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ENHANCING SUSTAINABLE URBAN AREAS THROUGH DIGITAL GREEN INFRASTRUCTURE: ACHIEVING TANGIBLE OUTCOMES

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The object of this research is integrating green infrastructure into sustainable urbanization zones within the context of digitalization. The problem addressed is the difficulty of ensuring urban sustainability without considering the green infrastructure in urban and suburban areas. The article argues that city sustainability cannot be effectively addressed without integrating green corridors that connect urban and suburban zones. The research proposes using optimization and simulation models to plan and manage the expansion of green corridors in sustainable urban areas. The results highlight the importance of a joint approach to green infrastructure development in urban and suburban areas, showing that interconnectivity is crucial for long-term environmental sustainability. Findings were interpreted by illustrating how simulation models can be used to assess the effectiveness of green infrastructure in real-time. The research demonstrates that the digital modeling of green corridors enhances planning precision, ensuring better connectivity between the city and surrounding areas. The key features that solved the problem include an optimization model, which enabled efficient planning for green corridor expansion, improving connectivity between urban and suburban areas. The paper uses digital simulation tools that allow for real-time assessment of green infrastructure's sustainability impact, leading to better-informed decision-making. The results are applicable in urban planning and sustainability management within rapidly urbanizing cities. The findings are most effective when cities have access to digital tools and aim to enhance green infrastructure's role in sustainability strategies

***Keywords:** green infrastructure, sustainability, green hybrid corridor, digital environment, urbanization zone, suburban area*

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1. Introduction

Urbanization is accelerating at an unprecedented rate, with over 50 % of the world's population now residing in cities, which contribute 80 % of global GDP [1]. These urban centers are hubs of capital investments, infrastructure, and technological innovations. However, the dense concentration of populations and industries within cities presents significant environmental and social challenges, including strain on infrastructure systems like utilities, healthcare, transportation, and housing [2]. As urban populations grow, so does the pressure on resources, driving the need for new approaches to urban development that prioritize sustainability and livability.

The concept of sustainable cities has evolved to address these challenges. Officially recognized in the UN's Sustainable Cities Program in 1991, sustainable cities aim to reduce environmental impacts while fostering social and economic development. According to the UN definition, "a sustainable city is one where achievements in social, economic, and physical development are enduring. A sustainable city has a continuous supply of natural resources necessary for sustainable development. A sustainable city also ensures the long-term safety of its residents, including protection from natural disasters" [3]. Sustainable urbanism, the theory of designing and constructing cities with long-term ecological and social viability in mind, advocates for dense urban areas with mixed land use, access to public transportation, and low environmental footprints. Such cities must balance positive effects, like increased efficiency, with potential negatives, such as changes in microclimate, reduced air quality, and increased urban heat islands.

One of the key strategies for addressing these issues is green infrastructure, which includes parks, green roofs, and other vegetation-based solutions. These spaces provide vital ecosystem services, such as improved air quality, temperature regulation, and enhanced biodiversity. However, the potential to integrate digital technologies into green infrastructure planning remains underexplored, especially when considering the need for cities to become greener and smarter. Leveraging the power of digital tools, such as IoT devices and data analytics, can optimize the planning, implementation, and management of green spaces, making cities more resilient and energy-efficient.

The growing potential of the digital environment offers new opportunities for optimizing urbanization processes to meet sustainability goals. This is particularly relevant for expanding and maintaining green infrastructure within densely urbanized areas, where land use is at a premium. By combining digital advancements with green infrastructure, cities can improve their environmental efficiency and quality of life, while mitigating the negative impacts of urbanization.

Therefore, research dedicated to developing green infrastructure in the digital context is highly relevant for addressing the sustainability challenges posed by rapid urbanization.

2. Literature review and problem statement

Sustainable development, which does not create problems for future generations, necessitates collaborative efforts in building inclusive and resilient economic relationships. Sustainable development should aim to realize the potential of an inclusive society by ensuring green economic growth. As a complex and often contradictory process, the sustainability of urbanization processes must encompass numerous characteristics. The paper [4] presents the results of research on the integration of urban, social, and environmental processes necessary for achieving sustainable urbanization. Their work highlights the complexity of urban sustainability and its direct connection to the quality of life in densely populated urbanized areas. It demonstrates the importance of coordinated urban planning and green infrastructure efforts to mitigate environmental degradation and enhance social resilience. However, unresolved issues persist regarding the role of energy efficiency in larger urban territories and the full integration of green infrastructure with economic processes, especially in the context of new digital technologies.

The paper [5] underscores the need for comprehensive green infrastructure development within cities and surrounding areas as a key factor in sustainable urbanization. They show the interdependence between urban growth and surrounding green spaces, which is critical in maintaining ecosystem balance. Despite this, their work does not fully address the role of digital tools in managing these processes or the potential for digitization to support energy efficiency in urban and suburban areas. Thus, there is a gap in understanding how digital solutions can optimize resource management within these territories.

The paper [6] examines the role of sustainability indicators in assessing the weaknesses in the relationship between the economy, environment, and society. Their research indicates that quantitative assessment of urban sustainability indicators could reveal the weak links between these sectors and help identify problem areas. However, their focus remains on sustainability indicators, leaving room for further exploration of how digital tools and technologies, such as AI and simulation models, can enhance this assessment and facilitate the development of green infrastructure, especially in urbanized zones where intense economic activities occur.

The study [6] focuses on the need for a quantitative approach to evaluating urbanization processes from an economic feasibility and efficiency perspective. It argues that sustainability criteria should be based on economic viability and efficiency when assessing urbanization zones. However, while the study provides valuable insights into economic evaluation, it does not adequately explore the role of digital technologies in assessing and improving the sustainability of urbanization processes. This leaves a gap in understanding how digital tools could optimize economic and environmental trade-offs in urban planning.

The research [7] emphasizes the importance of green corridors in mitigating air pollution, enhancing air quality, and reducing noise levels in urban environments. It shows that green corridors, such as forest plantations, can absorb substantial amounts of carbon dioxide and produce oxygen, playing a vital role in creating healthier urban spaces. However, while Grunwald's work provides valuable data on the environmental benefits of green corridors, it does not address how digitalization could further optimize the management and planning of these green spaces within sustainable urbanization models.

The paper [8] contributes to the discourse by examining the role of artificial intelligence (AI) in managing urban green spaces. They argue that AI can significantly improve the efficiency of green infrastructure management and planning, especially in terms of real-time data collection and predictive modeling. However, their research does not fully integrate how AI-driven green management can be aligned with urban planning priorities or the broader involvement of stakeholders, including civil society organizations, in ensuring sustainable urban development. The potential for digital technologies to enhance collaboration among various actors remains an underexplored issue in their study.

The paper [9] investigates the concept of hybrid green corridors and mobile networks in urban areas, suggesting the integration of green spaces with pedestrian and bicycle infrastructure to create sustainable transportation systems. While this approach shows potential in reducing traffic congestion and promoting eco-friendly mobility options, the study does not explore how digitization or smart city technologies could enhance the planning, monitoring, and optimization of these green and mobile networks in real-time.

Additionally, studies [10, 11] further underscore the role of urban green infrastructure in reducing carbon emissions and tackling climate change. [10] provides evidence of green spaces improving air quality and mitigating climate impacts. [11] emphasizes green infrastructure's contribution to biodiversity protection and temperature regulation in cities. Yet, both studies overlook the increasing role of the digital environment in improving the efficiency and management of these green spaces. Their research highlights the environmental benefits but does not fully explore how digital technologies can further integrate with these sustainable practices.

In summary, while substantial research has been conducted on the importance of green infrastructure in sustainable urban development, there is a significant gap in integrating digital tools into these efforts. The role of digitization in optimizing energy efficiency, resource management, and urban planning remains underexplored. Future research is necessary to investigate how digital environments, including AI, simulation models, and smart technologies, can further enhance the sustainability of urbanization zones, particularly through the development and management of green infrastructure.

3. The aim and objectives of the study

The aim of the study is to identify practical solutions for enhancing sustainability in densely populated urban zones by leveraging digital tools, such as simulation models.

To achieve this aim, the following objectives are accomplished:

– to analyze the current state of green infrastructure in urban areas and assess its role in promoting sustainability;

– to develop a framework for integrating digital tools with green infrastructure to enhance urban sustainability;

– to implement a cost optimization model for green corridor zones in the studied large city.

4. Materials and methods

The object of the study is the process of integrating green infrastructure into sustainable urbanization zones, which includes the development, implementation, and management of ecological solutions aimed at improving the quality of the urban environment. In the context of digitalization, this process gains new momentum through the use of modern technologies.

The main hypothesis of the study, which focuses on the integration of green infrastructure into sustainable urbanization zones in the context of digitalization, is formulated as follows: to ensure the sustainability of urbanized areas, it is necessary to create green corridors connecting urban and suburban territories.

The study makes several key assumptions. The integration of green infrastructure into sustainable urbanization zones is seen as a way to enhance the ecological resilience of urban environments, reduce pollution levels, and improve the quality of life for the population. The creation of green corridors connecting urban and suburban areas is proposed to ensure functional interaction between various ecosystems and support biodiversity conservation. Digitalization is identified as opening new opportunities for designing, monitoring, and managing green spaces, allowing for the consideration of factors such as climate change, demographic characteristics, and economic feasibility. Additionally, green infrastructure is viewed as a potential cornerstone of strategic planning, capable of integrating environmental, social, and economic aspects to achieve sustainable development goals in the context of urbanization.

This paper adopts several simplifications to streamline the analysis. It assumes that the integration of green infrastructure directly correlates with improved ecological and social outcomes, without fully accounting for regional variability or unique urban characteristics. The study treats digital tools and technologies as universally accessible and equally effective across different urbanization contexts, without addressing potential limitations in resources, infrastructure, or expertise. It also simplifies the relationship between green corridors and biodiversity by focusing on general trends rather than specific ecological dynamics. Furthermore, the economic feasibility of green infrastructure projects is abstracted by assuming that their long-term benefits outweigh initial costs, without conducting detailed cost-benefit analyses for diverse scenarios. These simplifications enable a more focused exploration of the core hypothesis but may limit the application of findings to specific real-world cases.

Urbanization zones are economically active territories centered around large cities. To determine the level of sustainability of urbanization zones [12], indicators such as population concentration accompanied by sustainable urban development and the increasing role of cities in public life are characterized. Trends in sustainability, such as realizing economic potential on a technological basis and integrating activity, are recommended to be assessed.

Digital innovations, including digital platforms, aim to ensure the sustainability of urbanization zones. Thus, under this approach, digital innovations allow citizens to participate in governance, develop ecological volunteerism, increase environmental literacy, collect more environmental information, and, as a result, improve management [13]. For the use of digital twins in managing suburban urbanization processes, applying a simulation modeling system, including optimization models is recommended. Such an approach has been implemented using the example of the Baku agglomeration [14].

Expanding the scale of green infrastructure in sustainable urbanization zones, it is advisable to analyze and forecast the possibilities of expanding hybrid green corridors in Baku, which has a polycentric urban perspective. It is necessary to select $\{x=x_{ij}, i=1, n\}$ elements of green infrastructure (land plot units) to connect to the green corridor so that costs are minimized while achieving the intended benefits. The benefits primarily include air purification, expressed in noise reduction, human health, and labor productivity. The mathematical model, developed by the authors, can be represented as follows:

$$\sum_{i=1}^{m}\sum_{j=1}^{n} e_{ij}x_{ij} + \sum_{i=1}^{m} b_i e_i \to \min, \quad (1)$$

$$\sum_{i=1}^{n} b_j x_{ij} = 1, \quad (2)$$

$$\sum_{ij} b_{ij}x_{ij} + \sum_{i=1}^{m} e_i b_i \geq P. \quad (3)$$

Here, i – the number of potential plots of land in terms of connecting to the green corridor;

c_i – the costs required to include the i-th plot in the green corridor;

e_i – the benefit of connecting the i-th plot to the green corridor;

P – the required increase in benefits;

m – the number of potential land parcel units;

n – the selection options for new land parcel units to be connected to the green corridor (considering three options, i. e., $j=1,n$; $n=3$);

e_{i1}, b_{i1} – the costs and benefits of completing the process of connecting i-th land parcel unit to the green corridor (where b_{i1} is equal to 0);

e_{i2}, b_{i2} – the costs and benefits of achieving connectivity to the green corridor under current conditions;

e_{i3}, b_{i3} – the costs and benefits of alternative selection for achieving connectivity to the green corridor.

The results obtained from applying model (1)–(3) are presented below in Table 7.

Let it be noted that if the inclusion of a potential land unit into the green corridor is deemed unacceptable, its number is taken as zero.

The role of the digital environment factor in revealing the possibilities of sustainability of urbanization zones and their implementation is increasing [15]. Sustainable development of urbanization zones largely depends on mutual benefit relationships with suburban agriculture, including energy efficiency. The economic justification for the specialization of suburban agriculture in supplying the city with fresh food products in terms of economy and energy consumption is substantiated. However, research shows that large cities currently cannot supply fresh food products, mainly fresh vegetables, milk, and eggs, from their suburban agricultural territories. The suburb can play a unique role in the reuse of agricultural organic and energy waste, in the sustainable development of the urbanization zone.

The organization of green production in the profile of suburban areas can contribute to the sustainability of the urbanization zone. Digital twins are a very valuable tool for forecasting the future movement of cities, choosing projects that meet the goals of more efficient management of suburban parks, and so on, as well as improving urban planning in general. When it comes to creating digital twins of suburbs, it is recommended to use a system of simulation models for this purpose. Research conducted in the direction of creating digital twins of sustainable suburban areas suggests that in this case, it is necessary to take into account the factor of distance from the city.

The presence of a sustainable land use system and improvement of green infrastructure in the urbanization zone has a direct impact on air quality. An increase in the number of fine particles is a sign of air pollution. By attracting relevant data (Fig. 1) to intelligent analysis, it is determined whether the amount of fine particles in the air meets the permissible limit [16].

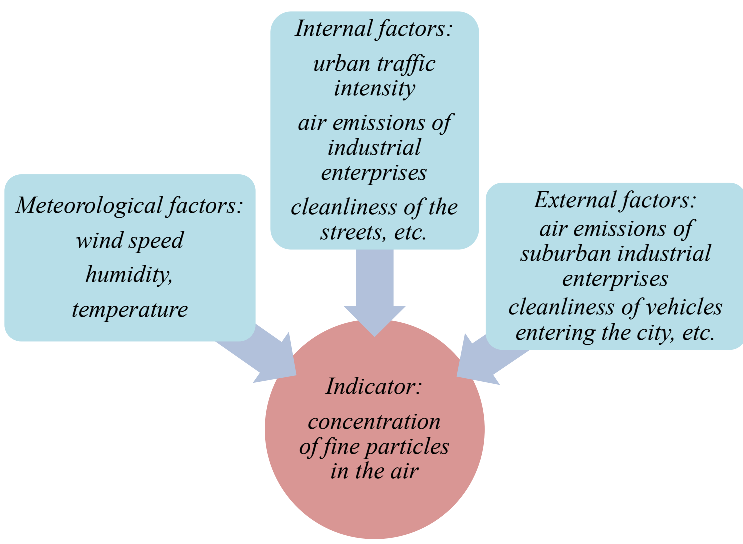

Fig. 1. Information base of the air pollution degree indicator in the digital twins of green infrastructure management in the urbanization zone

It is appropriate to compare the following two approaches to the application of digital technologies to identify opportunities for developing the city's green infrastructure in terms of the sustainability of urbanization zones [17]. The first approach involves using remotely obtained data on the city's green infrastructure through digital technologies to improve ecosystem services. The second approach can ensure that the data mentioned in the first approach can be used to assess the state of green corridors, the functional and ecological compatibility of plant species, their spatial position, and the improvement of ecosystem services. The second approach will fully leverage the benefits of the digital environment in developing green infrastructure.

5. Results of studying the strategic integration of digital technologies and green infrastructure in achieving tangible outcomes

5. 1. Analysis of the current condition of green infrastructure within urban areas and examination of its contribution to enhancing sustainability

To assess the level of sustainability in urbanization zones, it is recommended to characterize the following trends based on sustainability indicators: the process of population concentration in cities is accompanied by sustainable urban development; the increasing role of cities in all aspects of human life; industrial concentration of productive forces; complexity of functions in the computational network; integration of activities. Characteristics of green infrastructure development, including the level of development, should be linked to these indicators.

When studying the sustainability issues of urbanization zones, significant importance is given to sources that eliminate negative environmental consequences of urban and adjacent area development and meet the increased demand for resources through local resource potential. This approach brings up the issue of prioritizing local opportunities in the transition of cities and adjacent areas to a green economy.

There are other approaches. It is believed that to assess the opportunities for sustainable development of urbanization processes in the digital environment arising from economic feasibility, the following indicators can be used: agglomeration effect; minimization of movements as a special case, effects of joint financing; distribution effect [17].

To ensure inclusivity, safety, viability, and sustainability of cities in sustainable development goals, the following factors are primarily included (Table 1).

As demonstrated in the following resource, rapidly growing cities are often faced with choosing between various development options to ensure sustainability. This decision-making process rarely occurs as an isolated decision made by individual participants or institutions but, in most cases, involves national and local governance structures, investors, representatives from the private sector, as well as local communities and civil society organizations [18].

The research object chosen as the urbanization zone was the city of Baku and its surrounding territories encompassing the Absheron Peninsula. Baku, the capital of Azerbaijan, is the largest city in the Caucasus region. Approximately 40 % of the country's population and 70 % of its industrial potential are concentrated in the researched urbanization zone. Significant changes have occurred in the scale of Baku's green infrastructure over just one century. While in 1880, the city's green area was only 3 hectares, exactly one hundred years later, in 1980, it amounted to 9520 hectares [19].

The air quality in Baku city and its surrounding Absheron Peninsula can be considered satisfactory, especially on windy days and during precipitation. Measures are being taken to assess the situation through the registration of green areas in Baku. All green plantations within the city's administrative territory, including trees in parks, road verges, and backyard plots, are being registered. The process started at the end of 2022, and data on each tree are being entered into an electronic database.

Table 1

Goals and indicators of sustainable development of cities

Goal	Indicators
Safe and affordable housing	The share of urban population living in slums and informal settlements
Accessible and sustainable transportation system	The proportion of the population with convenient access to public transportation by gender, age, and disability status
Sustainable urbanization rates	Ratio of land use to population growth rates
Urban planning management	Proportion of cities with a structure of direct participation of civil society in urban planning and management
Protection of cultural and natural heritage	Total expenditure per capita on the preservation and maintenance of cultural and natural heritage by funding sources (governmental, private), heritage type (cultural, natural), and management level (national, regional, and local/municipal)
Reduction of negative consequences of natural disasters	Number of deaths, missing persons, and directly affected individuals from natural disasters per 100,000 population
Solid waste management	The proportion of solid household waste collected and disposed of in controlled areas in the total volume of household waste generated in cities
Air pollution in cities	Average annual levels of fine particles in cities
Vacancies in cities	The average proportion of areas open to public use for people by gender, age, and disability status in the built-up area of cities
Safe spaces in cities	Percentage of people with limited physical abilities in the past 12 months by gender, age, disability status, and location

Source: [18].

The data obtained will be used to evaluate the current state of the city's green infrastructure shortly. Baku's urbanization zone is adorned with approximately 150 types of decorative trees and shrubs, and their species composition enriches with each passing year [19].

Baku's Master Plan presented until 2040 and covering its entire administrative territory (212.3 thousand hectares), places significant emphasis on green infrastructure [18]. In two decades, it is planned that there will be 8 square meters of green space per capita in the capital. As an example of suburban green hybrid corridors, we can mention the "Hojahasen-Lokbatan Corridor" envisaged in Baku's Master Plan. In the northern part of Lake Hojahasen, located near Baku, oil extraction is planned to be stopped, territories cleaned, and the sewage system restored. Along the Green Hybrid Corridor, a new botanical park will be created, primarily cultivating local plant species.

5. 2. Integration of green hybrid corridors in a large city

As one of the main conceptual approaches to ensuring the sustainability of urbanization zones, green hybrid corridors should serve to provide free and high-quality air movement in the city, improve the microclimate, expand the infrastructure of pedestrian (bicycle) paths, and develop green infrastructure. Urban green infrastructure planning and optimization of green corridors can play an important role in improving the environment, protecting biodiversity, and, as a result, accelerating the transition to a green economy.

According to the master plan of Baku, by 2020 the area of public parks in the city will be 920 hectares, and the area of forests and planted trees – 615 hectares, a total of 1535 hectares. By 2040, it is planned to bring into common use 2535 hectares of green plantations. Currently, natural and open green areas, including public parks, forest parks, afforestation, and protected natural areas, occupy an area of about 11,830 hectares, which is 5.56 percent of the total project area. Within the framework of the master plan, it is planned to increase the share of natural greenery and open spaces in the total area to at least 10 % [19].

The parameters of the model for selecting the expansion of green corridors for the development of green infrastructure in Baku are as follows (Table 2). It should be noted that the expected level of existing expenditure per unit area of green infrastructure is assumed to be 1.

Here are the intervals intended for modeling the selection model of green corridors with various coefficient values in the objective function of the optimality model and constraint conditions (Table 3).

Table 2

Parameters of the model for selecting the expansion of green corridors in the city of Baku

The symbols and parameter names	Price
n –number of potential land parcels for creating a green corridor, units i=1, m (i – indicates the number of potential plots of land in terms of connecting to the green corridor)	100
j=1, n – number of options for selecting new land parcel objects to be connected to the green corridor, units	3
e_i – cost required to connect i-th unit of land area to the green corridor, coefficient	1
b_i – benefit from connecting i-th unit of land area to the green corridor, coefficient	1
e_{i1} – cost of discontinuing the process of connecting the i-th land parcel to the green corridor	0
b_{i1} – benefit of discontinuing the process of connecting the i-th land parcel to the green corridor	0
e_{i2} – cost of completing the green corridor in its current state	1
b_{i2} – benefit of completing the green corridor in its current state	1

Source: Parameters of the selection model were determined using sources [17, 18].

Table 3

Parameters of the selection model for optimizing the costs of connecting to the green corridor are intended to be modeled on intervals

The symbols and parameter names	Interval
P – required increase in benefit, coefficient	1.10–1.15
e_i – cost from connecting a unit area to the i-th green corridor	0.8–1.0
b_i – benefit from connecting a unit area to the i-th green corridor	1.00–1.10
e_{i3} – costs of the alternative option for connecting to the green corridor	0.3–0.5
b_{i3} – benefits of the alternative option for connecting to the green corridor	1.1–1.2

Source: The simulation limits on intervals were calculated by the authors based on interviews and surveys with experts.

Although there are different approaches to constructing modeling scenarios, it is considered feasible to determine the lower limit of the sizes of new green spaces in terms of the impact of green corridors on the microclimate. In our opinion, this approach can be considered acceptable in large cities with favorable natural and climatic conditions for creating green corridors. To enhance the effectiveness of green spaces on the microclimate of adjacent areas, green strips 75–100 meters wide should be created every 400–500 meters [19]. One concern here may be that these strips are isolated from each other.

Planning green infrastructure should take into account not only the area of green spaces but also their distribution across the urban territory, ensuring an even coverage of green zones. This helps create more comfortable living conditions for residents by reducing the urban heat island effect and improving air quality. The use of simulation models to optimize the location of green corridors allows for forecasting their impact on the urban climate and assessing their efficiency in terms of both costs and environmental benefits.

One of the key aspects is the economic component of the project. Cost optimization for the creation and maintenance of green corridors, including expenses for tree planting, irrigation infrastructure, and maintenance, as well as the organization of pedestrian areas, requires careful assessment. It is crucial to use models that consider not only direct costs but also long-term benefits such as improved environmental quality and reduced healthcare expenses due to better public health conditions.

5. 3. Implementation of the cost optimization model for green corridor zones in Baku

According to the World Health Organization's recommendation, in urban conditions, for climatic purposes, it is considered appropriate for the minimum width of green corridors to be 50 meters, and ideally more than 300 meters [19]. Baku, green spaces with a cross-section of green corridors of at least 15–20 meters can be created. These open spaces should provide access to rural areas and cultural landscapes. The indicated open spaces should be created within the railway line.

Based on the results of land and road studies in Baku [20] and considering the above, the lower limit for modeling the sizes of areas to be included in green corridors was adopted as follows (Table 4).

Table 4

Parameters for modeling the expansion of green corridors, and a model for optimizing green infrastructure costs in Baku

Costs and benefits	Additional areas to green corridors (D), sq.m.		
	≥500	≥1,000	≥1,500
P	1.1	1.15	1.2
e_{i3}	0.15	0.20	0.25
b_{i3}	1.1	1.2	1.3
b_i	0.75	0.85	0.90

Source: Calculated by the authors using sources [18–20], interviews and survey materials with experts.

In the city's green infrastructure, the selection of plant composition is a crucial issue when integrating old and new green spaces. In the creation of green corridors, both local and imported trees and plants, as well as their mixed composition, are used.

The cost structure for connecting green corridors in the capital, including the cost, composition of objects, and the work performed, is as follows (Table 5).

The numerical data on the prices for the implementation of decorative and other tree seedlings are taken from sources [18], and the General Plan of Baku for 2040 [19]. As stated in the explanatory text of the mentioned General Plan, in Baku, "The costs for constructing 1 hectare of territorial zones for the development of parks and open spaces/landscape zones may vary within the range of 4.98–8.99 million manats" [19]. The average cost of these expenses is estimated at 7.00 million manats" [18] (Table 6).

Table 5

Costs for connecting additional areas to green corridors, per 1 sq. meter in manats (at the time the data was obtained, 1 Azerbaijani manat was equal to 0.5882 USD. This rate remains unchanged at present

Plant composition of green corridors	Local trees and plants		Imported trees and plants		Mixed composition	
	Upper limit	Lower limit	Upper limit	Lower limit	Upper limit	Lower limit
Assessment of the area, landscaping project design, selection of suitable plants	26 (15.3)	30 (17.6)	46 (27.1)	57 (33.5)	37 (21.8)	42 (24.7)
Clearing of land plots and water bodies	188 (110.6)	315 (185.3)	229 (134.7)	313 (184.1)	201 (118.2)	296 (174.1)
Garbage collection from the area and clearing of undamaged vegetation	14 (8.2)	17 (10)	14 (8.2)	17 (10)	14 (8.2)	17 (10)
Delivery of fertile soil	27 (15.9)	40 (23.5)	82 (48.2)	90 (52.9)	39 (23.6)	106 (62.3)
Construction of communications	40 (23.5)	50 (29.4)	75 (44.1)	75 (44.1)	58 (34.1)	65 (38.2)
Installation of irrigation systems and equipment	35 (20.6)	70 (41.2)	35 (20.6)	75 (44.1)	38 (22.4)	68 (40)
Organization of security for green areas, care for existing trees, shrubs, and grass	18 (10.6)	23 (13.5)	23 (13.5)	23 (13.5)	23 (13.5)	23 (13.5)
Laying pathways, construction of benches	56 (32.9)	56 (32.9)	56 (32.9)	56 (32.9)	56 (32.9)	56 (32.9)
Planting of trees and plants	6 (3.5)	10 (5.9)	9 (5.3)	12 (7)	8 (4.7)	11 (6.5)
Laying lawns, shaping them appropriately	24 (14.1)	28 (16.5)	27 (15.9)	36 (21.2)	25 (14.7)	33 (19.4)
Care until completion	70 (41.2)	100 (58.9)	104 (61.2)	129 (75.9)	103 (60.6)	140 (82.4)
Normative interval	498 (292.9)	899 (528.8)	498 (292.9)	899 (528.8)	498 (292.9)	899 (528.8)
Total actual costs	498 (292.9)	732 (430.6)	694 (408.2)	871 (512.3)	596 (350.6)	853 (501.7)

Source: Calculated by the authors using sources [18, 20], interviews, and survey materials with experts.

Table 6

Relative weight of future works in the cost of connecting additional areas to green corridors, %

Future works \ Plant composition of green corridors	Local trees and plants		Imported trees and plants		Mixed composition	
	Upper limit	Lower limit	Upper limit	Upper limit	Lower limit	Upper limit
Assessment of the area, landscaping project design, selection of suitable plants	5.2	4.1	6.6	6.5	6.2	4.9
Clearing of land plots and water bodies	37.8	43.0	33.0	35.9	33.7	34.7
Garbage collection from the area and clearing of Undamaged vegetation	2.8	2.3	2.0	2.0	2.3	2.0
Delivery of fertile soil	5.4	5.5	11.8	10.3	6.5	12.4
Construction of communications	8.0	6.8	10.8	8.6	9.7	7.6
Installation of irrigation systems and equipment	7.0	9.6	5.0	8.6	6.4	8.0
Organization of security for green areas, care for existing trees, shrubs, and grass	3.6	3.1	3.3	2.6	3.9	2.7
Laying pathways, construction of benches	11.2	7.7	8.1	6.4	9.3	6.6
Planting of trees and plants	1.2	1.4	1.3	1.4	1.3	1.3
Laying lawns, shaping them appropriately	4.8	3.8	3.9	4.1	4.2	3.9
Care until completion	14.1	13.7	15.0	14.8	17.3	16.4
Normative interval	100	100	100	100	100	100
Total actual costs	498	732	694	871	596	853

Source: Calculated based on the data of Table 5.
Note: Minor errors are associated with rounding numbers.

In connecting green corridors in urbanized areas, the habitat conditions for decorative trees and shrubs, introduced from outside and having a significant place in the city's green infrastructure, should be optimized. In addition to socio-economic (and energy) factors, special attention should be paid to the selection factor in this process. According to experts, scientific selection work should be considered together with the results of public selection. The use of indigenous plants in hybrid green corridors is economically viable and helps protect plants [16].

According to experts, the natural-climatic conditions of Baku and its adjacent territories are not so favorable for the appearance of mixed greenery on limited land [20]. Alternating hybrid green corridors with different types of buildings and objects allows this fact not to hinder biodiversity. At the same time, observations show that the construction of mixed-content green corridors regularly requires unforeseen expenses.

The coefficients in the constraint conditions (1)–(3) of the proposed optimality model were modeled within the intervals described above. In machine experiments on optimizing costs for connecting hybrid green corridors in the city of Baku for the years 2026–2028, the following results were obtained regarding the woody-plant composition and field characteristics (Table 7).

Table 7

Results of implementing the selection model for optimizing costs in the green corridor areas in the city of Baku in 2026–2028 (expected level of current expenses assumed to be 1)

Plant composition of green corridors	Additional areas to green corridors (D), sq.m.				
	≥500	≥1,000	≥1,500	≥2,500	≥5,000
Local trees and plants	0.711	0.676	0.649	0.651	0.668
Imported trees and plants	1.137	1.126	1.113	1.164	1.251
Mixed composition	0.876	0.869	0.880	0.853	0.819

Source: The selection model (1)–(3) was calculated by solving the optimality problem by simulating on intervals.

Costs for hybrid green corridors created from imported trees and plants are much higher than those for corridors with local trees and plants.

6. Discussion of the experimental results related to improving sustainable urban areas through the integration of digital green infrastructure

The results of this study can be explained through the effective integration of optimization and simulation models, which together provide a comprehensive framework for enhancing urban sustainability via green corridors (Fig. 1). The optimization model (1)–(3) identifies the best strategies for developing green infrastructure by considering factors such as budget constraints, resource availability, and community needs. Meanwhile, the simulation model allows for a dynamic analysis of how various components of green infrastructure interact with each other and the environment (Tables 6, 7). This dual approach not only highlights the importance of green corridors but also demonstrates their significant benefits in mitigating the negative impacts of urbanization.

One of the key features of the proposed solutions is their emphasis on local flora in establishing green corridors. By demonstrating that using native trees and plants leads to reduced costs and increased effectiveness in maintaining these green spaces, the study highlights the practical advantages of this approach. This stands in contrast to similar studies that may overlook the specificity of local biodiversity, thus providing a unique perspective on green infrastructure development. Additionally, this research surpasses existing literature by focusing on integrating the digital environment in managing urban and suburban green infrastructure, an underexplored area.

The solutions proposed in this study effectively address the problematic aspects by demonstrating that a comprehensive understanding of urban and suburban ecological interconnections is vital for sustainable urbanization. The joint digital modeling of urban and suburban areas fosters a holistic view, enabling urban planners to make informed decisions regarding green infrastructure development. This synergy is critical for creating sustainable urban environments that can withstand the pressures of urbanization.

However, several limitations must be acknowledged. The study's reliance on expert opinions, which can vary widely and may lack practical case studies, poses challenges in the accuracy of the results. Moreover, methodological limitations arise from incomplete data specific to Azerbaijan, which could impact the generalizability of the findings. Future research should prioritize gathering more detailed and extensive datasets to strengthen the validity of the results.

The study also presents opportunities for further research, particularly in developing digital twins of green infrastructure. This approach would allow for the simulation of various management scenarios and their impacts on urban sustainability, thereby enhancing decision-making processes in real-time. By exploring the relationship between the digital environment and suburban green infrastructure, future studies can provide deeper insights into energy efficiency and sustainable development practices.

In conclusion, this research underscores the vital role of green corridors in enhancing the sustainability of urbanization zones, particularly when integrated with digital tools. By addressing the limitations and identifying avenues for further exploration, the study paves the way for advancing the discourse on sustainable urban environments.

7. Conclusions

1. The current state of green infrastructure in urban areas and its contribution to sustainable development has been examined. The focus is on qualitative indicators such as air purification, noise reduction, and public health improvement. Quantitative parameters, including the costs of integrating green infrastructure elements, are also considered. Digital tools, such as simulation models, are used to select optimal solutions for planning green corridors in large cities. As a result, the implementation of green infrastructure enhances the sustainability of the urban environment while minimizing financial costs.

2. Based on existing data, the role of green corridors and other ecological elements in the sustainable development of cities has been assessed, using both qualitative and quantitative indicators. For the selection and expansion of green corridors in cities, it is necessary to consider various parameters such as available land area, current environmental indicators (e.g., pollution levels), population density, traffic flows, and more. These parameters help make informed decisions on which areas require priority integration.

3. To enhance urban sustainability for the years 2026–2028, a selection model was developed and implemented to optimize costs for green corridor zones in a large city. This model takes into account multiple factors, including economic efficiency, environmental indicators, and the integration of digital tools for managing and monitoring green infrastructure. The model is aimed at reducing expenses associated with the creation and maintenance of green areas by selecting the most efficient greening solutions. For example, it identifies optimal tree planting locations to achieve maximum air quality improvement at minimal care and maintenance costs. Digital tools, such as simulation models, are used to evaluate the effectiveness of various greening scenarios.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

Financing

The study was performed without financial support.

Data availability

Data will be made available on reasonable request.

Use of artificial intelligence

The authors have used artificial intelligence technologies within acceptable limits to provide their own verified data, which is described in the research methodology section.

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