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Review Article

CbSDI for Ecological Sustainability and Smart Urban Development in Kigali: An Integrated Approach to Building Resilient Cities

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Abstract

Urbanization presents pressing challenges for sustainability, requiring cities to balance equity, economic growth, and environmental preservation. Kigali, Rwanda's capital, has emerged as a model for integrating ecological sustainability with smart city development. This study examines Kigali's initiatives in green infrastructure, biodiversity conservation, waste management, renewable energy, and sustainable transportation, highlighting their role in enhancing resilience and livability. Projects such as the Nyandungu Urban Eco-Park, car-free zones, and solar energy installations demonstrate the city's commitment to harmonizing urban growth with environmental protection. Smart city approaches, including ICT-enabled transportation systems and real-time environmental monitoring, further optimize resource use and reduce ecological impacts. The findings reveal that Kigali's strategies supported by government commitment, collaborative partnerships, and innovative technologies have significantly advanced ecological restoration and sustainable urban planning. However, challenges remain, including limited resources, infrastructure gaps, and socio-economic inequalities. A SWOT analysis underscores opportunities in green investment, circular economy practices, and international collaboration, while identifying threats such as climate change, land scarcity, and technological dependencies. Overall, Kigali's experience illustrates how developing cities can leverage nature-based solutions and smart technologies to achieve ecological sustainability. The research concludes that continued investment in green infrastructure, renewable energy, and sustainable mobility, alongside long-term impact assessments, will be critical for scaling Kigali's model to other urban contexts. By prioritizing environmental health and social well-being, Kigali sets a benchmark for resilient, inclusive, and sustainable cities.

Keywords

Community, Biodiversity, Landscape, Planning, Ecology, Development

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1. Introduction

Urbanization has raised concerns about the sustainability of cities, demanding a balance between equity, economic viability, and environmental preservation. The Brundtland Report emphasizes the need for sustainable development that meets present needs without compromising future generations' ability to meet theirs [1, 11]. Rapid population growth, especially in urban areas, often surpasses the capacity of environmental resources, leading to challenges in housing, healthcare, food security, and energy [57]. Concurrently, biodiversity faces significant threats, with species extinction accelerating at unprecedented rates. Although debates persist about the exact Figures, there is consensus that actions can still reverse this decline [15, 19, 36].

Ecological sustainability in urban landscapes and smart cities focuses on harmonizing urban development with environmental preservation. This involves practices like green infrastructure parks, urban forests, and green spaces to mitigate pollution, enhance biodiversity, and improve residents' quality of life [6, 27]. Sustainable urban design emphasizes renewable energy, water efficiency, and reducing energy consumption [9]. Smart cities complement this vision by employing technology and data analytics to optimize urban systems such as traffic flow, waste management, and resource use, thus minimizing environmental impacts [25, 44]. Nature-based solutions, including green roofs, permeable pavements, and urban agriculture, alongside sustainable transportation systems, are crucial to achieving ecological sustainability [33, 46]. These efforts aim to create resilient, livable cities that benefit both current and future generations [60].

Kigali, Rwanda's capital, exemplifies ecological sustainability in urban landscapes and smart cities. Over recent decades, the city has pursued green infrastructure projects, effective waste management systems, and renewable energy initiatives, striving to align urban development with environmental preservation [8, 55]. These efforts demonstrate the potential for integrating sustainability principles and smart technologies in developing countries [5, 16, 62]. Kigali's experience highlights the challenges and opportunities of implementing ecological sustainability, making it a relevant case study for exploring strategies to create environmentally friendly and technologically advanced urban environments [2]. The research aims to explore the role of biodiversity, social and economic factors, wetland restoration, green spaces, sustainable planning, and initiatives like car-free days in promoting ecological sustainability and resilience in urban landscapes.

2. Literature Review

The rapid growth of the global population and globalization has profoundly impacted the environment, altering its structure and function. The integration of worldviews, products, and ideas, while fostering international connections, has compromised natural resources and environmental health [30, 35]. Kigali, Rwanda's capital, exemplifies efforts to reverse these effects through ecological restoration initiatives. Notable projects include the transformation of degraded areas like Kanyinya and Mount Kigali into urban forests and the restoration of wetlands such as Nyandungu Urban Eco-Park, which serve crucial ecological functions like water filtration and biodiversity support [41, 43, 53]. Sustainable land management practices, including reforestation and agroforestry, combat soil erosion and improve land fertility [56].

Kigali has embraced green infrastructure, creating parks and urban gardens that enhance biodiversity, recreation, and climate regulation [16]. Sustainable transportation is also a focus, with initiatives such as public bicycle-sharing programs and electric motorcycles, reducing greenhouse gas emissions and improving air quality [1, 63]. A significant 52% share of non-motorized trips in Kigali demonstrates the city's commitment to eco-friendly mobility solutions [32]. These measures underscore Kigali's integrated approach to urban sustainability, utilizing nature-based solutions and innovative transportation strategies to restore ecosystems, conserve biodiversity, and foster resilience [54, 59].

Urbanization presents both challenges and opportunities for sustainability, particularly in pursuing SDG 11 on sustainable cities. Despite its environmental and social pressures, urbanization allows for the adoption of advanced technologies to optimize resource efficiency, promote sustainable land use, and alleviate ecosystem stress [10, 17]. These strategies aim to improve economic and societal outcomes while advancing the governance of sustainable urban development [49]. Kigali's approach reflects a transformative model for integrating ecological restoration and sustainable urban planning to create a livable and sustainable urban environment.

3. Contextual Analysis of Kigali City

Kigali, the capital of Rwanda, is situated in the country's central region on hilly terrain surrounded by lush green valleys. Spanning approximately 730 square kilometers, the city's elevation ranges from 1,300 to 1,600 meters above sea level, offering unique opportunities and challenges for ecological sustainability [28]. Rapid population growth, fueled by urbanization and rural-urban migration, has increased demands for infrastructure, services, and resources, raising concerns about ensuring social inclusivity and equity [34, 58].

Kigali's ecological landscape integrates natural and urban environments, featuring green spaces, urban forests, and parks that enhance its aesthetic appeal and offer recreational opportunities [47, 51]. The city is committed to preserving its wetlands, which are critical for water regulation and biodiversity. However, urbanization and inadequate management have degraded key wetlands like Nyandungu, impairing their ecosystem services and increasing flood risks during heavy rainfall [21]. Other wetlands, such as those near industrial areas like

Gikondo, have also experienced environmental stress. Kigali's efforts to address these challenges underscore its dedication to ecological sustainability and environmental conservation, balancing urban development with the need to protect critical ecosystems and ensure a resilient urban environment.

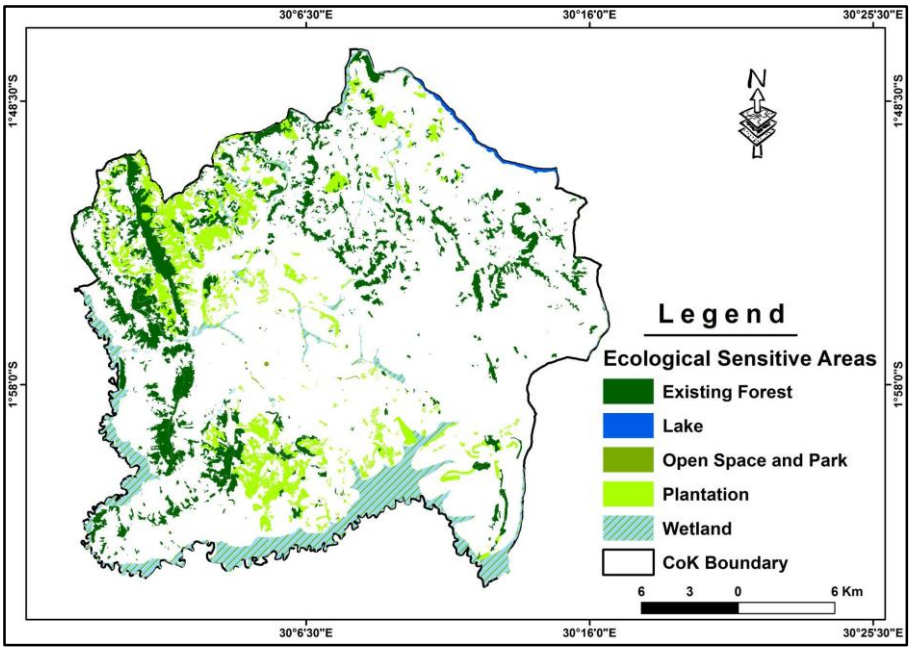


Figure 1. *Kigali ecological sensitive areas data source: CoK Masterplan database 2020.*

Kigali serves as Rwanda's economic hub, hosting government administration, business, and industries such as tourism, IT, and finance. The city's rapid economic growth, bolstered by local and international investments, presents opportunities for innovation but also challenges in resource consumption, waste management, and environmental sustainability [22, 48]. To address urbanization pressures and population growth, Kigali has prioritized ecological sustainability to balance development with environmental conservation, ensuring resilience and livability for future generations [13, 61].

Kigali has implemented key policies and initiatives promoting sustainability and smart city development. The Kigali Conceptual Master Plan emphasizes sustainable land use, compact urban design, and green infrastructure to minimize urban expansion's ecological footprint [7]. Projects such as the Nyandungu Urban Eco-Park showcase ecological restoration, enhancing biodiversity and creating recreational spaces. Sustainable transportation initiatives, including a public bicycle-sharing program and electric motorcycles, reduce traffic congestion and greenhouse gas emissions, advancing eco-friendly mobility options.

The city has also focused on waste management and renewable energy. Waste reduction and recycling programs, including sorting centers and composting practices, contribute to a circular economy. Solar energy projects, such as installing solar panels on public infrastructure, reduce reliance on fossil fuels and carbon emissions. Through initiatives like the Kigali Innovation City project, the city aims to drive technology-driven solutions for sustainable development and economic growth, underscoring its commitment to creating a sustainable and resilient urban environment [7, 22].

4. Ecological Sustainability Initiatives

Kigali is dedicated to achieving ecological sustainability by addressing key environmental challenges, including deforestation, waste management, renewable energy adoption, sustainable transportation, and urban food production. Its vision emphasizes creating a greener, more resilient, and livable city that ensures residents' well-being while preserving the natural environment. By integrating green infrastructure, conserving urban biodiversity, implementing efficient waste management systems, and advancing renewable energy and eco-friendly transportation, Kigali adopts a holistic approach to sustainable urban development. These initiatives not only tackle pressing environmental issues but also enhance the city's resilience and quality of life [8]. Through its comprehensive efforts, Kigali exemplifies how cities can promote ecological sustainability across multiple sectors, setting a benchmark for other urban areas aiming to build a greener and more sustainable future.

a) Green Infrastructure

Kigali has prioritized green infrastructure to advance ecological sustainability, implementing initiatives that expand green spaces, urban forests, parks, and permeable pavements. These efforts improve air quality, regulate temperature, manage stormwater, and enhance biodiversity, creating a resilient

and livable urban environment [31]. Since 2015, the Global Green Growth Institute (GGGI) has partnered with Rwanda on green urbanization and climate-resilient development. Additionally, the Rwanda Green Building Organization (RwaGBO), launched in 2016, promotes sustainable construction practices by providing certification and training based on government-adopted green building indicators [37, 38]. This initiative unites stakeholders in the construction industry to drive sustainability.

b) Urban Biodiversity Conservation

Kigali places emphasis on conserving urban biodiversity and preserving natural ecosystems within the city. The establishment of protected areas, such as the Nyandungu Urban eco-Park, contributes to biodiversity conservation and habitat restoration [52]. The city also promotes the planting of native species and the creation of green corridors, which enhance wildlife habitats and support ecological connectivity. Furthermore, there are ongoing projects such as Gikondo wetlands located in Rwandex, Rwampara, Nyabugogo, Gacuriro, Mulindi and Masaka wetlands- which will be worked on to the same level as the recently completed Nyandungu Eco-Tourism Park [45].

c) Waste Management Systems

The Rwanda Environment Management Agency (REMA) estimates that between 1,800 and 2,000 tons of solid municipal wastes are generated in the city per day while other studies put it at a more realistic 400-800 tons per day. Kigali city's waste is exclusively disposed of at Nduba landfill, located in Gasabo district [24, 40, 42] and this is a serious issue as where the waste generated is increasing day by day especially food waste. Kigali has implemented effective waste management systems to address the growing waste generation in the city. The establishment of waste sorting centers and recycling facilities promote waste reduction and recycling practices. Kigali encourages residents to separate their waste into different categories, facilitating proper disposal and recycling. These initiatives contribute to minimizing the environmental impact of waste and promoting a circular economy approach.

d) Renewable Energy

Energy policy instruments might include trade remedies, industrial policy, or regulatory instruments such as certificates, emissions limitations, renewable energy quotas [18]. According to NST1, *"Halve the number of households depending on firewood as a source of energy for cooking from 79.9% (2016/17) to 42% by 2024. This will be achieved by focusing on promoting use of alternative fuels such as cooking gas and biogas. Efforts will be concentrated on promoting use of cooking gas in urban areas"*. And also, Kigali has embraced renewable energy sources as part of its commitment to sustainability. The city has implemented solar power projects, including the installation of solar panels on public buildings, streetlights, and traffic lights. In addition, the city of Kigali has promoted the usage of cooking gas usage as the key steps to reduce continuation of ecological degradation. This transition to renewable energy and smart energy initiatives help to reduce reliance on fossil fuels, lower carbon emissions, and enhance energy efficiency.

e) Sustainable Transportation

Kigali has implemented sustainable transportation initiatives to address traffic congestion and reduce air pollution [3]. These include a public bicycle-sharing program and the adoption of electric motorcycles, which promote eco-friendly mobility and lower carbon emissions. Information and Communications Technology (ICT) further enhance smart transportation through cashless systems, traffic flow management, and real-time project monitoring, ensuring minimal ecological impact [39]. Policies and strategies focusing on safety and sustainability aim to reduce transportation-related accidents and promote non-motorized and public transport options [37, 38].

The city has also introduced car-free zones, such as Imbuga City Walk and Biryogo, along with bi-monthly car-free days, fostering sustainable mobility and reducing air pollution [43]. These initiatives encourage active transportation modes like walking and cycling while enhancing urban air quality and reducing particulate matter [PM2.5 (μ/m3), 17]. Moreover, integrating health interventions, such as diabetes risk stratification during car-free days, optimizes resource allocation and supports public health goals [23, 26]. These measures contribute to creating vibrant, sustainable urban spaces and improving residents' quality of life to the city's community.

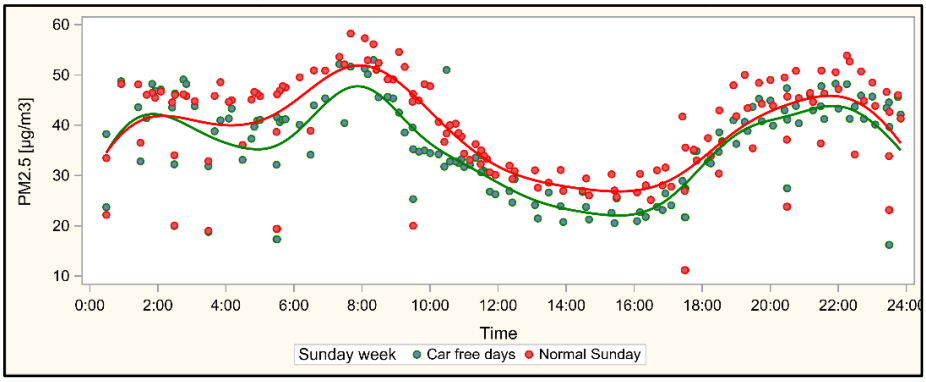


Figure 2. *Hourly mean variation of PM2.5 from 2017 to 2020 in Kigali Source: [17].*

Kigali's initiatives have established it as a vibrant, green, and smart city, emphasizing innovation and ecological restoration. Projects like the Nyandungu Eco Park highlight its commitment to biodiversity, low carbon emissions, and public health. These efforts align with sustainable development principles, making Kigali a model for ecological sustainability and resident well-being.

f) Smart City Approaches:

Kigali has embraced smart city strategies to enhance efficiency, sustainability, and quality of life. Initiatives include smart transportation systems like public bicycle-sharing and electric motorcycles [50], renewable energy projects such as solar power installations, and the Kigali Innovation City, which fosters innovation and entrepreneurship. These strategies leverage technology to improve urban living, sustainability, and economic growth.

Smart city technologies support ecological sustainability through real-time monitoring of environmental factors like air quality, water usage, and waste management [4]. Data analytics optimize resource allocation and inform sustainable policies, while smart energy management systems improve energy efficiency and reduce carbon emissions [20, 29]. These technologies enable better resource management and foster resilient urban environments. While smart city approaches offer benefits such as enhanced environmental monitoring, energy efficiency, and data-driven decision-making [14], they also present challenges. These include high costs, technological dependencies, privacy concerns, and the need for skilled personnel [12]. Addressing these requires strategic planning, stakeholder collaboration, and continuous evaluation to align smart city technologies with Kigali's ecological sustainability goals.

5. Case Study Analysis and Findings

Kigali, the capital of Rwanda, has undergone significant transformation to become a model of ecological sustainability and smart urban development. Key initiatives to drive this change include the establishment of car-free zones like Imbuga City Walk and Biryogo, which promote active transportation and reduce air pollution. The city also emphasizes green infrastructure and wetland restoration, with projects such as the Nyandungu Eco Park preserving biodiversity and enhancing ecosystem resilience. Additionally, Kigali has embraced smart city technologies, using ICT for real-time monitoring and resource optimization. These efforts have positioned Kigali as a green, smart city, balancing environmental health, social well-being, and economic growth, setting an example for cities worldwide.

Table 1. *Strengths, Weaknesses, Opportunities, and Threats (SWOT) Encountered in the Community-based Ecological Sustainability Initiatives and Smart City Approaches in city of Kigali.*

Strengths	Weaknesses
Government Commitment	Limited Resources
Collaborative Partnerships	Infrastructure Challenges
Innovative Technological Solutions	Data Availability and Accessibility
Green Infrastructure Integration	Regulatory and Policy Framework
Public Engagement and Awareness	Socioeconomic Inequalities
Opportunities	Threats
Green Investment and Financing	
Knowledge Exchange and Capacity Building	Climate Change Impacts
Tourism and Sustainable Development	Limited Institutional Capacity
Circular Economy Practices	Land Scarcity and Urbanization Pressures
Green Job Creation	Socio-economic Disparities
International funding and supports	Technology Dependencies and Risks
Integration of nature-based solutions	

The assessment of strengths, weaknesses, opportunities, and threats in the implementation of ecological sustainability initiatives and smart city approaches in Kigali provides valuable insights into the city's progress and challenges. By capi-

talizing on its strengths, addressing weaknesses, exploring opportunities, and mitigating threats, Kigali can enhance its ecological sustainability efforts and emerge as a leading model for sustainable and smart cities. The city's commitment to prioritizing the health of the environment, while meeting the needs of its residents and businesses, will contribute to a more livable, resilient, and prosperous future for all.

6. Conclusion and Recommendations

This research concludes that Kigali has made notable strides in integrating ecological sustainability with smart city development. Initiatives such as car-free zones, green infrastructure, wetland restoration, and smart city strategies have significantly improved sustainability and the quality of life for residents, positioning Kigali as a leading example for other cities. To further advance its sustainability goals, recommendations include continued investment in green infrastructure, the promotion of sustainable transportation, and the expansion of renewable energy solutions. Future research should focus on assessing the long-term impacts of these initiatives, exploring their socio-economic benefits and challenges, and evaluating the potential for scaling Kigali's approaches to other urban contexts.

Abbreviations

SDG	Sustainable Development Goals
NST1	National Strategy for Transformation 1
GGGI	Global Green Growth Institute
RwaGBO	Rwanda Green Building Organization
REMA	Rwanda Environment Management Agency
ICT	Information and Communications Technology
PM2.5	Particulate Matter (≤2.5 Micrometers)
CoK	City of Kigali
CbSDI	Community-based Sustainable Development Interventions

Author Contributions

Joel Ndayisaba: Conceptualization, Methodology, Project administration, Software, Supervision, Writing – review & editing

Theodore Nshimiyumuremyi: Writing – original draft, Writing – review & editing

Mucyo Ndera Tuyizere: Data curation

Janvier Hitimana: Writing – original draft, Writing – review & editing

Eric Ndagijwenimana: Writing – review & editing

Conflicts of Interest

There are no conflicts of interest.

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