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A Route to Environmental Sustainability in the Kingdom of Saudi Arabia: A Comprehensive Review of Challenges, Initiatives and Future Directions

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ABSTRACT: Environmental sustainability demands an immediate attention for the Kingdom of Saudi Arabia (KSA) as the nation takes forward a deep economic transformation under Vision 2030. Despite the pivotal role of environmental sustainability in promoting long-term human well-being, the relationship between environmentally sustainable practices and long-term human needs fulfilment remain an under explored in the Saudi context context. The current study carried out a thorough review in addressing this gap by systematic evaluation of sustainable practices in KSA, identifying the structural and behavioural barriers in the implementation process. Further, the study puts forward an integrated Environmental Sustainability Framework that unequivocally integrates sustainability interventions with basic needs fulfilment across four key domains. A systematic review based on PRISMA guidelines is carried out. 127 records were identified by systematic search of Scopus, Web of Science, Google Scholar, and ScienceDirect. The initial screening generated 68 records. These along with 45 peer-reviewed articles, government reports, and policy publications between 2017 and 2026 were included in the final thematic synthesis. Data were synthesised across four domains: renewable energy, water conservation, waste management, and land restoration. The present research unveils potential advancements and intractable hurdles. The landmark projects like Sakaka Solar PV facility and the Dumat AI Jandal Wind Farm has driven KSA's renewable energy capacity from 0.4 GW in 2020 to 13 GW by 2025, including 15 Power Purchase Agreements indicating 24.389 GW signed in 2025. The Saudi Green Initiative devotes focus on decarbonisation with funding $187 billion, afforestation of 10 billion trees and a net-zero emissions level by 2060. The Saline Water Conversion Corporation (SWCC), has topped the global largest desalination programme, while functioning with 33 desalination plants and a unified daily production capacity of 7.5 million cubic metres. However, per-capita daily water utilisation records at 263 litres — which doubles the global average of 140 litres — demanding a goal of 43% reduction to meet the 2030 mark of 150 litres. Groundwater extraction continues at 321% of the renewable recharge volume, endangering long-term water security. In waste management, total waste generation hit 135.1 million tons in 2024, with organic waste comprising 45.7% and 22.8% including construction waste of the total stream, emphasizing the importance of circular economy mechanisms. An integrated Environmental Sustainability Integration Framework is put forward, connecting Vision 2030's three pillars — a dynamic society, a flourishing economy, and an aspiring nation — to the realisation of basic needs through integrated water, energy, waste, and land management pathways. Besides, establishing policy recommendations that include sustainable governance mechanisms that span across industries, emphasis was laid on expediting to achieve a target of 130 GW for renewable energy production, deploying both demand-side water administration and and desalination scaling, corroborating circular economy infrastructure with public-private partnerships. Further, land restoration was employed through Al Baydha permaculture model. Endowed with financial assets, geographical attributes and political resolve, place KSA in sustainable leadership position internationally, however, success demands translation of obligations into verifiable, finite actions at the community and institutional levels.

1. INTRODUCTION

Humanity in twenty-first century is confronted with The twenty-first century tackles humanity with an unmatched conflux of environmental crises, that include escalating change in climate conditions, imbalance in biodiversity, inadequate freshwater and extinction of resources. Which has a subsequent impact on the realisation of basic human needs. The basic human needs for clean water, air and food security are fundamental biological and social commodities that support human well-being. These go beyond economic relevance. The Intergovernmental Panel on Climate Change (IPCC) has consistently warned that without transformative alleviation and adjustment measures, these intersecting pressures will inordinately impact arid and semi-arid regions, positioning populations in water-stressed environments at the highest peak of cascading scarcity. It is within this global context that the environmental sustainability trajectory of the Kingdom of Saudi Arabia acquires particular urgency and scholarly significance.

Saudi Arabia which is situated in one of the hyper -dry, desert climate with scarce surface water resources and non-renewable fossil groundwater resources that are depleting quickly. Be the world's largest exporter of petroleum and responsible for 12% of oil production globally. The economic development of KSA heavily is dependent on fossil fuel extraction and energy-intensive water production. KSA holds advantageous position with respect to geopolitical and environmental contexts. Increased urbanization coupled with alarming population growth which expected to go beyond 40 million by 2030, and conventionally discounted energy prices have collectively increased per capita consumption to levels that are environmentally unsustainable. Understanding how KSA steers the tension between economic development imperatives and environmental sustainability obligations is therefore a matter of both domestic policy concern and global environmental significance (Alshuwaikhat & Mohammed, 2017; Khalil & Husain, 2013).

The Saudi Vision 2030 in April 2016 launched by Crown Prince Mohammed bin Salman marked a turning point in the Kingdom's developmental trajectory. Vision 2030's ambitions in line with environmental sustainability goals are not incidental but structurally relevant. (Jaouadi et al., 2026; Khan et al., 2020). Vision 2030 founded on the three independent pillars, a vibrant society with high quality life and strong cultural indetity. And an economy directing its growth away from oil reliance to tourism and innovation. And an efficient governance, fiscal discipline with global immersion and connectivity. Each of these pillars rest on environmental sustainability dimensions. A nation wanting to position itself in environmental sustainable agenda. Hence, access to clean water, fresh air and green public spaces must eventually rest on renewable resources for it to be sustainable.

The Saudi Green Initiative (SGI), launched in 2021, gives robust form to these environmental ambitions. With a total committed investment of $187 billion, the SGI includes the planting of 10 billion trees across the Arabian Peninsula, a $3.2 billion National Tree Planting Program, a $2.1 billion Air Quality Improvement Initiative, and a $1.8 billion Marine and Coastal Protection Program. The SGI also comprises the Circular Carbon Economy National Program, depicting a $15 billion commitment to carbon capture, utilisation, and storage technologies. Critically, the Kingdom has committed to achieve net-zero greenhouse gas emissions by 2060 — a target that requires a fundamental restructuring of the energy system, a dramatic intensification of renewable deployment, and the prevalent acceptance of circular economic principles across all productive sectors (Tiwari et al., 2024).

The four sustainability domains examined in this review — renewable energy, water, waste, and land — are not independent sectors but are deeply intertwined through material and energy flows that birth both risks and opportunities when dealt in isolation. The energy-water nexus is perhaps the most urgent of these interdependencies. This deficit is substantial because effective sustainability governance needs comprehending the systemic interdependencies between water, energy, waste, and land: the energy-water nexus, the food-water-energy trilemma, and the circular economy connecting between waste streams and resource recovery all demand holistic analytical frameworks (Tiwari et al., 2024; Jaouadi et al., 2026).

KSA's environmental challenges are both severe and well-documented. Per-capita water consumption at 263 litres per day is nearly double the global average; groundwater abstraction occurs at 321% of the renewable recharge rate; 89% of water demand is met by over-pumping non-renewable aquifers. Waste generation reached 135.1 million tons in 2024, depicting a 21.3% increase from 111.4 million tons in 2023. The country's carbon emissions remain among the highest per capita globally, though the renewable energy transition has gained substantial momentum. These challenges are compounded by extreme ambient temperatures — routinely exceeding 45°C in summer — which drive energy consumption for cooling, accelerate water evaporation, and constrain outdoor productive activity. Addressing these interconnected pressures needs not mere sector-specific strategies but a coherent, cross-sectoral sustainability framework that can steer policymakers, practitioners, and communities toward integrated solutions (Alotaibi et al., 2023; Vellaiyan et al., 2025).

Against this context, the present review seeks four principal research objectives: (1) to evaluate the present condition of environmental sustainability programs in KSA and their efficacy in satisfying fundamental human needs across the domains of water, energy, clean environment, and food security; (2) to determine the principal issues and challenges to the implementation of viable practices at technical, institutional, behavioural, and governance levels; (3) to propose innovative, context-specific interventions to optimize sustainability while addressing fundamental needs within the socio-cultural and climatic realities of the Arabian Peninsula; and (4) to devise a integrative Environmental Sustainability Integration Framework for incorporating sustainability concepts into regional development policies synchronized with Vision 2030.

The rest of this article is organized as follows: Section 2 portrays the systematic review methodology; Section 3 exhibhits the results and analysis across the four sustainability domains and provides a SWOT analysis of KSA's overall sustainability posture; Section 4 discusses the integrated implications of the findings, including international comparisons and policy coherence considerations; and Section 5 presents conclusions and specific policy recommendations for quickening KSA's transition to environmental sustainability.

2. METHODOLOGY

This study utilises a holistic systematic review design following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. The systematic review methodology was selected because it makes a structured, replicable, and transparent approach to synthesising a dispersed body of literature, thereby reducing selection bias and empowering the identification of patterns across divergent domains of inquiry. Given the multi-sectoral nature of environmental sustainability in KSA, a thematic synthesis approach was implemented to incorporate findings from across the water, energy, waste, and land management literatures.

2.1. Literature Search Strategy

A comprehensive literature search was conducted across four major scientific databases: Scopus, Web of Science, Google Scholar, and ScienceDirect. The search strategy devised a blend of Boolean operators and regulated vocabulary terms to optimise recall while maintaining precision. Primary search strings included: "environmental sustainability" AND "Saudi Arabia" AND ("Vision 2030" OR "basic needs" OR "water scarcity" OR "renewable energy" OR "waste management" OR "circular economy" OR "desalination" OR "land restoration"). Additional targeted searches were conducted for sector-specific terms, including "Saudi Green Initiative," "SWCC desalination," "SIRC recycling," and "Al Baydha permaculture."

2.2. Inclusion and Exclusion Criteria

Articles were incorporated if they: (1) were published between 2017 and 2026 in peer-reviewed journals, or constituted government reports, official policy documents, or internationally recognised technical reports from the same duration; (2) were written in the English language;

(3) focused precisely on environmental sustainability dimensions within the Kingdom of Saudi Arabia; and (4) addressed at least one of the four basic analytical domains (water, energy, waste, or land management). Seminal pre-2017 employs that established foundational theoretical frameworks or baseline data for KSA sustainability research were regarded on a case-by-case basis and incorporated where they offered unavoidable contextual anchoring.

Articles were omitted if they: (1) were published in non-peer-reviewed channels without governmental or institutional authority; (2) did not aim mainly on KSA environmental conditions or policies; (3) were published before 2017 without offering foundational contextual value; or (4) addressed sustainability in a mainly social or economic sense without significant environmental dimensions. Conference abstracts without full-text access were also omitted.

2.3. Screening and Data Extraction

The search process yielded 127 initial records after de-duplication. Title and abstract filtering diminished this to 68 records meeting the broad incorporation criteria. Full-text assessment identified 45 articles and reports that satisfied all inclusion criteria and provided substantive data or analytical insights relevant to the research objectives. Data were extracted systematically across four analytical domains: renewable energy statistics and policy developments; water resource management data, institutional arrangements, and governance reforms; waste generation data, management strategies, and circular economy mechanisms; and land restoration initiatives, biodiversity conservation, and the Al Baydha case study.

2.4. Quality Assessment and Analytical Framework

Quality assessment of the included observational and empirical studies was carried out using a modified Newcastle-Ottawa Scale adapted for environmental sustainability research. Studies were evaluated on three domains: the exemplary and viability of the study design; the sufficiency of data sources and measurement instruments; and the transparency and rigour of reporting. Government and institutional reports were estimated using criteria for credibility, authority, and recency of data.

Thematic synthesis was used to systematize derived data into logical domains, identify cross-cutting patterns, and cultivate higher-order themes relating to barriers, facilitators, and integrated solutions. A SWOT (Strengths, Weaknesses, Opportunities, Threats) framework was employed at the macro level to offer a structured assessment of KSA's overall environmental sustainability posture. The Environmental Sustainability Integration Framework puts forward in this article was advanced iteratively through an abductive reasoning process, traversing between the empirical evidence base and theoretical constructs from sustainability science, comprising the Nexus framework, the basic needs stratification, and the circular economy model. The framework progression process extracted on comparative analysis with analogous arid-region contexts, including the UAE, Qatar, Oman, and Australia's arid zones.

3. RESULTS AND ANALYSIS

3.1. Renewable Energy Transition

KSA's renewable energy transition displays possibly the significant transition in the Kingdom's energy landscape since the discovery of oil. Solar irradiance magnitudes in the Arabian Peninsula are among the maximum globally — averaging 2,200–2,400 kWh/m^2/year — rendering KSA one of the advantageous position globally for solar energy usage. The Kingdom has transitioned with growing immediacy to leverage this capacity, powered by both the financial imperatives of Vision 2030 (reducing domestic oil consumption to free up export revenues) and the international climate commitments of the Paris Agreement and the SGI (Selim & Alshareef, 2025; Zohbi & Alamri, 2020).

The growth trajectory is remarkable. KSA's cumulative renewable energy capacity remained at approximately 0.4 GW in 2020 — a figure that indicated decades of underinvestment in substitutes to oil-fired power generation. By the culmination of 2024, solar capacity alone had moved to 4,665 MW, and by end-2025 the total renewable energy portfolio had jumped to approximately 13 GW, with solar comprising approximately 12.5 GW and wind including the rest. This displays more than 30-fold expansion in renewable capacity over five years — a noticeable achievement at global level. In 2025, approximately

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7.8 GW of solar capacity was included to the grid, displaying an accelerating deployment pipeline. The 700 MW already linked to the grid by mid-2025 was approximated to power approximately 311,000 households yearly (PV Magazine, 2026).

The flagship projects driving this transition consists the Sakaka Solar PV Plant in Al Jouf Province — one of the Kingdom's first utility-scale solar installations at 300 MW — and the Dumat Al Jandal Wind Farm in Al Jouf, with a capability of 400 MW and the uniqueness of being the largest wind energy project in the Middle East at the period of its commissioning. These projects have displayed the technical sustainability of large-scale renewable implementation in harsh desert environments and have created the procurement and operational frameworks now being replicated at scale across the Kingdom (Selim & Alshareef, 2025).

The policy momentum is equally important. In 2025, KSA signed 15 Power Purchase Agreements (PPAs) indicating a combined capacity of 24.389 GW — a single-year procurement acquisition that goes beyond the cumulative renewable capacity of many developed nations. The National Renewable Energy Program, implemented, by the Saudi Power Procurement Company, has established highly competitive bids that have gradually driven down the cost of solar energy in the Kingdom to among the lowest in the international markets. The long-term target of 50% electricity production from renewables by 2030, underpinned by a 130 GW installed capacity objective, would — if achieved — include one of the most fast and thorough energy system transitions in modern economic history (Selim & Alshareef, 2025).

Contributing to the the renewable deployment agenda is KSA's support of the Circular Carbon Economy (CCE) framework, is an epitome of KSA’s support for renewable energy utilisation agenda. Further, this complements carbon capture and utilisation (CCU) and carbon elimination to the conventional avoid-reduce-mitigate hierarchy. Capturing the heart of this strategy is located The Saudi Aramco Carbon Capture Hub at Jubail which captures 9 million metric tons of CO_2 annually by 2027. Thus, the CCE puts KSA in an advantageous position beyond passive emitter reducing its carbon footprint but also an active player in the development of carbon management technologies which can be exported to hydrocarbon-inclined economies that are in the similar energy transformations. This is displayed in Figure 2.

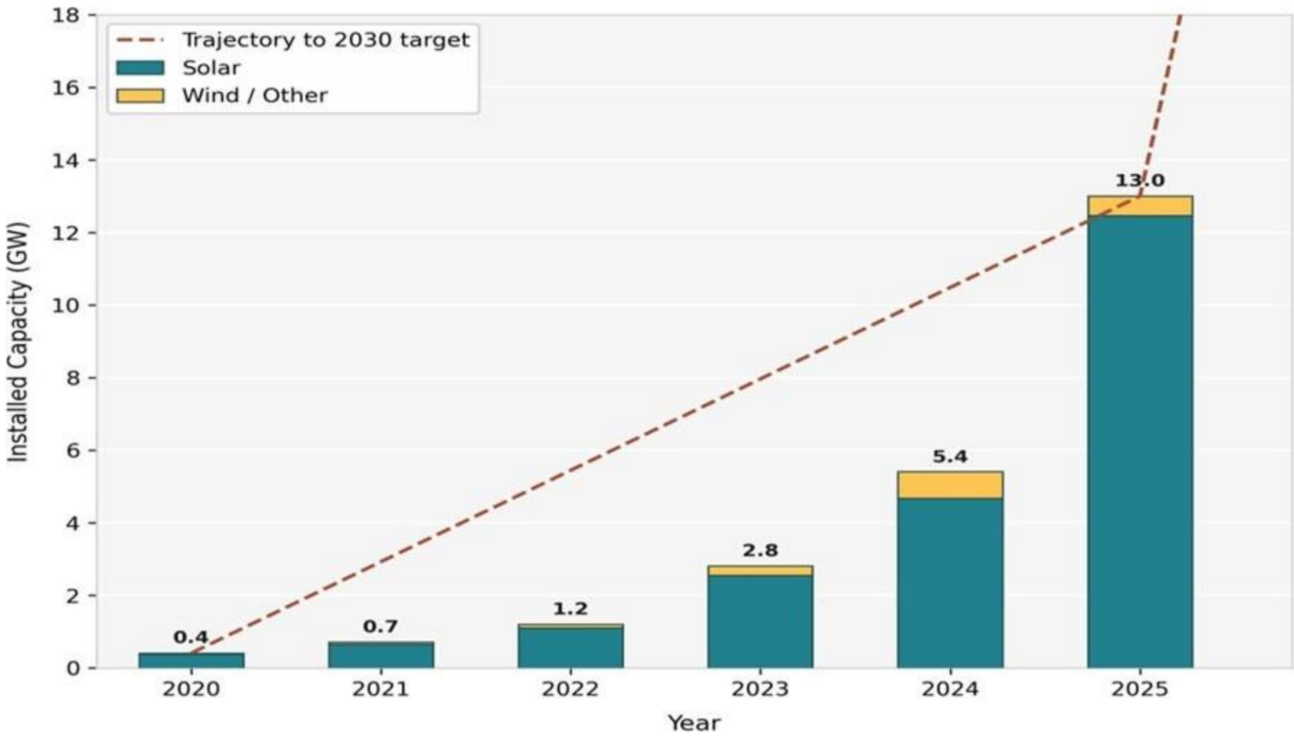

Figure 2. Surge in Renewable energy deployment in in the Kingdom of Saudi Arabia (2020–2025), indicating a rapid expansion from 0.4 GW to 13 GW powered by large-scale solar and wind projects.

Table 1. Summary of Saudi Vision 2030 Environmental Sustainability Targets and Progress

Domain	Key Initiative	Target	Current Status	Progress Rating
Renewable Energy	National Renewable Energy Program; 15 PPAs (24.4 GW) signed in 2025	50% electricity from renewables; 130 GW by 2030	13 GW capacity (~10% share); 7.8 GW added in 2025	On Track
Water Conservation	National Water Strategy 2018; SWCC 33 plants; wastewater reuse expansion	Reduce per-capita use to 150 L/day; 25% wastewater reuse	263 L/day consumption (43% reduction needed); 17.3% reuse	Needs Acceleration
Waste Management	SIRC 65+ cities; Riyadh C&D recycling plant; Ministry 2024 Strategy	Recycle 95% waste; 3 GW WTE by 2030; 100 M tons/yr processing	135.1 M tons generated (2024); 9.7%/yr recycling growth	Early Stage
GHG Emissions	Saudi Green Initiative; Circular Carbon Economy; Aramco CCS Hub	Reduce 278 M tons/yr by 2030; net-zero by 2060	20 M tons/yr reduction targeted; 9 M t CO_2 CCS by 2027	On Track
Afforestation	Saudi Green Initiative; National Tree Planting Program ($3.2B)	10 billion trees; 30% land under protection	Al Baydha model scaling; 85% tree survival in desert	Progressing
Marine Protection	Coastal Protection Program ($1.8B); coral reef restoration	Protect Red Sea & Arabian Gulf ecosystems	Active programs in Red Sea and Arabian Gulf regions	Progressing

3.2. Water Conservation and Management

Owing to the harsh dry weather conditions of KSA, which has no perennial rivers or lakes with a yearly precipitation of less than 100mm in multiple regions and dropping below 30 mm in the regions of interior desert. Water security has essentially become the striking challenge of KSA region. Despite this extreme dryness or drought, KSA has a continued population of over 35 million with per-capita water consumption that goes beyond both regional and international averages, a paradox made possible only through the energy-intensive desalination of seawater and the unsustainable mining of non-renewable fossil aquifers (Alotaibi et al., 2023; Baig et al., 2023).

Saudi Arabia has launched the Saline Water Conversion Corporation (SWCC) which runs with with daily production capacity of 7.5 million cubic meters across 33 desalination plants in the regions of Red Sea and Arabian Gulf Coasts put together. This accounts to 9.3% of the water demand primarily for municipal and industrial utilisation in coastal regions. This desalination programme provides a dependance and deployable water source, however, this itself is taxing as it consumes 15-20% of KSA's electricity generation. This establishes a direct loop between water scarcity and energy consumption (Vellaiyan et al., 2025).

KSA's primary water source is ground water accounting for 89% of total national water demand. This ground water which is available in in deep aquifers of the Saq-Ram and Wajid aquifers. The ground water reserves of KSA are utilised three times after than it is replenished. This is indicated with its estimated reserves from 259 to 761 billion cubic metres, and the annual replenishment rate volume is approximately, 886 million cubic metres. With these figures, the ground water exploitation is 321% of its replenishment. These figures pose a threat indicating the exhaustion of primary aquifer systems with in decades posing a threat to the agricultural systems and rural communities that are dependant on them (Baig et al., 2023).

KSA's agriculture sector is highly ineffective as it draws 80% of its water from ground water, which depletes the ground water significantly. With the surge in irrigated wheat and forage production from 1970s to 1990s, which are heavily backed up ground water, has become a challenge in of the most arid regions on the earth. Since 2015, the government has applied strategic crop production restrictions — particularly on wheat, which was earlier subsidised to the extent that KSA became a significant wheat exporter— shrinking agricultural water utilisation by approximately 60%. This policy change indicates a major realignment, though the legacy infrastructure and residual groundwater dependency remain challenges for water governance (Alotaibi et al., 2023).

Per-capita daily water consumption of 263 litres indicates specifically acute management concern. This figure doubles the global average of 140 litres per day and approximately 75% above the WHO minimum suggested mark for comfortable water security. In the past, suppressed water prices — with discounted tariffs that masked the true environmental and economic cost of water production — have inhibited conservation behaviours and investment in effective appliances and irrigation technologies. The National Water Strategy 2018 establishes a target of reducing per-capita consumption to 150 litres per day by 2030, which would require a 43% reduction — a unavoidable behavioural and infrastructural challenge. Wastewater treatment capacity is being expanded from 5.6 million m³/day (2018) to a targeted 8.4 million m³/day by 2030, and treated wastewater reutilisation is being increased from 17.3% to 25% by 2025 (Vellaiyan et al., 2025; Alotaibi et al., 2023). The water resource condition is explained in Figure 4, and key estimates are outlined in Table 2.

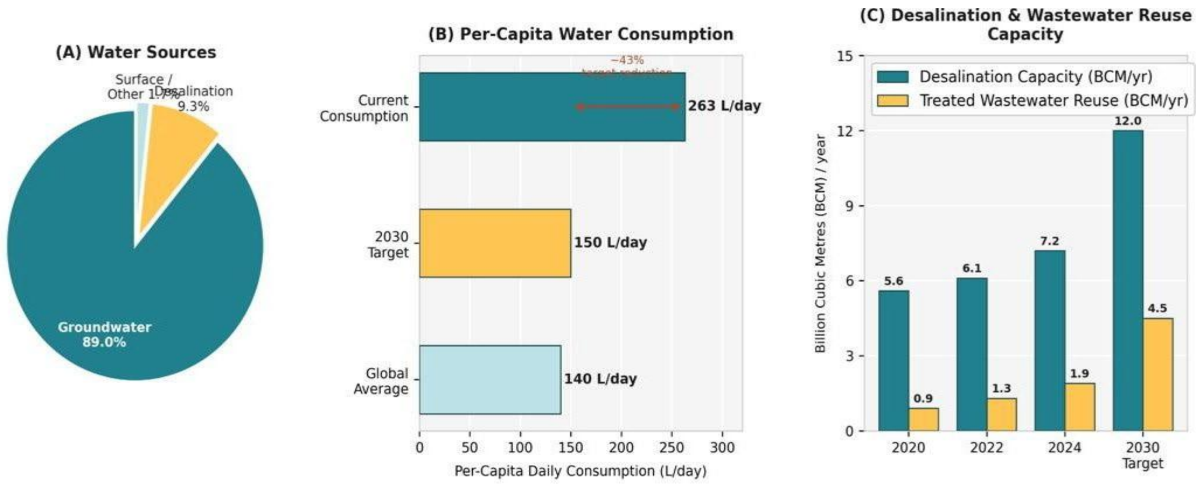

Figure 4. Water Resources Management in the Kingdom of Saudi Arabia, illustrating the flow of water supply from desalination and groundwater sources through distribution networks to end-use sectors.

Table 2. Water Resource Statistics in the Kingdom of Saudi Arabia

Indicator	Value	Source
Total water demand	~25 billion m³/year	Alotaibi et al. (2023); Baig et al. (2023)
Groundwater share	~89% of total demand	Vellaiyan et al. (2025)

Desalination share	9.3% of total demand	Alotaibi et al. (2023)
Per-capita daily consumption	263 liters/day (target: 150 L/day by 2030)	National Water Strategy 2018
Desalination plants (SWCC)	33 operational plants	SWCC Annual Report
Daily desalination capacity	7.5 million m³/day	SWCC; Alotaibi et al. (2023)
Groundwater reserves (estimated)	259–761 billion m³ (non-renewable fossil)	Baig et al. (2023)
Annual groundwater recharge	Only 886 million m³/year	Baig et al. (2023)
Groundwater abstraction rate	321% of renewable volume	Vellaiyan et al. (2025)
Agricultural water use share	>80% of total water resources	Alotaibi et al. (2023)
Wastewater treatment capacity	5.6 million m³/day (target: 8.4 M m³/day by 2030)	National Water Strategy
Treated wastewater reuse rate	17.3% (target: 25% by 2025)	National Water Strategy 2018

3.3. Waste Management and Circular Economy

The rapid urbanisation, increased spending capacity, population growth and significant construction activity related to Vision 2030's mega projects have birthed waste management as a significant governance challenge. Waste management is one of the pressing governance challenges in KSA, propelled by significant urbanisation, population increase, increasing consumer affluence, and potential construction activity related with Vision 2030's mega projects. The waste generation surged from 111.4 tonnes in 2023 to 135.1 tonnes in 2024 which accounts to an increase of 21.3%. This is the largest by its numbers for any nation's economy. This depicts effective waste data collection and measurement. Further, this also throws light on the increased material throughput from agricultural strengthening, construction booms and municipal consumption (Aldhafeeri & Alhazmi, 2022; Ghaithan et al., 2020).

Inspecting the KSA 's waste patterns unveils significant insights. Highest share of the waste i.e., 45.7% coming from organic category which amounts to 61.7 million tons, thus opening up potential resource for biogas production and composting. Followed by construction and demolition (C&D) waste records with a share of 22.8%, this indicates the massive infrastructure development in KSA, — from NEOM to the Red Sea Project to expanded industrial zones in Jubail and Yanbu. Household and municipal solid waste (MSW) share the smallest fraction of 5.8% of total waste accounting to 20.5 million tastes, Followed by manufacturing and plastic waste with totals of 20.5 million tons, and 8 million tons (5.8%) respectively. These figures are alarming and pose a grave challenge in achieving sustainable environment targets (Alghafis et al., 2025).

The institutions handling waste management in KSA is set to undergo significant structural shifts in the recent past. The Saudi Investment Recycling Company (SIRC), a government-backed entity, has set an operational mark to 35 million tons per year by 2035 stretching its operational footprint to 65 or more cities. SIRC's flagship Riyadh C&D recycling facility which has set a benchmark performance showcasing the technical flexibility for complex waste processes functions at 600 tons per hour with 90% material recovery. Riyadh's broader municipal strategy mark of 81% diversion of MSW from landfill, which would achieve a world-class diversion performance for a city of its scale and growth trajectory (Mohammed et al., 2022).

The Ministry of Environment's 2024 waste management strategy has set ambitious target of recycling 95% of nation's waste sector and levelling upto a 100 million tons per year. Realisation of these goals can position KSA as a global leader in circular waste management. The Waste-to-Energy (WTE) sector market has a projected growth of CAGR 8.08% during 2026-2034, touching 1,436.3 million USD by 2034. Further, this sector is aimed to assist 3 GW of electricity generation capability by 2030. This has got a compelling economic rationale. The waste management currently contributes to SR 120 billion (approximately $32 billion) to national GDP and generate more than 100,000 direct and indirect employment positions. Recycling particularly is projected to grow at 9.7% per year through 2031 (Aldhafeeri & Alhazmi, 2022; Alghafis et al., 2025). These statistics are described in Figure 3 and outlined in Table 3.

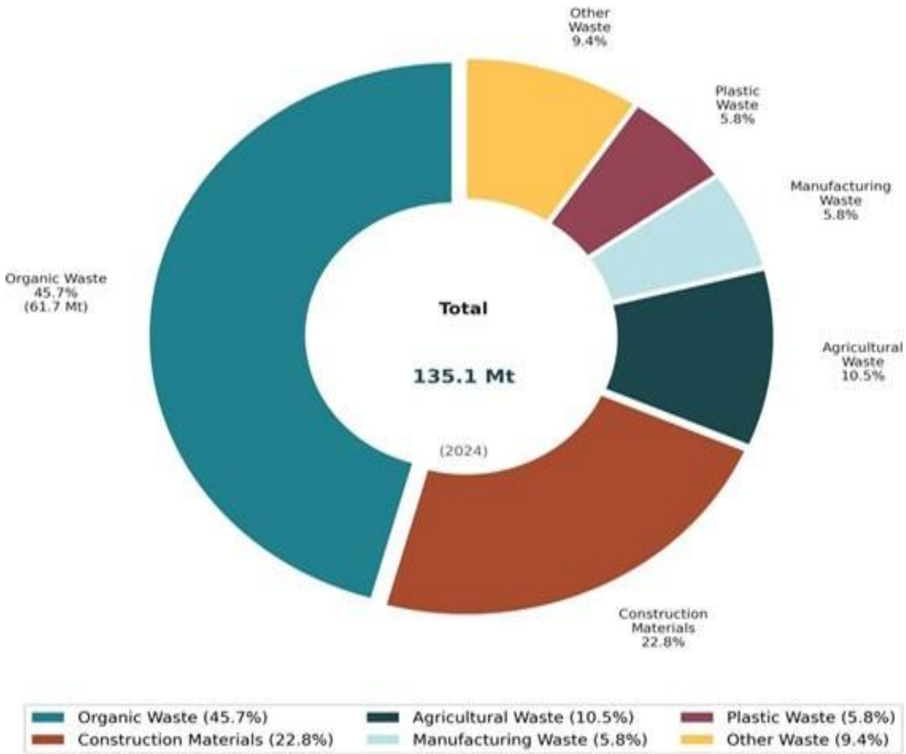

Figure 3. Waste Composition in the Kingdom of Saudi Arabia (2024), showing the proportional distribution of organic, construction, household, manufacturing, and plastic waste streams.

Table 3. Waste Management Statistics and Targets in KSA (2024)

Indicator	Current Value	Target	Timeline
Total waste generated	135.1 million tons	95% recycling; 100 M t/yr processing	2030
Organic waste share	45.7% (61.7 million tons)	Increase biogas/compost recovery	2030
Construction	22.8% (32.2 million tons)	90% material recovery (Riyadh model)	2030
Household/municipal solid waste	20.5 million tons	81% MSW diversion (Riyadh target)	2030

Indicator	Current Value	Target	Timeline
Waste-to-Energy capacity target	Currently minimal	3 GW WTE capacity	2030
Recycling market growth rate	9.7% per year (current)	Maintain	Through 2031
SIRC processing capacity	Operational in 65+ cities	35 million tons/annum capacity	2035
Economic GDP impact	SR 120 billion (~$32 billion)	Full realization	2030
Job creation target	Programs underway	100,000+ direct and indirect jobs	2030

3.4. Land Restoration and Biodiversity

KSA's land environment encounters pressures from desertification, soil erosion, overgrazing, and the direct physical footprint of rapid urban and infrastructure. Approximately 95% of Saudi territory is classified as arid or hyper-arid, with biodiversity concentrated in the southwestern Asir highlands, the Red Sea coastal mangroves, and the coral reef systems of the Red Sea and Arabian Gulf. The Saudi Green Initiative has launched diverse programs as a part of land restoration. These include National Tree Planting Program, investing $3.2 billion targeting 10 billion trees across the Arabian Peninsula, and the Air Quality Improvement Initiative with $2.1 billion investment targeting a 70% reduction in air pollution levels. A $1.8 billion investment was made for protecting marine and coastal ecosystems which includes coral reef restoration, mangrove conservation, and maritime pollution control (Saudi Green Initiative Roadmap).

The Al Baydha Project which has created a striking achievement in a previously barren desert. The trees established during the planting phase thrived after man made irrigation was discontinued in 2016. This can be attributed to the soil preparation, water harvesting conditions and self-sustaining vegetations. This has been the most appraised and documented case study in the extreme dry conditions of Arabian peninsula. The land in the context was discovered in 2009, close to 50km south of Mecca in the Makkah Province. The land has got barren due to overgrazing and agriculture misuse. Permaculture principles were religiously adopted, to reverse desertification through a combination of rainwater harvesting structures (rock terraces, gabion check dams, swale lines), drought-resistant afforestation deploying date palms (Phoenix dactylifera), Ziziphus Spinachristi, and Moringa Peregrina, and the regeneration of natural soil biological communities.

The AI Baidya model achieved an 85% tree survival rate under these conditions — a figure that compares exceptionally inclined with conventional desert afforestation endeavours (Spackman, 2020).

The project received commendation from Prince Khaled Al Faisal, and has been cited as "a template for the reforestation of millions of desert landscapes in the Arabian Peninsula" — an acknowledgement of both its ecological success and its reproducibility at scale. The Al Baydha methodology is directly applicable to the Saudi Green Initiative's afforestation targets: if the water harvesting and soil preparation techniques pioneered at Al Baydha can be systematically deployed across suitable terrain in the Hijaz and Asir regions, the feasibility of achieving the 10 billion tree planting target is significantly increased. Marine ecosystem protection efforts similarly reflect a growing recognition that healthy coastal ecosystems provide critical ecosystem services — fisheries productivity, storm protection, carbon sequestration — that underpin both human food security and climate resilience.

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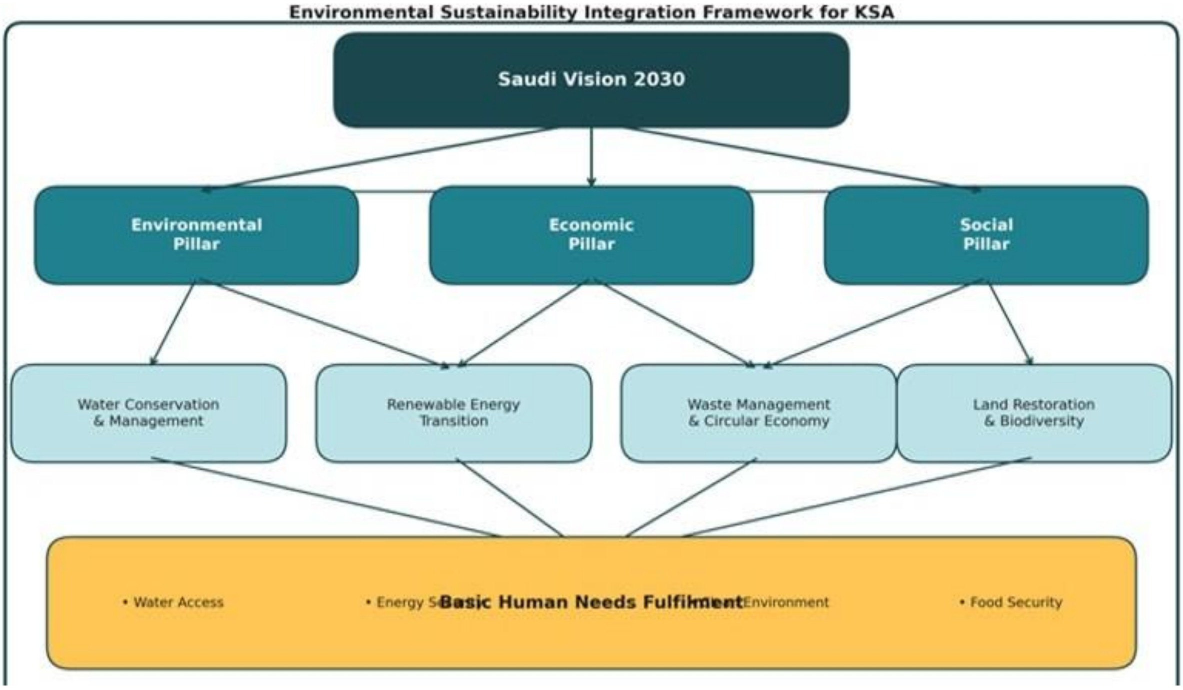

Figure 1. Environmental Sustainability Integration Framework for the Kingdom of Saudi Arabia, linking Vision 2030's three pillars to basic needs fulfilment through coordinated water, energy, waste, and land management pathways.

3.5. SWOT Analysis of Environmental Sustainability in KSA

A structured SWOT analysis was applied to synthesise the cross-domain findings and offer a holistic evaluation of KSA's environmental sustainability posture (Figure 5).

KSA's key strengths compromise exceptional solar energy capability (among the highest irradiance levels globally), an unparalleled financial capacity to invest in sustainability infrastructure, demonstrated technological leadership in desalination, strong and centralised governmental commitment to Vision 2030, and a strategic geographic position at the intersection of major global trade routes that offers technology access and green hydrogen export markets.

Principal weaknesses consist structural economic dependency on fossil fuel revenues that produces institutional resistance to energy system transformation, per-capita water and energy consumption that stays among the highest globally, limited public environmental awareness and conservation culture partially attributable to decades of energy and water price subsidisation, an emerging rather than mature circular economy infrastructure, and a comparative dearth of domestic technical expertise in sustainability science and engineering disciplines.

Significant opportunities are accessible to KSA. The Kingdom is strategically positioned to become the world's leading green hydrogen producer and exporter, leveraging abundant solar resources and existing energy infrastructure. The Circular Carbon Economy framework provides a distinctive "fourth pillar" of carbon management that synchronises with KSA's comparative advantage in large-scale industrial operations. The Saudi Green Initiative provides an opportunity for KSA to become a regional sustainability model indicating that hydrocarbon-dependent economies can produce credible environmental transitions. The domestic waste management transformation, if successfully implemented, could produce substantial economic value through resource recovery and green employment creation.

Major threats to KSA's sustainability ambitions include the accelerating pace of climate change itself — which is shown to reduce renewable water resources by 20–30% by mid-century, rise intense heat events, and endanger coastal infrastructure through sea level rise. Rapid urbanisation stretches the infrastructure and resource demand base much faster than efficiency improvements can offset. The political economy of oil dependency provides structural barriers to the pace of energy system transformation required by 2060 net-zero commitments. The 21.3% surge in waste generation documented in 2024 depicts the challenge of decoupling economic growth from material throughput within existing governance frameworks.

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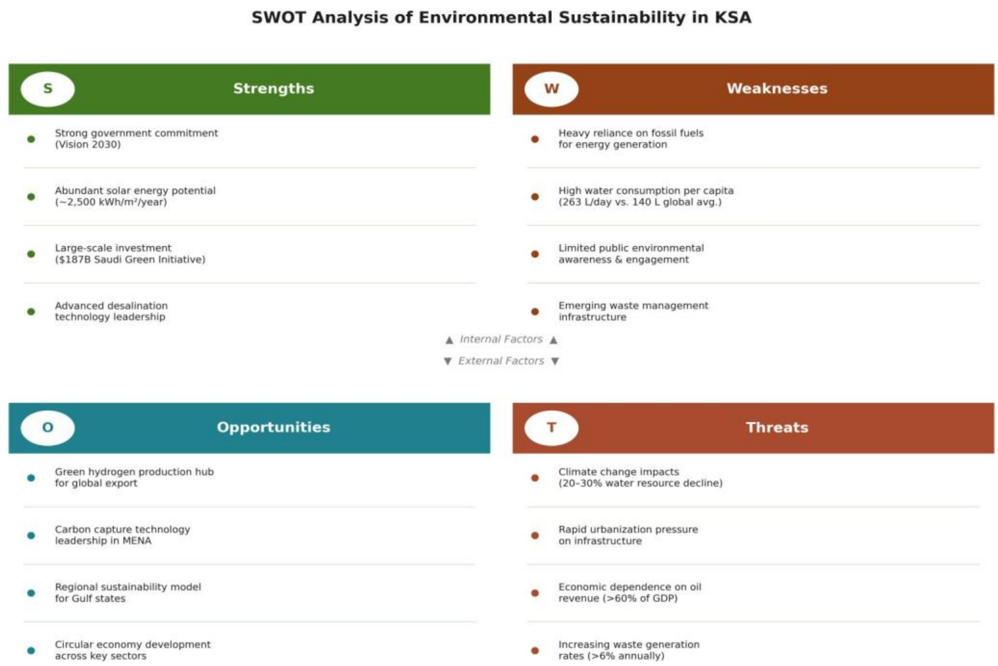

Figure 5. SWOT Analysis of Environmental Sustainability in the Kingdom of Saudi Arabia, evaluating internal strengths and weaknesses alongside external opportunities and threats.

4. DISCUSSION

The current study reveals KSA’s potential and consistent advancements in various analytical domains. However, though the results have been dramatic in some sectors pertaining to environmental sustainability, it comes with its significant challenges with respect to structural, institutional and behavioural barriers that threaten the fulfilment of Vision 2030’s. The discussion explores the integration of these findings, the proposed Environmental Sustainability Integration Framework, international comparisons, and the critical policy and governance considerations that will determine whether KSA's sustainability transition excels.

4.1. Integration of Findings: The Cross-Domain Nexus

The four sustainability domains examined in this review — renewable energy, water, waste, and land — are not independent sectors but are deeply intertwined through material and energy flows that birth both risks and opportunities when dealt in isolation. The energy-water nexus is perhaps the most urgent of these interdependencies. KSA's desalination capability generates 7.5 million m³ of potable water per day but utilises approximately 15–20% of national electricity generation in doing so. As renewable energy capacity expands, the carbon intensity of desalination reduction — a direct beneficial interaction. Contrary to this, desalination plant construction and operation have coastal environmental footprints (brine discharge, marine thermal pollution) that must be organized as part of the marine protection agenda (Vellaiyan et al., 2025; Baig et al., 2023).

The KSA’s annual waste of 135.1 million tons, contains ample energy content, which includes 45.7% of organic and 5.8% of plastic fractions. If WTE levels upto 3 GW by 2030 is met, the renewable energy target of 2.3% could have been achieved. This eventually reduces landfill volumes and related methane emissions. Further, the land revival agenda and afforestation is enabled by soil amendments which is a part of organic waste composting, this establishing a a direct circularity loop between urban waste management and the Saudi Green Initiative's tree planting targets (Ghaithan et al., 2020; Alghafis et al., 2025).

The Environmental Sustainability Integration Framework suggested in the current study (Figure 1) traces, how the conflux of the different domains- water security, energy, a clean environment and food security support the fulfilment of basic human needs. This is achieved through designing interventions around vision. For a holistic sustainability performance, The framework establishes the feedback loops between domains and establishes cross-sectoral governance as the facilitating condition for holistic sustainable performance. Lack of effective coordination processes can produce suboptimal or even counter effective outcomes at the system level— such as an inter-ministerial sustainability council with enforcement authority

International Benchmarking

Comparison with international peers in similar arid contexts — the UAE, Qatar, Oman, and Australia's arid regions — generates useful insights on KSA's advancements and trajectory (Table 4). The UAE offers perhaps the most instructive comparative assessment, having pursued a parallel sustainability transformation from a fossil fuel-based economy with similar climatic and hydrological challenges. The UAE's renewable energy portfolio of approximately 6 GW, while smaller than KSA's 13 GW in absolute terms, has been achieved alongside a treated wastewater reuse rate exceeding 60% — nearly four times KSA's current 17.3% reuse rate — and a municipal recycling performance that significantly goes beyond KSA's current estimates. This comparison recommends that KSA's water demand management and wastewater reuse agenda has enough room for increased progress, and that the UAE's institutional frameworks for water efficiency incentives and building standards may provide transferable lessons (Toukabri & Chaabi, 2026).

Qatar's sustainability experience illustrates the challenges of reconciling the world's highest per-capita resource consumption with credible sustainability commitments. The nation's approximately 4 GW renewable capacity is contributed by near-total desalination dependency, and per-capita water consumption is among the highest globally. Qatar's experience with large-scale event-driven sustainability initiatives — including the FIFA 2022 World Cup sustainability programme — has garnered useful application lessons around stakeholder engagement and short-cycle infrastructure deployment that may be related to KSA's expo and giga-project contexts. Oman's sustainability trajectory, while less capitalised than KSA's, offers interesting lessons in blending traditional water management practices (the falaj irrigation system) with modern water governance — a model significantly used for KSA's rural groundwater governance constraints. Australia's arid zone experience denotes what advanced circular economy infrastructure can aim for. recycling rates approaching 60%, sophisticated managed aquifer recharge systems, and large-scale renewable deployment — offering a long-run benchmark for KSA's ambitious marks (Lytras & Yusuf, 2023).

Table 4. Comparative Analysis of Sustainability Initiatives in Arid Regions

Country/Region	Renewable Energy Capacity	Water Strategy	Waste Recycling Rate	Key Initiative
KSA	13 GW (2025); 130 GW target 2030	National Water Strategy; SWCC desalination; 321% over-abstraction	Early stage; 9.7%/yr growth; 95% target	Saudi Green Initiative ($187B); Vision 2030
UAE	~6 GW solar; 44% clean energy target 2050	Treated wastewater reuse >60%;	~52% recycling; robust	Net Zero by 2050; Green Economy Initiative
		desalination reliance	municipal programs	
Qatar	~4 GW solar (Al Kharsaah 800 MW flagship)	Near-total desalination dependency; per-capita highest globally	Improved collection; targets 38% diversion	Qatar National Vision 2030; World Cup sustainability
Oman	~3.5	Falaj traditional	National	Oman Vision 2040;

	GW renewable; 30% target by 2030	irrigation; desalination expansion	recycling programs; early stage	Blue Economy strategy
Australia (arid)	~60 GW installed (leading	Water recycling >30%; rainwater harvesting; Murray-Darling Basin	~60% recovery; advanced circular programs	Net Zero by 2050; National Water Grid Fund

4.3. Progress vs. Targets: Gaps and Trajectories

Evaluation of KSA's growth against its goals indicate the need for sustained policy action. For example, the annual per capital consumption for water is set at 150L/day, however, the current consumption being at 230L/day indicates a potential gap that needs an urgent attention. However, this cannot be attributed to infrastructure alone. This demands a prominent behavioural shift accompanied by pricing reform and public awareness outreach activities and robust governing standards for efficient water management and irrigation. However, the reduction in per-capita consumption to 43% by 2030, would be ambitious for a society with conservation culture. Besides this, the renewable energy momentum which is said to achieve 130 GW by 2030 seems ambitious, however it is achievable. The currently, the renewable energy sector has achieved 13 GW by 2025 and 24.839 GW in PPA's signed during 2025, though the figure does not seem encouraging right now, however, it is possible through procurement and grid integration. When it comes to waste management, this domain indicates its still at an early stage: the 21.3% high in waste production denotes that the consumption is outpacing waste reduction (Aldhafeeri & Alhazmi, 2022).

4.4. Governance, Awareness, and Behavioural Dimensions

The technical and financial solutions designed to overcome the KSA sustainability challenges are inadequate. Therefore, to ensure sustainable environmental outcomes at societal level, programs that bring a behavioural change across the millions of households, thousands of businesses and hundreds of government bodies. Lack of adequate awareness among the public towards Vision 2030's goals and timeframes, the magnitude of under ground water depletion, the per-capita resource intensity of their daily water usage. Hence, environmental education programmes imparted formally through school and university curriculum, and informally through media and community engagement- are therefore a critical enabling condition for behavioural sustainability transitions (Khan et al., 2020; Alshuwaikhat & Mohammed, 2017).

Policy coherence across government ministries is another governance imperative. Environmental sustainability in KSA encompasses the mandates of at least seven ministries — Energy, Environment, Water and Agriculture, Industry and Mineral Resources, Economy and Planning, Municipal and Rural Affairs, and Education — as well as major parastatal entities including Saudi Aramco, SWCC, and SIRC. Well coordinated institutionalised mechanisms, help achieve system-level sustainability overcoming sector-specific optimisation risks. The development of integrated sustainability metrics — a national environmental sustainability index broken down by region, sector, and demographic group — would provide a common measurement framework that could provide cross-sectoral accountability and public engagement (Jaouadi et al., 2026; Tiwari et al., 2024).

4.5. Technology Transfer and Innovation

KSA has instituted programmes in institutions like King Abdullah University of Science and Technology (KAUST) which has become a potential torch bearer for research in solar photovoltaics, water desalination, and marine environmental science. The university hosts programmes that sensitise the community on renewable energy, water resources and environmental monitoring. Apart from establishing on the foundations of sustainability, the university has played a pivotal role in establishing links between different stakeholders like research institutions, government procurement agencies and private sector implementers which further increases the absorption of best-practice sustainability technologies across the Kingdom (Selim & Alshareef, 2025; Almulhim et al., 2024). Sustainability transition creates significant opportunities for technology development, transfer, and domestic innovation. The Kingdom's investment in solar energy, green hydrogen, advanced desalination, and carbon capture technologies positions it as both a consumer and — increasingly — a developer and exporter of sustainability technologies.

Study Limitations

This current study has several limitations. First, the extant literature on environmental sustainability in KSA is less comprehensive compared to that of well documented literature available for comparable high-income countries with extended sustainability research traditions; Further, gaps with respect to data were discovered for sub-national and community level sustainability performance. Second, the government reports may not have captured the complete data at field level. Third, though the current review captures the latest data, with increasing policy evolutions and technological landscape shifts, some estimates discussed in the current study may have been substituted by latest statistics. Further, longitudinal studies should be conducted. Which focus on tracking the actual implementation of Vision 2030 sustainability targets, community-level on environmental awareness and conservation behaviour, and mixed-methods studies quantitative performance data with qualitative analysis of institutional and governance processes.

5. CONCLUSION AND POLICY RECOMMENDATIONS

5.1. Summary of Key Findings

This comprehensive systematic review has estimated the trajectory, achievements, and persistent challenges of environmental sustainability in the Kingdom of Saudi Arabia across four interconnected domains: renewable energy, water conservation, waste management, and land restoration. The evidence base reveals a nation at an inflection point — one that has mobilised unprecedented financial resources and institutional will toward sustainability transformation under Vision 2030, yet which continues to face structural challenges rooted in decades of resource-intensive development, cultural norms shaped by subsidised abundance, and the fundamental tension between hydrocarbon revenue dependence and decarbonisation commitments.

The renewable energy transition represents the area of greatest verifiable progress, with 13 GW of capacity by 2025 and 24.389 GW in signed PPAs creating a credible pathway toward the 130 GW by 2030 target. The Saudi Green Initiative provides the overarching financial and strategic framework linking afforestation, carbon management, air quality, and marine protection into a unified environmental agenda. Water conservation and waste management present more complex pictures, with significant institutional and infrastructure investments underway but consumption trends and waste generation rates that still run ahead of efficiency improvements and circular economy capacity (Alotaibi et al., 2023; Aldhafeeri & Alhazmi, 2022).

5.2. The Proposed Framework

The Environmental Sustainability Integration Framework proposed in the current study offers an organized approach to transforming Vision 2030’s three pillars into actionable, cross- sector sustainability interventions provide a structured approach to translating Vision 2030's three pillars into actionable, cross-sectoral interventions connected to fulfillment of basic human needs. The current study takes a unified approach in connecting. Water, energy and clean environment as integrated needs and cannot be addressed in silos. Hence, policymakers, researchers, and practitioners are invited to deploy and use this tool as an integrated sustainability planning, performance monitoring, and stakeholder communication in the KSA context and in comparable arid-region governance environments globally.

5.3. Policy Recommendations

Based on the synthesis of evidence and the framework analysis, seven specific policy recommendations are proposed:

1. Accelerate renewable energy deployment to meet the 130 GW target: Expand grid integration, sync environmental evaluation processes for renewable projects, institute green hydrogen export pathway, invest in battery storage and grid balancing infrastructure, and create a green hydrogen export pathway that takes advantage of KSA's solar contribution in the global market.

2. Implement demand-side water management alongside desalination expansion: Reform water process to represent the total production costs and include progressive pricing that incentivises conservation; mandate water-efficient building standards for all new construction under Vision 2030 mega-projects; scale up treated wastewater reuse from 17.3% toward the 25% target and beyond; and support precision irrigation technology adoption in the agricultural sector.
3. Strengthen circular economy mechanisms through enhanced recycling infrastructure and public-private partnerships: Prioritise the commissioning of SIRC's 35 million tons per year capacity mark; institute extended producer responsibility schemes for packaging, electronics, and construction materials; develop the WTE sector at scale to divert organic and residual waste from landfill; and produce economic incentives for private sector investment in recycling and resource recovery enterprises.
4. Scale up land restoration using the Al Baydha model: Commission a national replication programme that adapts Al Baydha's permaculture and rainwater harvesting methodology for diverse terrain conditions across the Kingdom; integrate land restoration targets into Vision 2030 regional development plans; and support community-based land stewardship programmes that engage local populations in afforestation and watershed restoration activities.
5. Enhance environmental education and public awareness programmes: Introduce comprehensive environmental sustainability education across all levels of the national curriculum; launch sustained public communication campaigns — comparable in ambition and budget to those for economic diversification — that communicate KSA's sustainability challenges and the individual behavioural changes required; and engage civil society organisations, mosques, and community networks as vectors of environmental awareness and conservation norms.
6. Establish cross-sectoral sustainability governance coordination: Create a National Sustainability Council with representation from all relevant ministries and major parastatal entities, mandated to develop an integrated national sustainability strategy, allocate cross-sectoral budgets, and hold agencies accountable for integrated performance targets rather than sector-specific outputs.
7. Develop sustainability metrics and monitoring frameworks: Establish a national environmental sustainability index, disaggregated by region, city, sector, and socioeconomic group, publicly reported annually; create a digital sustainability monitoring platform that integrates satellite remote sensing, IoT sensor networks, and administrative data to provide real-time visibility of progress across all four sustainability domains.

5.4. Vision for KSA as a Global Sustainability Leader

Saudi Arabia possesses the unique combination of financial resources, geopolitical influence, technological ambition, and geographic endowment that could position it as a genuine global leader in arid-region environmental sustainability. A KSA that achieves its 130 GW renewable target, reduces per-capita water consumption to 150 litres per day, recycles 95% of its waste, and restores millions of hectares of degraded land would not merely fulfil its domestic sustainability obligations — it would demonstrate to every hydrocarbon-dependent, water-stressed nation that a credible and ambitious sustainability transition is achievable. The Environmental Sustainability Integration Framework and the policy recommendations advanced in this review offer a structured pathway toward that vision, grounded in the best available evidence and aligned with the aspirations of Vision 2030. Realising this vision will require sustained commitment, adaptive governance, and the active engagement of all stakeholders — government, private sector, academia, civil society, and citizens — in a shared project of environmental stewardship for present and future generations.

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