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Green Technologies in Smart Cities

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Abstract: Modern cities are faced with the need to adapt to environmental and social challenges caused by accelerated urbanization and man-made impacts on the environment. The use of green technologies in the structure of smart cities creates conditions for the sustainable functioning of urban infrastructure and helps to reduce anthropogenic load. The article discusses approaches to greening the urban environment through technological solutions, the integration of digital management systems with resource-saving principles, as well as examples of the implementation of such initiatives in global and Russian megacities. The study identifies areas in which technological progress can transform the urban development model towards sustainability, environmental responsibility and energy efficiency. The participation of the population and the private sector, as well as the importance of a multidisciplinary approach in the process of implementing green practices, are analyzed. It is shown how the combination of technological innovations and environmental strategies can become a factor in a qualitative change in the urban environment and a prerequisite for the formation of new forms of urban governance.

1 INTRODUCTION

Growing urbanization, accompanied by an increase in population density and resource consumption, gives rise to many problems that directly affect the sustainability of the urban environment. At the same time, traditional methods of organizing urban infrastructure are no longer effective in the context of increased anthropogenic pressure. Along with this, the international scientific agenda is increasingly interested in finding models of spatial and functional urban development that would allow maintaining a balance between technological progress and environmental sustainability (Casini , 2017).

The emergence of the "smart city" concept was a response to the need to rethink the principles of urban development. It involves the use of digital systems aimed at improving the efficiency of city services, resource management and improving the quality of life. However, digitalization alone is not capable of ensuring the environmental safety of the urban environment. There is a need to rethink the technological content of urban transformation, where the idea of implementing green solutions occupies a significant place (Ramli , 2024).

Modern urban approaches are increasingly focused on integrating environmentally sound technologies into architecture, energy, and transport. These solutions are developed taking into account long-term effects and are aimed at reducing the carbon footprint, optimizing the use of natural resources, and creating a favorable living environment (Srivastava , 2022). Smart cities that apply green design principles are becoming spaces where digital innovation and environmental guidelines form a single field of urban development.

This study aims to analyze the mechanisms of implementation of green technologies in smart urban infrastructure, study the trends associated with their distribution, and identify the factors that determine the effectiveness of the ecological transformation of the urban environment.

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2 METHODS

The study used theoretical analysis methods aimed at identifying the essential characteristics of green technologies in the structure of smart cities. Particular attention was paid to the interpretation of scientific sources published over the past five years, which made it possible to establish current directions for the development of the topic under study. A comparative analysis of international and domestic practices made it possible to trace the differences in approaches to the formation of a sustainable urban environment and to determine the factors influencing the degree of integration of environmentally oriented solutions into the infrastructure of modern cities.

When studying the empirical material, elements of retrospective analysis and a structural-functional approach were used, which made it possible to identify the relationship between the level of digitalization of management and the degree of dissemination of green initiatives in individual urbanized areas. Strategic documents and reports on the implementation of sustainable development programs in megacities with varying degrees of technological maturity were analyzed. Comparison of quantitative and qualitative characteristics made it possible to substantiate conclusions about the prospects for the further dissemination of green technologies in the context of accelerating digital transformation of the urban environment.

3 RESEARCH RESULTS

Modern cities, faced with environmental and social challenges, are looking for ways of sustainable development based on technological solutions aimed at reducing anthropogenic load and improving the quality of life (Nikolov , 2024). One of the most promising areas of transformation of urbanized spaces has become green technologies, systematically integrated into the concept of a smart city. In Russia and, in particular, in Moscow, this process is taking on specific outlines, which allows us to talk about the beginning of the formation of a new type of digital urbanism ecosystem.

Moscow has demonstrated significant progress in the application of environmentally friendly solutions in recent years. The city is actively developing “green” infrastructure, combining digitalization with ecological design. One of the key areas has become the installation of solar panels at city infrastructure facilities. According to the Moscow Department of Housing and Public Utilities, by 2024 the total number of municipal facilities with photovoltaic installations reached 250 units, including schools, administrative buildings and electric vehicle charging stations. These measures are aimed at reducing dependence on traditional energy sources and partially covering electricity needs with renewable resources (Belov, 2023).

The number of objects with solar panels in Moscow is presented in Table 1.

Table 1: Number of objects with solar panels in Moscow.

Year	Quantity objects
2020	48
2021	96
2022	150
2023	200
2024	250

There has been a steady increase in the number of solar powered buildings, indicating the progressive institutionalization of sustainability principles in urban policy.

As the number of such facilities increases, the city is introducing intelligent energy management systems. For example, the Skolkovo Park residential complex uses a system that allows for lighting and heating to be regulated based on weather data and occupancy. Such solutions reduce energy consumption by 15-20 % without compromising user comfort (Belov, 2023).

Along with energy modernization, the vertical gardening direction is developing. In Moscow, "green wall" projects have been implemented on the facades of buildings, including transport infrastructure facilities. Experimental areas with an automatic irrigation and microclimate monitoring system were installed on the facades of MCC stations and some shopping centers. This practice reduces dust levels, increases air humidity and improves the thermal insulation properties of buildings. According to research results, the temperature on the wall surface in summer is on average 4°C lower than on similar non-green facades (Makarov, 2023).

Comparison of facade temperatures in Moscow, summer 2023 is presented in Table 2.

Table 2: Comparison of facade temperatures in Moscow, summer 2023.

Type facade	Average temperature , °C
Ordinary facade	34.1
Vertically greened	29.9

Reducing the temperature of the facades helps to reduce the thermal load on the building and reduces energy consumption for air conditioning.

Against the background of increasing summer periods and the frequency of temperature peaks, green facades demonstrate the ability to stabilize the thermal regime both at the level of individual buildings and within local areas of urban development. This effect becomes especially noticeable in dense urban environments, where heat accumulation leads to the formation of microclimatic anomalies. The temperature buffer effect created by the vegetation layer reduces the need to use climate control systems during the daytime, especially with southern and western orientation of facades. In the long term, such measures help to reduce operating costs and form architecture that is more resistant to overheating (Chernykh, 2023).

In the field of waste management, the capital is implementing zero-waste principles . At the beginning of 2024, there were more than 9,000 separate waste collection points in the city, including specialized collection points for batteries, electronics, and clothing. According to the Mospriroda report , the level of household waste recycling increased from 8% in 2019 to 24% in 2023. Success has been achieved thanks to the introduction of digital waste accounting platforms, incentives for market participants, and environmental education of the population (Makarov, 2023).

The share of recycled waste in Moscow is presented in Table 3.

Table 3: Share of recycled waste in Moscow.

Year	Share processing (%)
2019	8
2020	12
2021	17
2022	21
2023	24

The increase in the share of recycling indicates the systemic nature of the reform of the waste management sector and the intensification of the work of both public and private organizations in this area.

Moscow's experience shows that the effectiveness of implementing green technologies largely depends on the synchronous interaction between various sectors of management, business and the population. One example of such interaction is the Green Office project, within the framework of which more than 300 Moscow companies have implemented energy and resource-saving practices in office buildings, including the transition to LED lighting, ventilation automation and the use of recyclable materials. The results of the program are recorded on a digital platform, which allows monitoring the dynamics and developing new incentive measures.

At the federal level, similar projects are being implemented in Kazan, Yekaterinburg, St. Petersburg and other cities. For example, in Kazan, a smart lighting complex based on solar panels and motion sensors operates, which has reduced energy consumption by 30% in residential areas. St. Petersburg is implementing projects to restore reservoirs using IoT to monitor water composition, and in Sochi, “green roof” systems with modular landscaping are being tested, providing additional thermal insulation (Chernykh, 2023).

Kazan is actively implementing a smart street lighting system based on solar panels and motion sensors. As a result of the implementation, according to the mayor's office, in 2023, energy consumption of street lighting in a number of residential areas decreased by 30%. Management is carried out centrally through a city platform, which allows for prompt monitoring of faults and optimization of the network. Solar-powered lighting is also used in park areas and on bicycle routes (Chernykh, 2023).

St. Petersburg is implementing digital water monitoring projects. In 2022, a program was launched to install IoT sensors in rivers and canals to monitor pollution levels, oxygen content, and water temperature. The system collects data in real time and transmits it to a single environmental monitoring center. This allows for timely detection of violations and response to deterioration of the aquatic environment. The program is being implemented with the participation of local universities and environmental NGOs (Voronkov, 2023).

The technology of "green roofs" with modular landscaping is being tested in Sochi on a number of public buildings and hotel complexes. During the experiments in 2023, a reduction in the cost of air conditioning of premises by up to 18% in the summer was recorded, as well as an improvement in water drainage during heavy rains. Research conducted jointly with the Southern Federal University confirmed a positive impact on the microclimate in areas with dense development (Chernykh, 2023).

The reduction in energy consumption of street lighting in Kazan (residential areas) is presented in Table 4.

Table 4: Reduction of energy consumption of street lighting in Kazan (residential areas).

Year	Decrease consumption (%)
2020	—
2021	10
2022	22
2023	30

By introducing solar panels and touch control, it was possible to achieve a consistent reduction in energy costs.

The results of implementing these technologies are reflected not only in energy consumption statistics, but also in changing the approach to managing urban infrastructure. The daily operation of street lighting becomes predictable and controllable through automation, and the burden on municipal budgets is reduced in the long term (Burmatova , 2021). At the same time, a new model of resource planning is being formed, in which energy saving is considered a measurable result of digital modernization. A system focused on self-regulation and adaptation to external conditions allows you to build maintenance algorithms based on actual data, rather than formal standards.

The impact of green roofs on the microclimate of buildings in Sochi is presented in Table 5.

Table 5: Impact of green roofs on the microclimate of buildings in Sochi.

Indicator	Normal roof	Green roof
Temperature surfaces in summer (°C)	48.3	35.6
Peak load on air conditioners	100%	82%
Volume of water discharge during heavy rainfall (l/m²)	100	63

Green roofs have a stabilizing effect on the temperature regime of buildings and reduce the load on the city's stormwater system.

Global experience also confirms the high efficiency of combining green technologies and digital solutions. For example, Singapore has an automated waste collection system using underground pipes, and Tokyo uses a system of adaptive street lighting depending on the density of pedestrian traffic. Amsterdam is developing a network of ecological logistics hubs that eliminate the use of internal combustion engine vehicles in the central part of the city (Zheming , 2023).

These models, tested in urbanized spaces with a high technological level, demonstrate a stable tendency to reduce the impact on the environment while simultaneously increasing the efficiency of urban infrastructure. Institutional support in the form of environmental regulation, tax incentives and integrated urban planning allows these practices to be consolidated as a structural part of urban policy.

The vacuum waste removal system implemented in Singapore operates on a closed pipeline network, eliminating the need for ground-based equipment and significantly reducing emissions. This scheme not only optimizes waste management logistics but also reduces air pollution in residential areas. The integration of this system with digital platforms ensures continuous monitoring of the network load and prevents overloads.

Tokyo's adaptive lighting model is based on collecting data from motion sensors installed along pedestrian areas. It allows for the lighting level to be adjusted depending on the traffic intensity, time of day, and weather conditions. This not only reduces energy consumption, but also reduces light pollution, helping to restore the natural rhythm of the urban landscape.

In Amsterdam, the approach to organizing logistics flows is based on the concept of the “green last kilometer.” Special hubs near the city center receive goods, which are then delivered to their destinations by electric bicycles or on foot. This mechanism has reduced the use of traditional vehicles by 40% in the historic center, while improving both air quality and conditions for pedestrians (Zheming , 2023).

At the same time, as a comparative analysis shows, Moscow is demonstrating positive dynamics and has the potential for development in the direction of a green smart city, especially given the expansion of inter-municipal exchange of practices and the activation of mechanisms for public participation in environmental design.

It should be noted that sustainable urban development is impossible without technological transformation, combining digital and nature-oriented solutions. The use of green technologies in Moscow is already bringing concrete results, expressed in resource savings, improved microclimate and increased quality of the urban environment. However, to consolidate these trends, support is needed at the level of regional strategies, as well as the institutionalization of feedback

mechanisms between citizens and government bodies.

4 CONCLUSION

The implementation of green technologies in urban infrastructure confirms its practical effectiveness both at the level of individual objects and on the scale of entire megacities. Analysis of the dynamics of energy saving, waste recycling and climate stabilization indicators indicates a transformation of established models of urban management. This transformation involves a shift from a reactive approach to environmental threats towards the active formation of an environment that is resistant to external loads and focused on long-term results.

Trends recorded in Moscow, Kazan, Sochi and other cities indicate that the synthesis of digital and environmental solutions is becoming the basis of a new paradigm of urban development. The success of such projects depends on the ability of urban systems to adapt to changing conditions and on the degree of involvement of institutions, businesses and citizens in the transformation process. Prospects depend not on isolated initiatives, but on the formation of a comprehensive architecture of interaction, in which green technologies are perceived not as a temporary measure, but as a structural element of the future city.

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