GREEN SOLUTIONS FOR SUSTAINABLE CITIES

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Abstract. Accelerated urbanization and climate change are two of the most pressing challenges of the 21st century. In this context, the development of sustainable cities, which provide a healthy living environment while minimizing environmental impact, has become a global priority. Sustainable urban development involves integrating innovative solutions into infrastructure, mobility, energy, and resource management. Cities must prioritize energy efficiency through the use of renewable sources, adopt circular economies that reduce waste, and create green spaces to improve quality of life. Technology also plays a key role through the implementation of smart cities, where transport systems, buildings, and utilities are connected and optimize resource consumption. This article aims to explore various visions and innovative solutions for creating green and sustainable cities. Various approaches and innovative solutions for sustainable urban development are analyzed in the context of current climate and demographic challenges. Several challenges and perspectives that guide modern urban planning and management are described, with a focus on integrating natural elements, energy efficiency, and sustainable mobility. The article highlights the importance of a holistic and interdisciplinary approach in creating sustainable, resilient, and viable cities in the long term.

Keywords: urbanization, environment, biophilic city, circular city, sustainable solutions.

Rezumat. Soluții verzi pentru orașe sustenabile. Urbanizarea accelerată și schimbările climatice reprezintă două dintre cele mai presante provocări ale secolului XXI. În acest context, dezvoltarea unor orașe sustenabile, care să ofere un mediu de viață sănătos și să minimizeze impactul asupra mediului, devine o prioritate globală. Dezvoltarea urbană sustenabilă presupune integrarea unor soluții inovative în infrastructură, mobilitate, energie și managementul resurselor. Orașele trebuie să prioritizeze eficiența energetică prin utilizarea surselor regenerabile, să adopte economii circulare care reduc risipa și să creeze spații verzi pentru îmbunătățirea calității vieții. Tehnologia joacă, de asemenea, un rol cheie, prin implementarea orașelor inteligente, unde sistemele de transport, clădirile și utilitățile sunt conectate și optimizează consumul resurselor. Acest articol își propune să exploreze diverse viziuni și soluții inovatoare pentru crearea unor orașe verzi și durabile. Sunt analizate diverse abordări și soluții inovatoare pentru dezvoltarea urbană sustenabilă, în contextul provocărilor climatice și demografice actuale. Sunt descrise mai multe provocări și perspective care ghidează planificarea și managementul urban modern, cu accent pe integrarea elementelor naturale, eficiența energetică și mobilitatea sustenabilă. Articolul evidențiază importanța unei abordări holistice și interdisciplinare în crearea unor orașe sustenabile, reziliente și viabile pe termen lung.

Cuvinte cheie: urbanizare, mediu, oraș biofil, oraș circular, soluții sustenabile.

INTRODUCTION

Accelerated urbanization is one of the most significant global trends of the 21st century. According to the United Nations, by 2050, approximately 68% of the world's population will live in urban areas (***. UNITED NATIONS, 2019). This exponential growth in the urban population, coupled with the challenges posed by climate change, places enormous pressure on urban infrastructure, resources, and ecosystems.

In this context, the traditional urban development paradigm, based on intensive resource consumption and territorial expansion, proves to be unsustainable. Rees and Wackernagel introduced the concept of the "ecological footprint" to quantify the urban impact on the environment, demonstrating that modern cities consume resources and generate waste far beyond the carrying capacity of local ecosystems (REES & WACKERNAGEL, 1996).

Climate change exacerbates urban vulnerabilities, exposing cities to increased risks of floods, heatwaves, and other extreme events. The Intergovernmental Panel on Climate Change (IPCC) emphasizes the urgent need for urban-level adaptation and mitigation measures to reduce these risks (***. IPCC, 2022).

In this context, sustainable cities play a crucial role in the transition towards a greener and more resilient future. The concept of the "sustainable city" has significantly evolved in recent decades, from an initial focus on environmental aspects to a holistic approach that integrates the ecological, economic, and social dimensions of sustainability. Newman and Jennings define the sustainable city as "an urban system that enhances the well-being of citizens and local, regional, and global ecosystems over the long term" (NEWMAN & JENNINGS, 2008).

This integrated vision is also reflected in the United Nations' Sustainable Development Goals, particularly Goal 11: "Sustainable Cities and Communities," which emphasizes the importance of creating inclusive, safe, resilient, and sustainable human settlements (***. UNITED NATIONS, 2015).

In the search for solutions to create long-term viable cities, diverse perspectives and innovative approaches have emerged in the recent years. These visions, ranging from Edward O. Wilson's "biophilic city" concept (WILSON, 1994) to the "circular city" idea promoted by the Ellen MacArthur Foundation (***. ELLEN MACARTHUR FOUNDATION, 2017), offer conceptual frameworks and practical strategies for reconciling urban development with ecological imperatives.

Technology plays a crucial role in this urban transformation. The "smart city" concept (GIFFINGER et al., 2007) proposes the use of information and communication technologies to optimize urban services and improve quality of life. However, Kitchin warns of the need to critically and ethically approach the implementation of these technologies to avoid exacerbating social inequalities and privacy issues (KITCHIN, 2014).

Against this complex and multifaceted background, this article aims to explore various innovative visions and solutions for creating green and sustainable cities. Through a critical analysis of different approaches and the presentation of relevant case studies, the article seeks to provide an integrated perspective on transforming urban environments into resilient, efficient, and nature-harmonious systems.

MATERIALS AND METHODS

To identify the most effective green solutions for sustainable cities, the following research methods were used:

a. Documentation and bibliographic analysis. A detailed analysis of specialized literature was conducted, including previous studies, reports, articles, and books, to identify proposed solutions and models already applied in different cities. Data from official sources, international organizations, and academic articles were also consulted.

b. Case study by analysing representative cities that have successfully implemented pollution reduction measures, such as Copenhagen, Curitiba, and Singapore. The specific strategies adopted and their impact on the environment and urban quality of life were examined. The models implemented in these urban communities were described, focusing on pollution reduction and identifying green solutions for sustainable cities.

c. A simulation method for creating a model sustainable city, using a multidisciplinary approach that integrates economic, social, environmental, and technological variables to model an optimal city in terms of sustainability and resilience.

d. Comparative analysis to review the different solutions implemented in the three mentioned cities, aiming to identify the most efficient and sustainable models compared to the benchmark sustainable city.

These varied methods ensure a comprehensive perspective on pollution reduction solutions and ways to create sustainable cities, with an emphasis on the interaction between technology, public policies, and community involvement.

To transform cities into pollution-free, resilient, and sustainable spaces, the use of innovative and eco-friendly materials is essential. These materials not only reduce the environmental impact but also increase energy efficiency and the resilience of cities to climate challenges. Essential materials for achieving these objectives include:

1. Eco-friendly construction materials

Low-carbon concrete. Produced through methods that reduce CO2 emissions, eco-friendly concrete uses industrial waste (slag, fly ash) to replace traditional materials, thereby minimizing environmental impact.

Cross-laminated timber (CLT). This durable, lightweight, and renewable material is an alternative to concrete and steel. It is strong and capable of supporting tall buildings while also helping capture carbon dioxide from the atmosphere.

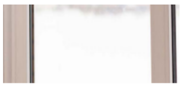
Bricks made from biomass or recycled materials. Bricks made from biodegradable or recycled materials (recycled plastic, glass, etc.) reduce waste and CO2 emissions associated with traditional brick production.

2. Materials for insulation and energy efficiency

Sheep wool and hemp. These natural, biodegradable materials are effective for thermal and sound insulation, reducing the need for energy for heating and cooling.

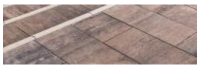
Recycled cellulose insulation foam. Made from recycled newspapers and paper, this insulation has low environmental impact and provides high thermal performance.

Thermal insulating and low-emissivity (low-e) windows. These energy-efficient windows reduce heat loss and minimize the need for air conditioning, contributing to lower energy consumption in buildings.



3. Materials for efficient water management

Permeable pavements. These allow rainwater to infiltrate the soil, reducing the risk of urban flooding and supporting groundwater recharge.



Water tanks made from recyclable materials. Used to capture and reuse rainwater for irrigation or non-potable purposes, these tanks are essential for reducing water consumption in cities.

4. Materials for green mobility and infrastructure

Recycled asphalt and alternative mixtures: Made from recycled materials (e.g., used tires), sustainable asphalt helps reduce waste and emissions in transport infrastructure.

Natural plants for green roofs and facades: vegetation helps with thermal insulation, air purification and increases urban biodiversity while reducing pollution.

5. Materials for renewable energy

Organic solar panels: Made from bio-compatible materials, these flexible solar panels are lightweight and less expensive than silicon-based panels.

Graphene batteries and advanced compounds: These batteries store renewable energy for long periods, supporting urban infrastructure in transitioning to clean energy sources.

6. Materials for the circular economy and waste management

Biodegradable plastic or plant-based plastic (bioplastic). Biodegradable plastic is used to reduce plastic waste, supporting the circular economy.

Composite made from recycled waste. Composites made from plastic and natural fibers (e.g., agricultural waste) are used in construction and for urban furniture, reducing both waste and carbon emissions.

7. Materials for innovative solutions and digitalization

Smart sensors and materials. These materials are integrated into urban infrastructure to monitor real-time energy consumption, water usage, and environmental conditions. IoT (Internet of Things) sensors enable the optimization of resource usage.

Self-repairing construction materials. Materials like self-healing concrete use bacteria that automatically seal cracks, extending the life of infrastructure and reducing maintenance costs.

8. Materials for climate resilience and safety

Climate-resistant membranes and coatings. These are used to protect buildings and infrastructure from floods, fires, and storms.

Tempered glass and fire-resistant materials. To protect buildings in case of fire or extreme weather conditions, fireproof materials and tempered glass are used.

The use of these innovative and sustainable materials can transform cities into green and resilient spaces, reducing the carbon footprint and increasing energy efficiency. These materials, integrated into eco-friendly infrastructure and urban development policies, will create safe, healthy, and future-ready cities.

RESULTS AND DISCUSSIONS

Sustainable urban development is a concept that has rapidly evolved over the past decades, proposing innovative solutions to address the challenges posed by accelerated urbanization and climate change. In this context, three main models dominate future visions: biophilic cities, circular cities, and smart cities. Each of these offers a unique perspective, focusing on harmonizing the relationship between people, nature, and technology to build a resilient and eco-friendly urban future.

Biophilic city. The concept of the "biophilic city" has its roots in the biophilia hypothesis formulated by Edward O. Wilson, which argues that humans have an innate affinity for nature and other forms of life (WILSON, 1994). The application of this idea in the urban context was further developed by researchers such as Timothy Beatley, who defines the biophilic city as "a city that incorporates natural systems into its urban structure and nurtures (rather than erodes) residents' close contact with nature" (BEATLEY, 2011).

The theoretical foundation of a biophilic city is based on extensive research demonstrating the multiple benefits of integrating nature into the urban environment:

a. Benefits for physical and mental health. Some studies have shown that exposure to nature in urban settings can reduce stress, improve recovery from illness, and enhance overall well-being (ULRICH et al., 1991). Kaplan highlights the ability of natural environments to restore attention and combat mental fatigue (KAPLAN, 1995).

b. Improving the quality of the urban environment. Research in this field highlights the crucial role of urban vegetation in improving air quality, reducing the urban heat island effect, and managing stormwater (NOWAK et al., 2014).

c. Promoting biodiversity. A biophilic city emphasizes creating habitats for various species within the urban environment. Relevant studies demonstrate the potential of cities to support significant biodiversity through appropriate design and management (ARONSON et al., 2014).

The implementation of the biophilic city concept involves a series of strategies and innovative solutions:

a) Creating extensive and interconnected green spaces. This includes the development of urban parks, ecological corridors, and "urban forests." Forman proposes the concept of an "urban green matrix" to describe an interconnected network of green spaces throughout the city (FORMAN, 2014).

b) Using green facades and roofs. These solutions not only improve the energy performance of buildings, but also provide habitats for various species. Comprehensive analyses have been conducted on the ecological benefits of green roofs (OBERNDORFER et al., 2007).

c) Integrating natural elements into urban infrastructure. This can include solutions such as "green streets," bio-retention systems, and rain gardens. Echols and Pennypacker explored the aesthetic and functional potential of these approaches in stormwater management (ECHOLS & PENNYPACKER, 2015).

d) Promoting urban biodiversity. Strategies include creating diverse habitats, restoring degraded ecosystems, and adaptive management of green spaces. Apetrei et al. emphasize the importance of a multi-scalar approach to promoting urban biodiversity.

e) Education and community engagement**.** The biophilic city emphasizes reconnecting people with nature through educational programs and community involvement initiatives. Such programs can stimulate urban socio-ecological resilience (KRASNY & TIDBALL, 2015).

Therefore, the vision of the biophilic city offers a holistic framework for reconciling urban development with ecological imperatives, promoting a symbiotic relationship between people, nature, and the built environment. This approach not only improves the quality of life in cities, but also contributes to increasing urban resilience in the face of climate and environmental challenges.

Circular City. The concept of a "circular city" is based on the principles of the circular economy, adapted to the scale and complexity of urban systems. The circular economy, in contrast to the traditional linear model of "extract-produce-consume-dispose," proposes a regenerative system in which resources are used efficiently, and waste is minimized or eliminated (***. ELLEN MACARTHUR FOUNDATION, 2013).

The circular city is defined as "a city that practices the principles of the circular economy to close resource loops, in partnership with citizens, communities, and businesses" (PRENDEVILLE et al., 2018). The theoretical foundation of the circular city is based on several interconnected concepts and theories:

a. Industrial Ecology. This field studies material and energy flows in industrial systems, seeking to optimize them to mimic natural processes. Applying the principles of industrial ecology at the urban scale can lead to more efficient resource use and reduced environmental impact (GRAEDEL & ALLENBY, 2010).

b. Biomimicry. Inspired by nature, this concept proposes design and engineering solutions based on natural processes and systems. Applying biomimetic principles in urban development can lead to the creation of more efficient and resilient cities (BENYUS, 2002).

c. Performance Economy. This economic model, proposed by Stahel, focuses on selling services and performance rather than products, thus encouraging longevity and reuse (STAHEL, 2010).

The implementation of the circular city concept involves a series of strategies and innovative solutions:

a) Optimizing resource flows. This involves creating a framework for implementing the circular economy at the urban level, with an emphasis on mapping and optimizing material and energy flows (KALMYKOVA et al., 2018).

b) Integrated waste management systems. The importance of implementing advanced waste collection, sorting, and recycling systems, as well as energy recovery technologies, is emphasized (GHISELLINI et al., 2016).

c) Promoting the sharing economy and collaborative concepts. The principles of sharing economy can be applied in various urban sectors, from mobility (car-sharing, bike-sharing) to living and working spaces (co-living, co-working) (FRENKEN & SCHOR, 2017).

d) Developing renewable and decentralized energy systems. Integrated urban energy systems combine renewable sources with energy storage and smart grids (LUND, 2014).

e) Regenerating natural capital. The circular city not only minimizes negative impacts but also actively contributes to ecosystem regeneration. Girardet proposes the concept of the "regenerative city," which goes beyond sustainability, towards a positive relationship with the biosphere (GIRARDET, 2014).

The circular city offers a promising vision for sustainable urban development. By optimizing resource use, minimizing waste, and promoting innovation, this approach can significantly reduce the urban ecological footprint and increase resilience to environmental and economic challenges (POPA & POPA, 2021).

In conclusion, the concept of the circular city provides a comprehensive framework for reconciling urban development with planetary limits, promoting a vision where cities function in harmony with natural ecosystems, contributing to the regeneration of natural and social capital.

Smart City. The concept of the "smart city" has evolved significantly in the recent decades, becoming the central paradigm in discussions about sustainable urban development. Although there is no universally accepted definition, a smart city is characterized by "the use of information and communication technologies (ICT) to improve the quality of life, the efficiency of urban operations and services, and competitiveness, while ensuring that the needs of present and future generations regarding economic, social, and environmental aspects are met" (ALBINO et al., 2015).

The theoretical foundation of the smart city is based on several interconnected concepts and theories:

a. The complex systems theory. Cities are complex adaptive systems, and the smart city approach allows for a better understanding and management of this complexity (BATTY, 2013).

b. The open innovation theory. This type of innovation and collaboration between various urban actors is essential for developing smart city solutions (PASKALEVA, 2011).

c. The network governance theory. New forms of collaborative governance in the context of smart cities are particularly important (MEIJER & BOLÍVAR, 2016).

The implementation of the smart city concept involves a series of strategies and innovative solutions:

a) Digital infrastructure and IoT (Internet of Things). Zanella et al. describe the architecture and applications of IoT in the urban context, highlighting the potential of this technology for improving urban services (ZANELLA et al., 2014).

b) Big data analysis and artificial intelligence. The role of big data in transforming urban governance and planning underscores both the opportunities and ethical challenges associated with it (KITCHIN, 2014).

c) E-governance platforms and civic participation. The impact of digital technologies on democratic processes and urban decision-making is analysed (MEIJER & BOLÍVAR, 2016).

d) Smart traffic and mobility management systems. Benevolo et al. offer a comprehensive analysis of smart mobility solutions and their impact on urban sustainability (BENEVOLO et al., 2016).

e) Smart energy grids. Farhangi describes the architecture and benefits of smart energy grids in the urban context, highlighting their potential for energy efficiency and the integration of renewable sources (FARHANGI, 2010).

f) Smart buildings and neighbourhoods and their integration into the broader urban ecosystem (GHAFFARIANHOSEINI et al., 2016).

The implementation of the smart city concept also presents significant challenges:

a. Cybersecurity and data protection. There are vulnerabilities associated with the massive collection of data in smart cities, and robust security measures are urgently needed.

b. Digital inclusion. There is a risk of exacerbating existing inequalities through the implementation of smart city technologies (GRAHAM, 2002).

c. Governance and interoperability. Adequate governance frameworks and interoperability standards are necessary to maximize the benefits of smart city technologies.

d. Long-term sustainability. It is important to integrate smart technologies with long-term sustainability goals.

The smart city concept offers a promising framework for addressing complex urban challenges through technology and innovation. The success of its implementation depends on a holistic approach that integrates technological, social, economic, and environmental aspects. A truly smart city must emphasize human and social capital, democratic participation and sustainable development, not just technological solutions.

Models of sustainable, resilient, and safe cities

Cities that excel in sustainability, resilience, safety play a key role in defining a new urban paradigm, where economic development, environmental protection, and citizens' well-being are in dynamic balance. These cities become benchmarks for modern urban planning and represent exemplary models at the global level. The following cities have been selected for case studies in this field: Copenhagen, Singapore, and Curitiba.

Copenhagen - a leader in sustainable mobility and carbon neutrality

Copenhagen is often cited as a model for sustainable urban development, particularly in the field of mobility and carbon neutrality goals.

Copenhagen is renowned for its cycling culture, having gradually transformed the city from one dominated by cars to one centered on cyclists and pedestrians (GEHL & SVARRE, 2013).

Key strategies used include:

a) Dedicated infrastructure. An extensive network of bike lanes, including "bicycle highways."

b) Traffic priorities. Synchronized traffic lights for cyclists ("green wave").

c) Integration with public transport. Bicycle parking facilities at train and metro stations.

Copenhagen aims to become the first carbon-neutral city by 2025. Key strategies for this include:

a) Renewable energy. Transition to wind energy and biomass.

b) Energy efficiency. Renovation of existing buildings and strict standards for new constructions.

c) District heating system. One of the most efficient systems in the world, utilizing residual heat.

Copenhagen's model has inspired many other cities to adopt similar strategies for sustainable mobility and emissions reduction.

Singapore, garden city and innovation in resource management

Singapore is recognized for its innovative approach to integrating nature into the urban environment and efficiently managing limited resources.

The concept of a "garden city" for Singapore was initiated by former Prime Minister Lee Kuan Yew in 1967. Neo et al. analyse the evolution of this vision and its impact on Singapore's urban development (NEO et al., 2017).

Key strategies used:

a) Extensive green spaces. Over 47% of the city's area is covered by vegetation.

b) Urban biodiversity. Conservation and restoration of natural habitats within the city.

c) Green architecture. Integration of vegetation into buildings.

Resource management is a model worth following. Singapore has developed innovative solutions for managing limited resources, particularly water. Key strategies include:

a) NEWater, an advanced wastewater recycling system that supplies up to 40% of the city's water needs.

b) Rainwater harvesting. Two-thirds of Singapore's land area is designated as water catchment areas.

c) Desalination. Use of advanced technologies for seawater desalination.

Results and impact: Singapore has successfully turned a vulnerability (lack of natural resources) into an advantage, becoming a global leader in water management technologies and green urban development. Singapore is a model "biophilic city."

Curitiba, Brazil – a pioneer in integrated urban planning and sustainable transport

Curitiba is often cited as a success story in integrated urban planning and the implementation of innovative public transport systems in the context of a developing country.

Integrated urban planning. Under the leadership of architect and urban planner Jaime Lerner, Curitiba implemented an innovative master plan that integrated transport, land use, and housing.

Key strategies include: a. Axial development. Concentrating development along main transport corridors; b. Mixed zoning. Encouraging mixed-use land development to reduce travel needs; c. Extensive green spaces. Creation of numerous urban parks, many on former flood-prone areas.

Curitiba was a pioneer of the bus rapid transit (BRT) system, which has since been adopted by many cities around the world. The evolution and impact of this system in Curitiba have been thoroughly analysed and researched (LINDAU et al., 2010).

Key strategies in this field include: a. Dedicated bus lanes. Ensuring high speeds and frequencies; b. "Tube" stations facilitating quick boarding and access for people with disabilities; c. Integrated fare system. A unified fare system for the entire transport network.

Results and impact: a. 45% of trips in Curitiba are made using public transport, far above the average for similar cities in Brazil; b. Fuel consumption per capita is 30% lower than in other comparable Brazilian cities; c. Curitiba has one of the highest rates of green space per capita in Latin America (52 m^2 per capita). These case studies illustrate various approaches to implementing sustainable urban development principles, adapted to specific local contexts. They demonstrate that, although the challenges are significant, there are innovative and effective solutions for creating more sustainable and resilient cities.

Each of these cities offers valuable lessons for other urban communities aspiring to implement sustainable development strategies. At the same time, it is important to note that the success of these initiatives depends on several factors, including political leadership, community involvement, technological innovation, and cross-sector integration.

CONCLUSIONS

Developing sustainable cities represents one of the most important challenges and opportunities of the 21st century. This article has explored various visions, strategies, and innovative solutions for creating resilient, efficient urban environments that are harmonious with nature.

Sustainable urban development requires a holistic approach that integrates ecological, social, economic, and technological aspects. Sustainable cities need a systemic approach that recognizes the interconnections between infrastructure, ecosystem services, institutions, and human behaviors.

This integrated approach involves collaboration among various urban actors, including public administrations, the private sector, local communities, and academia.

The innovative solutions presented in this article, from green-blue infrastructure to sustainable mobility and urban agriculture, demonstrate the potential of innovation in transforming cities. Sustainable urban innovation is not just about technology, but also about new governance models, social practices, and institutional arrangements.

The presented case studies illustrate that there is no universal solution for sustainable urban development. Strategies must be adapted to the local context, taking into account factors such as geography, culture, economy, and institutional capacity. The specific urban context plays a crucial role in shaping sustainable urban transition trajectories.

In the context of increasing challenges related to climate change, developing resilient and adaptable cities becomes crucial.

Sustainable urban development must explicitly address issues such as equity and social inclusion.

As cities continue to evolve and adapt to emerging challenges, new research and innovation directions are taking shape, such as: a) artificial intelligence and big data in urban planning. b) circular economy and regenerative cities. c) urban health and biophilic design.

Thus, the transition to sustainable cities represents a complex challenge, but also a unique opportunity to reimagine and rebuild urban environments in a way that improves life quality, protects the environment, and ensures long-term prosperity. The success of this transition will depend on our ability to innovate, collaborate, and adapt solutions to specific local contexts while maintaining a global vision of sustainability.

The transition to sustainable cities is not only an ecological necessity, but also an opportunity to create more equitable, healthier, and more prosperous communities. It is an ambitious project that requires the involvement of all urban actors and a fundamental reimagining of how we design, build, and live in cities.

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