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THE CAATINGA AS A LIVING LAB: CLIMATE, RESILIENCE AND SMART CITIES

LESSONS FROM BRAZIL'S SEMI-ARID REGION FOR GLOBAL URBAN FUTURES

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ABSTRACT
*This article reflects on the challenges and opportunities of building smart and sustainable cities in semi-arid regions, with a focus on the Caatinga biome in Brazil. Based on the Strategic Guide for Smart and Sustainable Cities in the Semi-Arid (*SGSAC*), it emphasizes how climate pressures and socio-environmental vulnerabilities can be transformed into drivers for resilience, innovation, and inclusive governance. Using the quadruple helix as a guiding framework, the Caatinga is framed as a living lab for testing urban strategies. The paper highlights its potential contributions to global debates on climate adaptation and smart city futures.*

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1. The Caatinga as a Living Lab for Smart Sustainable Cities

This article explores how semi-arid regions can advance smart and sustainable cities, with a particular focus on the Caatinga biome in Brazil. These territories face critical issues such as recurrent droughts, water scarcity, and social inequality, which are increasingly exacerbated by climate change. At the same time, semi-arid contexts provide opportunities to test innovative strategies for adaptation, renewable energy, and inclusive governance. Framing the Caatinga as a living lab, the article highlights how climate pressures can be transformed into drivers of resilience, innovation, and sustainable urban transformation.

The primary objective of this study is to analyze how semi-arid regions, often marginalized in global debates on smart cities, can contribute innovative lessons to the international agenda. By connecting local practices with global frameworks, the article seeks to identify pathways that integrate resilience, strategic planning, and the quadruple helix of innovation as central components for sustainable futures.

1.1. Climate Pressures and Resilience

Semi-arid cities are more vulnerable to climate risks, but they also demonstrate strong adaptive capacity. Recurrent droughts, vulnerable ecosystems, and infrastructure limitations require new responses, from community-based water management to technological solutions for resource efficiency. A city in the Caatinga that builds resilience is capable of addressing environmental risks and transforming constraints into new paths, promoting inclusive governance and sustainable practices that can inspire other regions of the world.

2. Methodology and Sources

A qualitative, exploratory analysis of official frameworks and strategic documents was conducted, with emphasis on the Brazilian Charter for Smart Cities (Brazil, 2021), the Strategic Guide for Smart and Sustainable Cities in the Semi-Arid (SGSAC)(INSA, 2024), and global references (United Nations, 2015; 2016). These sources were critically adapted to the semi-arid context (climate vulnerability, water scarcity, urban–rural interactions). The quadruple helix (government, academia, industry, civil society) was adopted as the operational lens to examine collaborative governance, knowledge co-production, and innovation aligned with sustainability. This methodological approach is qualitative and exploratory, which implies limitations in terms of empirical validation.

3. Why Smart and Sustainable Cities in Semi-Arid Regions

Historically, Brazil's Semi-Arid region has been marked by persistent environmental, social, and economic challenges, which are increasingly amplified by climate change and development pressures (Marengo et al., 2021). Inequalities, recurring droughts, and limited development paradigms inhibit the full progression of both urban and rural territories (Dos Santos & Pessoa, 2025; Sena et al., 2018).

Smart and sustainable cities provide an integrated framework for this transformation. International agendas such as the United Nations 2030 Agenda and the New Urban Agenda emphasize that urban development must align innovation, environmental responsibility, and social inclusion (United Nations, 2015, 2016). At the national level, the *Brazilian Charter for Smart Cities* defines smart cities as those committed to sustainable urban and digital transformation, operating in an inclusive and networked manner, and reducing inequalities while promoting resilience and improving quality of life (Brazil, 2021).

Developing smart and sustainable cities in the Semi-Arid therefore requires the mobilization of diverse stakeholders, following the quadruple helix model of innovation. This collaborative approach not only enhances decision-making but also accelerates the creation of context-specific solutions for resource efficiency, renewable energy transitions, and sustainable urban governance.

3.1. Smart Cities and Global Agendas

Smart and sustainable cities are not limited to metropolitan areas; they encompass municipalities, small towns, and even rural communities that face growing pressures from climate change, urbanization, and economic transitions. In this sense, the concept of "cities of the future" is not only about technological innovation but also about strengthening social justice, economic viability, and environmental resilience across diverse contexts (García Fernández & Peek, 2020; Valencia-Arias et al., 2025). In this regard, Silva et al. (2024) highlight the constrained institutional and techno-social responses in cities under climate stress. Specifically, in Brazilian semi-arid municipalities, adaptive capacity management remains weak, underscoring high vulnerability to climatic risks (Dos Santos & Pessoa, 2025).

Global frameworks such as the Sustainable Development Goals (SDGs) of the 2030 Agenda (United Nations, 2015) and the New Urban Agenda (United Nations, 2016) reinforce the importance of inclusive and collaborative approaches to urban development. These frameworks converge on three fundamental challenges, such as ensuring economic viability, guaranteeing social justice, and maintaining environmental resilience under increasing climate pressure. Meeting these challenges requires long-term strategic planning, digital innovation, participatory governance, and citizen engagement.

3.2. The Quadruple Helix Innovation

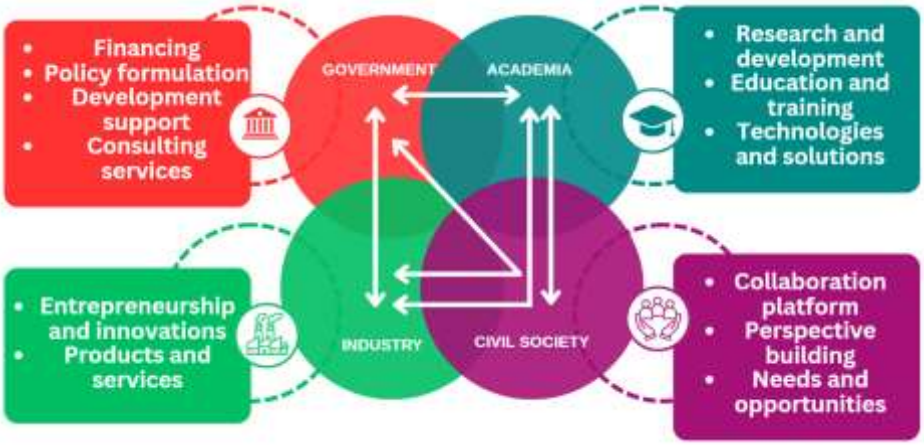
Innovation in semi-arid regions requires the articulation of diverse actors capable of addressing both present challenges and future risks. A useful conceptual basis for this is the Quadruple Helix model of innovation, originally proposed by Carayannis and Campbell (2009), which frames collaboration between government, academia, industry, and civil society as the foundation of innovation ecosystems. This framework, while not developed specifically for semi-arid contexts, offers a transferable perspective that can guide strategies for building smart and sustainable cities under climate pressures.

Recent scholarship highlights that the Quadruple Helix enhances the capacity of cities to integrate open innovation practices, enabling both internal and external knowledge flows that strengthen adaptive governance (Marchesani & Ceci, 2025). It is also increasingly recognized as a framework for co-producing urban transformation, aligning digital technologies and innovation with inclusiveness and citizen participation (Paskaleva, 2021). By embedding multi-stakeholder collaboration, the model enables technological transitions and the design of socially and environmentally aligned solutions, including nature-based strategies (Olbertz et al., 2025).

In the broader debate on urban sustainability, Quadruple Helix co-creation has been identified as a central mechanism to advance smart city agendas and to strengthen urban resilience capacities (Stephens, 2025). Furthermore, regional studies demonstrate how the model functions as a dynamic system of knowledge sharing that accelerates sustainable development beyond metropolitan areas, supporting both local adaptation and long-term innovation pathways (Hakeem et al., 2023). Complementary perspectives from innovation studies reinforce that such ecosystems are crucial for advancing green innovation efficiency and building transformative urban agendas (Evans et al., 2025; Guo et al., 2023).

In line with international commitments such as the SDGs, the Quadruple Helix offers semi-arid cities a pathway to expand resilience, generate social and economic opportunities, and build urban systems that are environmentally responsible and socially just. Figure 1 illustrates this perspective, showing how the Quadruple Helix of Innovation connects diverse actors in shaping sustainable futures.

Figure 1. The Quadruple Helix of Innovation: interactions between government, academia, industry, and civil society.



Source(s): Elaborated by the authors, adapted from the SGSAC (INSA, 2024).

The integration of the Quadruple Helix with the three core dimensions of sustainability (social, environmental, and economic) reinforces its systemic nature. Aligning innovation networks with sustainable practices and smart technologies enables cities to maximize social inclusion, economic competitiveness, and environmental responsibility (van Bueren et al., 2025). This approach is corroborated by studies on green innovation networks, which show que redes de inovação orientadas à sustentabilidade equilibram lucro, sociedade e meio ambiente (Pattinson et al., 2023). The intersection of estes domínios evidencia que o desenvolvimento urbano deve ir além de soluções meramente tecnológicas, incorporando governança participativa e resiliência de longo prazo à agenda urbana (Frantzeskaki et al., 2021).

Figure 2 illustrates this multidimensional perspective, showing how the interaction among actors of the Quadruple Helix is intrinsically linked to sustainability outcomes.

Figure 2. Sustainable Dimensions and the Quadruple Helix

Source(s): Elaborated by the authors, adapted from the SGSAC (INSA, 2024).

4. Motivations for the Strategic Guide for Smart and Sustainable Cities (SGSAC 2030)

This section explains why the present decade represents a critical moment for designing strategic frameworks for cities. Facing the combined pressures of urban growth, climate change, and inequality, cities must move beyond isolated responses. A structured and evidence-based approach can help transform these challenges into opportunities for resilience, inclusion, and sustainable innovation.

Accelerating urbanization, climate pressures, and widening social inequalities converge to stress urban systems, especially in contexts of scarce resources. Rapid urban expansion coupled with climate change can overwhelm water, energy, mobility, housing, and health infrastructures (Das et al., 2024; Shah et al., 2025). Moreover, urban resilience scholarship emphasizes that these challenges must be addressed in a multidimensional and integrated way (Kapucu et al., 2024). Pressures on local ecosystems and environmental services further intensify urban inequalities, reducing the adaptive capacity of cities (Atisa & Racelis, 2022).

In this context, moving from isolated projects to integrated, multi-actor governance becomes essential. Cities that rely on fragmented responses risk exacerbating social divides and missing opportunities for systemic innovation. A forward-looking, evidence-based guide can support municipalities in aligning local strategies with global sustainability agendas, such as the SDGs and the New Urban Agenda (United Nations, 2016).

A strategic guie aims to protect quality of life, ensure competitiveness, and respect ecological limits through 2030. By translating global frameworks into actionable domains for municipal practice, such a guide enables cities to anticipate risks, enhance resilience, and foster inclusive growth. Its foundations rest on principles of knowledge co-production, long-term planning, and collaborative governance, which are increasingly recognized as prerequisites for sustainable urban transformation (Evans et al., 2025; Frantzeskaki et al., 2021).

4.1. Why now: from sustainable development to climate emergency

Since the Brundtland Report defined sustainable development as “meeting the needs of the present without compromising the ability of future generations to meet their own needs” (World Commission on Environment and Development, 1987), the urgency to align urban development with intergenerational justice has only increased. In the current climate emergency, cities, particularly in emerging economies, face mounting risks while still pursuing growth and inclusion (IPCC, 2023). A forward-looking urban agenda is therefore not optional; it is the condition for safeguarding social well-being, economic competitiveness, and environmental integrity through 2030 and beyond.

Together, these motivations highlight that building smart and sustainable cities is not just a technological endeavor but a societal project. The SGSAC aims to provide municipalities with actionable tools and collaborative frameworks to navigate this transformation toward 2030.

4.2. Urbanization and infrastructure pressure

Rapid urbanization concentrates population, demand, and vulnerability in metropolitan regions. As cities expand, often with unplanned vertical or horizontal growth, pressures intensify on water supply, energy systems, housing, mobility, health, and sanitation. Without strategic planning, this growth amplifies inequality, environmental degradation, and fiscal stress (Angel et al., 2021; Seto et al., 2017; United Nations, 2019). Smart and sustainable city strategies offer an integrated response by coupling data-informed planning with inclusive governance.

4.3. Air quality and the resource nexus

Deteriorating air quality and constraints on water, energy, and food form a critical “nexus” that threatens public health and economic productivity. Research on the water–energy–food nexus emphasizes that integrated policies and technologies often generate co-benefits that outweigh their costs, including cleaner air, more efficient resource use, and enhanced resilience

(Bleischwitz et al., 2018). By positioning cities as testbeds for such solutions, municipalities can accelerate transitions to renewable energy, circular economy practices, and sustainable water management, thereby reducing emissions and strengthening adaptive capacity.

4.4. From isolated projects to systemic governance

City services are the backbone of everyday life, yet when actions remain fragmented, outcomes tend to be punctual or even regressive. Moving toward systemic governance, based on open, multi-actor, and evidence-driven processes, enables municipalities to plan, finance, and deliver more effective services while aligning local action with national and global agendas, such as the SDGs (Ansell & Gash, 2008). Within this approach, the Quadruple Helix of Innovation provides the operational logic for collaboration, reinforcing that smart and sustainable urban development requires participatory, networked, and adaptive governance frameworks (Meijer & Bolívar, 2016).

Recent research highlights how digital technologies are reshaping co-production and governance models, creating both opportunities and risks for inclusion and accountability (Lember et al., 2019). Urban governance must also address structural dynamics such as urban sprawl, which influences social and economic mobility (Smith & Blizard, 2021), and the ethical implications of emerging technologies, as seen in debates on surveillance and racial justice (Johnson et al., 2022). Together, these studies stress that systemic governance is not only about efficiency, but also about safeguarding equity, trust, and democratic legitimacy in smart city transitions.

4.5. Principles for resilient, smart, and sustainable cities

To move from concept to practice, cities should adopt guiding principles that translate into policy and design criteria. Building on established global frameworks, recent analyses emphasize that resilience, equity, and sustainability must be treated as cross-cutting priorities in urban development (IPCC, 2023; OECD, 2020; UN-Habitat, 2020).

Principles for resilient, smart, and sustainable cities:

- Accessibility: universal access to quality services, housing, mobility, and digital connectivity.
- Availability of Natural Resources: stewardship of water, soil, and energy; efficiency and diversification.
- Sharing & Commons: open data, shared infrastructure, and collaborative platforms that multiply public value.
- Safety: public safety, disaster risk reduction, and cybersecurity by design.
- Desirability: quality of life, public space, culture and citizen participation as core outcomes.

These principles frame investment, regulation, and innovation so that growth is compatible with equity and ecological limits.

4.6. Strategic alignment with the SDGs

Smart and sustainable city policies directly support multiple SDGs, particularly SDG 11 (sustainable cities and communities), while enabling progress on poverty reduction, health, education, water and sanitation, clean energy, industry and innovation, climate action, and biodiversity. Framing local initiatives within these targets strengthens accountability and mobilizes partnerships and finance (OECD, 2020; UN-Habitat, 2020; United Nations, 2015).

4.7. Socially Just and Smart Cities (SJSC)

The pursuit of socially just and smart cities (SJSC) requires moving beyond the technocratic view of "smartness" to critically interrogate how inclusion, equity, and citizen participation are embedded in urban transformation. In practice, many smart city agendas risk reinforcing inequalities when technology is not accompanied by governance models that prioritize social

justice and accessibility. Caragliu & Del Bo (2023), in their research on smart cities and the urban digital divide, demonstrate that urban "smartness" can either exacerbate the digital divide or actively reduce it, depending on how policies are designed to include marginalized groups. This duality highlights the need for critical reflection on how smart city policies are implemented in diverse socio-economic contexts.

Other recent scholarship has also clarified the justice dimension of smart cities, stressing that digital innovation must be anchored in democratic values, rights, and fairness rather than efficiency alone (Alizadeh & Sharifi, 2023a; Hacker & Neyer, 2023). The concept of a "societal smart city" underlines that citizen participation must be substantive and rights-based, otherwise "smart" risks becoming a rhetorical label disconnected from lived realities (Alizadeh & Sharifi, 2023b).

The Brazilian Charter for Smart Cities articulates the ambition to promote inclusive, sustainable, and digitally transformative urban development, emphasizing equity, resilience, and the safe use of data (Brazil, 2021). However, questions remain as to how these normative commitments translate into practice in semi-arid regions, where structural inequalities and climate vulnerabilities intersect.

In these territories, active citizenship is often challenged by limited digital infrastructure, uneven access to essential services, and socio-environmental vulnerabilities that test the very premise of socially just and smart cities (Aditya et al., 2023; Dos Santos & Pessoa, 2025; Kolotouchkina et al., 2024). This tension reveals the importance of SJSC as both a framework for reflection and a lens to challenge existing models. At the same time, socially just and sustainable cities cannot exist without active citizens. The central challenge therefore becomes how urban life can evolve to be more sustainable and efficient while meeting the needs of present and future generations.

Quality of life is not an automatic outcome of smart city policies, but rather the cornerstone that must be intentionally pursued through universal access to services, inclusive governance that values cultural identity, and equitable opportunities for long-term prosperity (Jang & Gim, 2022; Kummitha, 2025). Maheshwari & Chopra (2025) also stress the risks of adopting urban models without questioning their equity implications, as illustrated by debates on the "15-minute city," where accessibility metrics can obscure deeper issues of justice and displacement.

Aligning SJSC with the SDGs, particularly SDGs 1, 2, 3, 4, 5, 10, 11, and 16, requires cities to move from declarative visions to actionable and accountable policies. As Creutzig et al. (2024) argue, this demands place-based approaches that integrate social equity, climate adaptation, and participatory governance. Table 1 summarizes how SJSC domains contribute to inclusive urban development, reflecting both international agendas and context-specific challenges.

Table 1. Domains for a Socially Just and Smart City

Domain	Description
Living Together and Quality of Life	Aims to enhance quality of life through inclusive strategies across all age groups. Focuses on social and digital inclusion, improved healthcare, elderly care, food security, housing quality, and the development of smart buildings using IoT, fostering a more efficient and sustainable region.
Social and Human Capital	Seeks to transform citizen interaction with public and private sectors by promoting social and digital inclusion through education, while emphasizing skill development to stimulate economic growth. Encourages civic participation, creativity, and innovation, positioning the city as a model of equity and efficiency.
Integrated, Smart, and Sustainable Governance	Represents a comprehensive system designed to optimize citizens' quality of life by combining strategies for health, elderly care, safety, housing, and smart infrastructure. Prioritizes skills development and education while leveraging IoT and innovative solutions for more inclusive and sustainable cities.

Source(s): Elaborated by the authors, adapted from the SGSAC (INSA, 2024).

These domains, as adapted from the SGSAC (INSA, 2024), illustrate the multidimensional approach required for advancing socially just and smart cities. While they address quality of life, social capital, and integrated governance, their effectiveness ultimately depends on how cities operationalize these principles in contexts marked by inequality and vulnerability. This reinforces the need for critical reflection on the translation of such frameworks into practice in semi-arid regions.

4.8. Economically Viable and Smart Cities (EVSC)

The economic dimension is foundational for advancing smart and sustainable cities. Smart cities can act as ecosystems that foster entrepreneurship through infrastructure, governance, and innovation (Bukhari et al., 2024). However, the configuration of economic models and entrepreneurial trajectories diverges markedly across municipalities depending on their institutional and regional contexts (Kummitha, 2019).

In semi-arid regions, where climate challenges, environmental stress, and resource scarcity prevail, ensuring economic viability requires tailored strategies that combine resilience with innovation. Water resource management is fundamental for both human well-being and productive systems, while sustainable agriculture must adapt to scarce and highly variable rainfall (Rathore, 2024).

Renewable energy generation, particularly solar and wind, plays a central role in enabling clean growth in arid environments (Abdoos et al., 2025; Karimi et al., 2020). However, large-scale deployment of these technologies can also bring negative externalities, including land-use change, risks to biodiversity, and the displacement of vulnerable communities without fair compensation (Avila, 2018; Sander et al., 2024; Wang et al., 2025).

Key investments include infrastructure for communication networks, sustainable transport systems, renewable energy, and digital connectivity, alongside robust research and development that accelerates smart solutions (Sharifi et al., 2024). Evidence from entrepreneurial ecosystems also highlights the roles of internet access, transportation, human capital, and governance in enabling urban innovation (Zhao et al., 2023).

Education and workforce training remain central to building adaptive capacity, while job creation improves quality of life and helps retain talent (Virah-Sawmy & Sturmberg, 2025). At the same time, entrepreneurship ecosystems and public–private partnerships can foster adaptive economic models, particularly when supported by institutional innovation and inclusive governance (Abdelaziz et al., 2024; Quan & Solheim, 2023).

Taken together, these elements are essential to enable regional development and to strengthen resilience to climate adversity and ensure the long-term sustainability of local economies (Creutzig et al., 2024). The main domains that characterize economically viable and smart cities are summarized in Table 2.

Table 2. Domains for an Economically Viable and Smart City

Domain	Description
Smart Economic Model	Initiatives that strengthen local vocations, improve the business environment, attract startups and investors, and promote innovative, sustainable growth.
Smart Physical and Digital Infrastructure	Investments that ensure access to essential services (water, energy, transport) while fostering digital connectivity, innovation, and knowledge-based economies.
Integrated, Smart, and Sustainable Governance	A governance model that connects government, citizens, businesses, and civil society, rethinking service delivery through transparency, efficiency, and innovation.

Source(s): Elaborated by the authors, adapted from the SGSAC (INSA, 2024).

By aligning efforts with the United Nations SDGs 8, 9, 11, 12, 16, and 17, economically viable and smart cities support decent work and growth, resilient infrastructure, sustainable consumption and production, justice and strong institutions, and global partnerships. Together, these investments not only enhance present well-being but also secure a more equitable, sustainable, and prosperous future.

4.9. Environmentally Sustainable and Smart Cities (ESSC)

Cities in semi-arid regions face critical challenges related to the environment, biodiversity, and the sustainable management of natural resources. To address these conditions, they must balance growth with conservation by reducing pollution, managing resources responsibly, and preserving local identity. Yet, evidence shows that environmental policies in smart cities are not neutral, as transitions to renewable energy, for example, can reproduce inequalities or displace vulnerable groups if justice is not incorporated into planning (Levenda et al., 2021; Regier et al., 2025).

Key environmental domains for future urban sustainability are summarized in Table 3, highlighting the integration of natural resource management, sustainable mobility, and holistic governance. In this sense, protecting urban and rural ecosystems and conserving biodiversity are indispensable, since green infrastructure and nature-based solutions provide multifunctional benefits for resilience, well-being, and ecological integrity (Kabisch et al., 2022; Paudel & States, 2023).

Table 3. Domains for an Environmentally Sustainable and Smart City

Domain	Description
Intelligent Environment	Refers to municipal strategies for managing both the built and natural environment, incorporating innovative technologies and sustainable regulations. Focuses on waste reduction, pollution management, emission reduction, water efficiency, energy transition, and resilient urban planning.
Smart Mobility	Aims to improve efficiency and accessibility of mobility services through integrated multimodal systems, sustainable logistics, and citizen-centered approaches. Promotes high-quality mobility that reduces environmental impact while ensuring inclusivity.
Integrated, Smart, and Sustainable Governance	Represents a holistic system that balances intelligent development with environmental sustainability. Involves the adoption of technologies and regulations to optimize water, energy, and environmental management, while fostering resilience and innovation.

Source(s): Elaborated by the authors, adapted from the SGSAC (INSA, 2024).

At the same time, advancing sustainable mobility requires integrated planning and governance that move beyond technological fixes to tackle accessibility and equity challenges (Cavoli et al., 2025). Ensuring access to clean water and sanitation further underpins both public health and environmental quality, making ecosystem conservation, energy transition, and adequate sanitation foundational for resilient and equitable communities.

These efforts are directly aligned with the United Nations SDGs, particularly SDG 6 (Clean Water and Sanitation), SDG 7 (Affordable and Clean Energy), SDG 11 (Sustainable Cities and Communities), SDG 13 (Climate Action), SDG 14 (Life Below Water), and SDG 15 (Life on Land). Aligning local policies with these goals not only addresses environmental pressures but also strengthens quality of life for present and future generations.

5. Present and Future of Semi-Arid Cities

The semi-arid region of Brazil represents one of the most populous dryland areas in the world, comprising 1,477 municipalities across eleven states (IBGE, 2024; CONDEL/SUDENE, 2024). Despite its unique biodiversity and sociocultural richness, the region continues to face persistent

challenges, including water scarcity, desertification, poverty, and unequal access to basic infrastructure (Alvalá et al., 2019). These vulnerabilities make the semi-arid context a critical testing ground for smart and sustainable city strategies.

Drawing on the SGSAC, this section presents an integrated diagnosis of current conditions and explores potential economic, social, and environmental futures that may unfold depending on policy choices, governance models, and collective action. The analysis underscores both structural constraints and emerging opportunities, particularly the potential to harness renewable energy, strengthen human capital, and promote inclusive governance.

By systematizing these perspectives, the Caatinga biome is framed as both urgent, given its exposure to climate risks and structural inequalities, and promising, as a living laboratory for adaptation, innovation, and resilience. Workshops conducted during the preparation of the Guide, involving diverse stakeholders, elicited three scenarios: baseline, optimistic, pessimistic, and implications. These scenarios synthesize how local actors perceive trajectories in their municipalities. The subsections below summarize these pathways across three dimensions: economic viability, social inclusion, and environmental sustainability.

5.1. Economic Scenarios: Viability, Productivity, and Innovation

- **Baseline**: Local economies remain anchored in primary production (animal and vegetal chains), with incremental technological uptake limited to a few value chains and territories. Water scarcity is partially mitigated by alternative sources and efficiency measures, enabling continuity of existing activities but restricting diversification and value addition. Informality persists, while rural-to-urban migration continues to reshape labor markets, exerting pressure on urban services without translating into productivity gains.
- **Optimistic**: Strategic investments in water security (rainwater harvesting, loss-reduction, reuse), soil restoration, and renewable energy (solar and distributed generation) reduce production risks and attract private capital. Cluster policies and cooperative arrangements strengthen local chains, fostering a transition from commodities to higher value-added products. Human capital policies, such as technical and vocational training aligned with regional vocations, increase employability and retain qualified youth. The result is a smart economic model (Table 2) that integrates digitalization, logistics, and finance with circular practices (energy and water efficiency), enhancing competitiveness and municipal revenues.
- **Pessimistic**: Intensified hydrological stress, weak resource governance, and limited innovation diffusion trigger business discontinuity in agriculture and related services. Biodiversity loss and land degradation expand production into fragile areas, while skilled labor out-migration reduces productivity and entrepreneurship. Disarticulated chains and credit constraints increase transaction costs, locking municipalities into low-value, high-vulnerability paths and heightening the burden on social protection systems.
- **Implications**: Economic resilience depends on the alignment of three pillars: (i) infrastructure for reliability (water, energy, logistics), (ii) skills and institutional density (cooperatives, extension services, data and market intelligence), and (iii) innovation and finance (R&D, blended finance, PPPs). These findings operationalize the EVSC agenda presented in Section 4.8.

5.2. Social Scenarios: Inclusion, Capabilities, and Quality of Life

- **Baseline**: Programs improve food and nutrition security unevenly. Educational expansion advances, but infrastructure deficits and teacher retention in remote areas remain significant barriers. Community engagement supports the implementation of ongoing projects; however, disparities in service access and digital connectivity persist, sustaining moderate inequality.
- **Optimistic**: Integrated policies guarantee universal basic services (water, sanitation, primary health) and expand lifelong learning opportunities aligned with local economies. The valorization of local culture and the strengthening of community organizations enhance adherence and outcomes. Targeted support for associative and cooperative enterprises decentralizes access to resources and increases household incomes, contributing to inequality

reduction. The result aligns with the SJSC agenda (Section 4.7), reflected in improved human development indicators, stronger civic participation, and safer, more vibrant public spaces.

- **Pessimistic**: Barriers to land access, discontinuity of social programs, and environmentally blind industrialization exacerbate food insecurity and school dropout, deepening exclusion. Limited digital access and weak entrepreneurship ecosystems confine workers to low-value jobs. Urban precarization intensifies through inadequate housing and public safety, increasing vulnerability and driving out-migration.
- **Implications**: Social resilience depends on three interconnected pillars: capability formation (education and digital inclusion), service universality (health, water, sanitation), and institutional continuity (stable programs with multi-year funding). Leveraging the quadruple helix fosters co-produced solutions, such as edtech for remote learning, telehealth for dispersed populations, and civic tech for participatory budgeting, consistent with Table 1 domains.

5.3. Environmental Scenarios: Ecosystems, Water, and Energy Transitions

- **Baseline**: Municipalities adopt selective measures for pollution control, basic conservation, and limited climate-smart agriculture. Yet, fragmented governance and weak enforcement constrain landscape-scale outcomes. Access to potable water improves in certain areas, but losses and contamination persist. Energy transitions advance only in specific niches.
- **Optimistic**: A systems approach to land and water management is scaled up. Reforestation and ecological restoration curb desertification, while integrated watershed governance reduces scarcity and enhances resilience. Nature-based solutions deliver multifunctional benefits for adaptation. Universal sanitation and safe water access strengthen public health. The rapid deployment of clean energy and efficiency measures (buildings, public lighting, irrigation) lowers emissions and operational costs. Mobility transitions toward multimodal and citizen-centered systems reduce pollution and expand accessibility. This scenario reflects the ESSC agenda (Section 4.9) and advances SDGs 6, 7, 13, 14, and 15.
- **Pessimistic**: Population pressure near rivers without water-loss management, unchecked burning, and soil mismanagement accelerate environmental degradation. Weak enforcement in protected areas, program discontinuity, and institutional fragmentation entrench the "drought industry," intensifying conflicts over water. Climate risks worsen through prolonged droughts and extreme heat, with cascading effects on health, productivity, and security.
- **Implications**: Environmental resilience requires three core elements: governance integration (clear roles, monitoring, and enforcement), investment in water and sanitation as both health and productivity policy, and clean-energy and mobility transitions that generate local co-benefits such as jobs and operational savings. Municipal planning must mainstream risk and adaptation metrics and employ open data as a tool for guiding decisions, consistent with Table 3 domains.

6. Strategic Pathways to 2030

Looking ahead, Brazil's semi-arid Caatinga biome is both a space of urgent vulnerabilities and transformative potential. Global megatrends such as demographic growth, accelerating climate change, disruptive technologies, and shifting generational values intersect with local challenges, demanding a reimagination of urban and rural futures. In this context, the SGSAC (INSA, 2024) outlines prospective pathways to guide municipalities toward 2030 in alignment with international agendas.

Rather than prescriptive solutions, these pathways emerge from exploratory foresight that identifies weak signals, current patterns, and transformative trends which, if adequately harnessed, may unlock resilient and inclusive trajectories for semi-arid cities. They emphasize that the future is not predetermined but contingent upon governance choices, policy coherence, and the capacity to integrate technological, social, and environmental innovations into context-sensitive models.

By 2030, semi-arid cities can evolve toward becoming:

- **Economically viable and innovative**, with circular economies, local productive vocations, and entrepreneurship as engines of prosperity.
- **Socially just and inclusive**, where health, education, housing, and digital literacy are universally accessible, supported by participatory and transparent governance.
- **Environmentally sustainable and resilient**, through effective resource management, renewable energy adoption, and strategies to adapt to and mitigate climate risks.

These strategic visions are supported by three foundations: (i) governance models that are transparent, participatory, and adaptive; (ii) investments in infrastructure, digitalization, and human capital; and (iii) policies that prioritize equity, innovation, and environmental stewardship.

Achieving these futures, however, requires overcoming critical barriers such as political discontinuity, insufficient investment in education and technology, weak institutional capacity, and persistent inequalities in access to services. The *Guide* consolidates these barriers across the economic, social, and environmental dimensions (Tables 4–6), emphasizing that without systemic responses, the semi-arid may remain trapped in cycles of vulnerability.

Table 4. Obstacles and Risks for the Economic Dimension

Smarter Economic Model	Smarter Governance	Smart Physical and Digital Infrastructure
Lack of political will may lead to inadequate policies for sustainable development in semi-arid region.	Concentration of power hinders democratic participation.	Lack of integration undermines efficiency.
Low investment in education reduces the population's capacity to acquire skills to drive smart economic models.	Lack of knowledge on key issues undermines effective solutions.	Inadequate choice of technologies wastes investments.
Limited water availability is a major obstacle in the semi-arid region.	Resistance to change may hinder policy innovation.	Insufficient state support delays development.
High energy costs may constrain growth.	Institutional discontinuity during political transitions undermines policies and projects.	Misuse of public resources leads to financial waste
Weak internet infrastructure limits access to information and innovation.	Lack of resources challenges sustainable development.	Technical and financial complexity overloads infrastructure projects.
Lack of adaptation to best productive practices generates inefficiencies and economic stagnation.	Poor data quality hinders planning.	Loss of citizen data threatens privacy and security.
Low productivity undermines competitiveness.	Loss of local identity weakens community, tourism, and culture.	Infrastructure not aligned with future climate needs.
Regional out-migration results in talent loss.		

Source(s): Elaborated by the authors, adapted from the SGSAC (INSA, 2024).

Table 5. Obstacles and Risks for the Social Dimension

Smarter Human Capital	Smarter Governance	Smarter Physical and Digital Infrastructure
Lack of access to education beyond formal schooling limits development of labor-market skills.	Lack of transparency undermines trust in government institutions.	Economic vulnerability and limited income drive high unemployment.
Linguistic barriers that exclude minority groups and immigrants from educational opportunities.	Ineffective public policies fail to address population needs.	Uncontrolled urban growth harms air quality and health.
Prejudice and social stigma hinder individuals' full development.	Inequality in access to quality public services.	Unequal access to healthy food due to uneven distribution.
Unequal access to mental health services and emotional support.	Lack of accountability mechanisms for government leaders.	Lack of green and recreational spaces in urban and rural areas.
Scarcity of lifelong learning opportunities limits skills development.	Resistance to adopting e-government technologies that could improve efficiency and transparency in public service delivery.	Digital exclusion limits access to essential online services.

Source(s): Elaborated by the authors, adapted from the SGSAC (INSA, 2024).

Table 6. Obstacles and Risks for the Environmental Dimension

Smarter Environment	Smarter Mobility	Smarter Governance
Absence of environmental concerns in the municipality or lack of a specific agency in the area, along with insufficient environmental education actions.	Absence of a municipal agency dedicated to mobility, resulting in lack of focus and coordination in managing this vital aspect.	Political leaders maintaining clientelist and coercive practices, undermining the effectiveness of environmental actions.
Poor population education on environmental issues.	Disconnect between mobility policies and the real needs of the population, leading to inadequate solutions.	Continuous dependence of the population on politicians, which weakens independence in environmental decision-making.
Persistence of environmental degradation and its consequences in the municipality.	Lack of urban planning leading to the isolation of rural and agricultural areas.	Resistance to change, resulting from lack of training and awareness on environmental issues.
An economic model that does not prioritize the conservation of natural resources.	Lack of public awareness about the importance of accessibility and sustainable mobility.	Governance difficulties in implementing new systems and processes, leading to delays in environmental management.
Mismanagement of natural resources.	Lack of measures to facilitate citizen access to infrastructure.	Lack of interest from public management in implementing a smart city model, hindering the advancement of sustainable practices.

Low educational attainment and lack of responsibility regarding contemporary issues and their environmental impacts.	Accessibility problems, including inadequate sidewalks and lack of proper urbanization, as well as preference for individual motorized transport.	Lack of continuity in environmental projects, interrupting ongoing actions.
Lack of government engagement in environmental preservation and management.	Scarcity or excess of mobility equipment, which can cause harm if not adequately used by the population.	Scarcity of financial resources, limiting the implementation of environmental services.

Source(s): Elaborated by the authors, adapted from the SGSAC (INSA, 2024).

Ultimately, the pathways to 2030 reaffirm that semi-arid cities can act as laboratories of resilience and innovation, where global agendas are translated into locally grounded solutions. By linking strategic foresight with inclusive governance, these municipalities hold the potential to confront adversity and generate models that inspire other regions facing comparable climatic and structural challenges.

6.1. Technological Enablers for Semi-Arid Smart Cities

The transformation of semi-arid cities increasingly depends on technological enablers that integrate sustainability and innovation. Digital solutions such as the Internet of Things (IoT) support environmental monitoring, optimize water and energy use, and strengthen disaster preparedness. Renewable energy systems and energy storage reduce emissions and increase resilience, while digital platforms expand local markets and foster entrepreneurship. Blockchain enhances transparency in public management, and artificial intelligence (AI) improves efficiency in infrastructure and service delivery.

AI tools can also underpin predictive models for drought management, optimize energy distribution in smart grids, and improve decision-making in urban governance by analyzing large-scale socio-environmental data. In semi-arid contexts, the combination of AI, IoT, and remote sensing enhances adaptive capacity, enabling the monitoring of water resources, prediction of agricultural productivity under irregular rainfall, and early detection of drought-related risks (Kamilaris & Prenafeta-Boldú, 2018). Evidence from global studies further shows that AI integration in renewable energy systems and smart grids improves stability, efficiency, and resilience, key factors for regions exposed to climate stress (Wang et al., 2025).

When aligned with circular economy practices, local knowledge, and citizen engagement through participatory digital platforms, these enablers offer practical pathways to accelerate the transition toward more inclusive, resilient, and sustainable cities in the semi-arid region.

7. Conclusion

This article examined the Caatinga as a living laboratory for smart and sustainable cities, showing how climate pressures, socio-environmental vulnerabilities, and structural inequalities can become drivers of resilience, innovation, and inclusive governance. Based on the SGSAC, the analysis positioned the region not as peripheral, but as a pioneering arena where urban strategies can be tested, adapted, and scaled.

The scenarios outlined both risks and opportunities. While pessimistic pathways reveal the persistence of structural barriers, baseline and optimistic trajectories demonstrate that strategic governance, investments in infrastructure and human capital, and alignment with global agendas can unlock transformative futures. The integration of the quadruple helix and technological enablers such as IoT, renewable energy, digital platforms, and artificial intelligence shows that resilience extends beyond adaptation to proactive, innovative, and inclusive systems.

From a policy perspective, three priorities stand out: (i) strengthening transparent and long-term governance mechanisms, (ii) ensuring investments in infrastructure and human capital suited to semi-arid contexts, and (iii) promoting equity-oriented innovation that reduces inequalities while fostering resilience. These principles reinforce the need for stable policies

across political cycles, capable of mobilizing public–private partnerships and integrating social justice with ecological limits.

Ultimately, the Caatinga demonstrates that semi-arid cities can serve as global exemplars of how to reconcile ecological limits, social justice, and economic viability. By 2030, if collaborative, forward-looking, and innovative pathways are effectively implemented, the semi-arid region may not only overcome its historical challenges but also inspire sustainable futures far beyond its borders.

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