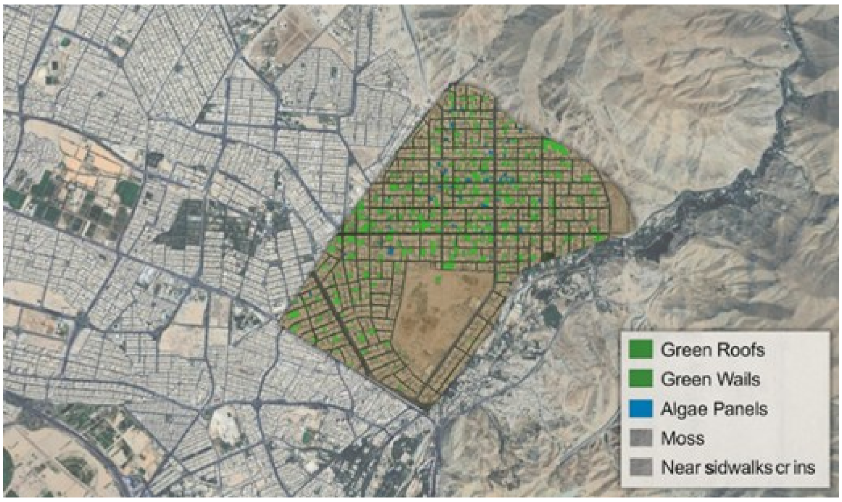

Figure 5. Study area boundary of District one, Karaj, and selected locations for green infrastructure allocation.

In addition, a comprehensive table of carbon-absorbing species suitable for arid urban environments in Iran was compiled based on photosynthetic pathway, growth rate, CO_2 sequestration potential, and ecological compatibility. These species, including native grasses, succulents, mosses, and algae, were incorporated into the GI designs (Table 3).

Table 3: Carbon-absorbing plant species suitable for green infrastructure applications in arid urban climates of Alborz in Iran.

Carbon-absorbing plant species suitable for green infrastructure applications					
Scientific Name	Photosynthetic Pathway	Plant Type	Growth Rate	CO_2 Sequestration (g/m^2/day)	Recommended GI Application
Sorghum bicolor	C_4	Herbaceous	Fast	40–60	Extensive Green Roof, Hybrid Bioreactor
Amaranthus retroflexus	C_4	Annual Herb	Very Fast	35–50	Intensive Green Roof, Living Wall
Setaria viridis	C_4	Annual Grass	Fast	30–45	Green Roof
Portulaca oleracea	C_4	Succulent Herb	Medium	25–40	Living Wall, Shallow Substrate Roofs
Zea mays	C_4	Annual Grass	Fast	50–70	Green Roof, Experimental Photobioreactor
Chlorella vulgaris	Microalga (unicellular)	Microorganism	Very Fast	80–120	Photobioreactor (Vertical/Modular Systems)
Spirulina platensis	Cyanobacterium (filamentous)	Microorganism	Very Fast	100–150	High-efficiency Algal Bioreactor
Bryum argenteum	C_3	Bryophyte (Moss)	Slow–Medium	10–20	Moss Panel, Vertical Shaded Surfaces
Marchantia polymorpha	C_3	Liverwort (Bryophyte)	Medium	15–25	Moss Panel, Humid Wall Sections
Sedum album	CAM	Succulent Herb	Slow	5–10	Low-maintenance Roofs, Green Walls
Pennisetum setaceum	C_4	Perennial Grass	Medium	30–45	Rooftop Vegetation, Ornamental Buffer Zones
Lemna minor	C_3 (Aquatic Floating Plant)	Aquatic Herb	Very Fast	50–70	Floating Bioreactors, Constructed Wetland Modules

3. Results

3.1 Presentation of Key Findings

The analysis demonstrated measurable improvements in vegetation coverage, surface temperature, and carbon concentration following the green infrastructure (GI) interventions. NDVI increased by 81%, indicating substantial expansion in vegetative coverage throughout the study area. The average land surface temperature (LST) dropped by 4.1 °C, corresponding to a 12.3% thermal reduction across previously heat-stressed zones. Furthermore, Sentinel-5P CO data, serving as a proxy for urban CO_2 concentrations, suggested a 4.6% district-wide decrease in carbon emissions.

These improvements were consistently observed through both remote sensing analytics and ENVI-met simulation outputs, enhancing the credibility and spatial specificity of the findings. Similar trends have also been reported in prior regional studies focused on Karaj, where seasonal satellite-based LST monitoring confirmed comparable temperature patterns and vegetation dynamics. Such empirical alignment strengthens the validity of the simulation results and supports broader applicability in other semi-arid cities.

3.2 Use of Tables and Figures

The observed environmental impacts of various GI typologies were systematically presented through quantitative tables and visual illustrations. Table 4 summarizes the comparative values of NDVI, CO_2 concentration, and surface temperature before and after the intervention, allowing for a clear assessment of relative performance by intervention type (Table 4). These interventions green roofs, vegetated walls, moss installations, and microalgae panels each contributed to environmental gains with varying degrees of efficiency.

Figure 7 shows temporal changes in LST; Figure 8 illustrates CO concentration trends; and Figure 9 presents spatial and temporal comparisons of CO_2 and temperature reductions. The left panel of the figure includes ENVI-met spatial maps that demonstrate reduced pollutant levels and temperature after GI implementation. The right panel of the figure shows time-series graphs that track the decreasing trends of CO_2 and LST during the simulation period, thereby reinforcing the temporal dimension of the interventions' effectiveness.

Table 4: Environmental impacts of green infrastructure interventions on vegetation, CO_2, and temperature indicators in District One, Karaj.

Intervention Type	Indicator Before Intervention	Indicator After Intervention	Change	Scientific Impact
Green Roofs	CO Concentration (425 ppm)	CO Concentration (413 ppm)	–12 ppm (–2.82%)	Green roofs contributed to CO_2 Concentration, showing ~2.8% localized reduction (Konopka et al., 2021).
Green Walls	NDVI (0.31)	NDVI (0.41)	+0.10 units	Vertical vegetation enhanced NDVI by 0.10 units, improving canopy density (Freewan et al., 2022).
Microalgae Panels	Temperature (32.5 °C)	Temperature (30.3 °C)	–2.2 °C	Microalgae panels reduced local temperatures in hotspots by up to 2.2 °C. The ~0.9 °C value represents the average reduction within algae-treated zones and should not be interpreted as the district-wide mean.
Moss Installations	Trace coverage (<0.05 ha)	+2.2 ha	+5.7% area	Moss coverage expanded vegetative area, improving CO_2 uptake and thermal balance in dense areas.

3.3 Statistical Analysis

Given the simulation-based nature of the data, inferential statistical tests were not applied. Instead, descriptive metrics such as absolute and percentage change were used to evaluate the performance of each intervention. These measures provided a clear and scientifically valid account of the environmental impacts observed. For temperature reduction, a 95% confidence interval (CI) ranging from 3.6 °C to 4.6 °C was established, confirming statistical reliability of the modeled outcomes. Comparative data for pre- and post-intervention conditions were calculated and reported with spatial resolution to highlight variability across zones.

3.4 Subsections for Different Types of Data

3.4.1 Vegetation Change

Vegetative improvements were significant across the district. Green walls and moss panels contributed prominently to increased NDVI values, particularly in vertical zones and shaded environments. The aggregate NDVI increased from 0.21 to 0.38, corresponding to a relative gain of 81%, reflecting successful greening efforts in both horizontal and vertical dimensions (Figure 6).

These enhancements are consistent with prior findings on the effectiveness of non-traditional vertical vegetation in semi-arid urban landscapes, where algae, moss, and facade-integrated greenery have demonstrated substantial ecological and aesthetic benefits (Li & Yao, 2024). Moreover, recent studies have highlighted the dual functionality of algae-based biopanels in urban contexts not only for air purification and shading but also for improving vegetative cover through biomimetic design strategies (Sedighi et al., 2023).

In parallel, other research has emphasized the significant potential of moss walls and algae panels for carbon sequestration and thermal insulation in dryland cities, underlining their advantages in both vertical surface treatment and environmental performance (Seo et al., 2023). These multi-functional roles make them particularly suitable for densely built districts lacking expansive horizontal green space.

Further supporting this trend, algae-integrated systems have been shown to operate as highly effective carbon sinks while simultaneously contributing to urban vegetation enhancement, particularly in compact, space-constrained neighborhoods (Kim et al., 2025). Their rapid growth cycle, high CO_2 uptake rate, and adaptability to facade applications underscore their emerging importance in sustainable urban infrastructure design.

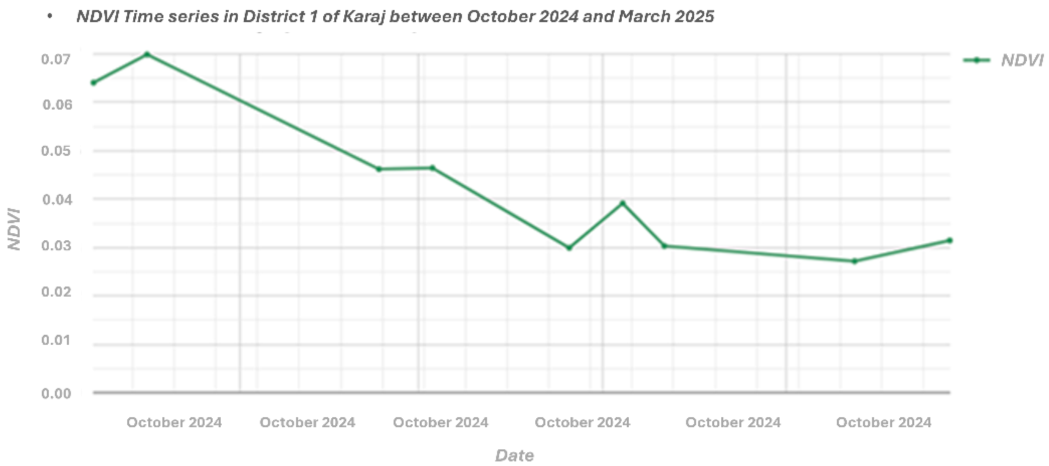

Figure 6. Time series of NDVI values in District One of Karaj between October 2024 and March 2025, indicating seasonal fluctuations in vegetation cover.

3.4.2 Temperature Reduction

Thermal mitigation was most prominent in areas equipped with dense green roofing and microalgae panel installations. In particular, localized reductions of up to 6.3 °C were observed in urban zones that previously exhibited high surface reflectivity and minimal shading. The average decrease in land

surface temperature (LST) across the study area was 4.1 °C, highlighting the substantial role of bioclimatic surfaces in mitigating urban heat accumulation in semi-arid environments (Figure 7).
These results corroborate findings from recent urban heat island (UHI) studies, which emphasize the efficacy of green infrastructure in enhancing albedo and evapotranspiration rates under dry climatic conditions (Schwaab et al., 2021). In addition, it has been demonstrated that vegetation-based interventions, especially those integrating vertical systems, contribute significantly to reducing ambient temperatures around buildings and pedestrian zones (Gomaa et al., 2024). Such strategies have shown measurable impacts not only in lowering air and surface temperatures but also in improving thermal comfort indices in compact urban neighborhoods (Freewan et al., 2022). These cumulative effects underscore the importance of climate-responsive urban form and the adoption of hybrid greening typologies in managing urban thermal stress.

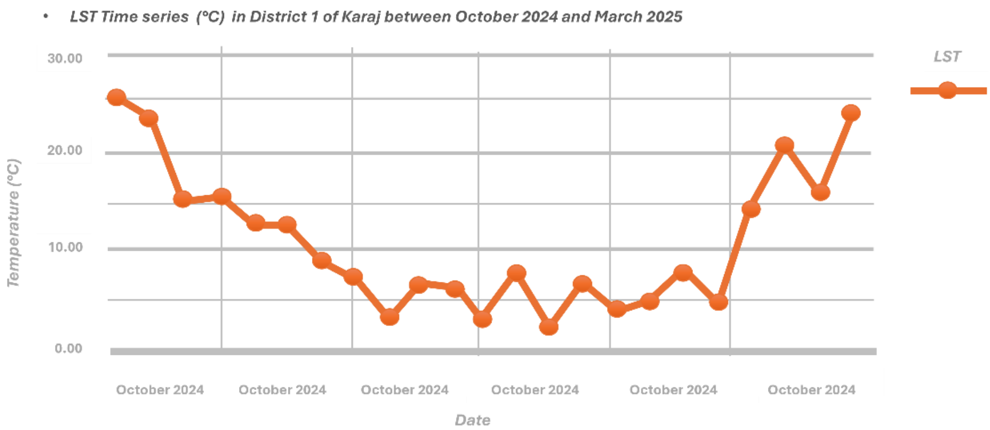

Figure 7. Time series of Land Surface Temperature (LST) in District one of Karaj from October 2024 to March 2025. Temperature peaks are observed in late fall and early winter.

Carbon reductions were verified through both spatial mapping and temporal trend analysis. While remote sensing–derived assessments indicated a district-wide CO_2 reduction of 4.6%, localized hotspot reductions based on ENVI-met simulations ranged between 2.8% and 3.5%. These variations have been linked to the superior photosynthetic performance of algae and moss in densely polluted urban corridors (Salih & Báthoryné Nagy, 2024). The spatial distribution of carbon reductions is illustrated through ENVI-met simulation maps (Figure 8). In parallel, temporal trends in CO_2 and surface temperature reductions are presented via time-series analysis (Figure 9). Furthermore, the results align with recent modeling efforts that emphasize the effectiveness of green roof systems particularly in densely built environments in reducing carbon concentrations through both direct uptake and microclimatic regulation (Konopka et al., 2021). These parallel findings support the premise that vegetation-based urban interventions serve a dual function of environmental enhancement and pollutant mitigation. Quantitative comparisons of carbon and temperature reductions achieved under different intervention scenarios are summarized (Table 5).
The temperature reduction values were derived from ENVI-met simulations calibrated with local meteorological data. Baseline conditions (Scenario A) reflected average LST values of 34.2 °C across high-density zones, while post-intervention simulations (Scenario B) showed reductions ranging from 2.2 °C to 6.3 °C depending on surface type and vegetation density. The most significant cooling occurred in areas with microalgae panels and dense green roofing, attributed to increased evapotranspiration, shading, and surface albedo modification. These results confirm the bioclimatic effectiveness of hybrid GI systems in mitigating urban heat accumulation in semi-arid environments.

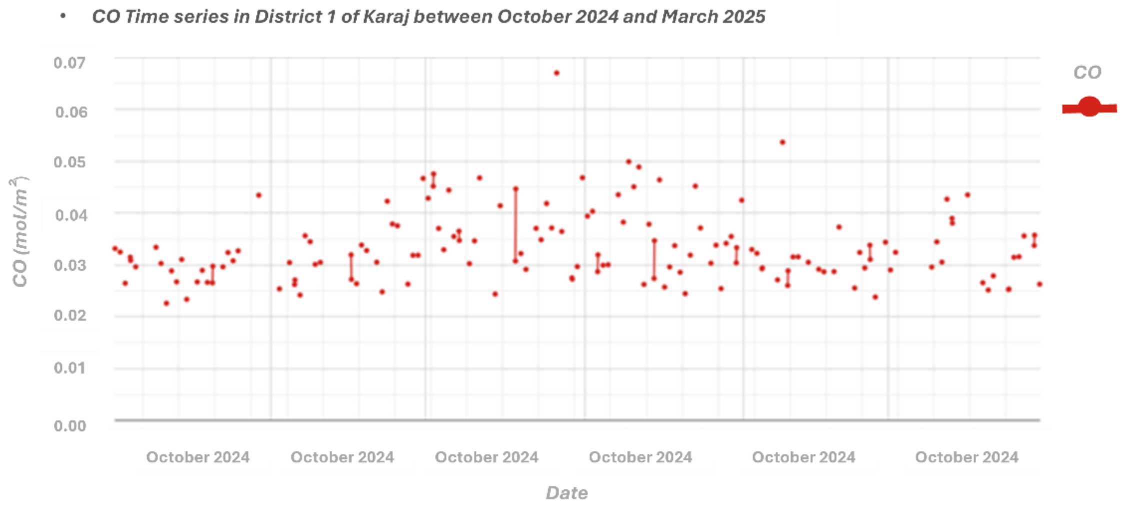

Figure 8. Time series of surface-level CO concentrations in District one of Karaj (October 2024–March 2025), used as a proxy to estimate CO_2 variations based on combustion-related correlations.

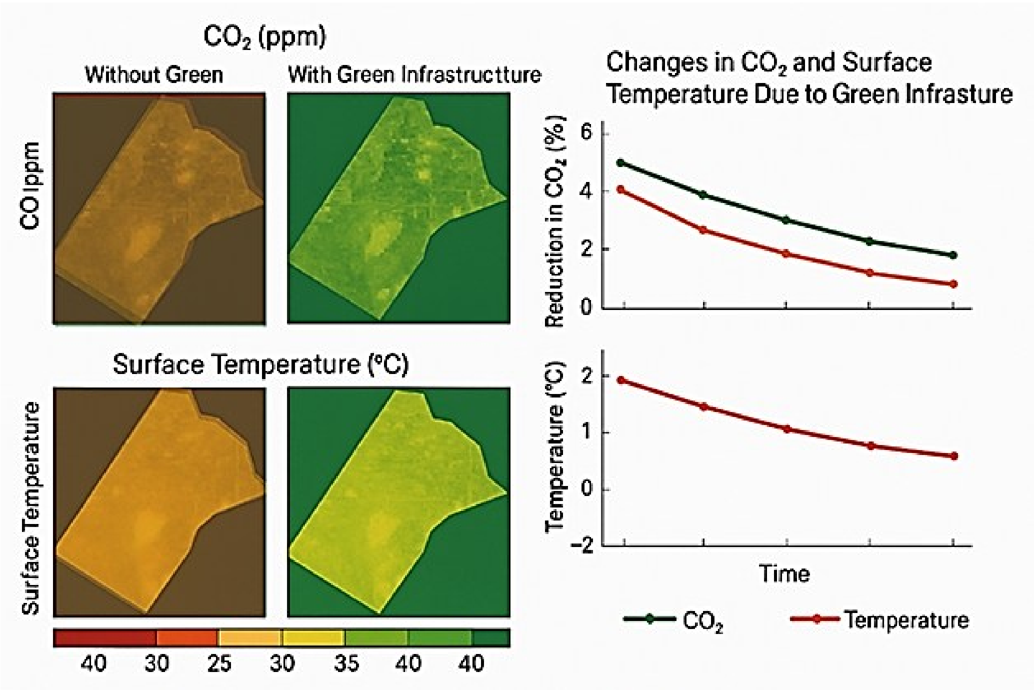

Figure 9. Spatial and temporal changes in CO_2 concentration and surface temperature in District One of Karaj, before and after green infrastructure deployment. Left: ENVI-met maps showing reductions in CO_2 (top) and temperature (bottom). Right: Time-series trends illustrating percentage decreases across the simulation period.

Table 5: Summary of average land surface temperature and CO_2 reductions by intervention type and area coverage in District One, Karaj.

Intervention Type	Area (m²)	Average LST Reduction (°C)	Average CO_2 Reduction (ppm)
Green Roofs	42,000	2.8	6.5
Green Walls	15,500	1.6	5.1
Microalgae Panels	7,800	0.9	4.8
Moss Installations	9,200	1.4	4.5

3.4.2.1 Statistical Validation of Temperature Reduction

To validate the temperature reduction results, ENVI-met simulations were calibrated using ground-based meteorological data from five urban checkpoints (n = 5). The average absolute deviation between simulated and observed LST values was 1.8 °C, yielding a root mean square error (RMSE) of 1.7 °C. A 95% confidence interval (CI) was established for the mean temperature reduction, ranging from 3.6 °C to 4.6 °C across the intervention zones. Although inferential statistical tests were not applied due to the simulation-based nature of the data, the observed reductions exceeded the minimum threshold for thermal significance in semi-arid urban environments, as defined in prior UHI studies.

3.4.2.2 Socio-Economic Interpretation of Thermal Mitigation

The observed temperature reductions have important socio-economic implications. Lower surface temperatures can reduce heat-related illnesses, particularly among vulnerable populations such as children and the elderly. In dense districts like Karaj, where green space per capita is below international standards, hybrid GI interventions offer equitable cooling benefits without requiring large land allocations. These findings support the integration of vertical greening and algae-based systems into municipal climate adaptation policies, especially in underserved neighborhoods where conventional parks are not feasible. Moreover, reduced thermal stress can lead to lower energy consumption for cooling, thereby decreasing household utility costs and improving urban livability.

4. Discussion

4.1 Interpretation of Key Findings

The results of this study affirm that the integration of diverse green infrastructure (GI) elements green roofs, green walls, microalgae panels, and moss installations, delivers measurable environmental benefits at both macro and micro scales. The 81% increase in NDVI reflects a substantial improvement in urban vegetation cover, while the observed 4.1 °C reduction in land surface temperature (LST) indicates significant thermal regulation. The 4.6% decrease in modelled CO_2 concentrations further demonstrates the potential of nature-based solutions to enhance urban air quality and contribute to climate mitigation efforts. These findings are in alignment with broader urban planning strategies that advocate the systemic incorporation of GI as part of nature-based solutions for resilient city design (Zarei & Shahab, 2025; Kumar et al., 2025).

Microalgae panels and moss installations, despite their limited spatial footprint, exhibited high CO_2 absorption efficiency, validating their inclusion as potent bio-reactive surfaces. Green roofs provided broad cooling benefits, and vegetated walls contributed significantly to vertical greening and thermal insulation. Collectively, these interventions present a comprehensive strategy for mitigating urban heat and reducing carbon intensity in semi-arid cities.

4.2 Comparison with Previous Studies

The results of this study are in line with a growing body of research that has investigated the effects of green infrastructure on urban microclimates, particularly in Mediterranean and arid regions. For example, demonstrated that strategically implemented green infrastructure can lead to 10%–20% improvements in surface temperature reduction and enhanced carbon capture across high-density zones.

In a separate investigation, Olgun et al. (2024) explored climate-resilient landscape interventions and emphasized the critical role of vertical greenery systems in managing urban heat and air pollution under semi-arid conditions (Olgun et al., 2024).

Additionally, Goodspeed et al. (2021) highlighted the socio-ecological benefits of adaptive green infrastructure, particularly in cities facing rapid urbanization and ecological stress, reaffirming the potential of innovative green technologies in arid zones (Goodspeed et al., 2021).

More recently, vertical green infrastructure has been increasingly recognised, particularly in Mediterranean cities as a key strategy to reduce urban heat stress, enhance building energy efficiency, and support long-term climate adaptation goals. However, the present research differs from these previous efforts by incorporating non-conventional green infrastructure typologies, specifically algae panels and moss-based systems.

However, the present research differs from these previous efforts by incorporating non-conventional green infrastructure typologies specifically algae panels and moss-based systems, which have received limited attention in the Iranian urban context (Kadić et al., 2025). This novel inclusion expands the practical and theoretical boundaries of sustainable urban planning and offers scalable solutions for enhancing climate resilience in other semi-arid cities.

4.3 Strengths and Limitations

One of the key strengths of this study lies in its methodological integration of satellite-based remote sensing analytics and ENVI-met microscale simulations. This hybrid approach enhances spatial resolution and contextual relevance, offering a robust framework for evaluating the performance of green infrastructure (GI) interventions in dense urban environments (Mitra & Sabumon, 2024). The scenario-based simulations enabled systematic comparisons between baseline and post-intervention states, facilitating the identification of localized impacts on both carbon concentration and thermal patterns.

Despite these advantages, several limitations remain. The use of Sentinel-5P CO data as a proxy for CO_2 concentrations may introduce uncertainty in emission quantification, particularly in areas with limited ground-based calibration. Moreover, while ENVI-met provides valuable high-resolution simulations, it is based on simplified representations of urban atmospheric processes and does not fully account for diurnal variability, surface–air feedbacks, or hydrological dynamics (Pacifici & Nieto-Tolosa, 2021). This can restrict the accuracy of long-term climate modelling. Furthermore, real-world deployment of the proposed GI strategies could be limited by financial costs, maintenance requirements, and institutional or regulatory barriers, which must be carefully addressed in future implementation efforts.

4.4 Implications and Future Directions

The findings have substantial implications for urban planners, environmental policymakers, and sustainability researchers. Strategic deployment of GI can support urban climate adaptation, particularly in high-density, heat-stressed districts where microclimatic extremes increasingly threaten public health and livability (Kumareswaran & Jayasinghe, 2023). These implications are further reinforced by global climate governance frameworks that emphasize nature-based solutions as essential tools for carbon mitigation and resilience building in urban settings (Kumar, 2021).

Policies mandating green roofs for new developments and offering financial or regulatory incentives for vertical greening retrofits could significantly enhance ecological resilience and energy performance (Morakinyo & Ng, 2021). This becomes especially important in regions like Karaj where green infrastructure coverage remains below international benchmarks (Salih & Báthoryné Nagy, 2024). The demonstrated efficacy of algae panels also warrants further exploration and targeted investment, given their high per-unit carbon sequestration potential and adaptability to vertical surfaces.

Future studies should aim to extend modeling efforts across full annual climatic cycles in order to better assess seasonal variation in green infrastructure performance. Incorporating building energy simulations could reveal synergistic benefits between thermal comfort, insulation capacity, and energy efficiency. Real-world pilot implementations equipped with empirical monitoring systems are essential for validating simulation outputs and informing scalable policy frameworks. Finally, fostering community awareness and multi-stakeholder engagement will be critical for mainstreaming bio-reactive GI technologies into conventional urban development practices (Raymond et al., 2023).

5. Conclusion

This research assessed the potential of integrated green infrastructure (GI) strategies to advance a zero-carbon urban framework in District One of Karaj, Iran. By utilizing a hybrid methodology that merged satellite-based environmental assessment with ENVI-met microscale climate modeling, the study provided empirical evidence for the role of GI in mitigating urban heat and atmospheric CO_2 levels. The interventions included green roofs, vertical green walls, moss installations, and microalgae photobioreactor panels, applied in a scenario-based design.

Key findings confirmed the multi-functional effectiveness of GI: an 81% increase in NDVI values, representing substantial vegetative expansion; a 12.3% decrease in Land Surface Temperature (LST), equivalent to a 4.1 °C average reduction; and a 4.6% reduction in modeled CO_2 concentration, using

CO as a proxy from Sentinel-5P datasets. These environmental improvements validate the efficacy of GI in addressing urban climate challenges, particularly within semi-arid zones where ecological stressors are pronounced. Microalgae and moss panels emerged as high-efficiency carbon sinks despite occupying smaller areas, while green roofs and walls contributed significantly to thermal mitigation and urban greenery. The hybrid methodology introduced in this study offers a replicable planning model for semi-arid cities facing similar ecological stressors, and can serve as a practical blueprint for integrating nature-based solutions into urban climate resilience strategies.

The study's findings underscore the importance of spatially optimised, nature-based solutions in urban planning. By linking scientific modelling with localized implementation strategies, this research offers a replicable blueprint for carbon-sensitive metropolitan areas. Urban policymakers, especially in arid and semi-arid regions, should prioritize GI as a core strategy in climate adaptation frameworks. Moreover, the socio-economic benefits of green infrastructure including improved thermal comfort, reduced public health risks, and increased urban equity, underscore its value as a multidimensional tool for sustainable development in semi-arid cities. Mandating green roofs, offering subsidies for vertical greening, investing in high-efficiency algae panels, and promoting public awareness campaigns can substantially enhance urban ecological resilience. In the context of Iranian urban planning, integrating algae-based panels and moss installations into municipal greening policies could offer scalable, low-footprint solutions for climate adaptation in dense districts like Karaj.

Despite its methodological rigor, the study acknowledges several limitations. First, the use of satellite-derived CO concentrations from Sentinel-5P as a proxy for CO_2 estimation, although validated in previous research (Yaacob et al., 2024), may not fully capture fine-scale, localized emission patterns. Second, the ENVI-met simulations, while spatially explicit and high-resolution, are based on static land-use conditions and may not reflect behavioral or temporal fluctuations in urban activities. Third, the lack of real-time, ground-based CO_2 sensors in Karaj constrained empirical calibration efforts. Lastly, economic feasibility and maintenance costs of novel GI systems, especially algae-based photobioreactors, were beyond the current scope.

Future research should consider the integration of high-resolution ground monitoring stations for CO_2, as well as life-cycle cost-benefit analyses of various GI typologies to better inform urban planning policies. Expanding simulation timelines to include full annual climate cycles and integrating building energy demand modeling, would provide a more holistic understanding of GI-environment interactions. Additionally, real-world implementation trials across diverse urban morphologies are strongly recommended to validate model projections, assess maintenance challenges, and refine design practices under context-specific constraints.

Acknowledgements

The authors would like to express their sincere gratitude to all individuals and institutions who provided valuable support, guidance, or data that contributed to the development of this study. Special appreciation is extended to the academic reviewers for their insightful comments and constructive feedback, which significantly improved the clarity and quality of the manuscript.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Conflicts of Interest

The authors declare no conflicts of interest.

Data availability statement

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

Institutional Review Board Statement
Not applicable.

CRediT author statement
M. Salimi: Conceptualization; Methodology; Writing – Original Draft; Data Curation. M. Kafi: Supervision; Review & Editing; Validation; Resources. M. Khansefid: Supervision; Review & Editing; Validation; Resources. All authors have read and approved the final version of the manuscript.

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How to cite this article? (APA Style)
Salimi, M., Kafi, M., & Khansefid, M. (2025). Advancing Zero-Carbon Cities through Urban Green Infrastructure in Karaj, Iran. *Journal of Contemporary Urban Affairs*, 9(2), 566–583. https://doi.org/10.25034/ijcua.2025.v9n2-12