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Green Infrastructure for Sustainable Urban Development: A Case Study from Tehran

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Abstract: The integration of green infrastructure (GI) in urban areas is vital for achieving sustainable development, and this article researches this interaction in Tehran, which accommodates more than 9 million inhabitants. In facing the critical challenge of balancing rapid urbanization with environmental sustainability, GI can play a key role, requiring a holistic approach encompassing diverse elements and location-specific strategies. The research adopts a case study approach to map and analyze the location of GI in District 2 of Tehran, which spans an area just west of the city center, stretching up to the northern border of the Tehran municipality. A novel Geographic Information Systems-based methodology is deployed to identify and assess eight distinct GI types, including parks, green roofs, and river corridors. The article concludes that this categorization of GI types can provide a methodology for the comprehensive analysis of GI distribution, which underscores the importance of location-specific GI strategies for mitigating air pollution and fostering urban sustainability. The study provides a valuable case example that can be used in cities with similar urban environments. By identifying spatial disparities in GI performance, context-specific solutions can be developed that can be integrated into the urban planning and development processes to create a network of green spaces that improve air quality, reduce the urban heat island effect, and promote biodiversity. GI can provide a framework for integrating green spaces, urban forests, green roofs, and other nature-based solutions into the urban fabric, thereby enhancing the overall sustainability and resilience of the urban environment.

Keywords: green infrastructure, GI, urban sustainability, urban heat island, biodiversity, environmental quality, urban planning

1. Introduction

In recent years, there has been a growing worldwide movement to address climate change and foster sustainable development. This has served to highlight the importance of embracing environmentally responsible practices in a variety of industries and organizations [1]. Government agencies, city authorities, and private enterprises have responded to climate change with various green policies and measures [2]. In this context, green infrastructure (GI) is seen as an effective tool in the coordination of environmental, social, and economic development, and as a strategic tenet in the pursuit of sustainable development in the urban environment. As Ying et al. [3] argue, GI plays a crucial role in achieving "harmonious coexistence between humans and nature", making it a cornerstone of sustainable urban planning. GI can play a part in confronting a range of challenges in the city environment—mitigating surface run off, reducing on-point source pollution, enhancing resilience in the face of climate change, and alleviating negative urbanization impacts [4].

The GI concept surfaced in the 1990s as part of the Maryland Greenway Movement [5] where it was seen as a strategic approach to land conservation to counter the adverse social and ecological effects of urban sprawl [6]. In 1999, the U.S. government put forward the concept of urban green infrastructure (UGI) as a key strategy for sustainable development and the support of natural systems [7]. UGI encompasses the development and conservation of peri-urban forests, street trees, and other green spaces, which collectively bolster regional ecosystem service capacity [8], and the term can be considered more or less synonymous with the GI concept. At its core, GI refers to the network of interconnected natural areas and open spaces that offer valuable ecosystem services and community benefits [9]. As cities aim to become more sustainable, planning for GI development emerges as a key activity to meet the demands of burgeoning urban populations for green space for leisure and recreational activities [10]. Urban planners and policymakers are increasingly adopting GI initiatives to establish elements of the natural world within the city environment [11].

While GI offers transformative solutions for urban sustainability, they are often integrated with traditional gray infrastructure. Since the late 20th century, developed countries have increasingly embraced the concept of "green buildings," supported by a range of assessment standards, that have accelerated their global adoption [12]. At the city level, there is an opportunity to create new urban designs that incorporate ecosystem services into the built environment while also revitalizing

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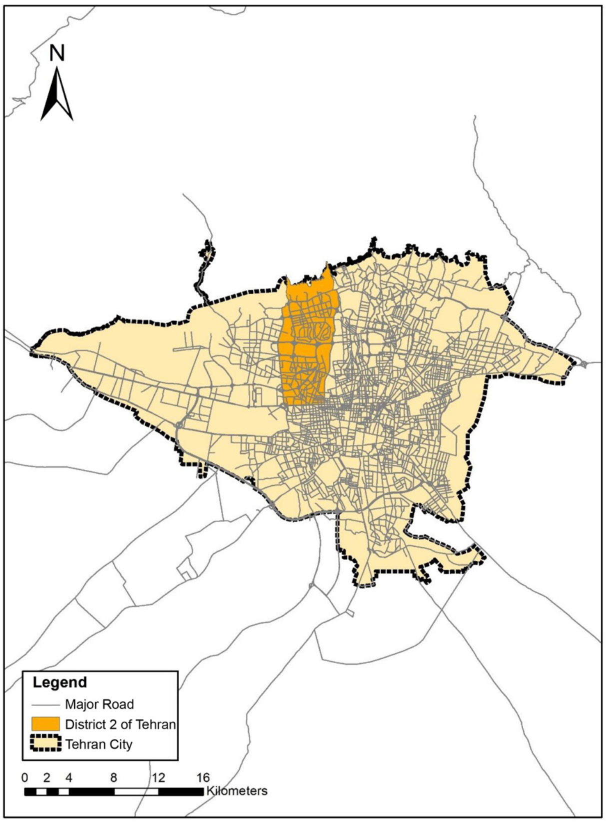
degraded ecosystems [13]. GI can play a central role in addressing the environmental, social, and economic challenges of urbanization.

Comprehending how urban design interacts with ecological functions is essential for advancing sustainability efforts [14]. In arid and semiarid cities, GI can offer residents important regulating ecosystem services. Additionally, the financial advantages can be significant, thanks to energy savings and decreases in runoff and pollution [10]. Buildings are a major source of carbon emissions, underscoring the importance of green buildings. These structures are designed, constructed, and operated to enhance environmental sustainability, economic efficiency, health, and productivity compared with traditional buildings [2].

Tehran, the capital of Iran, exemplifies the challenges and opportunities associated with urban sustainability. With a population of over 9 million people and an area of approximately 730 km² divided into 22 Districts, Tehran faces several critical environmental challenges. These include excessive traffic from gasoline-powered vehicles, a high number of factories, and a shortage of green spaces. These factors have contributed to the creation of urban heat islands, air pollution, respiratory illnesses, and other environmental issues. District 2 of Tehran, the focus of this study, encompassing 10% of the city area, is a mixed zone of residential and business land uses, interspersed with a variety of green zones, stretching between the Darkeh and Farahzad river valleys (Figure 1). Notable features include the Naser Alley Hills, the Pardisan Forest Park, and the historic settlements of Darkeh and Farahzad villages. The green spaces offer vital recreation for residents and contribute to Tehran's urban environment [15].

The distinct river valley network in District 2 offers a valuable context for analysing the relationship between vegetation cover and water quality, as has been done in other river valleys in Iran [16]. Rapid urbanization has significantly impacted the ecological assets of the city's five river valleys (Darabad, Darband, Darkeh, Farahzad, and Kan). Highway expansion and residential development have disrupted the ecosystem, leaving leveled terrain behind. While efforts to increase park space have been made, a more comprehensive GI approach is needed to address the city's ecological challenges [15].

Figure 1
Location of District 2 of the Tehran Municipality



This study classifies GI in District 2 of Tehran into two overarching categories: natural and seminatural (and subsequently in 8 GI types). This classification helps to better understand the status of green spaces and identify areas of shortages. The study thus aims to highlight opportunities to enhance GI and encourage residents and local authorities to make appropriate initiatives, particularly in residential (R), service (S), and mixed residential and commercial (M) zones, which cover a significant part of District 2. Additionally, the study seeks to support the formulation of urban policies that increase green spaces and motivate residents to protect and develop GI, thereby contributing to long-term urban resilience and environmental balance.

Several studies have examined green space in Tehran [15, 17], as well as research in District 2 focused on quality-of-life indicators [18], hospital site selection [19], and social capital and public trust [20]. This research, however, investigates how GI can be integrated into built-up areas using District 2 as a case study. No study to date has attempted a comprehensive analysis of the limitations and opportunities for GI implementation within the area. This study thus addresses this gap by providing a detailed evaluation of relevant factors and the current status of GI in District 2 and answers the following research questions (RQs):

- RQ1. What is the status of GI in the case study area?
- RQ2. How is GI evidenced in the existing Detailed Plan for the case study area?

Following this brief introduction, Section 2 provides a review of relevant literature. Section 3 then outlines the research methodology, and Section 4 sets out the results of the study. Section 5 then discusses some key themes that are evidenced in the research findings. Finally, Section 6 presents a conclusion to the study, notes its limitations, and records possible future areas of research in this field.

2. Relevant Literature

This section consists of two subsections. First, in Subsection 2.1, the concepts of GI and blue infrastructure (BI) are discussed, and the benefits of GI are examined. Based on the extant literature, GI types are identified and set out. Then, in Section 2.2, various aspects of how GI is evidenced and integrated within urban settings are examined, noting and explaining the significance of Building Information Modeling (BIM), green mobility, and the barriers to successful GI deployment.

2.1. Concept origins and definition

The concept of GI has developed from two main foundational principles: the connection of parks and green spaces to benefit communities, and the integration of natural areas to improve biodiversity and tackle habitat fragmentation [21]. GI can be defined as a carefully planned network of natural and seminatural areas [22, 23], including both green and blue spaces, the latter sometimes being defined separately as BI. Such networks can be designed and managed to deliver a diverse array of ecosystem services [24]. Natural green spaces refer to "spaces that have been barely developed by humans, and include forest, grasslands, and wetlands on a city scale, recognizing the pivotal role natural green spaces play in protecting ecological balance and biodiversity" [25]. In urban areas, seminatural spaces encompass both green and blue elements. Green spaces include parks, street trees, and other vegetated areas, while blue spaces comprise natural and artificial water features such as ponds, lakes, rivers, and coastal areas. BI, in particular, plays a critical role in mitigating urban heat through mechanisms such as temporary water storage, long-wave radiation emissions, short-wave radiation absorption, and evaporative cooling. These processes contribute to reducing both surface and air temperatures, making water bodies essential components of urban climate regulation [26].

In addition to standalone green and blue elements, hybrid gray-green-blue infrastructures such as green roofs and green walls have gained prominence for their multifunctional benefits [14]. Green roofs and walls not only mitigate urban flooding and regulate indoor temperatures, but also reduce heat island effects, improve air quality, and dampen noise pollution [27]. These systems are increasingly being adopted in developed countries, as green buildings can create a favorable environment for the health and well-being of the population [28]. The evolution of such hybrid infrastructures can be traced back to earlier urban planning concepts, including parkways, green belts, and garden cities [14].

More recently, GI has emerged as a key strategy for enhancing urban sustainability and resilience due to its multifaceted benefits. GI planning involves the strategic development of interconnected and multifunctional networks of green and blue spaces that can deliver a diverse array of environmental, social, and economic benefits, making GI a vital tool for improving urban livability [29]. By providing essential ecosystem goods and services, GI enhances the well-being of city residents and contributes to the overall sustainability of urban environments [30].

The benefits of GI can be categorized into the following main areas:

1) Environmental protection: GI serves to protect the environment through runoff control and stormwater management, as well as enhancing environmental soundness and climate change adaptation [31].
2) Land value: GI reduces city cost overheads by decreasing reliance on costly gray infrastructure and lowering maintenance costs. It also enhances property values, attracts investment, generates job opportunities in the green economy [32], and provides a foundation for sustainable development in urban areas [24]. Urban green spaces offer a variety of functions, services, and benefits that help make cities more fruitful and sustainable to live in [33].
3) Quality of life: From a social perspective, GI enhances urban residents' quality of life by providing green spaces, recreational opportunities, and aesthetic improvements [32, 34]. GI can enhance landscape aesthetics and improve the built environment. It can also increase social capital and provide educational opportunities. In addition to reducing the ecological footprint, GI integration within the urban environment can enhance livability through improved access to nature [35].
4) Public health: GI can improve air quality and reduce the urban heat island effect. It can also increase physical activity and reduce stress, providing important public health benefits [31].
5) Hazard mitigation: GI can play a crucial role in flood risk reduction and climate change resilience, helping local governments comply with stormwater management regulations [34]. However, the advantages of GI are not distributed equally across socioeconomic groups. Factors like location, type, and size all play a significant role in determining their environmental impact in different areas of the city [25].

GI has evolved from being primarily associated with standalone natural spaces like parklands, forests, wetlands, and greenbelts that provided ecosystem services, to a wider, more comprehensive concept with an approach that aims to achieve environmental, economic, and social benefits at the city level [34]. This includes all green spaces within a city, which, together, create a diverse network and a complex ecosystem that operates on multiple scales and serves various functions [7]. GI can offer a variety of ecosystem services [35], including the ability to mitigate the urban heat island effect through shading and evapotranspiration. The development and preservation of urban green spaces, such as peri-urban forests, street trees, and other greenery, can enhance the overall ecosystem service capacity at the city and even the regional level [8]. Drawing upon existing literature, an initial conceptual framework [36] is put forward, comprising nine GI types that can be grouped into four main categories, as shown in Table 1 [25, 37-39]. This initial conceptual framework is further refined and developed in the research case study. The four main GI categories, as shown in Table 1, are:

1. Urban green areas: parks, gardens, open spaces, and swales within urban environments [25]. These include man-made green areas in

Table 1
Green Infrastructure Categories and Types

GI categories	Object type	Object category	Types of GI in articles
Urban green areas	Parks (mainly public space, but some access restrictions may apply)	Park, pocket park, and botanical garden	Parks Open spaces Urban agriculture
Residential green spaces	Gardens (mainly private space linked to dwellings)	Balcony, private garden, and shared common garden area	Residential garden
	Constructed GI on infrastructure	Green roof and green wall	
	Amenity areas (areas designed primarily for specific amenity uses)	Sports field (assume grass), school, playground, golf course, and shared open space	Schools
Trees	Linear features/routes (linked to routeways, geographical features, and boundaries)	Street tree, cycle track, footpath, road verge, and railway corridor	Road median strips and green streets City street trees Roadside
Natural green spaces	Forests	Wooded areas	River corridor
	Grasslands	Open fields	
	Water bodies (blue space features)	Wetland, river/stream, canal, lake, and sea	

settlements, such as areas with public greenery, parks, green plazas, squares, and alleys, and greenery in residential areas, cemeteries, and private gardens [40].

2. Residential green spaces: elements such as green roofs, green walls, and designated green areas within residential areas. Green roofs offer a range of benefits, including stormwater management, aesthetic value, insulation, and habitat provision. These multifunctional green spaces can also mitigate urban heat, improve air quality, reduce noise, and promote public health and well-being. The ecological, social, and economic advantages of green roofs underscore their importance in sustainable urban development [41].
3. Trees: linear greenery elements, such as biocorridors, alleys, green avenues, greenways, and green belts [40]. Green alleys serve as an example of how various site- or neighborhood-specific GI innovations can come together, offering multiple benefits and providing a comprehensive approach to climate adaptation [34]. Urban trees provide multiple benefits, including air pollution removal, cooling and shading, stormwater management, and supporting biodiversity. These ecosystem services contribute to the health and well-being of city residents [38].
4. Natural green spaces: spaces that have been barely developed by humans, including forests, grasslands, and wetlands on a city scale [25]. Urban forestry can also include green belts surrounding cities that help protect waterways and manage development. Additionally, it can involve acquiring and managing land to safeguard urban watersheds, ensuring the quality and supply of drinking water [34].

2.2. Integration of GI within the built environment

The need to consider the sustainability of urban infrastructure during the urban design phase is increasingly recognized [41]. Green building practices have emerged as a viable solution to environmental concerns, focusing on reducing a building's impact throughout its lifecycle. In parallel, BIM has had a significant impact on the planning, design, execution [1], and life cycle assessment [42] of the building process. As the advantages of BIM in expediting construction become more evident, researchers see the potential of combining BIM with environmentally friendly practices [1]. BIM can facilitate effective resource monitoring, informed sustainable design decisions, collaborative efforts, and thoughtful site planning. These attributes align closely with the principles of green building practices, promoting efficient resource use, the integration of environmentally friendly design choices, and a holistic approach to achieving sustainability goals from the very beginning of a project. There is a recent tendency to focus on environmental, economic, and social assessment during the building design process. BIM-based technologies, lean methods (construction and environmentally lean and efficient production), and BIM-based life cycle sustainability assessment methods can provide new perspectives to these standard approaches [42, 43].

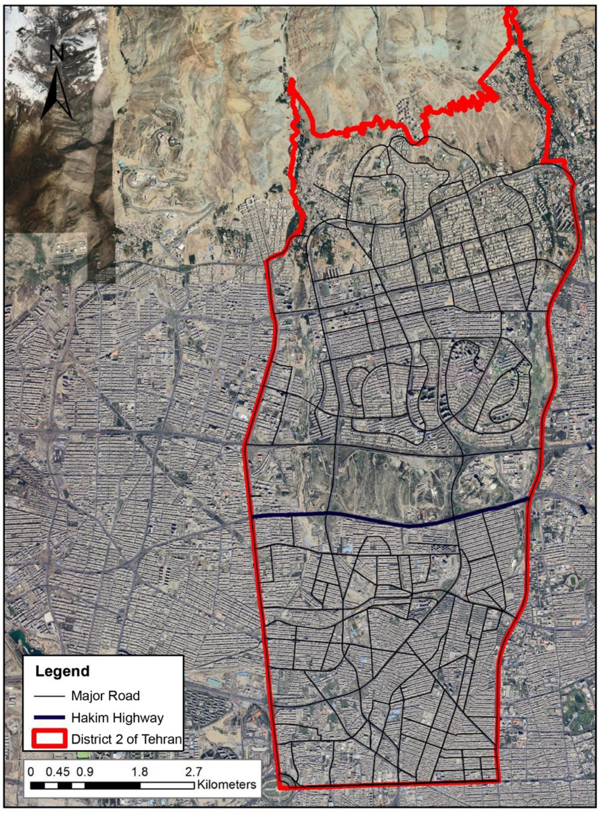
The BIM-based approach has positively impacted the construction industry by actively fostering the development of new sustainable services and manufacturing processes, while "leveraging synergies between green aspects (environmental analysis, environmental science, and sustainable development) and BIM and lean construction" [43]. The BIM for green buildings approach facilitates data sharing among stakeholders, ensures traceability, and supports the integrated management of buildings. This method also addresses key issues that enhance the sustainability of the built environment [45]. Green building has become a primary concept for realizing sustainable development, promoting health, safety, and energy-saving environments in buildings [46]. The connection between BIM and green buildings is encapsulated in the concept of "green BIM". This idea has been explored in previous studies that focus on related topics such as green buildings, sustainable design, and sustainable construction [44]. In China, the green BIM approach has provided a novel perspective for researching green performance and constructing, for example, environmentally friendly university campuses [47].

BIM can function as both a project and a process simulation. Careful planning and intentional implementation are crucial for producing simulations [48]. One of the key strengths of BIM for sustainability is its capability in analyzing energy use and pinpointing opportunities for cost savings, leading to significantly reduced energy consumption and enhanced energy efficiency in green building projects [1]. The swift advancement of BIM and its related applications has opened up new opportunities to support green building practices. These include various analyses such as acoustic assessments, carbon emission evaluations, management of construction and demolition waste, lighting analysis, operational energy use assessments, and water usage evaluations [49]. BIM can serve as a foundation for sustainable green building initiatives and conservation efforts, drawing on the insights gained from these analyses [50]. In the realm of green and sustainable buildings, BIM can be seamlessly integrated with a variety of design considerations, such as the following: utilizing natural ventilation, lighting, and shading; incorporating solar energy solutions; implementing rainwater recycling and waste management systems; using permeable surfaces for outdoor areas; selecting environmentally friendly materials; and prioritizing ecological maintenance. BIM software includes functionalities like energy-efficient computing, natural ventilation analysis, and performance assessments to effectively support these green design principles [51].

In similar vein, some authors have introduced the concept of "green mobility" which Almatar [52] suggests "is associated with the incremental investment, timesaving, reduction of traffic congestion, climate protection, improving health benefits, air quality betterment, and diversification of energy supply" (para. 1). Almatar's study of green mobility in Saudi Arabian cities concluded that "overall, this study's findings have emphasized the need for an integrated and clear policy designed within a national framework" (para. 1). Other relevant and related themes include BI, noted above, which complements GI and focuses on the planning and development of water-related elements in urban areas [6]. The integration of GI and BI emphasizes the synergy between water management and vegetation-focused systems [53]. This is particularly effective in addressing functional and infrastructural challenges by incorporating natural, seminatural, and artificial spaces and networks of spaces that mimic natural processes [27]. Such networks may include interconnected water reservoirs, wetlands, and open spaces developed along rivers, which collectively enhance flood resilience and biodiversity [54]. In a wider context, water quality and quantity in Iran have been studied in a number of environments, notably in the Karkheh river basin, to the southwest of Tehran [16, 55].

Nevertheless, it is clear that there are a number of potential barriers that hamper the successful implementation of GI [56]. A primary challenge is the limited knowledge of ecology and land management practices among engineers and maintenance workers, roles that are essential for designing and maintaining GI facilities. Resistance to changing existing design and maintenance practices further complicates adoption. Public awareness is another critical issue, as residents often lack understanding of stormwater management problems and how to address them at the household or business level. Ambiguity regarding maintenance responsibilities—whether the government or residents should manage GI facilities—also poses a significant obstacle. Lastly, site suitability emerges as a barrier when GI is proposed for locations that are environmentally or logistically unsuitable.

Figure 2
District 2, Tehran: Road Network



3. Research Method

District 2 of Tehran was selected as the case study area due to its high population density, diverse urban characteristics, and significant environmental challenges, making it a representative example for examining the role of GI in densely populated urban settings. The district (Figure 2)[1] had a population of around 743,000 people in 2020 and is divided into nine areas and 30 neighborhoods. Its selection was based on its relevance to the research objectives, including its mix of residential, commercial, and green spaces, as well as its susceptibility to issues such as urban heat islands and water scarcity. These factors make it an ideal location for studying the spatial distribution of GI and the implications for sustainable urban development.

The research process, culminating in the preparation of the final GI plan for the district, is illustrated in Figure 3. Initially, the maps were generated using data from the Detailed Plan, land use information gathered from Tehran's municipal offices, and Google Earth images for District 2 of Tehran. Through overlay analysis, maps of green zones from the Detailed Plan and the existing GI were combined to identify the key areas with green spaces, which are critical for promoting sustainability.

More specifically, to address the research questions, a combination of remote sensing data, Geographic Information Systems (GIS) analysis, and observational data was used. For RQ1, GIS data were employed to create a baseline GI map for District 2. Landsat remote sensing data served as the primary source for obtaining generalized land-cover information [57]. A significant aspect of the connection between remote sensing and landscape ecology is the ability to collect spatial information over large areas. This capability is particularly evident with satellite imagery, where individual image scenes can capture regions spanning tens to hundreds of kilometers [58]. The authors considered the spatial resolution of Landsat data to be suitable for the needs of this project [57].

In addressing RQ2, the study utilized updated information to revise the official plan data for District 2 of Tehran, which was outdated and required revision. The methods mentioned earlier were employed to meticulously examine and update the status of green streets in Google Earth, which were then represented as features within GIS.

To accurately depict residential buildings, offices, and educational green spaces, all existing building parcels in the area were analyzed, and their data were transferred to GIS. Additionally, the official Detailed Plan for the research area, developed in 2019, was reviewed to identify both existing and proposed green zones. The classification of existing GIs into natural and seminatural categories was also assessed to evaluate their development status. Overlaying current and proposed GI provided a further perspective on the potential for the future provision of GI in the district.

4. Results

4.1. RQ1. What is the current status of GI in the case study area?

One notable feature of the landscape in District 2 is the natural terrain created by the Alborz mountain range to the north of the area. Overall, the district is characterized by a diverse landscape, featuring natural and seminatural elements such as the Pardisan Forest Park, Goft o Go Park, the Najaf Al-Ballagh Park, Jurassic Park, Parvaz Park, and the city of Ara Park, and gardens like Tarasht Gardens, Faiz Garden, and the gardens of the Evin neighborhood. Nevertheless, the provision of green space in District 2 has decreased significantly in recent decades, declining from 1,026 hectares in 1986 to 810 hectares in 2016. In contrast, the built-up area has increased from 2,359 acres to 3,611 acres over the same period [15]. Given these trends and the availability of necessary capacity to preserve and enhance GI in the area, the creation of new green spaces and the strengthening of their infrastructure are required to safeguard the future sustainability of the area.

The following zoning of the lands is based on information derived from the 2019 Detailed Plan of District 2, as shown in Figure 4 [15]. In this plan, the existing lands are categorized into four classes: Residential (R), Green (G), Mixed Residential and Commercial (M), and Service (S). Approximately half of the district is designated for residential use, followed by the green zones, which cover over 25% of the district, representing an unusual emphasis on GI.

Focusing now on actual land use (as opposed to zoning), the detailed land use map of District 2, derived from GIS data (Figure 5), reveals a distinct disparity in the distribution of vegetation cover and green spaces between the northern and southern parts of the region. Specifically, the northern part of the region, situated above the Hakim highway, exhibits a more favorable condition in terms of vegetation cover and green spaces compared with the southern part, located below the Hakim highway. This disparity is attributed to the proximity of the Alborz Mountains to the north, which results in higher rainfall and a more favorable climate.

Additionally, the presence of two rivers, Farahzad and Darakeh, contributes to the fertility of the surrounding land and the creation of parks and agricultural land. The residential land use, with an area of

[1] Constructed by the authors based on Google Earth. https://earth.google.com/web/search/District+2,+Tehran,+Iran/@35.74958299,51.36914718,1409.14542891a,21966.60533051d,35y,0h,0t,0r/data=CoYBGlgSUgokMHgzZjhlMDc3NjQzNjY1ZjcxOjB4MTQ3NGVkZGZiY2E0ZWYxGSWJb3lJ30FAIT0d2abCrUlAKhhEaXN0cmljdCAyLCBUZWhyYW4sIElyYW4YAiABIiYKJAlHAUydTedBQBHRabajXthBQBkD8K47D8JJQCHKcPappZxJQEICCAE6AwoBMEICCABKDQj___________8BEAA

Figure 3
Research Process Flow Chart

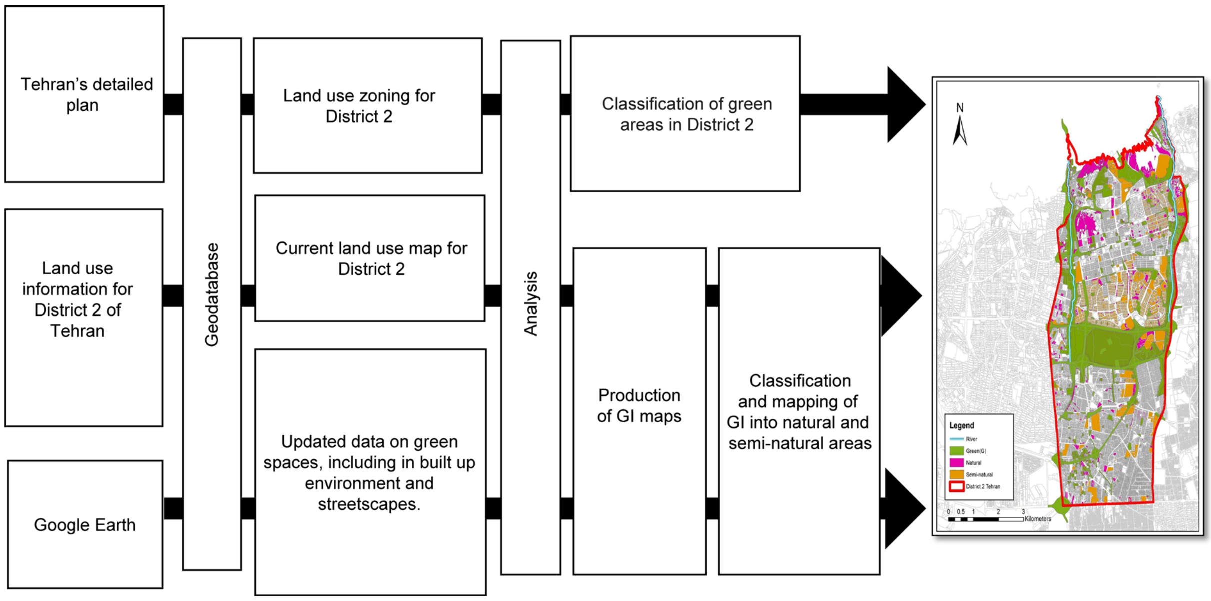


Figure 4
Zoning Map in District 2, Tehran

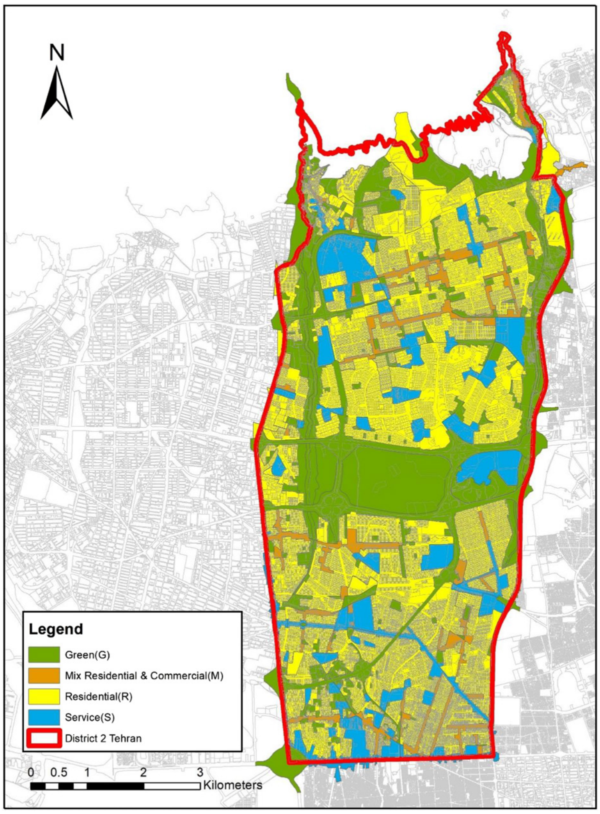
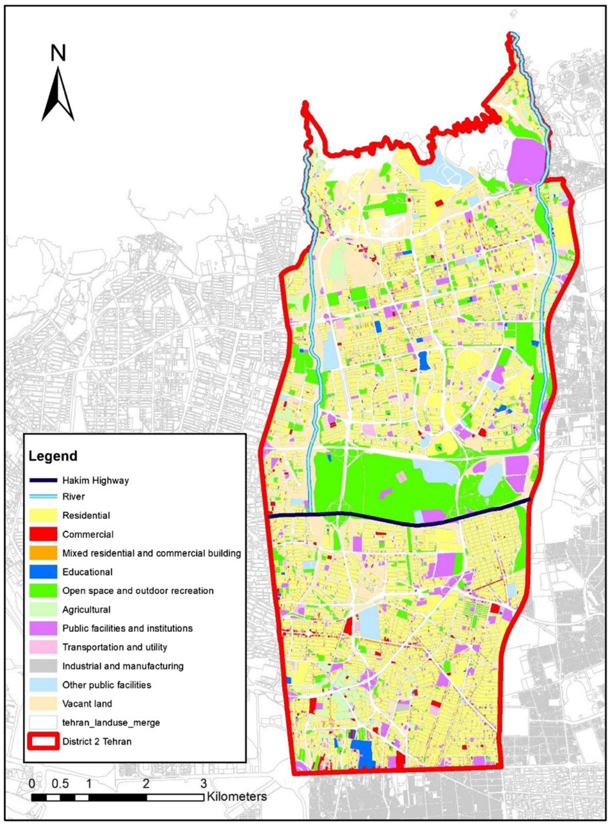


Figure 5
Land Use in District 2, Tehran



approximately 15 km², constitutes about 42% of the land area, which is the largest share in District 2. Following that, vacant land and open space and outdoor recreation occupy the second and third positions with 20% and 18%, respectively (Table 2). The acceptable per capita green space in Iranian cities is considered to be between 7–12 m² per person, and this figure is set at 13.9 m² per person in the comprehensive plan of Tehran [59]. In 2020, the per capita green space in District 2 was significantly below that figure, at 8.42 m² per person.

More specifically, as regards GI, 8 main categories of GI are recognized in the study area. This builds upon the initial conceptual framework, derived from the literature, shown in Table 1. Table 3 indicates the data sources for each of the eight GI types. Figure 6 schematically presents the location of these GI types in the case study area. An overview of each GI type is given below.

Open spaces: These constitute the largest portion of green spaces in District 2, playing a crucial role in improving air quality and reducing pollution. These areas need increased tree planting and must remain accessible to the public. The importance of maintaining these open spaces lies in their capacity to serve as green lungs for the city, acting as buffers against urban heat islands. Open spaces also provide essential ecosystem services such as stormwater management, habitat for urban wildlife, and recreational opportunities for residents.

Educational gardens: In contrast, educational gardens, such as those found in higher education centers and schools, are small in size and overall land area. Despite this, these green spaces are crucial for the mental and physical well-being of students and staff. They improve air quality and offer a calming ambiance, thereby reducing stress and enhancing the learning environment. Integrating more GI within educational institutions promotes environmental awareness and sustainability among the young generations.

River corridors: The Farahzad and Darakeh rivers provide not only green spaces but also a unique and favorable microclimate for the surrounding areas. River valleys are vital for sustaining biodiversity, regulating local temperatures, and providing natural flood management. The preservation and enhancement of these corridors are critical for maintaining the ecological health of the area.

Table 2
Land Use of District 2

Types of land use	Area (m2)	Percentage
Agricultural	1,138,219.5	3%
Commercial	534,150.7	1.5%
Educational	355,717.2	1%
Industrial and manufacturing	107,352	0.5%
Mixed residential and commercial building	550,974.7	1.5%
Open space and outdoor recreation	6,259,607.4	18%
Other public facilities	1,386,825.1	3.8%
Public facilities and institutions	2,824,053.7	8%
Residential	14,999,119.7	42%
Transportation and utility	256,056.4	0.7%
Vacant land	7,303,149.7	20%

Parks: They enhance air quality and provide valuable recreational opportunities, with many urban parks offering high social and ecological value. The importance of parks as a GI component cannot be overstated. As noted by Ramyar et al. [60], public green areas such as parks traditionally form the backbone of GI networks. Studies by Korkou et al. [30] and Alanbari et al. [39] emphasize the role of such networks in enhancing resilience, economic gains, biodiversity conservation, and climate change adaptation. Notably, there is a scarcity of parks in the southern part of District 2, which will require targeted initiatives to ensure equitable access to green spaces.

Green streets: These function as urban connectors and are in evidence across the study area. Green streets contribute to the reduction of urban heat islands, improve air quality by absorbing pollutants, and provide aesthetic and psychological benefits to urban dwellers. They also support urban biodiversity by creating continuous green corridors that connect larger green spaces.

Residential gardens: Given that 42% of District 2 is given over to residential use, these gardens have a pivotal role. They contribute to the overall green cover, thus enhancing local air quality and providing private, aesthetically pleasing outdoor spaces for residents.

Green public facilities: Green public spaces in facilities like government offices, hospitals, and service areas are vital for improving air quality. Given the high cost of land and the economic benefits of development in Tehran, there is a tendency for construction within parks, emphasizing the need to maintain appropriate green spaces to balance urban development.

Urban agriculture: Urban farms occupy a small percentage of the land in District 2. The Detailed Plan designates some of these areas as green zones for creating parks and green spaces. Urban agriculture provides significant benefits, including local food production, reduced food transportation emissions, and opportunities for community engagement and education in sustainable practices.

4.2. RQ2. How is GI evidenced in the existing Detailed Plan for the case study area?

To address RQ2, a further categorization of GI (as it exists) in District 2 of Tehran into natural and seminatural GI was introduced (Figure 7). This distinction is based on human intervention. Areas

Table 3
Green Infrastructure in District 2

Type of GI	Description	Area or length (ha) in the study area	Data sources
Parks	Urban and neighborhood parks	387.35	GIS and Google Earth
Residential gardens	Gardens in residential complexes or villas	461.15	Google Earth (Satellite Data)
Open spaces	Unutilized green spaces without a specific use	482.56	GIS and Google Earth
Urban agriculture	Urban gardens and agricultural land	114.59	GIS and Google Earth
Green streets	Streets with greenery or green buffers	96.48	Google Earth
River corridors	Green spaces along rivers without a specific use	63.26	GIS and Google Earth
Educational gardens	Gardens in universities, schools, or educational institutions	56.23	Google Earth
Green public facility	Green spaces in government offices, hospitals, and highway service areas	324	Google Earth

Figure 6
Types of GI in District 2, Tehran, Iran

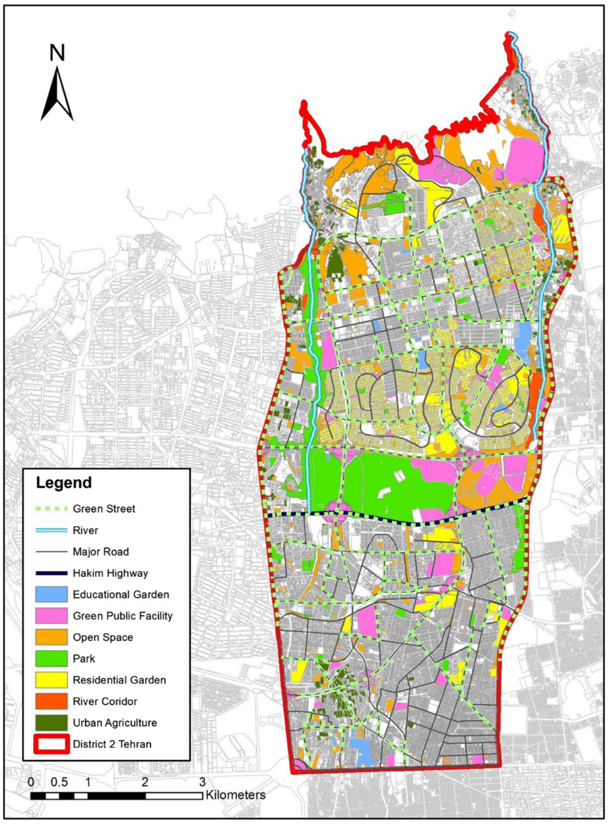
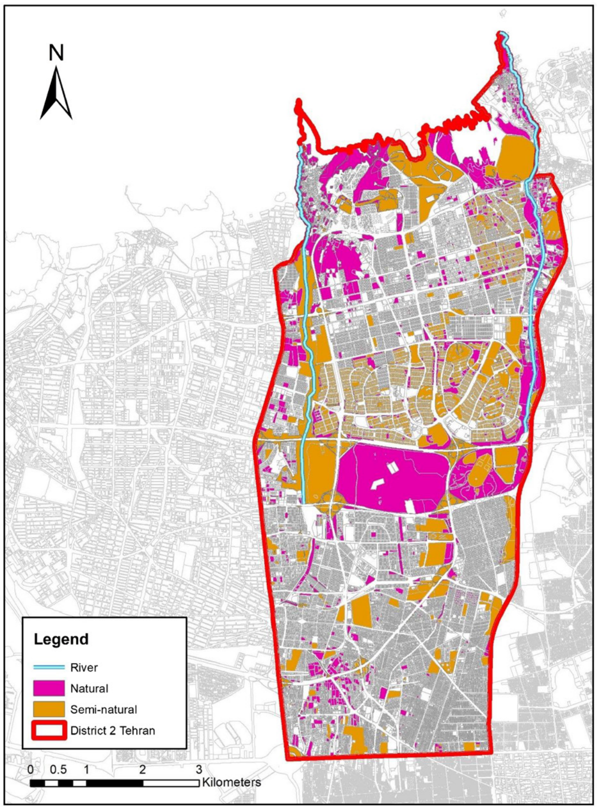


Figure 7
Existing Natural and Seminatural GI in District 2, Tehran



where humans have made modifications, such as residential gardens, parks, green streets, educational gardens, and green public facilities, are categorized as seminatural. Forest parks, green corridors, and urban agricultural lands are classified as natural.

Of the 4,956 ha of District 2, natural GI covers approximately 849 ha, and the seminatural areas encompass about 1,035 ha—38% of the district in total. Of this, the largest portion of natural infrastructure is found in the northern, western, and eastern parts of the district due to the presence of river valleys, which create favorable ecological conditions in the surrounding areas. In contrast, the southern part of the district, characterized by older buildings and thoroughfares, has a lower percentage of natural GI. The higher percentage of seminatural GI reflects past initiatives to improve conditions through the creation of GI.

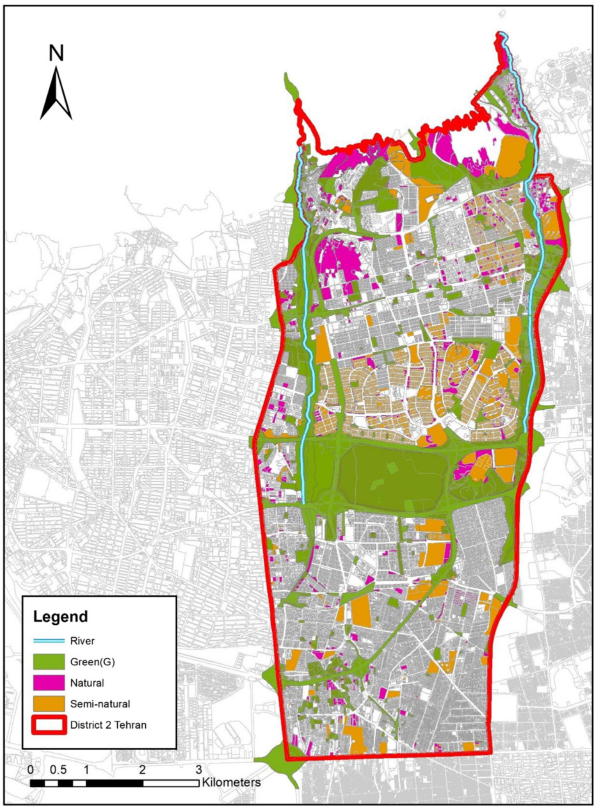
To assess the appropriateness and feasibility of the designated green zones (G) in the Detailed Plan, the zonings were compared with existing GI land use. Figure 8 indicates the overlap between the designated green zones (G) and the existing GI, categorized into natural and seminatural. The areas classified as green zones are, in the main, aligned with existing GI, both the natural and seminatural categories. However, in addition to GI existing within classified green zones, significant other areas of GI lie outside these areas, notably on the northern borders of the district. Further, residential gardens are located in the residential zones, and educational gardens and green public facilities are situated in the services zones (Figure 4). The GI in these zonings plays a significant role in the overall GI provision in the area, which can be supported by encouraging residents to create gardens in their homes or even develop roof gardens. Zones other than those classified as "green" play a vital and fundamental role in the formation, development, and preservation of GI in the area.

5. Discussion

The above findings raise some issues worthy of further discussion. First, the categorization of GI into different types highlights the unique contributions of each one to urban sustainability. Parks and open spaces are essential for improving air quality and reducing pollution, while residential and educational gardens offer localized green benefits and enhance community well-being. The river corridors, as highlighted by Nasehi et al. [15], are significant components of the overall GI. Their linear extension and connectivity support other green structures, underscoring the need for assessing GI around these urban river valleys before making development and conservation decisions. Utilizing natural features such as river valleys to support green structures and integrating advanced monitoring technologies are valuable future strategies. Embracing these approaches will enable urban areas to bolster their resilience and sustainability, helping to make GI accessible to all residents. A thorough understanding and strategic implementation of GI are essential for progressing sustainable urban environments in rapidly developing cities like Tehran.

Second, there is clearly a tension between urban development and preserving GI, as evidenced in other parts of Tehran, where economic pressures and high land costs have led to construction in parks and green spaces. To ease this conflict of interests, fallow lands in the urban periphery could be converted into parks to maintain environmental quality in rapidly urbanizing cities like Tehran, and incentives and regulations should discourage encroachment into green areas. GI not only boosts community growth by increasing property values, creating jobs, reducing energy costs, and lowering stormwater management expenses [61], but it can also attract tourists and stimulate local

Figure 8
Green Zones (G) in the Detailed Plan for District 2 and Existing GI



economies. GI also promotes health, social cohesion, and economic development, supporting sustainable urban growth [62].

Given Tehran's recent classification as one of the most polluted cities globally, converting these underutilized lands into green spaces would help combat air pollution, mitigate urban heat island effects, and enhance the overall quality of life for residents. By implementing these strategies, District 2 can develop a robust and resilient GI network that meets the current needs of its residents while supporting wider sustainable urban growth across the city. GI can also foster social cohesion by providing spaces for recreation, cultural events, and community interaction, strengthening social networks and promoting inclusivity in urban areas [61, 62].

Third, urban planning and policy play a critical role in advancing GI initiatives. In Iran, urban planning and development policies have often failed to adequately protect or mitigate the degradation of urban green spaces. In some cases, economic incentives have actively driven policies that undermine these vital ecosystems, as the prioritization of economic profitability from land conversion has often outweighed environmental considerations. To counter this, incentive-based programs promoting the preservation and expansion of GI are required. Regulatory mechanisms must be established to mandate the integration of designated green spaces in development projects while preventing the destruction of existing vegetation. Such measures are crucial for achieving sustainable urban development that balances economic and environmental imperatives. For example, Korkou et al. [30] highlight the advantages of green roofs in fostering sustainable urban development. Forward-thinking solutions could include incorporating green roofs on highways and integrating green areas within educational and public facilities to address specific urban challenges. Public engagement and community-led initiatives are also essential to foster a sense of ownership and ensure that green spaces meet local needs.

Fourth, this study differs from other recent contributions in this field in a number of regards. This research examines GI in District 2 of Tehran, focusing on the distribution of vegetation cover, spatial disparities, and the application of GIS to advance sustainable urban development. It identifies eight distinct types of GI, highlighting the need for location-specific planning to foster balanced development and reduce spatial inequalities. Ramyar et al. [60], on the other hand, emphasize the role of GI in enhancing urban environmental quality and facilitating sustainable development on a metropolitan scale. Similarly, Chamanara and Kazemeini [63] investigate GI development in Tehran through a multi-scale integration approach aimed at establishing a continuous network of green spaces. Their focus spans various urban levels, from neighborhoods to the metropolitan scale, promoting multifunctional benefits such as pollution reduction, improved air quality, and enhanced quality of life. In contrast, this study provides a granular examination of District 2's current conditions, proposing actionable measures such as transforming vacant lands into parks, expanding tree-planting initiatives in the southern areas, and encouraging the establishment of residential gardens.

The analytical divergence is also notable: while this study employs GIS methodologies to evaluate spatial disparities, Chamanara and Kazemeini [63] prioritize strategies that emphasize connectivity within the green network. Similarly, while Malagnino et al. [45] as well as Liu and Wang [47] emphasize the importance of new technologies like BIM and its integration with green buildings, this article demonstrates the potential of GIS for mapping and analyzing GI in urban planning research. GIS provides critical insights into the spatial distribution of green spaces, identifies areas lacking green cover, and supports targeted interventions. The combined use of GIS and BIM should be expanded to enhance the planning, implementation, and management of GI. These technologies provide valuable data and facilitate more informed decision-making.

6. Conclusion

Tehran's warm and dry climate, combined with challenges such as water scarcity and high temperatures, necessitates innovative urban solutions to enhance environmental sustainability and improve the quality of life for its inhabitants. This case study, focusing on District 2 of Tehran, underscores the critical role of GI in urban planning and development. The study area contains a variety of GI types that enhance recreational opportunities and air quality, help mitigate urban heat island effects, and reduce the threat of flooding by improving water infiltration and storage. Additionally, the presence of numerous residential gardens and green streets in District 2 highlights the importance of community involvement in maintaining and expanding green spaces. District 2 provides a valuable blueprint for other cities aiming for sustainable urban development, illustrating both the potential and challenges of incorporating GI in densely populated areas. Successful implementation of GI requires a delicate balance between traditional gray infrastructure and innovative green solutions.

This study clearly has its limitations, as it focuses solely on one district in Tehran and does not attempt to make generalizations regarding GI provision in broader contexts. Nevertheless, it offers valuable insights for researchers and emphasizes the importance of a multifaceted approach to urban planning and development, utilizing advanced technological tools like GIS. These tools are instrumental in optimizing design processes, assessing sustainability comprehensively, and identifying energy-saving opportunities, thereby contributing to the creation of more resilient and sustainable urban environments. Future studies could examine the different classifications of GI put forward by various authors [25] [37-39], in addition to the categorization adopted here, to provide a universally agreed-upon categorization that would support cross-city comparisons. Future studies could also investigate the role of community participation in initiating and progressing GI initiatives, focusing on collaboration between policymakers, planners, and local residents. An examination of the barriers to GI implementation and how they have been overcome could also provide some exemplary case studies of value to both researchers and practitioners. At the same time, quantitative research could provide a different perspective in analyzing GI to complement the qualitative approach put forward here.

This study provides a viable method and process for cities with similar urban environments to shape and pursue GI objectives. By identifying spatial disparities in GI performance, context-specific solutions for preservation, enhancement, or mitigation can be developed. In Iran, cities such as Isfahan, Ahvaz, and those with comparable riverine systems are particularly appropriate to apply and benefit from this approach.

Future research in this field can also benefit from the deployment and integration of digital technologies. The application of artificial intelligence (AI) for the automated identification and monitoring of GI elements will enhance data accuracy and efficiency. As highlighted by Hosseini et al. [64], in the context of environmental protection and air quality, AI can support supervisory and alerting functions, facilitating the evaluation of air quality and the detection of particulate matter. In water resource management, AI identifies leaks in regional water distribution systems, reduces waste, and improves the regulation of this essential resource. In general, such systems enable automated and intelligent decision-making in various aspects of smart urban planning and management. This not only enhances the quality of life for citizens but also contributes to the sustainable development of cities. Moreover, the deployment of remote sensing, machine learning, and advanced GIS platforms will provide a deeper understanding of spatial dynamics, vegetation health, and their impact on urban environments [65]. These technological advancements will enable predictive modeling, supporting better-informed decision-making and the development of sustainable urban planning strategies.

Ethical Statement

This study does not contain any studies with human or animal subjects performed by any of the authors.

Conflicts of Interest

The authors declare that they have no conflicts of interest in this work.

Data Availability Statement

The GIS data analysis that supports some of the findings of this study are held in a university environment. Further enquiries can be made via the corresponding author.

Author Contribution Statement

Seyedeh Zahra Hosseini: Conceptualization, methodology, validation, investigation, resources, data curation, writing (original draft), writing (review and editing), supervision, and project administration. **Rojin Raofi:** Conceptualization, methodology, software, validation, formal analysis, investigation, resources, data curation, writing (original draft), writing (review and editing), and visualization. **Shayesteh Hamidkhaniha:** Conceptualization, validation, formal analysis, investigation, resources, data curation, writing (original draft), and writing (review and editing). **Farhad Daneshgar:** Conceptualization, software, investigation, resources, writing (original draft), and visualization. **Martin Wynn:** Conceptualization, methodology, validation, investigation, writing (original draft), writing (review and editing), visualization, and supervision.

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