Pathways to green urbanism: evaluating Jeddah’s environmental sustainability progress and prospects

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Abstract

This research provides a comprehensive analysis of environmental sustainability in Jeddah, focusing on the unique challenges and opportunities it faces as a rapidly urbanizing city in an arid region. The study evaluates Jeddah’s performance across multiple environmental areas, including energy and carbon dioxide emissions, land and building use, transportation, waste management, water use, sanitation and air quality. A detailed SWOT analysis identifies the city’s strengths, weaknesses, opportunities and threats in achieving sustainable urban development. The results reveal high per capita carbon dioxide emissions, energy consumption and waste generation, along with challenges in managing water resources and maintaining air quality. The study highlights Jeddah’s efforts in renewable energy policies, urban mass transportation and waste management strategies. The conclusion provides a set of comprehensive recommendations for policy improvement, focusing on the need for sustainable urban planning, energy conservation, improved waste and water management and public engagement. This research contributes significantly to the understanding of urban sustainability in arid environments, providing a valuable framework for policymakers and urban planners.

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1. Introduction

The pursuit of sustainable urban development presents unique challenges and opportunities, as demonstrated by many cities worldwide [1, 2]. In the arid regions, the city of Jeddah, Saudi Arabia demonstrates this overarching challenge but with different specialities and elements. This study aims to explore Jeddah’s efforts to become a sustainable green city, against the backdrop of its strategic economic role, the diversity of its population and its distinctive geographical location along the Red Sea coast. Jeddah’s journey is not only a reflection of its own urban and ecological dynamics but also offers broader visions for sustainable urban development in similarly arid environments.

Jeddah’s location as a major commercial center and its rapid urbanization pose complex challenges in managing environmental sustainability. These factors include high energy consumption due to reliance on air conditioning in its hot desert climate, water scarcity and the pressures of urbanization on land use and natural resources. However, the city also has strengths, such as its focus on renewable energy, especially solar energy, and its alignment with Saudi Vision 2030, which emphasizes economic diversification and sustainable development.
This study is crucial in understanding how cities like Jeddah can overcome the complexities of sustainable urban development in arid climates. It offers insights into managing environmental sustainability amidst economic pressures and rapid growth and offers lessons applicable to similar urban contexts globally. The primary objective of this research is to analyze the environmental performance of Jeddah City in various fields, including energy consumption, land use, transportation, waste management, water use, sanitation and air quality. In addition, the study aims to conduct a SWOT analysis to identify the strengths, weaknesses, opportunities and threats that the city faces in achieving sustainable urban development.

The research uses a comprehensive methodology, including data analysis, policy review and comparative studies with other arid urban centers. This multifaceted approach ensures a comprehensive understanding of Jeddah City’s environmental performance and the broader implications of sustainable urban development in similar contexts. This article is designed to first provide an overview of the geographical, economic and urban context of Jeddah. It then delves into a detailed analysis of environmental performance across various sectors, followed by a SWOT analysis. The conclusion synthesizes these findings into actionable recommendations for policymakers and urban planners. This introduction sets the stage for a nuanced exploration of urban sustainability in Jeddah, offering valuable insights for cities facing similar environmental challenges in arid regions.

2. Overview of Jeddah’s context

Jeddah, strategically located as the second largest city in Saudi Arabia, is located along the Red Sea coast (Figure 1). Its hot desert climate is characterized by very high summer temperatures, mild winters and rare rainfall [3]. This geographic situation presents unique challenges such as water scarcity, heat management and environmental pressure on local ecosystems.

As a vital economic center, Jeddah is not only central to Saudi Arabia’s economy but also plays a major role in the Middle East. The city’s economy is bolstered by its position as a major commercial center, a crucial port for maritime trade and its proximity to Islamic holy sites, which fuels its tourism sector. This economic vitality, while beneficial, also exerts pressure on the city’s environment through industrial emissions, increased energy demand and urban congestion.

Furthermore, Jeddah has experienced rapid urbanization, driven by economic growth and demographic shifts. The city’s population is diverse and growing, leading to expanding urban sprawl, increasing demand for housing and infrastructure development. This rapid urbanization has significant implications for land use, green space conservation, air and water quality and overall urban sustainability [4].

In the context of environmental management, Jeddah’s approach to environmental issues has mostly focused on immediate local concerns such as waste management and basic...
sanitation. Environmental considerations were often secondary to development objectives, resulting in ad hoc solutions and short-term fixes [5]. Over time, there has been a gradual shift towards more organized and proactive environmental management. This development has been influenced by global environmental awareness, technological advances and increasing recognition of the long-term benefits of sustainable practices.

Furthermore, aligning Jeddah’s environmental policies with Saudi Vision 2030 represents an important step towards integrating sustainability into the broader development agenda. This national vision emphasizes diversification away from oil dependence, promoting renewable energy and improving quality of life, all of which have direct implications for Jeddah’s environmental strategies [6].

Despite these positive developments, Jeddah faces challenges in effectively implementing and enforcing environmental policies. Coordination between various government agencies, effective allocation of resources and ensuring compliance at all levels remain major obstacles [5].

The environmental context of Jeddah is complex and multi-faceted, influenced by its unique geographical location, economic importance and rapid urban growth. The historical trajectory of environmental management in Jeddah shows a positive shift towards sustainability, but ongoing challenges highlight the need for continued efforts and strategic planning. Understanding these dynamics is essential for framing current and future environmental initiatives in Jeddah, and ensuring they are well aligned with local needs and broader sustainability goals.

### 2.1. Analysis of Jeddah’s unique challenges in urban planning.

In the discussion presented below, we explore the urban planning challenges of Jeddah. The city’s rapid growth presents issues like urban sprawl, congestion and infrastructure pressure. Urban planning must balance development with environmental sustainability, respect for cultural heritage and economic diversification. Key focuses include green urbanism, equitable housing and climate resilience, supported by effective regulatory frameworks. This analysis seeks strategies for a sustainable, adaptable and culturally sensitive development in Jeddah, addressing its unique needs and opportunities. Here are some key challenges:

- **Geographic and climate constraints:** Jeddah is located along the Red Sea coast, which presents both opportunities and challenges. The coastal location can lead to problems such as land erosion and flooding, especially during heavy rainfall. Furthermore, the city’s hot desert climate presents challenges in maintaining sustainable urban landscapes, requiring innovative urban design approaches that take into account heat management and water conservation.

- **Rapid urbanization and population growth:** Jeddah has witnessed rapid urbanization, creating problems such as urban sprawl, traffic congestion and pressure on infrastructure. This growth must be managed in a way that balances development, environmental preservation and sustainable use of resources.

- **Cultural and Historical Heritage:** As a city of rich cultural and historical importance, urban planning in Jeddah must respect and integrate historical sites and traditional architecture. This includes preserving heritage sites and incorporating traditional urban design principles into modern developments.

- **Economic diversification:** Saudi Arabia, including Jeddah, has historically relied on oil and is working to diversify its economy. Urban planning must support this transformation by creating spaces that encourage new industries, such as tourism, technology and finance while ensuring environmental sustainability.

- **Environmental sustainability and green urbanism:** Jeddah faces environmental challenges such as air pollution, water scarcity and the need for effective waste management. The detailed analysis will explore strategies for creating green spaces, promoting renewable energy and implementing sustainable water management systems.

- **Social and housing equity:** As the city grows, ensuring equitable access to housing, public services and amenities is critical. Urban planning must meet the needs of diverse social groups, including affordable housing and accessible public transportation.

- **Resilience and adaptation to climate change:** As the impacts of climate change become more apparent, Jeddah’s urban planning must include resilience strategies, such as flood defense mechanisms, sustainable drainage systems and emergency response planning.

- **Regulatory and policy frameworks:** Effective urban planning in Jeddah also depends on supporting regulatory frameworks and policies. This includes clear guidelines for sustainable development, incentives for green building practices and strong policy implementation and enforcement mechanisms.

### 3. Analysis of Jeddah’s environmental performance

In this section, a detailed examination of Jeddah City’s environmental performance is undertaken, a crucial aspect in understanding the city’s progress towards sustainability. This analysis covers a wide range of areas, from energy consumption and carbon dioxide emissions to land use, transportation, waste management, water use, sanitation, air quality and environmental governance. These areas of investigation are extracted from the Asian Green City Index [7] (Figure 2). The Asian Green City Index seeks to measure and assess the environmental performance of 22 major Asian cities across a range of criteria. Each area addresses specific elements that provide a comprehensive view of how these factors interact within the urban fabric of Jeddah. This approach not only highlights the city’s current environmental footprint but also highlights the effectiveness of current policies.
and practices, paving the way for informed strategies to advance Jeddah’s journey toward a sustainable future.

Using the Asian Green City Index to analyze sustainability initiatives in Jeddah provides multiple benefits. This index provides a comprehensive frame of reference that covers various sustainability indicators relevant to the unique geographic and climatic conditions of Jeddah, despite its focus on Asia. It allows comparison with similar coastal cities in arid regions and provides insights into effective sustainability management. Comparing Jeddah to cities going through similar stages of development helps identify best practices and areas for improvement. The index’s robust data and methodology enhance the credibility of the analysis, guiding policy formulation and decision-making in Jeddah towards more effective sustainability initiatives. In addition, it supports international learning and collaboration and leverages global insights to advance local urban sustainability efforts.

3.1. Energy and CO₂

3.1.1. CO₂ emissions per capita

Saudi Arabia’s per capita CO₂ emissions are reported to be 14.3 metric tons in 2023. This places the country among the largest per capita CO₂ emitters globally. Total carbon emissions in Saudi Arabia are estimated at 672.38 metric tons. It is important to note that these numbers can be affected by a range of factors, including energy consumption patterns, dependence on fossil fuels and industrial activities [8, 9]. Major contributors to these emissions include transportation, especially extensive use of private vehicles, industrial activities, power generation and residential energy use, especially the energy requirements of air conditioning systems in the city’s hot climate, which significantly increase the city’s carbon footprint. To mitigate these emissions, Jeddah will benefit from a multifaceted approach that includes enhancing public transportation, encouraging the adoption of energy-efficient technologies and transitioning to cleaner energy sources for both electricity generation and transportation. This combination of strategies is crucial to reducing the city’s carbon footprint and moving towards a more sustainable future.

3.1.2. Energy consumption per unit of GDP

This indicator reflects the energy efficiency of the city’s economy. Historically, the Saudi economy has been energy-intensive, a situation partly affected by the low cost of energy and the nature of its industrial base, especially in cities such as Jeddah. According to a report by CEIC Data, the primary energy consumption per unit of GDP in Saudi Arabia was 2768 kWh/international dollar in 2018 [8]. As Saudi Arabia pursues Vision 2030, there is a goal to diversify the economy, which could lead to a more energy-efficient GDP. This diversification will include expanding sectors such as technology, tourism and services, which are typically associated with a lower energy footprint compared to traditional industries such as oil and gas. Furthermore, measuring energy consumption relative to GDP provides valuable insight into the energy efficiency of a city’s economy. In the past, cities in Saudi Arabia have shown high energy consumption per unit of GDP,
a trend influenced by the economic structure and subsidized energy prices. This historical context underscores the importance of current efforts toward economic diversification and energy efficiency.

3.1.3. **Clean energy policy**
Saudi Arabia’s move toward renewable energy is a central element of its clean energy policy, including significant investments in solar and wind energy. Its commitment to renewable energy is a key component of its broader climate change strategy, which is summarized in the Saudi Green Initiative (SGI). Launched in 2021, the SGI initiative aims to reduce carbon emissions, improve quality of life and protect the environment for future generations. It supports the country’s ambition to reach net-zero emissions by 2060 and accelerates the transition to a green economy [10]. As part of the SGI initiative, significant investments have been made, including the development of renewable energy projects and tree planting. Furthermore, Saudi Arabia has set a target to develop 58.7 GW of renewable energy capacity by 2030 [11]. This target includes a significant portion of solar PV and wind capacity. The plan for 2023 was to significantly increase the clean energy target to 27.3 GW, from the previous target of 9.5 GW. This ambitious target reflects the country’s commitment to transition from its traditional oil-dependent economy to a more diversified and sustainable energy mix.

For Jeddah, this transition may entail increased adoption of solar energy, taking advantage of the city’s sunny climate. The policy framework is likely to include incentives for renewable energy projects and regulations that promote energy efficiency, along with potential subsidies or support mechanisms for the adoption of renewable energy technologies in both the public and private sectors. Furthermore, the shift towards renewable energy sources represents a crucial strategy, especially in Jeddah. Solar investments, designed to take advantage of a city’s geographical advantages, can play an important role in reducing carbon emissions associated with energy consumption.

3.2. **Land use and buildings**

3.2.1. **Green spaces per capita**
Evaluating Jeddah’s green spaces per capita includes evaluating the total area of public parks, recreation areas, green corridors and other accessible natural environments. This measure is essential for assessing urban quality of life, biodiversity and environmental health. In rapidly urbanizing cities like Jeddah, the challenge of maintaining or increasing green spaces is great. Urban green spaces play a critical role in improving quality of life, supporting biodiversity, and improving environmental health [12]. Given the city’s climate and urbanization rate, strategies to enhance green spaces are vital. This could include developing urban parks, creating rooftop gardens and integrating green spaces into residential and commercial areas. In this context, broader environmental initiatives in Saudi Arabia, such as the Saudi Green Initiative, highlight the national commitment to environmental sustainabil-

ity, which will likely influence urban planning in Jeddah [13]. However, without specific quantitative data, it is difficult to provide an accurate assessment of the status of green spaces per capita in Jeddah.

Possible strategies to address this issue may include developing more urban parks, creating rooftop gardens and incorporating green spaces into residential and commercial areas. These initiatives not only enhance the aesthetic appearance of the city but also contribute to improving air quality and providing recreational spaces for residents. In addition, integrating green spaces into urban planning is crucial. This may include implementing policies requiring a certain share of green spaces in new developments or transforming underutilized urban areas into vibrant, liveable green spaces, thus enriching the urban ecosystem and enhancing the overall living experience in Jeddah.

3.2.2. **Population density**
Population density in Jeddah seriously affects land use, infrastructure requirements and environmental pressure. Effective urban planning is essential in densely populated areas to ensure adequate living conditions, easy access to services and environmental sustainability. The population density of Jeddah in 2023 is estimated at 2500 people per square kilometer (6400 residents per square mile). This figure reflects Jeddah’s status as a densely populated urban area within Saudi Arabia, highlighting the challenges and opportunities associated with urban planning and environmental management in the city [14]. Density emphasizes the importance of efficient land use, infrastructure development and environmental sustainability in the context of rapid urbanization. While high population density presents challenges such as congestion and increased resource use, it also provides opportunities to increase the efficiency of public transportation and reduce per capita land use.

Proper management of high-density living can lead to sustainability and desirability, effectively countering urban sprawl and associated environmental degradation. Thoughtful planning in these areas is key to reducing extensive vehicle use, preserving natural habitats and reducing infrastructure costs. By embracing the dual aspects of challenges and opportunities in densely populated living, Jeddah can set a precedent for sustainable urban development. This approach balances the needs of residents with environmental conservation, demonstrating how strategic urban management can transform the living experience while maintaining ecological balance.

3.2.3. **Land use policy**
Land use policy in Jeddah needs to address the challenge of sustainable development, achieving a balance between economic growth and environmental protection. This requires careful planning to prevent unnecessary destruction of natural habitats and to ensure that urbanization is carried out in an environmentally responsible manner [4]. In this context, the Jeddah Municipality developed a master plan for the city that includes a comprehensive plan for land use. This plan places particular emphasis on
waterfront areas, identifying various uses including recreational, commercial and public spaces [12]. This indicates that Jeddah is actively participating in urban planning to meet the challenges of sustainable development and urban growth. This policy encourages smart growth strategies, such as mixed-use developments that integrate residential, commercial, and entertainment spaces and transit-oriented development, which emphasizes access to public transportation. In addition, protecting natural areas in and around the city is essential. This can be achieved by designating certain areas as protected areas and developing policies that limit harmful development activities in these areas, thus preserving the city’s natural heritage and environmental balance.

3.3. Transport

3.3.1. Superior public transport network

In Jeddah, developing a distinguished public transport network, including bus rapid transit systems, trams, light rail and metro, is crucial to providing efficient and reliable alternatives to the use of private vehicles. In addition, the total length of these networks, relative to the area of the city, is a key indicator of their accessibility and coverage. Although Jeddah may not have historically boasted an extensive public transportation system, recent initiatives, such as the Jeddah Metro Project, indicate a significant shift towards developing more comprehensive public transportation options. Moreover, expanding these networks is vital to meet the demands of the growing urban population.

Jeddah has already made great strides in developing a comprehensive public transportation network. The Jeddah Metro project is an essential element in this transformation, which aims to strengthen the city’s public transportation system [15]. The project includes 74 stations and extends over a distance of 160 kilometers across four roads in the city. This development is central to Jeddah’s broader goal of providing efficient and accessible public transport, thus reducing reliance on private vehicles and contributing to sustainable urban development. Moreover, the effectiveness of the transportation network also depends on its integration, ensuring seamless connectivity between different modes of transportation and key areas of the city, including residential, commercial, and industrial areas [16]. This integration is essential to create a cohesive and functional transportation system that can effectively meet the city’s needs.

3.3.2. Urban mass transport policy

Developing a strong urban mass transit policy in Jeddah involves more than just building public transportation infrastructure; It is about creating a system that is a convenient and attractive alternative to private vehicles. This means focusing on affordability, reliability, frequency and coverage to make public transportation the preferred choice for commuters. The effective implementation of this policy requires significant investments in infrastructure to ensure high quality of service. Besides, providing support for public transportation can increase its attractiveness and accessibility. However, Jeddah’s urban mass transit policy faces challenges due to the city’s heavy reliance on cars, due to wide roads, abundant cheap parking and low fuel costs. Thus, public transportation accounts for only 1–2% of all trips. With increasing urbanization and car use, coupled with international traffic, Jeddah’s current transportation system struggles to support mobility and sustainable growth [17]. This highlights the need for a strong policy that strengthens public transport infrastructure and encourages its use among the population. In fact, promoting the use of public transport through awareness campaigns and incentives is a crucial aspect of this policy. These campaigns can educate residents about the benefits of using public transportation, whether for personal comfort or environmental well-being. Such efforts, when combined with incentives such as discounted fares or loyalty programs, can encourage the shift from private vehicles to public transportation.

3.3.3. Congestion reduction policy

Jeddah’s approach to reducing traffic congestion, a critical aspect of its urban transportation strategy, is particularly important given the city’s rapid growth and high reliance on private vehicles, which often results in significant traffic challenges. To combat this, effective congestion reduction policies can include a variety of measures [18]. This may include implementing congestion charges to discourage excessive use of private vehicles, expanding and enhancing public transportation to offer viable alternatives and developing car-sharing initiatives to reduce the number of cars on the road. Furthermore, improving traffic management systems can improve traffic flow and reduce congestion. In addition to these measures, promoting nonmotorized transport options such as walking and cycling is vital. This can be achieved by developing dedicated lanes and safety measures, making these modes of transportation more attractive and feasible. Furthermore, encouraging telecommuting and flexible working hours can help distribute peak traffic loads more evenly, thus reducing congestion during traditional peak hours [19]. These joint efforts can significantly alleviate traffic congestion in Jeddah, enhancing the overall quality of urban life.

3.4. Waste

3.4.1. Share of waste collected and adequately disposed

In Jeddah, the proportion of waste that is collected and disposed of properly is a key indicator of the effectiveness of the city’s waste management system. This includes proper collection, transportation and disposal of waste, whether in sanitary landfills, incineration sites or regulated recycling facilities. Considering the size of the city and its rapid growth, effective management of the large volume of waste generated poses a major challenge [20]. In this context, the waste management situation in Jeddah represents a challenge, especially in light of the rapid population growth in the city. Jeddah currently produces more than 5000 tons of solid waste per day, and the main landfill in Buraiman receives about 1.5 million tons of waste annually. However, the city’s waste management infrastructure struggles to handle this.
volume. Significant improvements are needed in areas such as waste collection, segregation, recycling and disposal [21]. The environmental impact of current waste management practices, including issues related to wastewater and industrial waste, is also a concern. To enhance the efficiency of waste collection and disposal, strategies may include expanding and modernizing waste collection infrastructure. In addition, improving waste separation practices is critical to increasing recycling and disposal efficiency. Furthermore, ensuring that disposal facilities are not only adequate but also environmentally sound is essential to the long-term sustainability of waste management in Jeddah. These joint efforts are vital to keeping the city clean and the environment healthy.

3.4.2. **Waste generated per capita**
The total volume of annual waste generated per capita in Jeddah, including officially collected and uncollected waste, provides valuable information about the city’s waste footprint. The per capita waste generation is estimated at between 1.5 and 1.8 kg per person per day. This number reflects the challenges the city faces in managing its solid waste, especially given rapid urbanization and population growth [22]. A high rate of waste generation per capita can indicate prevailing consumption patterns and also reflect the effectiveness or lack thereof of waste reduction initiatives. Factors contributing to waste generation include urban lifestyle, consumer behavior and industrial and commercial activities. Therefore, reducing per capita waste generation requires a multifaceted approach. This approach should incorporate public awareness campaigns that educate residents about the impact of waste and the importance of reducing it, along with incentives that encourage waste reduction practices. In addition, implementing regulations that promote responsible waste management is crucial. Combined, these measures can effectively reduce Jeddah’s overall waste footprint, leading to a more sustainable and environmentally conscious city.

3.4.3. **Waste collection and disposal policy**
The comprehensive waste collection and disposal policy in Jeddah will include various aspects, such as ensuring regular and efficient waste collection services, promoting proper segregation of waste at source and advocating safe and environmentally responsible disposal practices [21]. It is necessary to develop and maintain the necessary waste collection and disposal infrastructure, which includes advanced waste treatment facilities. In addition, this infrastructure must adapt to the growing needs of the city while incorporating technological developments. Encouraging public participation and ensuring compliance with waste disposal regulations is also essential for the success of these policies. This may include implementing community programs and educational initiatives, as well as enforcing waste management regulations. Together, these measures will contribute to creating a more effective and sustainable waste management system in Jeddah, reflecting a commitment to environmental stewardship and public health.

3.5. **Water**

3.5.1. **Water consumption per capita**
In Jeddah, monitoring per capita water consumption is crucial, especially given the city’s arid climate and growing population. The importance of this metric is reinforced by the fact that high water use per person is often associated with a variety of factors, including lifestyle habits, the demands of industrial and commercial activities and the large amount of water needed to maintain a city’s urban green spaces. As of 2016, per capita water consumption in Saudi Arabia was ∼265 l/day. There was a target to reduce this to 200 l/day by 2020 under the National Transformation Programme, but this target was later revised. In 2018, ∼275 l of water per day were provided to municipal users in Saudi Arabia. This rate is nearly double the European average. The city’s total water consumption exceeded 1.2 million m³/day. These numbers confirm the challenges that Jeddah faces in managing its water resources, especially in light of its dry climate and population growth [23]. Addressing this high consumption rate involves a multifaceted approach: encouraging the use of water-saving appliances, implementing effective irrigation methods and launching comprehensive public awareness campaigns on the importance of water conservation. These efforts are of great importance in a region characterized by limited natural water resources.

3.5.2. **Water system leakages**
The proportion of water lost during transportation in Jeddah, often referred to as nonrevenue water, is a critical measure of the efficiency of the city’s water supply system. This loss is primarily due to several factors, including outdated infrastructure, lack of adequate maintenance and various inefficiencies within the system, resulting in significant water waste. In Jeddah, water system leakage, or nonrevenue water, is a major problem due to factors such as aging infrastructure and maintenance challenges. Initial estimates indicated water losses of ∼30% in the distribution network [24]. To address this issue, Jeddah implemented an advanced pressure management system, resulting in a 20% reduction in pressure and a 40% reduction in pipe bursts. In addition, leaks were reduced by 10%, saving ∼3201 m³ of water per day. These improvements not only reduced water waste but also reduced repair costs and extended the life of water infrastructure assets. In addition, implementing a system of regular maintenance and strict monitoring is indispensable to reduce water loss. Through these initiatives, the city of Jeddah can significantly enhance the efficiency and reliability of its water supply system. Not only are these improvements essential to reducing water waste, but they are also pivotal in ensuring the sustainable management of this vital resource, thus securing the city’s water future in an environmentally responsible manner.

3.5.3. **Water quality policy**
Jeddah’s comprehensive water quality policy is vital to protecting the health and safety of its residents. It includes regular monitoring of water quality, implementing treatment processes to eliminate pollutants and adhering to national and international
water quality standards. Jeddah and Riyadh are known to be leaders in the region in terms of water quality due to their efficient use of urban wastewater. As shown in the Arcadis Sustainable Cities Water Index, these cities’ efforts to reuse wastewater have contributed significantly to high-quality water standards [25]. However, the index also indicates that major cities in Saudi Arabia, including Jeddah, need greater investment and priorities to improve their resilience and adapt to climate challenges. This underscores the need for continued focus on water quality and sustainable management practices in the region. Furthermore, protecting water quality from the source to the distribution system is critical. This includes measures such as controlling pollution in water bodies, ensuring proper treatment of industrial effluents and ensuring that water undergoes effective treatment before distribution. These steps are necessary to maintain the overall quality of the water, thus ensuring that it remains safe and healthy for consumption and use by city residents.

3.6. Sanitation

3.6.1. Population with access to improved sanitation

The percentage of people with access to better sanitation facilities is an essential measure of public health and environmental standards. This access includes connection to sewage systems or the use of septic tanks and improved toilets that ensure cleanliness and privacy. As of 2020, access to improved sanitation in Saudi Arabia, including Jeddah, was estimated at 100%. The country’s sanitation system primarily involves on-site solutions, as about 40% of the population is connected to sewerage [26]. This indicates a high level of access to improved sanitation facilities for residents in Jeddah and throughout Saudi Arabia, reflecting significant progress in public health and environmental standards. Although Jeddah is experiencing rapid urban growth and a rising population, providing everyone with improved sanitation facilities is a major challenge. This endeavor requires significant investments in sanitation infrastructure. This involves not only expanding and maintaining sewerage networks but also creating sanitation solutions in areas where sewerage connections are not practical.

3.6.2. Share of wastewater treated

In Jeddah, the proportion of wastewater collected and treated is a key indicator of the efficiency of wastewater management in the city. Ensuring that wastewater undergoes at least basic or primary treatment is vital to preventing environmental pollution and maintaining public health. The situation of wastewater management is challenging. Nearly 85% of the city is not connected to sewer lines, resulting in sewage accumulating in underground drains. This wastewater is then transported by truck to Lake Breiman, which has become a landfill [27]. Only a small percentage of wastewater coming from homes connected to the sewage network is purified before being released into the Red Sea. The city’s current infrastructure is struggling to handle the volume of raw sewage, highlighting the need for significant improvements in wastewater treatment capabilities. To effectively manage city wastewater outputs, it is necessary to develop modern treatment facilities capable of treating volumes of domestic and industrial wastewater. In addition, sustainable wastewater management should include studying possibilities for reusing treated wastewater.

3.6.3. Sanitation policy

Jeddah’s sanitation policy is likely to be aligned with the broader Saudi National Water Strategy, which aims to address key challenges and restructure the water and sanitation sector for sustainable development. This comprehensive strategy includes enhancing water demand management, providing high-quality water and sanitation services and ensuring the conservation and optimal use of water resources. It also emphasizes effective management and private-sector participation. This strategic approach reflects an integrated and comprehensive perspective on sanitation, which is essential for maintaining high sanitation standards and ensuring environmental safety in Jeddah [28]. In this context, effective sanitation policy also requires cooperation between health agencies, community groups and the private sector. In addition, implementing and enforcing strict regulations and standards for sanitation facilities and waste treatment methods is crucial. These measures are essential to maintain a high level of sanitation in Jeddah, contributing to the public health and well-being of its residents while maintaining the environmental integrity of the city.

3.7. Air quality

3.7.1. Monitoring pollutant levels

In Jeddah, the main air pollutants include nitrogen dioxide (NO2), sulfur dioxide (SO2) and particulate matter (PM10). Nitrogen dioxide, which originates mainly from vehicle exhaust, industrial activities and power generation, can cause respiratory problems and contribute to smog and acid rain. Sulfur dioxide emissions, primarily from industrial processes using fossil fuels, pose respiratory risks and environmental damage and particularly contribute to acid rain. PM10, from human activities such as construction and vehicle emissions, as well as natural sources such as desert dust, is linked to serious health problems, including lung and heart disease. In Jeddah’s First Industrial City, a 2023 study found that levels of nitrogen dioxide (NO2) and sulfur dioxide (SO2) exceeded permissible limits in certain areas, although other standards generally met the National Center for Environmental Compliance limits [29]. The study noted a significant decrease in pollutants during the lockdown period due to the Coronavirus, indicating a strong correlation between reduced means of transportation and industrial processes and lower levels of pollution. These results highlight the importance of monitoring and managing air pollution to improve air quality in Jeddah city. To effectively monitor and reduce these pollutants, Jeddah must implement a comprehensive strategy. This includes stringent emissions standards for vehicles and industries, encouraging the use of clean fuels and enhancing public transportation to reduce reliance on private vehicles.
3.7.2. Urban heat island effect
In Jeddah, a city located in a hot desert climate, the urban heat island (UHI) effect can intensify already high ambient temperatures. This phenomenon often leads to increased demand for energy for cooling purposes and may have harmful effects on public health. According to the latest available data, Jeddah City is likely to experience a pronounced Urban Infrastructure Impact (UHI), mainly due to its dense urban fabric and the peculiarities of its desert climate. A 2023 study found that the impact of UHC in Jeddah has increased significantly over the years, especially between 2000 and 2022, as the urban area expanded by about 80% [4]. This expansion has led to a significant rise in UHI conditions, especially in the southern, northern and central-eastern parts of the city. Impermeable surfaces contributed significantly to the UHI effect, while vegetation and bodies of water tended to mitigate it. More than 80% of the Jeddah area now suffers from extremely high health conditions. This research is expected to assist in urban planning and policy-making to ensure sustainable management and improve the quality of life in Jeddah. In this context, addressing the impact of UHI in Jeddah’s hot desert environment represents a difficult but essential task. It is pivotal to reduce excessive energy consumption and enhance the overall livability of the city. Jeddah’s success in mitigating the impact of universal health insurance depends on several key factors. This includes effective policy implementation, significant investment in green infrastructure and integration of UHC mitigation strategies into urban planning and development. Such measures are vital to ensure a sustainable urban environment that can better withstand the challenges posed by the city’s extreme climatic conditions [30].

3.7.3. Clean air policy
A comprehensive clean air policy in Jeddah would address the diverse sources of air pollution through an integrated approach. This will include regulatory measures, technological innovations and public awareness campaigns. Given the large role that vehicle emissions play in air pollution, policy could prioritize improving fuel quality, advocating the use of electric and hybrid vehicles and expanding public transportation options [31]. The Kingdom of Saudi Arabia has implemented many environmental legislations and initiatives aimed at preserving and confronting environmental challenges. These initiatives include regulations to maintain clean air. The country has demonstrated a commitment to protecting the environment by issuing regulations and adopting strategies to address challenges such as cement factory waste and increased emissions [32]. In addition, for industrial emissions, the policy may include the implementation of stringent emission standards, encouragement of cleaner production techniques and incentives to adopt advanced pollution control technologies. Furthermore, educating the public about the causes and effects of air pollution is crucial. Involving them in initiatives to improve air quality, such as encouraging car sharing, using public transportation and participating in tree planting campaigns, can greatly contribute to the effectiveness of these measures.

3.8. Environmental governance
3.8.1. Environmental management
Effective environmental management in Jeddah involves a comprehensive approach that includes various initiatives and strategies, both at the city and national levels. Although there is no specific information about a dedicated environmental body in Jeddah, there are several ongoing initiatives and plans that are aligned with the broader goal of environmental sustainability [33]. There are new plans known as ‘Jeddah City Plans’ designed to guide Jeddah’s resilience and long-term sustainable growth [34]. These plans aim to accommodate growth, generate employment opportunities and improve the quality of the built and natural environments. It focuses on creating well-designed and well-serviced centers to enable better access to amenities, jobs and public transport, especially for women. This set of plans offers an integrated approach to long-term growth and sustainable economic development in Jeddah. These initiatives and plans indicate a significant effort towards integrating environmental considerations into urban planning, infrastructure development and broader policy-making in Jeddah. It reflects the commitment to promoting a sustainable and environmentally friendly growth model for the city.

3.8.2. Environmental monitoring
Environmental monitoring in Jeddah includes various aspects including air and water quality, waste management and energy use. However, specific details on the comprehensive deployment of advanced monitoring technologies, such as sensor networks and remote sensing methods, and the regular publication of environmental performance reports, are not readily available from existing sources. Regarding air quality, there are initiatives to monitor and address pollution. Two main sources of air pollution have been identified: point sources such as the Jeddah oil refinery, desalination plant, power plant and several industries and mobile sources including transportation [35]. Efforts have been made to reduce pollution from point sources, but compliance with standards remains a challenge. Air quality monitoring continues, with a focus on encouraging industries to adhere to environmental standards. While conducting environmental monitoring in Jeddah, especially concerning air and water quality, there are significant challenges and areas for improvement, particularly in ensuring compliance with environmental standards and addressing complex issues related to water pollution and waste management.

3.8.3. Public participation
Active public participation is essential for the success of environmental initiatives in Jeddah [36]. It is important to involve citizens from the project planning stages, through public consultations, to decision-making processes. In doing so, the community becomes an integral part of the environmental stewardship journey. Raising environmental awareness is another key aspect. Through educational campaigns, workshops and community programs, public participation can be encouraged and a culture of environmental
Table 1. SWOT analysis of Jeddah’s path to sustainability.

<table>
<thead>
<tr>
<th>Strengths</th>
<th>Weaknesses</th>
<th>Opportunities</th>
<th>Threats</th>
</tr>
</thead>
<tbody>
<tr>
<td>Commitment to renewable energy: Significant investments in solar and wind energy in Saudi Arabia, with ambitious targets, especially in Jeddah</td>
<td>High CO₂ emissions: High per capita CO₂ emissions in Saudi Arabia due to energy consumption patterns and reliance on fossil fuels</td>
<td>Economic diversification: Saudi Vision 2030’s aim for a more energy-efficient and environmentally friendly economy</td>
<td>Rapid urbanization and population growth: Straining the city’s infrastructure and leading to environmental degradation</td>
</tr>
<tr>
<td>Public transport developments: Initiatives like the Jeddah Metro project to enhance public transport networks</td>
<td>Energy-intensive economy: High energy consumption per unit of GDP indicating inefficiencies</td>
<td>Urban planning for sustainability: Potential for innovative strategies to enhance sustainability and living conditions</td>
<td>Climate change and water scarcity: Challenges related to water scarcity and impacts of climate change in an arid region</td>
</tr>
<tr>
<td>Advanced sanitation access: High access to improved sanitation facilities in Jeddah</td>
<td>Limited Green spaces: Challenges in maintaining or increasing green spaces in Jeddah</td>
<td>Public participation in environmental initiatives: Opportunities for enhanced public engagement and responsibility</td>
<td>Dependence on private vehicles: Leading to traffic congestion, high emissions and challenges in promoting public transport</td>
</tr>
<tr>
<td>Environmental governance: Ongoing initiatives, plans and monitoring systems focusing on sustainable growth</td>
<td>Inadequate waste Management Infrastructure: Need for improvement in waste collection, segregation, recycling and disposal</td>
<td>Enhancing waste Management: Modernizing waste management with improved recycling and sustainable disposal methods</td>
<td>Compliance and Enforcement Issues: Ensuring compliance with environmental policies and regulations</td>
</tr>
<tr>
<td>Water management improvements: Implementation of systems like advanced pressure management to reduce water loss</td>
<td>High water consumption: High per capita water consumption indicating a need for more efficient usage</td>
<td>Improvement in public transportation: Development of a comprehensive public transport network to reduce reliance on private vehicles</td>
<td>Urban heat island effect: Pronounced effect due to desert climate and urban expansion, increasing energy demands</td>
</tr>
</tbody>
</table>

5. Sustainable urban initiatives: comparative analysis and lessons for Jeddah

In the current section, a comparative analysis between Jeddah and other cities that have successfully implemented sustainable initiatives is presented. This can offer valuable insights and potential strategies that Jeddah could adopt or adapt to its context. Table 2 presents key aspects and examples of such a comparative analysis.

6. Conclusion and recommendations

To facilitate Jeddah’s transition to a sustainable urban environment, a comprehensive series of recommendations and future prospects have been formulated. These focus on different key areas including policy strengthening, strategic planning and capitalizing on key strengths and opportunities. The strategy includes focusing on energy and reducing carbon dioxide in the industrial and residential sectors through energy-saving technologies, in addition to switching to renewable energy, especially solar energy. Improving energy storage and the power grid are also crucial elements of this approach.

The plan also includes enhancing land use policies to achieve sustainable growth, which includes green building practices and the preservation of natural spaces. Developing an urban master plan that balances growth and environmental sustainability is an important part of this strategy. In addition, the strategy includes implementing stringent water conservation measures,
Table 2. Sustainable urban initiatives: lessons for Jeddah.

<table>
<thead>
<tr>
<th>Aspect</th>
<th>Examples</th>
<th>Key strategies</th>
<th>Application to Jeddah</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urban green spaces</td>
<td>Singapore’s ‘Garden City’, Vancouver’s ‘Greenest City 2020 Action Plan’</td>
<td>Singapore uses vertical greenery, rooftop gardens; Vancouver focuses on new trees and green spaces</td>
<td>Jeddah could use vertical gardens and green roofs to combat heat and develop water-efficient public parks</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Encouraging cycling and walking with dedicated lanes; efficient public transit systems</td>
<td>Creating bike lanes and pedestrian paths, enhancing public transit to reduce congestion, focusing on</td>
</tr>
<tr>
<td>Public transportation and reduced congestion</td>
<td>Copenhagen’s bike infrastructure, Amsterdam’s public transit</td>
<td></td>
<td>walkable neighborhoods</td>
</tr>
<tr>
<td>Energy efficiency and renewable energy</td>
<td>Reykjavík’s geothermal energy, Freiburg’s solar initiatives</td>
<td>Utilizing local renewable resources; installing solar panels on buildings</td>
<td>Promoting solar energy use and implementing energy-efficient building codes</td>
</tr>
<tr>
<td>Water management</td>
<td>Tucson’s rainwater harvesting, Tel Aviv’s water conservation</td>
<td>Rainwater harvesting in homes; advanced desalination and efficient irrigation</td>
<td>Adopting water-efficient landscaping, promoting water conservation technologies, considering desalination</td>
</tr>
<tr>
<td>Waste management and recycling</td>
<td>San Francisco’s zero waste goal, Seoul’s volume-based waste fee</td>
<td>Comprehensive recycling and composting programs; charging for non-recyclable waste production</td>
<td>Implementing recycling programs and incentivizing waste reduction to decrease landfill use</td>
</tr>
<tr>
<td>Sustainable urban planning</td>
<td>Curitiba’s integrated transport and land use</td>
<td>Well-planned bus rapid transit system and integrated green spaces in urban development</td>
<td>Focusing on transit-oriented development to synergize transportation infrastructure and urban planning</td>
</tr>
<tr>
<td>Building resilience to climate change</td>
<td>Rotterdam’s flood defenses, Miami’s sea-level rise strategies</td>
<td>Innovative water management, elevating roads and improving drainage systems</td>
<td>Developing coastal protection and enhancing urban drainage systems to adapt to climate change</td>
</tr>
<tr>
<td>Community engagement and social sustainability</td>
<td>Portland’s neighborhood involvement, Melbourne’s community-focused projects</td>
<td>Involving residents in sustainability initiatives and urban planning decisions</td>
<td>Encouraging community participation in environmental programs and urban development to ensure projects</td>
</tr>
<tr>
<td>Policy and governance</td>
<td>Stockholm’s congestion tax, Berlin’s energy transition policies</td>
<td>Using congestion pricing to reduce traffic, focusing on renewable energy and energy efficiency in buildings</td>
<td>Implementing policies that incentivize sustainable practices and establishing clear governance structures for sustainability</td>
</tr>
</tbody>
</table>

adoption of water-saving technologies, improving wastewater treatment, developing climate-resistant infrastructure and developing comprehensive climate change policies.

Finally, the strategy promotes recycling and waste reduction through public awareness and sustainable waste management policies. It also involves promoting renewable energy through public-private partnerships and promoting research in the field of renewable technologies. A large part of the plan is to engage the community in environmental conservation through campaigns, clean-up programs and environmental education in schools, ensuring a broad and comprehensive approach to sustainability.

Jeddah’s progress towards becoming an environmentally friendly city underscores the dynamic and complex nature of urban sustainability. The city’s proactive policies, innovative approaches and community engagement provide valuable insights into addressing environmental challenges. As Jeddah continues its journey towards sustainability, its experiences offer useful lessons for other cities striving to integrate urban development with environmental responsibility.

In conclusion, Jeddah’s transformation into a sustainable city depends on a diverse strategy that includes improving policies, strategic planning and exploiting available strengths and opportunities. This endeavor requires collaborative efforts from government agencies, the private sector and the community, to ensure a sustainable and greener future for the city.

Author contributions

Ibrahim Hegazy (Conceptualization [equal], Formal analysis [equal], Methodology [equal], Project administration [equal], Writing—original draft [equal]), Hazem Hammad (Data curation [equal], Formal analysis [equal], Investigation [equal], Validation [equal]), Ammar Munshi (Data curation [equal], Formal analysis [equal], Investigation [equal], Ahmed Alqurashi (Formal analysis [equal], Investigation [equal], Methodology [equal]), and Ibrahim Bahreldin (Conceptualization [equal], Methodology [equal], Supervision [equal], Writing—review and editing [equal]).

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