Urban Greening and Renewable Energy in Riyadh: Environmental and Public Health Perspectives within Saudi Arabia's Vision 2030

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ABSTRACT

This literature review critically examines the environmental and public health impacts of urban greening and renewable energy integration, especially in the context of Riyadh, Saudi Arabia. Framed within the national Vision 2030 sustainability strategy, the review synthesizes empirical studies that explore the role of green infrastructure and clean energy solutions in mitigating environmental hazards, such as air pollution, urban heat island effects (UHI), and respiratory health risks. Key initiatives—including the Saudi Green Initiative (SGI), Green Riyadh, and King Salman Park—illustrate the transformative potential of large-scale ecological projects that enhance biodiversity, lower surface temperatures, and improve air quality. The review finds that large-scale green infrastructure projects significantly reduce ambient temperatures, improve air quality, and enhance biodiversity. Renewable energy initiatives, particularly in solar and wind, contribute to reducing carbon emissions and fossil fuel dependence. These efforts collectively support Riyadh's KPIs under Vision 2030. However, gaps remain in financing, public engagement, and localized policy execution, especially compared to global benchmarks like China and Singapore. Urban greening and renewable energy offer transformative benefits for Riyadh's sustainability goals. Yet, success depends on adaptive governance, public participation, local expertise development, and flexible implementation tailored to Riyadh's unique socio-environmental context.

Keywords: Urban Green Infrastructure; Sustainable Urban Development; Urban Heat Island; Climate Resilience; Saudi Arabia Sustainability Initiatives; Urban Biodiversity

INTRODUCTION

Humans have long been drawn to greenery, for there is a deep-rooted connection, especially for those who have been seeking affinity and an intertwined relationship with nature. This bond began with practices like foraging, sustainability, and agriculture, which have evolved into more structured systems such as agroecology[1,2]. These early interactions with the natural world have influenced patterns of settlement, habitation, and later, urban development, including infrastructure growth and municipal planning, which have shaped modern cities. Today, green infrastructure methods, especially sustainable architecture and eco-friendly construction, are recognized as effective strategies for integrating nature into urban environments. Concepts such as urban ecology and green building are those that have been shown to offer multifaceted benefits across environmental, economic, and social dimensions[1,3,4]. They contribute to regulating urban climates, improving air quality, supporting local food production, and providing wildlife corridors, which enhance biodiversity, while also improving aesthetics and offering recreational spaces for residents[1-4].

Eco-centric urban planning, also known as sustainable infrastructure, includes natural features like public gardens, plants, wetlands, and city trees in city design to improve biodiversity, clean the air and water, and regulate local climates. This method serves as a practical remedy to urban issues like environmental contamination and urban heat islands (UHIs) while promoting ecosystem vitality, atmospheric cooling, and improved human health[5,6].

Elements such as vegetated rooftops, urban woodlands, and leafy pathways strengthen climate adaptability by alleviating flooding hazards, boosting air cleanliness, and enriching urban livability and economic value[7]. In Riyadh's extremely hot and arid climate, integrating greenery and reflective or porous materials has proven effective in decreasing nighttime temperatures by up to 8 °C and increasing air moisture levels, thereby cutting building energy usage[7].

The Saudi Green Initiative (SGI), introduced in 2021, emphasizes environmental restoration and climate action through large-scale afforestation, urban greening, and ecosystem enhancement. Riyadh's transformation includes projects like Green Riyadh, King Salman Park, and Sports Boulevard, creating a green network that promotes walkability and connects to the Metro, reducing reliance on private cars[7,8].

Riyadh's Environmental Revitalization Plan is a large-scale, strategic effort aimed at expanding green infrastructure across the city to enhance ecological, social, and economic conditions. This initiative, aligned with Saudi Arabia's Vision 2030 and the SGI, focuses on developing interconnected public gardens, botanical spaces, outdoor areas, community parks, environmental gardens, outdoor hubs, biodiversity corridors, and Urban woodlands to combat urban overheating, support biodiversity, and improve public health[7,9,10]. **The Kingdom's 2030 roadmap and ecological sustainability initiative have introduced groundbreaking efforts in response to the urgent challenge of rising urban temperatures, essentially creating a green transformation movement in Riyadh to strengthen environmental resilience[7,10].**

Key projects like Green Riyadh aim to increase the city's green

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space from 1.5% to 9%, plant 7.5 million trees, and reduce urban temperatures, carbon dioxide (CO2) levels, and energy consumption[7]. In addition, the design of the Sports Boulevard and King Salman Park aims to foster wellness, offer recreational areas, and enhance the city's climate resilience. These projects are part of a broader commitment to sustainability, supported by Riyadh's historical green initiatives like the Diplomatic Quarter and the restoration of Wadi Hanifah[7,11]. By 2030, Riyadh plans to plant 16 million trees, vastly increasing tree density and building an interconnected network of green spaces that will boost biodiversity, reduce heat, and improve the quality of life for its residents[7-12].

King Salman Park, located at the center of Riyadh, is the world's largest transformation of a former airport into a lush urban park. Spanning five times the size of New York's Central Park, the park features 800 plant species and integrates 70% of its area into gardens, forests, hiking trails, and green spaces, while the remaining 30% offers 150 attractions, including museums, sports facilities, and a sustainable convention center. Intending to decarbonize the built environment, the park's million trees and 14 million shrubs contribute to cooling the city, improving air quality, and providing healthier urban space. It is expected to attract 50 million visitors annually and support 96,000 residents[7,13].

Green Riyadh, as part of Saudi Arabia's Vision 2030, is aiming to become one of the world's most ambitious urban greening projects, designed to improve urban green spaces. Comparable large-scale endeavors include China's Sponge Cities initiative, aimed at bolstering urban resilience through the adoption of green infrastructure[14]; Singapore's "City in a Garden" strategy[15], which seamlessly integrates natural elements within the urban environment; and the Million Trees NYC initiative in the United States[16], which endeavored to plant and sustain one million trees across New York City. The Green Riyadh initiative has been strategically devised to position Riyadh among the world's top 100 most livable cities by expanding green spaces, introducing extensive tree planting throughout the urban expanse, and employing reclaimed water for irrigation purposes. This project aspires to enhance air quality, mitigate urban heat, and foster healthier lifestyles for its inhabitants, which is expected to contribute significantly to the city's sustainability[17,18].

OBJECTIVE AND SCOPE OF REVIEW

This paper aims to review and analyze the environmental and public health impacts of urban greening and renewable energy initiatives in Riyadh, assess their contribution to Vision 2030 goals, and benchmark Saudi efforts against global urban sustainability models. The review will explore several key research questions: First, what is the cumulative empirical evidence on how urban greening and renewable energy initiatives affect key environmental and health indicators, particularly in fast-growing urban settings such as Riyadh? Second, to what extent do the benefits of green infrastructure and clean energy solutions apply to Riyadh's unique climatic, urban, and socio-political context, especially in informing region-specific strategies? Third, which specific environmental hazards, such as PM2.5, elevated surface temperatures, and related health conditions, are most significantly mitigated by green infrastructure and clean energy solutions, based on findings in the literature? Fourth, how do the documented environmental and health outcomes of initiatives like Green Riyadh align with the strategic pillars, key performance indicators (KPIs), and environmental objectives of Saudi Vision 2030, particularly concerning urban sustainability, improved air quality, and public well-being? Fifth, what key knowledge gaps or implementation challenges hinder the effective formulation of urban policy and the localization of international best practices in Riyadh's green transformation, particularly in comparison to global models like China's sustainable urban initiative?

URBAN SUSTAINABILITY AND ENVIRONMENTAL TRANSFORMATION IN RIYADH: KEY INITIATIVES AND STRATEGIC FRAMEWORK FOR VISION 2030

As the administrative and economic nucleus of Saudi Arabia, Riyadh is undergoing an ambitious transformation as part of Vision 2030, which is designed to establish a diversified, sustainable, and competitive urban economy. There is a strategic framework in place for guiding this transformation, encompassing environmental, social, and infrastructural domains. For urban development, the city is pursuing a set of integrated KPIs that aim to elevate Riyadh into the top 100 most livable cities globally by 2030. Increasing green urban coverage to 9.1%, reducing per capita consumption of electricity and water, and enhancing public infrastructure are among the targets that have been established to improve environmental performance and quality of life[19-38]. A detailed summary of the KPIs for Riyadh, aligned with Vision 2030, is highlighted in Table 1.

LITERATURE REVIEW

Multiple severe environmental challenges arising from global economic development pose major threats to human health, including climate change and increased levels of greenhouse gases, along with PM2.5 pollution. Greenhouse gas emissions—carbon dioxide, methane, and nitrous oxide—are intensifying global warming. While using fossil fuels supports technological progress and economic development, it also leads to environmental degradation and widespread air pollution. In response, many countries are intensifying efforts to promote sustainable energy use, although significant dependence on nonrenewable resources remains. The advancement of Industry 4.0 relies heavily on energy consumption, yet the continued use of fossil fuels contributes to rising carbon emissions and worsening air quality[39-41].

Harmful airborne particles known as PM2.5 present substantial public health risks, as they are linked to asthma, chronic obstructive pulmonary disease (COPD), and lung cancer, as well as cardiovascular conditions such as heart attacks, strokes, and hypertension[42-45]. Exposure to high levels of PM2.5 has also been associated with neurological disorders, adverse pregnancy outcomes, and increased mortality. Middle Eastern countries face particularly severe consequences from air pollution due to their heavy reliance on low-cost fossil fuels, which contribute significantly to global pollution levels. The Paris Agreement represents a global response to these challenges by emphasizing the development of renewable energy, the reduction of emissions, and the promotion of environmental and public health protection[42].

The Paris Agreement represents a global response to these environmental and public health challenges by promoting renewable energy development, reducing emissions, and protecting ecosystems[53]. Renewable and sustainable energy (RSE) is considered the most suitable alternative to established energy sources because it provides cleaner energy and supports sustainable operations. Research shows that fossil fuels account for more than 80% of the Saudi energy market and total energy consumption, while also contributing to environmental issues. By 2032, the country's electricity demand is projected to exceed 120 GW. To meet rising demand, Saudi Arabia plans to reach 9.5 GW of RSE capacity by 2030 and aims to increase renewable energy use to 50% by 2050 [54] (see Table 2).

Table 1. Vision 2030 Environmental Health Interventions and Projects in Riyadh: KPIs, Hazards Addressed, and Expected Impacts

Vision 2030 KPI	Environmental Hazard Addressed	Intervention	Expected Health/Environmental Impact	Ref.
Increase public transport usage to 18%	Air pollution from private vehicles	Development of Riyadh Metro and public transport infrastructure	Traffic congestion ↓, Vehicular emissions ↓, and air quality ↑	[32]
Reduce carbon emissions by 278 million tons	Greenhouse gas emissions	Promotion of renewable energy, electric vehicles, and public transport	Carbon emissions ↓, Climate change mitigation ↑	[24, 25]
Improve air quality (reduce pollutants like PM and NO_x)	Air pollution	Implementation of stricter emission standards, expansion of green spaces, and monitoring systems	Air quality ↑, Respiratory and cardiovascular diseases ↓	[12, 33]
Increase green spaces and urban greening initiatives	Urban heat island effect, air pollution	Planting trees, creating parks, and implementing green roofs	Urban heat ↓, Mental health ↑, Air quality ↑	[23]
Increase total green coverage from 1.5% to 9%	Urban heat island effect, air pollution	Expanding green areas, developing parks, and promoting tree planting	Urban heat ↓, Improved air quality ↑, enhanced biodiversity ↑	[23]
Reduce temperature by 1.5°C to 2°C	Urban heat island effect	Riyadh Green Project, King Salman Park, Wadi Hanifah Redevelopment	Temperature ↓, Urban heat effect ↓, Air quality ↑	[23]
Promote water conservation and reduce waste	Water scarcity and waste mismanagement	Smart water management systems, waste reduction initiatives, recycling	Water use efficiency ↑, Waste ↓, Resource management ↑	[34]
Enhance urban resilience to climate change	Extreme weather events, flooding, heat waves	Development of climate-resilient infrastructure, green urban spaces	Climate-related risks ↓, Vulnerability to extreme weather ↓	[35]
Develop Sports Boulevard	Air pollution, limited recreational spaces	Creation of a multi-use recreational area with green spaces and sports facilities	Physical activity ↑, Mental health ↑, Community engagement ↑, Air quality ↑	[7, 11]
Develop Riyadh Art	Lack of cultural engagement, urban heat	Creation of public art spaces, cultural events, and green public areas	Community engagement ↑, Mental health ↑, Urban heat ↓	[36]
Redevelop Wadi Hanifah	Urban heat island effect, flooding	Environmental restoration, green spaces, and flood management	Temperature ↓, Biodiversity ↑, Improved water management, Flood risk ↓	[7, 11]
Create King Salman Park	Urban heat island effect, limited green space	Development of one of the world's largest urban parks with green areas and cultural spaces	Temperature ↓, Air quality ↑, Community health ↑	[7,13]
Solar Energy Projects (Riyadh Solar Power Project)	Greenhouse gas emissions, energy dependency	Large-scale solar energy projects in Riyadh	CO_2 emissions ↓, Renewable energy share ↑, Clean energy access ↑	[37]
Riyadh Green Project	Urban heat island effect, air pollution	Planting 7.5 million trees, creating green corridors, and expanding green rooftops	Urban heat ↓, Air quality ↑, Biodiversity ↑, Community well-being ↑	[23]
Development of Urban Wind Farms	Greenhouse gas emissions, energy dependency	Installation of urban wind farms and energy-efficient systems	CO_2 emissions ↓, Energy efficiency ↑, Urban sustainability ↑	[38]

Renewable energy adoption aligns with the pillars of sustainable development, including economic growth, capital formation, job creation, industrialization, productivity, cultural enrichment, healthcare access, quality of life, social welfare, ecosystem restoration, waste management, and climate resilience[55].

The UHI effect remains a major environmental concern because it influences suburbanization, gentrification, industrial growth, capital expenditures, and technological advancements. UHI

The combination of remote sensing, satellite imagery, and geospatial data through satellite technology serves as an effective environmental monitoring tool, specifically measuring vegetation coverage and Earth's surface temperature. Different parts of the electromagnetic spectrum enable these technologies to distinguish between land types, which include vegetation, soil, and water resources. Remote sensing provides precise data collection at a low cost, as it operates autonomously, making it optimal for tracking urban temperatures and observing the systematic evolution of vegetation[17,64,65].

Change detection, which involves comparing images or data collected at different times to identify environmental shifts, has been widely applied in forestry, agriculture, urban development, and coastal management for monitoring changes over time. Using satellite data and climate information, this study focuses on identifying UHI patterns in Riyadh, a city that has been experiencing a hot, dry climate and rapid urban growth. Previous research has shown a rising trend in Riyadh's temperatures, suggesting UHI influence. The Green Riyadh project was introduced as a response, aiming to improve sustainability and reduce heat through increased vegetation, especially for combating the UHI effect[17].

Table 2. Summary of Literature Regarding Environmental and Public Health Challenges and Renewable Energy Opportunities in Saudi Arabia

Focus of Study	Key Challenges/Issues	Impacts on Environment & Public Health	Strategic Solutions & Policy Initiatives	Ref.
Greenhouse Gas Emissions & Fossil Fuels	CO_2, CH_4, N_2O emissions from fossil fuels; energy-intensive industrial development	Global warming, extreme weather events, rising sea levels, and degraded air quality	Transition to a low-carbon economy, Paris Agreement goals, promotion of renewable energy sources	[46-52, 61]
Air Pollution (PM2.5)	Fine particulates from industrial emissions, vehicles, and the burning of fossil fuels	Linked to asthma, COPD, cardiovascular diseases, neurological issues, and increased mortality	Air quality standards, pollution control tech, awareness campaigns, urban air monitoring	[42–45]
Saudi Arabia's Energy Dependency	>80% reliance on fossil fuels; energy demand projected to exceed 120 GW by 2032	Depletion of finite resources, carbon pollution, and economic vulnerability	Vision 2030 energy diversification, targets: 9.5 GW (2030), 30% renewables by 2030, 50% by 2050	[54, 61]
Renewable Energy Resources	Untapped potential in solar, wind, biomass, geothermal, wave, and small-scale hydropower	Delayed green transition, missed economic opportunities in the clean energy sector	Projects like Dumat Al-Jandal Wind Farm, urban waste-to-energy facilities, PV installations in desert zones	[56–60]
Urban Heat Island (UHI) Effect	Urban expansion reduces vegetation and green spaces, increasing local temperatures	Increased electricity demand, heat-related illnesses, and reduced comfort in urban settings	Green Riyadh Initiative, planting trees, urban greening, and eco-friendly construction materials	[17, 63]
Remote Sensing & Monitoring	Lack of consistent monitoring of temperature, green coverage, and land-use changes	Insufficient data for policy, delayed climate response	Use of satellite imagery, geospatial data, and change detection for vegetation and temperature tracking	[17, 64, 65]
Dust Storm Pollution	Riyadh's desert climate, elevation, and urban construction increase the frequency of dust storms	Health risks: respiratory disease, cognitive effects in children, metal toxicity	Research expansion, pollution masks, improved city planning, vegetation buffers, and dust filtering tech	[66, 67]
Economic Diversification & Green Finance	Oil-dependent economy needs innovation, sustainable development, and non-oil sector growth	Risk of economic stagnation and low resilience to energy market shocks	Green bonds (15% by 2030; 30% by 2060), support for SMEs, investment in value-added industries	[62]
Vision 2030 and Saudi Green Initiative	Frameworks for a low-carbon, diversified economy, focused on environmental sustainability and a knowledge economy	Positive impact on global climate goals, economic modernization, and improved public health	Investments in clean tech, eco-tourism, carbon neutrality targets, and enhanced governance of environmental policies	[61, 62]
Industrialization & Urban Growth	Manufacturing and urban expansion drive emissions, reduce green space	A carbon-intensive growth model increases health risks and climate vulnerabilities	Adoption of energy-efficient systems, low-emission industries, and sustainable city planning	[61]

MATERIALS AND METHODS

This study is a structured compilation and evaluation of several reviews that have been conducted on a specific research topic, commonly referred to as a meta-analysis or a systematic review of reviews. A standardized methodology was employed, especially for ensuring consistency and rigor in the selection and synthesis process. In this meta-analysis, state-of-the-art approaches were used, and the study protocol was developed following the reporting guidelines outlined in the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA).

We conducted a comprehensive search of PubMed, Scopus, Web of Science, and Google Scholar using the search terms "urban greening," "renewable energy," "environmental health," and related subtopics such as "air quality" and "sustainable urban development," along with terms like "Vision 2030 Saudi Arabia" and "global environmental benchmarking." We applied a language restriction and included only studies published in English. No restrictions were applied regarding the region of publication. The search covered articles published between 2002 and 2025 to ensure the inclusion of up-to-date and pioneering research.

We focused on empirical studies that addressed the environmental and public health impacts of urban greening and renewable energy adoption, particularly concerning the sustainability goals outlined in Saudi Arabia's Vision 2030. Studies that did not meet these criteria or did not directly address the impact of these environmental interventions in Riyadh were excluded.

INCLUSION AND EXCLUSION CRITERIA

Committed to Saudi Arabia's Vision 2030 and the Sustainable Development Goals at both regional and global levels, this paper reviews environmental health outcomes resulting from urban greening and renewable energy initiatives in Riyadh. Studies were included if they focused on urban greening or renewable energy adoption in Saudi Arabia, particularly Riyadh, and reported environmental health outcomes such as air quality, thermal comfort, or sustainability performance. Only peer-reviewed articles, government reports, or credible institutional publications in English were considered. Preference was given to studies contributing to regional or global benchmarking relevant to arid or semi-arid environments and aligned with Vision 2030 goals.

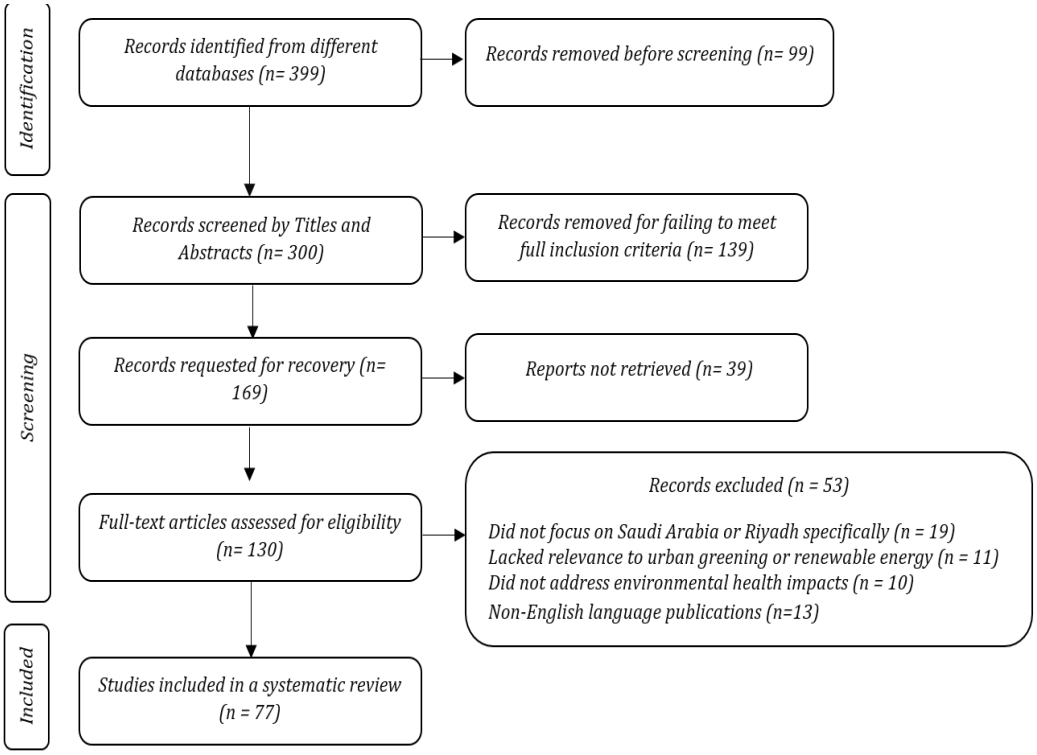

Figure 1. PRISMA Flow Diagram

Studies had to be excluded if: 1) they did not focus on urban greening or renewable energy in Saudi Arabia; 2) they lacked relevance to environmental health outcomes; 3) they were non-peer-reviewed sources (such as blogs or opinion pieces); or 4) they had not aligned with Vision 2030 goals or lacked sufficient data for analysis.

STUDY SELECTION

Following PRISMA guidelines, a comprehensive literature search was conducted to examine the environmental and public health impacts of urban greening and renewable energy in Riyadh. A total of 399 records were identified through searches across various databases. Before the screening stage, 99 records were removed due to duplication or irrelevance, leaving 300 records for title and abstract screening. Of these, 139 records were excluded for not meeting the full inclusion criteria. The remaining 169 records were requested for full-text retrieval; however, 39 could not be obtained. This led to 130 full-text articles being assessed for eligibility. During this stage, 53 articles were excluded for specific reasons: 19 did not focus on Saudi Arabia or Riyadh, 11 lacked relevance to urban greening or renewable energy, 10 did not address environmental health impacts, and 13 were non-English language publications. Ultimately, 77 studies met all the inclusion criteria and were included in the final systematic review (see Figure 1). These studies represent the most robust empirical evidence on the role of urban greening and clean energy strategies in enhancing air quality, mitigating urban heat, and improving public health outcomes in arid urban environments. The synthesis of these findings provides critical insight into region-specific sustainable development strategies and benchmarks Riyadh's progress against global best practices.

DISCUSSION

In this section, we discuss the findings concerning our research questions concerning the environmental and health impacts of urban greening and renewable energy initiatives in Riyadh.

What is the cumulative empirical evidence on how urban greening and renewable energy initiatives affect key environmental and health indicators, particularly in fast-growing urban settings?

Cumulative scholarly evidence underscores that urban greening and renewable energy initiatives exert a profound and beneficial influence on both environmental and public health metrics, particularly in rapidly urbanizing metropolises. Strategies such as afforestation, the establishment of urban parks, and the integration of verdant spaces serve to ameliorate air quality by attenuating pollutants, mitigate the urban heat island phenomenon, and enhance biodiversity. These green infrastructures also provide invaluable spaces for recreational and social activities, fostering mental well-being and mitigating stress, thereby yielding tangible improvements in both psychological and physiological health. Concurrently, the adoption of renewable energy technologies, such as solar, wind, and other sustainable energy solutions, contributes significantly to the reduction of carbon emissions, the enhancement of energy efficiency, and the attenuation of climate change impacts. These interventions not only cultivate more ecologically resilient urban environments but also mitigate public health risks, particularly those related to respiratory and cardiovascular afflictions, which are linked to pollution.

Sustainable development in urban populations relies on green spaces, as these areas provide a range of benefits that enhance air and water quality while also promoting public health and social well-being, thereby improving the overall quality of urban life. Green spaces encourage active lifestyles by offering opportunities for movement and exercise, which support both physical and mental health, as well as strengthen social connections among urban residents. Urban vegetation is central to public health research, as it has been associated with increased life expectancy and improved standards of urban living. The integration of urban green spaces contributes to environmental protection by reducing urban heat island effects, improving flood control, enhancing air quality, preserving wildlife ecosystems, and fostering ecological balance[68,69,70].

In response to global emission reduction targets and rising energy demands, many nations, including developing countries, are reassessing their energy strategies or transitioning to low-carbon energy. Public perception, ideology, and behavior play a pivotal role in shaping energy policy, as public support is vital for the success of renewable energy initiatives. In Saudi Arabia, despite being a top consumer of oil and natural gas, efforts are underway to diversify energy sources and reduce carbon emissions.

As part of Vision 2030, the Kingdom has set a target to produce 50% of its electricity from renewable sources by the year 2060. Initiatives such as the Sakaka Solar Plant, which is the nation's first utility-scale photovoltaic (PV) solar project with a capacity of 300 MW, and the Dumat Al-Jandal Wind Farm, which is the first large-scale wind energy project with a capacity of 400 MW, reflect Saudi Arabia's commitment to diversifying its energy portfolio. Despite these advancements, renewable energy still constitutes only a small portion of the country's overall energy mix[52].

To what extent do the benefits of green infrastructure and clean energy solutions apply to Riyadh's unique climatic, urban, and socio-political context, especially for informing region-specific strategies?

The advantages of green infrastructure and clean energy solutions are substantial; however, their applicability to Riyadh must be evaluated within the context of the city's distinctive climatic, urban, and socio-political conditions. Riyadh's hyper-arid climate, which is characterized by extreme heat and limited precipitation, poses challenges to traditional forms of urban greening that rely on water-intensive vegetation. Nonetheless, nature-based interventions that utilize drought-resistant and climate-resilient species can deliver significant benefits that include urban heat mitigation, improved air quality, and enhanced public health outcomes.

Riyadh's rapid urbanization and population growth highlight the need for sustainable energy and environmental design. The city's socio-political framework, shaped by Vision 2030, supports renewable energy and green infrastructure, aligning with national sustainability goals. Implementing these strategies, tailored to local conditions, can create region-specific models that address environmental challenges and enhance long-term urban resilience and quality of life[70,71].

Socio-politically, Saudi Vision 2030 drives ecological modernization, with initiatives like Green Riyadh showcasing a commitment to urban resilience and sustainability. However, for these initiatives to achieve their full potential, they must be calibrated to local socio-cultural dynamics, supported by multi-sectoral collaboration, and grounded in evidence-based policymaking.

In essence, while green infrastructure and renewable energy offer profound opportunities for Riyadh's sustainable transformation, their success hinges on adaptive planning, integrative governance, and the alignment of global best practices with indigenous imperatives.
Which specific environmental hazards, such as PM2.5, elevated surface temperatures, and related health conditions, are most significantly mitigated by green infrastructure and clean energy solutions, based on findings in the literature?

Airborne particulate pollutants, from both human and natural sources like desert dust and chemical reactions, impact environmental stability, ecosystem health, and community well-being. They also affect weather patterns, habitats, and regional climate conditions. Numerous epidemiological studies have associated exposure to fine particulates, especially those smaller than 2.5 μm (PM2.5)—with airway inflammation and circulatory problems, as they can penetrate deep into the lungs and enter the bloodstream. Coarser particles, under 10 μm (PM10), have been linked to adverse health outcomes, particularly in vulnerable populations such as children and the elderly[63].

Green infrastructure and clean energy solutions have been empirically validated to mitigate a spectrum of environmental hazards, particularly those related to atmospheric pollutants and urban thermal dynamics. Fine particulate matter (PM2.5), a pernicious agent associated with a myriad of respiratory and cardiovascular pathologies, is substantially attenuated through the deployment of vegetative interventions, such as arboreal canopy coverage, green roofs, and urban woodlands, which function as biotic filters, sequestering pollutants and improving ambient air quality. Additionally, elevated surface temperatures, which are exacerbated by the urban Heat island phenomenon, are significantly moderated through the integration of green spaces that facilitate shade provision, evapotranspiration, and natural cooling processes[64]. These interventions reduce extreme heat and heat-related illnesses, while clean energy systems like solar and wind lower greenhouse gas emissions and air pollutants linked to conditions such as COPD.

The rising global demand for energy, which is driven by the growing focus on sustainability, carbon footprint reduction, and decarbonization, has intensified the need for sustainable energy solutions. Traditional energy sources such as fossil fuels, natural gas, coal mining, and Oil drilling, which account for over 80% of global energy consumption, have significantly contributed to environmental degradation. These sources lead to ecosystem and soil degradation through the release of greenhouse gas emissions, which exacerbate climate change[54].

As a result, green energy, circular economy principles, clean technologies, bioenergy, and renewable energy alternatives have been considered as viable solutions to protecting the environment and public health. In Saudi Arabia (KSA), the rapidly growing population, rising electricity consumption, and increasing water desalination needs have contributed to a surge in energy demand. Energy consumption patterns, grid stability, power supply, and energy usage across utility services are projected to exceed 120 GW by 2032. In response to these challenges, the government's Vision 2030 aims to integrate renewable energy sources that help meet part of this demand and support the transition to a more sustainable energy future[54].

How do initiatives like Green Riyadh's documented environmental and health outcomes align with the strategic pillars, key performance indicators (KPIs), and environmental objectives of Saudi Vision 2030, particularly concerning urban sustainability, improved air quality, and public well-being?

The environmental and health results from projects like Green Riyadh are closely connected to the main goals, important measures, and environmental aims outlined in Saudi Vision 2030, especially regarding city sustainability, better air quality, and public health. Green Riyadh plays a pivotal role in advancing Vision's commitment to fostering sustainable urban environments by substantially increasing green coverage, thereby contributing to the mitigation of the urban heat island effect, the reduction of air pollutants, and the promotion of healthier, more active lifestyles.

The Green Riyadh project, launched in 2019 under Vision 2030, aims to plant 7.5 million trees using recycled water to improve air quality, reduce urban heat, and enhance residents' well-being. It features major parks, green spaces, and eco-friendly infrastructure across the city. Key features include major parks like Al-Urubah and those in Al Munsiyah, Al Rimmal, and Al Qadisiyah, with walking and cycling paths, play

areas, water features, and green technologies. Utilizing 72 native plant species, the project will also help conserve biodiversity, manage flood risks, and reduce energy use. Economically, it is expected to yield SAR 71 billion in returns by 2030 through energy savings, increased property values, and reduced healthcare costs. Additionally, it will open new avenues for private sector investment and support national programs aimed at promoting sustainability, improving quality of life, and enhancing environmental resilience[65].

Riyadh is transforming into a green, sustainable city through major initiatives like King Salman Park, Sports Boulevard, and Green Riyadh, all integral to Vision 2030 and the Saudi Green Initiative. King Salman Park, a massive conversion of a former military airbase into the world's largest urban park, spans five times the size of Central Park, offering gardens, forests, trails, and recreational amenities. It aims to enhance biodiversity, reduce the urban heat island effect, and contribute to carbon sequestration through a million trees and millions of shrubs. Sports Boulevard, a 135-km green corridor, connects neighborhoods, office areas, and entertainment hubs, promoting physical activity and eco-friendly mobility with cycling, running, and horse-riding paths. These green spaces are unified by Riyadh's new metro system, which is being built to create a comprehensive urban green network. These initiatives, alongside past projects like the Diplomatic Quarter and the restoration of Wadi Hanifa[66], demonstrate Riyadh's enduring dedication to environmentally sustainable development and water preservation. The city's ambitious planting goal of over 16 million trees by 2030 reflects a drive to create a cooler, healthier, and more resilient urban environment that reflects a commitment to sustainability and long-term urban development[7]

What key knowledge gaps or implementation challenges hinder the effective formulation of urban policy and the localization of international best practices in Riyadh's green transformation, particularly in comparison to global models like China's sustainable urban initiatives?

Riyadh's green transformation is impeded by several profound knowledge gaps and implementation challenges that hinder the effective formulation of urban policy and the localization of international best practices. A critical obstacle is the dearth of localized, context-specific research and data, which stifles the creation of tailored sustainability models attuned to Riyadh's unique environmental, economic, and socio-cultural fabric. In contrast to global exemplars such as China's sustainable urban initiatives, Riyadh encounters significant hurdles in terms of technological assimilation, capital mobilization, and public participatory mechanisms.

Many international best practices, developed for temperate or densely populated areas, don't easily apply to Riyadh's arid climate and unique urban fabric, particularly in policies on green spaces and energy use. Public engagement, which has been recognized as a crucial driver of green transformation, remains limited, and environmental literacy has not been adequately promoted. After being introduced, regulatory reforms often encounter bureaucratic inertia, stalling innovation and delaying progress. Riyadh has depended heavily on foreign technologies and external consultants, which has prevented the development of local expertise and sustainable innovation ecosystems. Securing long-term investment remains a challenge, particularly for initiatives that require diversification away from oil-based revenues. These intertwined challenges have been obstructing the effective localization of international models, and Riyadh continues to face difficulty in replicating the coordinated, well-resourced strategies that have been implemented in China's sustainable urban development initiatives.

Klingmann et al.[71] explore the potential connection between Saudi Arabia's societal and financial transformations, economic modernization, monumental urban developments, expansive infrastructure projects, and environmentally conscious urbanization, aiming to achieve sustainable urban development in Riyadh. There is a particular focus on enhancing the city's overall standard of living, improving social connectedness, advancing health outcomes, supporting mental health, and increasing quality of life (QoL), especially for residents, while also fostering foreign investment. The research evaluates five state-driven large-scale urban destinations and their development strategies, which have been compared with the objectives outlined in Saudi Arabia's Vision 2030 Quality of Life Program. Furthermore, it examines the extent to which these projects have been aligned with global sustainable urban development standards, urban resilience frameworks, global urban policy frameworks, and environmental impact assessment protocols, after being planned and implemented by relevant authorities.

CONCLUSION

The study examines how ecological urbanism, renewable energy, and environmental health align with Vision 2030 to transform Riyadh, particularly for arid urban development. Successful initiatives like Green Riyadh improve urban resilience and environmental quality but face challenges such as data opacity, fragmented regulations, and a lack of standardized implementation. These obstacles hinder alignment with global best practices and limit sectoral collaboration. Riyadh's centralized governance requires flexible approaches to engage communities and drive innovation, with transformative leadership and institutional change needed to catch up with global ecological models. The research presents both conceptual and practical grounds that cities can utilize for regional sustainable development, advocating for an urban paradigm that extends beyond simplistic environmental makeovers to establish cities as inclusive, health-oriented, and regenerative networks.

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