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Strengthening Ecosystems and Biodiversity Conservation in Response To Climate Change In Saudi Arabia

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ABSTRACT:
This study aims to assess the impact of climate change on Saudi Arabia's ecosystems, particularly water scarcity and biodiversity loss. It focuses on evaluating the effectiveness of current adaptation strategies, including innovative water conservation techniques, sustainable agricultural practices, and biodiversity protection efforts.
We employed a qualitative approach using the Delphi method to gather insights from a panel of 12 experts in climate science, biodiversity conservation, and water resource management. The experts evaluated the critical impacts of climate change on the environment and provided recommendations for improving adaptation strategies. Data collected through multiple rounds of expert feedback were analyzed to identify consensus on effective policy reforms and adaptive measures.
The findings suggest that Saudi Arabia must prioritize climate adaptation efforts as part of its Vision 2030 objectives, which aim to strengthen environmental sustainability and economic diversification. The study advocates for policy reforms that promote both ecological preservation and innovative solutions to climate challenges. It also underscores the importance of collaboration between governmental bodies, the private sector, and local communities to effectively address the escalating threats posed by climate change and to safeguard the country's fragile ecosystems for future generations.

Keywords: climate change, sustainability, ecosystems, water management, biodiversity

1. Introduction

Climate change poses an escalating global challenge, threatening the integrity of ecosystems and biodiversity worldwide, with particularly severe implications for arid and semi-arid regions like Saudi Arabia due to their inherent vulnerabilities. Recent projections indicate that temperatures in Saudi Arabia may rise by as much as 4°C by the end of the century, exacerbating existing water scarcity and jeopardizing biodiversity (Almazroui et al., 2021; IPCC, 2023). These environmental changes are already adversely impacting agriculture, water resources, and ecological stability, critical components for sustaining both human and natural systems (Abdallah & Bakr, 2022; Elnashar et al., 2022).

Recognizing the urgent need for effective climate adaptation, the Saudi government has integrated environmental sustainability into its Vision 2030 framework, a comprehensive strategy aimed at diversifying the economy, enhancing ecological resilience, and protecting the nation's diverse natural heritage. This framework emphasizes

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the importance of sustainable development (Vision 2030, 2023). However, the complex interplay between climate change and ecological vulnerabilities underscores the necessity for focused research to develop targeted adaptation strategies.

While there is an expanding body of literature addressing climate change impacts, specific studies examining the unique ecological challenges faced by Saudi Arabia are limited. Much of the existing research tends to generalize findings without adequately exploring the particular vulnerabilities of the country's ecosystems. This study aims to address this critical gap by investigating the vulnerabilities of Saudi Arabia's ecosystems to climate change, evaluating the effectiveness of existing adaptation strategies, and providing actionable recommendations for enhancing ecological resilience (Al-Juaidi & Othman, 2020; Khan et al., 2021).

To achieve these objectives, the research will focus on identifying key vulnerabilities of Saudi Arabia's ecosystems, evaluating the effectiveness of current adaptation measures, particularly in water management, biodiversity conservation, and agricultural practices, and providing actionable policy recommendations aligned with Saudi Arabia's Vision 2030 framework to enhance ecosystem resilience. The guiding research questions are as follows: What are the key vulnerabilities of Saudi Arabia's ecosystems in the context of climate change? How effective are the current adaptation measures in mitigating these impacts? What additional strategies can be implemented to strengthen ecosystem resilience and sustainability?

2. Theoretical Background

2.1 Global climate change impacts

Climate change poses a critical existential threat to global biodiversity and ecosystem stability, leading to profound ecological transformations across various regions. The Intergovernmental Panel on Climate Change (IPCC, 2023) emphasizes the heightened vulnerabilities faced by regions such as the Middle East, projecting a significant 20-40% reduction in precipitation coupled with increased desertification. These changes significantly undermine agricultural productivity and water security, particularly in countries within the MENA region, where arid climates severely restrict the availability of essential natural resources (Khan et al., 2021; Elnashar et al., 2022; Al-Mulali et al., 2021).

The ecological consequences of these climatic changes are alarming; habitat degradation and shifting climatic conditions have led to heightened extinction rates among numerous species (Sala et al., 2000; Parmesan & Yohe, 2003). A staggering estimate by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES, 2019) suggests that over one million species face the threat of extinction due to climate-related impacts, a trend likely to intensify if current trajectories continue (Bennett et al., 2016; Hughes et al., 2017). For instance, coral reefs—critical to marine biodiversity and coastal protection—are projected to decline by 70–90% with a 1.5°C rise in global temperatures, highlighting the urgent need for conservation efforts (Hughes et al., 2017; Ban et al., 2014; Kwiatkowski et al., 2021).

Moreover, climate change exacerbates existing pressures from land-use changes and resource extraction, leading to disruptions in ecological networks that result in cascading effects on food webs and essential ecosystem services (Doney et al., 2012;

Poloczanska et al., 2016). Alterations in predator-prey dynamics and declines in pollinator populations can destabilize ecosystems, threatening agricultural systems globally (Barton et al., 2013; Cardinale et al., 2012; Potts et al., 2016). The decline of pollinators, for instance, could lead to significant decreases in crop yields, intensifying food insecurity, particularly in vulnerable regions (Gallai et al., 2009; Klein et al., 2007).

The socio-economic implications of climate change are equally profound. Vulnerable communities that depend on natural resources for their livelihoods face increased risks as climate impacts lead to food insecurity and economic instability (Adger et al., 2003; Hsiang et al., 2017; Thomas et al., 2019). Research indicates that climate change could aggravate food shortages, with agricultural losses driving up prices and reducing the availability of staple crops (Brouwer et al., 2019; Schlenker & Roberts, 2009; Toukabri & Gharbi, 2022; Toukabri, 2021). Additionally, climate-induced disasters such as floods and droughts disproportionately impact low-income populations, exacerbating cycles of poverty and vulnerability (Hallegatte et al., 2016; IPCC, 2022; Tschakert et al., 2019).

Given these complex trends, localized research is urgently needed to assess specific vulnerabilities within ecosystems, particularly in regions like Saudi Arabia, where unique interactions between climate change and local conditions necessitate tailored adaptation strategies.

2.2 Climate change in Saudi Arabia: key vulnerabilities

Saudi Arabia's ecosystems are particularly susceptible due to their arid environment, characterized by limited water resources (see figure 1), extreme temperatures (see figure 2), and fragile biodiversity (see figure 3). The nation is experiencing rising temperatures, erratic rainfall patterns, and increased evaporation rates, all of which exacerbate existing water scarcity issues critical for both human populations and native biodiversity (Abdallah & Bakr, 2022; Almazroui et al., 2021; Al-Saadi et al., 2022). Groundwater, a primary source of freshwater, is being depleted at alarming rates, primarily due to unsustainable agricultural practices and rapid urbanization (Qadir et al., 2021; Alharbi et al., 2022; Al-Farhan et al., 2023).

Figure 1: Water stress in Saudi Arabia[1]

[1] *Note that Figure 1 is taken from World Bank official boundaries - https://www.worldbank.datacatalog.org/0038272dataset/search/. (Accessed November 27, 2024).*

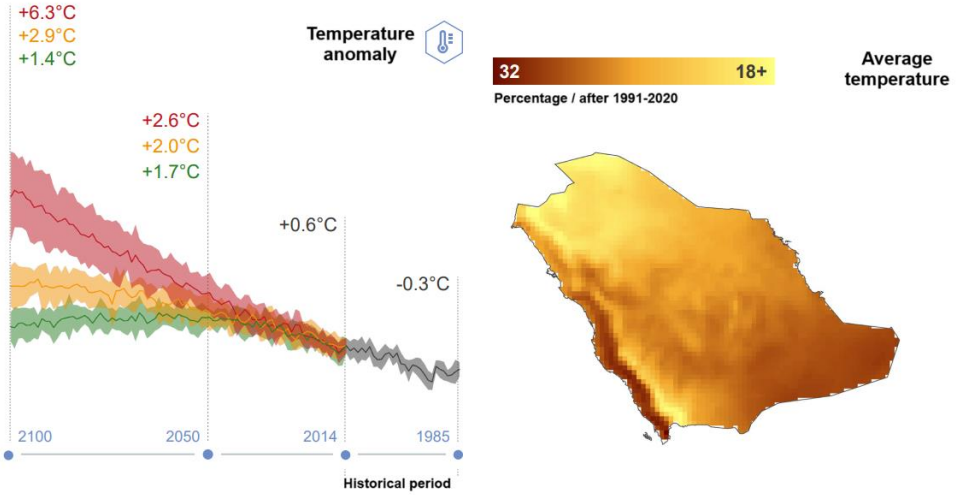

Figure 2: Rising temperatures in Saudi Arabia[2]

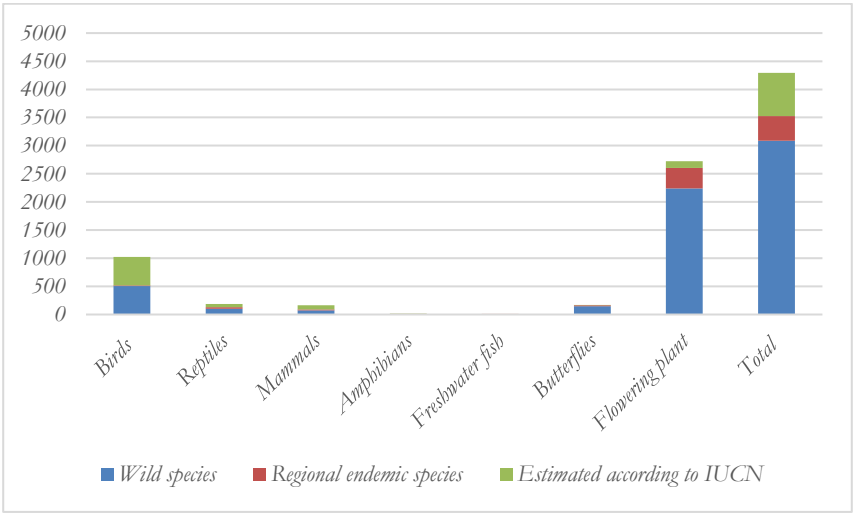

Figure 3: Biodiversity in Saudi Arabia[3]

These challenges are especially concerning for endemic species such as the Arabian Oryx and Arabian Sand Gazelle, which are already experiencing habitat loss and fragmentation due to climate change and anthropogenic pressures (Al-Juaidi & Othman, 2020; Azzam et al., 2022). While the Arabian Oryx has seen some recovery through conservation efforts, it remains threatened by ongoing habitat encroachment and climate

[2] *Note that Figure 1 is taken from World Bank official boundaries—https://www.worldbank.datacatalog.org/0038272dataset/search/. (Accessed November 27, 2024).*

[3] *Statistics taken from reports of the Saudi Ministry of Environment, Water and Agriculture (Accessed on November 27, 2024).*

stressors (Mason et al., 2020; Al-Farhan et al., 2021). Recent research underscores that species adapted to arid environments are increasingly vulnerable to rapid climatic changes, resulting in shifts in species distributions and altered ecosystem dynamics (Alharbi et al., 2022; El-Khalil et al., 2023).

Coastal ecosystems, particularly the coral reefs of the Red Sea, are under significant stress from climate change, facing threats from rising sea temperatures, ocean acidification, and pollution. Increased coral bleaching events jeopardize marine biodiversity and threaten the livelihoods of communities that depend on these ecosystems for sustenance and economic activities (Abualnaja et al., 2020; Zhan et al., 2023; Madan et al., 2021). Studies report alarming increases in coral mortality rates attributed to these climate-induced stressors, highlighting the urgent need for targeted conservation strategies to protect these vital habitats (Khalil et al., 2022; Zhan et al., 2023; see figure 4).

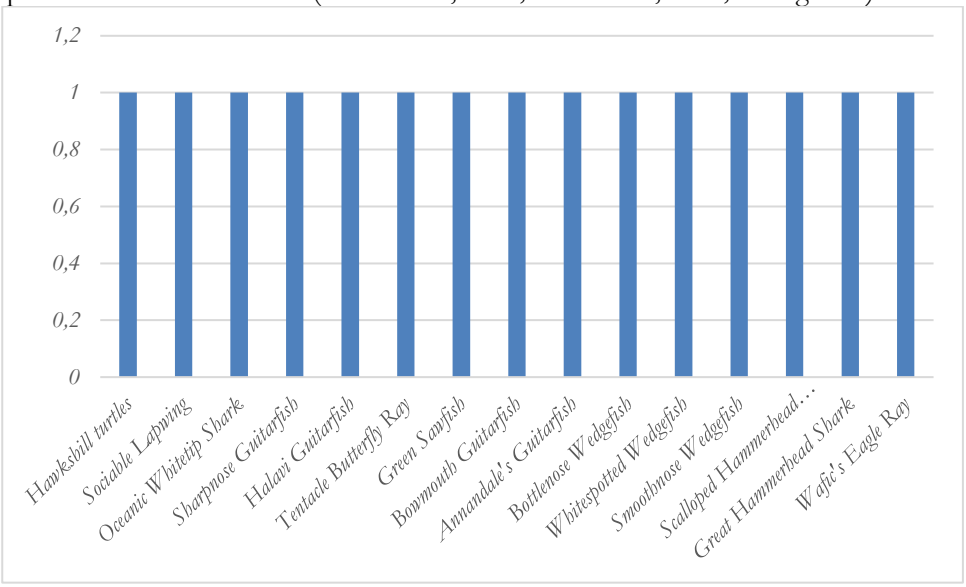

Figure 4: Endangered marine species[4]

The socio-economic ramifications of climate change in Saudi Arabia are significant, particularly concerning agricultural productivity. Altered rainfall patterns and increased temperatures threaten crop yields, disproportionately affecting vulnerable populations reliant on agriculture for their livelihoods (Azzam et al., 2022; Ameen et al., 2023). The intersection of environmental degradation and socio-economic challenges exacerbates inequalities, necessitating comprehensive adaptation strategies that address both ecological and social dimensions (Sullivan et al., 2019; Alharbi et al., 2021). Research indicates that climate change could further complicate food security, with potential declines in food production leading to increased prices and reduced availability of staple crops (Hoffman et al., 2023; Rosenzweig et al., 2014).

[4] *Statistics taken from reports of the Saudi Ministry of Environment, Water and Agriculture (accessed on November 27, 2024).*

Additionally, Saudi Arabia's reliance on oil production makes it particularly vulnerable to global transitions toward renewable energy and shifts in climate policy. This transition could significantly impact the nation's economy, necessitating diversification strategies to enhance resilience against climate-induced economic fluctuations (Khan et al., 2021; Al-Ahmadi et al., 2021; Alnashar et al., 2023). The Kingdom has recognized the imperative for proactive measures to bolster ecosystem resilience, exemplified by initiatives such as the Saudi Green Initiative, which aims to address climate change and biodiversity loss through afforestation and restoration of degraded lands (Vision 2030, 2023; Alsharif et al., 2023).

Furthermore, enhancing public awareness and community engagement is critical for successful adaptation to climate change. Studies indicate that improving local communities' understanding of climate impacts can lead to more effective conservation practices and resilience-building measures (Bryan et al., 2013; Lemos et al., 2012; Mastrorillo et al., 2016). Integrated policy approaches involving stakeholders from various sectors such as agriculture, energy, and urban planning are essential for developing comprehensive strategies that effectively address the multifaceted impacts of climate change on ecosystems (Khan et al., 2021; Abdallah & Bakr, 2022). In fact, we need to try to convince humans to make a major leap and change in their current way of life, as well as to get them to reassess their direct relationship to their surrounding built environment. In this area, Saudi Arabia has successfully recognized these challenges and identified them through comprehensive programs and regulatory changes at the local level through Vision 2030, in which it has significantly reduced its traditional dependence on oil, which can help it transform its economy into a more environmentally friendly one.

Additionally, local administrations are a group of institutions that play an equally important role in solving the problem of climate change. According to the United Nations Development Programme (UNDP), local administrations (localities) are taking nearly 70% of the actions needed to reduce the damage of climate change, and 90% of the actions needed to help citizens adapt to its effects. These data make a lot of sense, as traditional local administrations are tasked with planning and designing urban communities, implementing transportation and land use planning, constructing and repairing infrastructure, regulatory oversight, enforcing laws, and providing services. These functions make local administration on the front lines of any efforts to combat climate change.

Thus, it is important for the state to develop a regional and local policy to strengthen the local efforts of these administrations. For example, the responsibility for urban planning and climate change mitigation rests with local councils. The central government, on the other hand, is responsible for issuing general policy directives to local administrations to ensure that the development priorities and objectives of local administrations are consistent with the overall national objectives. As Local councils receive significant material and technical support from the central government so that they can implement their plans in the fight against climate change. The central government is also establishing a weather investment program to support the implementation of climate change programs in different countries. Under this program, local councils compete for grants from the central government by developing creative local strategies to adapt to climate change.

In summary, understanding the unique interactions between climate change and local ecosystems in Saudi Arabia is crucial for developing effective and sustainable adaptation strategies tailored to the local context (see figure 5). Integrating ecological conservation with socio-economic development is essential for enhancing resilience against climate change impacts and fostering sustainable development in the region (Schaeffer et al., 2022; Faraj et al., 2023; Akhtar et al., 2024).

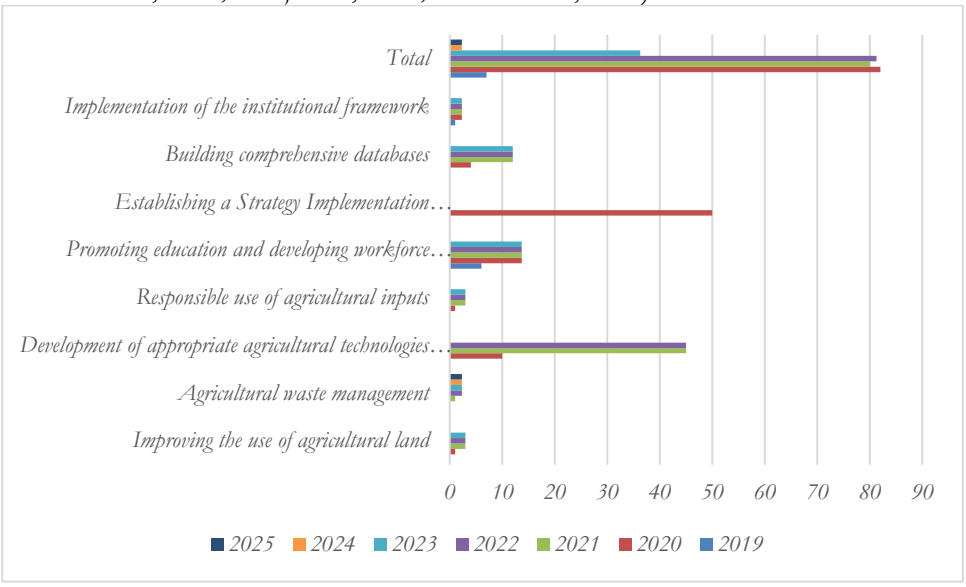

Figure 5: National Agriculture Strategy 2030[5]

3. Materials and Methods

3.1 Research design: Delphi method

This study utilized the Delphi method, a structured qualitative research approach that harnesses the insights of a carefully selected panel of specialists to reach consensus on complex climate-related issues affecting ecosystems and water management in Saudi Arabia. This method is particularly effective for addressing uncertain and multifaceted challenges, as it facilitates iterative dialogue and refines expert opinions through multiple feedback rounds (Hsu & Sandford, 2007; Linstone & Turoff, 2002; Kusiak, 2019).

3.2 Expert panel selection

The panel consisted of 12 experts with extensive knowledge and experience in climate change, biodiversity, and water resource management. The selection criteria were as follows:

[5]*Statistics taken from reports of the Saudi Ministry of Environment, Water and Agriculture (Accessed on November 27, 2024).*

- Professional Experience: Each expert had a minimum of 10 years of experience in relevant fields, encompassing positions in academia, government agencies, and non-governmental organizations (NGOs).
- Publications and Contributions: Experts were selected based on their records of published works in peer-reviewed journals, particularly focusing on climate change impacts, adaptation strategies, and ecological resilience (Bennett et al., 2016; Mastrorillo et al., 2016; Thomas et al., 2019).

Although the Delphi method has many advantages, it has a limitation that we think is interesting to examine in relation to our results. Indeed, the Delphi method refers to a limited number of experts, but this number is not representative of the population concerned. Thus, the recruitment of experts must consider all characteristics representing the population so that the results can be generalized.

Currently, the Delphi method offers an interesting alternative to test the acceptability of new ideas, such as in the case of our study. Indeed, in this case, the usual studies show their limits, and the company tends to follow an offer marketing approach: we "explain" to the consumer benefits that he should consider essential. The use of the expertise of a Delphi could make it possible to circumvent this type of problem.

The strengthening of ecosystems and biodiversity conservation in the face of climate change seems conceivable to us with a panel of experts managed according to the principles of Delphi questioning. The combination of this solution with the usual marketing techniques should produce practical solutions to the problem at hand.

3.3 Data collection

Data collection involved multiple rounds of structured surveys and interviews, allowing for anonymous feedback and iterative discussions among the panel members:

- Round 1: An initial survey gathered baseline information on expert perceptions regarding the impacts of climate change on biodiversity and water resources in Saudi Arabia. This round included open-ended questions to identify key vulnerabilities and potential adaptation strategies.
- Round 2: A follow-up questionnaire was developed based on insights from the first round. This survey aimed to refine findings and explore areas of disagreement. Experts rated the importance and feasibility of proposed adaptation strategies using a 5-point Likert scale, a widely accepted method in climate adaptation research (Fitzgerald et al., 2019; Tully et al., 2019).
- Round 3: In the final round, panel members discussed the aggregated feedback from previous rounds, allowing them to revise their opinions and deepen insights into the challenges and opportunities for climate adaptation in Saudi Arabia (Delbecq et al., 1975).

3.3 Data analysis

Qualitative data from the Delphi rounds were analyzed thematically using NVivo software, facilitating a systematic examination of the responses:

- Coding: Responses were systematically coded to identify recurring themes related to climate vulnerabilities and adaptation strategies.

- Thematic Analysis: Major themes were distilled from the experts' discussions, with particular emphasis on areas of consensus and divergence (Braun & Clarke, 2006; Nowell et al., 2017).
- Consensus Assessment: Consensus was defined as 75% agreement among experts on specific issues or strategies, providing a robust framework for understanding expert perspectives (Jorm, 2015).

4. Results and discussion

4.1 Key themes identified

The Delphi process highlighted several pressing themes concerning climate change impacts and necessary adaptation strategies in Saudi Arabia:

- Water Scarcity: Experts overwhelmingly identified water scarcity as a critical challenge, projecting a 20-30% reduction in renewable water availability by mid-century due to rising temperatures and changing precipitation patterns (Almazroui et al., 2021; Qadir et al., 2021; World Bank, 2020). This issue is compounded by the country's heavy reliance on groundwater, which is being depleted at unsustainable rates (Khan et al., 2021). Effective management strategies must include comprehensive measures such as water recycling and conservation techniques to address both supply and demand issues (Fischer et al., 2021).
- Biodiversity Loss: A strong consensus emerged regarding the urgent need to address biodiversity loss, particularly concerning endemic species like the Arabian Oryx and Houbara Bustard. Climate change and habitat degradation have significantly impacted these species, leading to population declines (Mason et al., 2020; Azzam et al., 2022; Guisan et al., 2017). This vulnerability highlights broader ecological concerns, as biodiversity loss can destabilize entire ecosystems and compromise vital services for human well-being (IPBES, 2019). Conservation efforts must adapt to changing climatic conditions to ensure species survival (Kreft et al., 2017).
- Innovative Adaptation Strategies: Experts underscored the necessity for innovative water management practices:
  - Desalination Technologies: The expansion and modernization of desalination plants were identified as crucial, with experts emphasizing the integration of renewable energy sources to enhance efficiency and reduce environmental impact (Zhou et al., 2020; Al-Harbi et al., 2018). Given the rising global demand for freshwater, desalination technology presents a viable pathway for meeting water needs while mitigating climate impacts (World Bank, 2021).
  - Agro-ecological Practices: There was widespread support for transitioning toward agro-ecological practices, including the promotion of drought-resistant crops and sustainable agricultural techniques (Abdallah & Bakr, 2022; Pimentel et al., 2016). Implementing such practices can enhance soil health and increase agricultural resilience in arid regions (Foley et al., 2011, Toukabri & AlGhaswyneh).
  - Public Awareness and Education: The need for enhanced public awareness and education regarding climate adaptation strategies emerged as essential for fostering community engagement and ensuring long-term sustainability (Elasha et

al., 2020; Stokes et al., 2017). Effective communication strategies can empower communities, encouraging proactive participation in climate adaptation initiatives (UNESCO, 2020).

4.2 Summary of expert consensus

The Delphi method effectively illuminated critical areas for climate adaptation interventions. Key findings reveal robust agreement among experts on several vital adaptation strategies:

- Water Management Innovations: Approximately 78% of experts rated innovative water management strategies as highly feasible, indicating strong recognition of the urgent need to develop and implement effective practices that ensure water security amid changing climatic conditions.
- Biodiversity Conservation Efforts: About 82% deemed biodiversity conservation strategies effective, reflecting a shared understanding of the necessity of protecting ecosystems in the face of climate change.
- These consensus findings provide a valuable framework for addressing the pressing challenges posed by climate change in Saudi Arabia, guiding future research and policy interventions.

4.3 Ecosystem vulnerabilities

The research identified several critical vulnerabilities in Saudi Arabia's ecosystems:

- Water Scarcity: Saudi Arabia faces one of the most severe water shortages globally. Climate change is anticipated to exacerbate this situation, with reductions in renewable water resources projected at 20-30% by mid-century (Almazroui et al., 2021). This escalating water crisis poses significant threats to agriculture and urban water supply systems, necessitating innovative management strategies (Fischer et al., 2021; Khan et al., 2021).
- Biodiversity Loss: Habitat degradation due to rising temperatures and reduced water availability has significantly impacted various species, particularly those in fragile desert and coastal environments. The populations of the Arabian Oryx and Houbara Bustard have seen substantial declines (Azzam et al., 2022; Guisan et al., 2017). The high extinction risk faced by several species emphasizes the urgent need for targeted conservation efforts (IPBES, 2019). Preserving biodiversity is crucial not only for ecological balance but also for maintaining the resilience of ecosystems against climate impacts.
- Agricultural Impacts: Changes in climate patterns are reducing growing seasons for staple crops such as wheat and barley. Increased salinization of soil due to reduced freshwater availability exacerbates agricultural challenges (Al-Omari et al., 2019). Addressing these impacts through adaptive agricultural practices is critical for ensuring food security in the region, necessitating a focus on research and innovation in agricultural methods (World Bank, 2020).

Political subsidies and incentives are some of the most important drivers of economic growth with their positive impact on the productivity of various sectors, and this applies to the productivity of drought-resistant crops and hydroponics in areas with

limited resources, which are in urgent need of all available growth potential, especially at a time when population growth poses a challenge to meet the demand for. The need for these policies increases in the Kingdom because it faces additional challenges by targeting the preservation of its non-renewable water resources and the nature of its weather, which tends to heat and drought.

Political subsidies and incentives contribute to many aspects, such as the provision of improved crop varieties and the sustainability of agricultural practices, such as the use of drones and artificial intelligence in crop cultivation, which have become necessary to adapt to resource scarcity and climate change. Political subsidies and incentives also play a supportive role in improving agriculture and rural development that affects. The results of this role are evident in improving living standards, reducing poverty, and reducing migration to urban areas.

Several pieces of evidence have shown the impact of subsidies and political incentives on easing initial investment barriers for farmers adopting sustainable practices and on improving the performance of their agricultural systems. Although the agricultural workforce is decreasing compared to decades ago, the productivity of the agricultural sector has doubled thanks to the easing of investment barriers. Relying on technology and innovation in the agricultural field, thus raising the contribution of the agricultural sector to the gross national product.

4.4 Adaptation strategies

Key adaptation pathways identified for enhancing resilience include:

- Water Management Innovations: The adoption of technologies such as drip irrigation, greywater recycling, and solar desalination is crucial for ensuring water security. While the Saudi government has heavily invested in desalination, transitioning to sustainable energy sources remains essential to minimize environmental footprints (Zhou et al., 2020; Al-Harbi et al., 2018). Innovative water conservation strategies are necessary to meet escalating water demands driven by population growth and climate change (World Bank, 2021).
- Agro-ecological Practices: Promoting drought-resistant crops and reducing reliance on groundwater are essential for safeguarding food security. Innovative farming methods such as vertical farming and hydroponics are being explored as solutions to combat reduced arable land availability (Abdallah & Bakr, 2022; Pimentel et al., 2016). These practices can enhance resilience and reduce dependence on conventional agricultural systems, improving sustainability (Foley et al., 2011).
- Biodiversity Conservation: Expanding protected areas and restoring degraded habitats are vital steps toward preserving Saudi Arabia's rich biodiversity. Initiatives like the Saudi Green Initiative, which aims to plant 10 billion trees, contribute to both climate mitigation and ecosystem restoration (Al-Ghamdi et al., 2022; Tohidi et al., 2021). These initiatives not only aim to enhance carbon sequestration but also promote ecological balance, ensuring the survival of diverse species in the face of climate change.

The findings of this study underscore the urgent challenges that climate change presents to water resources and biodiversity in Saudi Arabia. The expert consensus derived from the Delphi method provides a robust framework for developing effective adaptation

strategies critical for enhancing resilience and sustainability in the region. Proactive research and policy measures will be essential for addressing the multifaceted impacts of climate change.

4.5 Water scarcity: the urgent need for sustainable management

The unanimous acknowledgment of water scarcity as a critical issue underscores the findings of numerous studies highlighting the severe water crisis in arid regions. Experts project a 20-30% reduction in renewable water resources by mid-century, consistent with broader literature documenting similar trends across the Middle East (Almazroui et al., 2021; Qadir et al., 2021). The ramifications of such reductions are profound, impacting not only human consumption and agricultural productivity but also economic stability and social cohesion (Gleick, 2014; World Bank, 2021).

To bolster resilience, innovative water management practices are essential. The panel's emphasis on desalination technologies as a vital adaptation strategy reflects global trends toward water recycling and resource optimization (Zhou et al., 2020). While Saudi Arabia has significantly invested in desalination infrastructure, transitioning to renewable energy sources for these processes is imperative for enhancing sustainability (Al-Harbi et al., 2018). Future research should focus on assessing the economic viability and environmental impacts of such transitions, particularly regarding energy consumption and carbon emissions (Fischer et al., 2019).

4.6 Biodiversity conservation: a call to action

The consensus on the urgent necessity for biodiversity conservation highlights the vulnerabilities faced by endemic species in Saudi Arabia, especially under shifting climatic conditions. The decline of species such as the Arabian Oryx and Houbara Bustard signifies broader ecological risks posed by habitat degradation and climate variability (Mason et al., 2020; Azzam et al., 2022). Research indicates that preserving biodiversity is not only crucial for ecological balance but also essential for maintaining the ecosystem services that humans depend on (Cardinale et al., 2012).

The proposed expansion of protected areas and habitat restoration initiatives aligns with international biodiversity goals, including the Convention on Biological Diversity. The Saudi Green Initiative, which aims to plant 10 billion trees, represents a substantial commitment to ecological restoration (Al-Ghamdi et al., 2022). Engaging local communities in conservation efforts can enhance the effectiveness of these strategies, as community-based approaches have proven to yield positive outcomes in biodiversity preservation (Berkes, 2017).

4.7 Innovative adaptation strategies: pathways to resilience

The identification of innovative adaptation strategies reflects a growing recognition of the need for sustainable agricultural practices in the face of climate challenges. Experts advocated for agro-ecological practices and technologies, such as vertical farming and hydroponics, to enhance food security while minimizing resource use (Coe et al., 2020; Abdallah & Bakr, 2022). This shift is particularly critical given the anticipated changes in climate patterns that threaten staple crop production.

Research supports the effectiveness of such practices in improving resilience to climate change by enhancing soil health, increasing water efficiency, and reducing reliance on chemical inputs (Foley et al., 2011; Pimentel et al., 2016). Future studies should investigate the scalability of these innovative agricultural practices and their potential for integration into existing farming systems in Saudi Arabia.

4.8 Public awareness and education: engaging communities

The emphasis on public awareness and education as vital components of climate adaptation strategies highlights the necessity for community engagement in addressing climate change. Research indicates that informed communities are better equipped to adopt sustainable practices and support conservation efforts (Elasha et al., 2020; Stokes et al., 2017). Educational initiatives should aim to bridge the gap between scientific knowledge and local practices, empowering individuals and communities to take actionable steps toward sustainability.

Moreover, participatory approaches that involve stakeholders in decision-making processes can enhance the legitimacy and effectiveness of adaptation strategies (Sutherland et al., 2019). Collaborating with local organizations, educators, and governmental bodies can foster a comprehensive approach to climate adaptation that is responsive to community needs and values.

5. Future research directions

This study lays the groundwork for future research on climate adaptation in Saudi Arabia. Exploring the socio-economic impacts of adaptation strategies on vulnerable populations can provide valuable insights into equity and justice considerations (Kreft et al., 2017). Additionally, long-term studies evaluating the effectiveness of specific interventions will be crucial for refining strategies and informing policy decisions.

Collaboration among academic institutions, government entities, and local communities will be essential for developing a holistic framework that addresses the diverse challenges posed by climate change. Future research should also explore the integration of traditional ecological knowledge with scientific approaches to create culturally relevant and effective adaptation strategies. Indeed, adaptation strategies can integrate traditional ecological knowledge in several forms: first, they propose proven practices for sustainable agriculture, fishing, and hunting while maintaining ecological balance. Second, they provide insight into local biodiversity and contribute to conservation efforts and identify endangered species. Third, they inform strategies for adapting to climate variability, including seasonal forecasts and resilience-building practices. Fourth, they preserve Saudi Arabia's cultural identity, spirituality, and traditional practices while promoting community cohesion and cultural heritage. Fifth, adaptation strategies complement science by offering alternative perspectives and methodologies for holistic environmental management. Finally, adaptation strategies promote social justice by recognizing indigenous rights, cultural diversity, and contributions to sustainable development.

In summary, the findings from this Delphi study emphasize the urgent need for comprehensive climate adaptation strategies in Saudi Arabia. By focusing on innovative

water management, biodiversity conservation, sustainable agricultural practices, and community engagement, the country can enhance its resilience to climate change and safeguard its unique ecosystems for future generations.

6. Conclusions

This study highlights the pressing vulnerabilities of Saudi Arabia's ecosystems in the face of climate change, particularly concerning water scarcity and biodiversity loss. The expert consensus underscores an urgent call to action, as projected reductions in renewable water availability of 20–30% by mid-century threaten not only the environment but also food security and economic stability (Almazroui et al., 2021; Bader et al., 2018). The decline of endemic species like the Arabian Oryx and Houbara Bustard signifies an alarming trend that necessitates immediate intervention to preserve biodiversity (Mason et al., 2020; Azzam et al., 2022).

To address these critical challenges, several actionable recommendations emerge. First, Saudi Arabia should prioritize investments in sustainable water management systems, incorporating innovative technologies such as solar desalination and wastewater recycling, which will enhance water security and energy efficiency (Fischer et al., 2019; Zhou et al., 2020). Second, expanding biodiversity conservation initiatives through reforestation and habitat protection is vital; protective measures for vulnerable species must be enacted, leveraging community engagement for improved outcomes (Mason et al., 2020; Stokes et al., 2017). Third, integrating climate adaptation strategies into national development plans is crucial for fostering resilience across sectors. This holistic approach will facilitate a coordinated response to climate change impacts, ensuring sustainable growth (Kreft et al., 2017; Elasha et al., 2020).

While this study provides valuable insights, it acknowledges limitations, notably the potential biases inherent in the Delphi method, which may not capture broader community perspectives (Hsu & Sandford, 2007). Future research should incorporate diverse stakeholder voices to enhance the generalizability of findings. Additionally, longitudinal studies are necessary to evaluate the long-term effectiveness of climate adaptation measures, providing empirical evidence for policy decisions (Cardinale et al., 2012). Investigating the socio-economic impacts of these measures will further enrich understanding, particularly concerning community engagement in environmental protection initiatives (Nowell et al., 2017).

In recent decades, Saudi Arabia has invested heavily in renewable energy, given its positive impact on its economy. Indeed, it has launched a comprehensive national development strategy to support the diversification of energy sources. In this field, solar energy is used in water desalination by collecting solar energy and converting it either into heat through solar capacitors and then using it to operate thermal desalination units or by generating electricity from solar cells and using it in the management of desalination units. In addition, solar energy is widely used in the agricultural sector. Thanks to them, water pumping machines manage irrigation, crop drying, chicken hatching, drying organic fertilizers, and producing some crops outside of their natural seasons throughout the year through plastic greenhouses, which collect heat from the sun and prevent its leakage at the same rate.

This national and even international cooperation, taken by the authorities in Saudi Arabia, could play an important role in the context of today's climate change: in information, promotion, and transfer of the best desalination technologies and criteria of excellence in energy and the environment; in training and preparation for the future for employment and water professions; and in helping to set up partnerships for the development of a real industrial project, for which there is complementarity between Saudi Arabia and other countries.

In conclusion, addressing the challenges posed by climate change in Saudi Arabia requires a multifaceted approach that integrates sustainable practices across sectors (Toukabri, 2023). The recommendations outlined in this study provide a roadmap for enhancing ecosystem resilience, ensuring that both the environment and communities thrive amidst a changing climate.

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