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Article

Climate change dynamics in Tunisian agriculture: A rigorous examination of impact, adaptation, and resilience

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Abstract: This study systemically examines the numerous impacts of climate change on agriculture in Tunisia. In this study, we establish an empirical and comprehensive methodology to assess the effects of climate changes on Tunisian agriculture by investigating current climatic patterns using crop yields and socioeconomic variables. The study also assesses the types of adaptation strategies agriculture uses in Tunisia and explores their effectiveness in coping with climate-related adversities. We also consider some resilience factors, namely the ecological aspect and economic and social camouflage pursued by the (very) men in Tunisian agriculture. We also extensively discuss the complex interconnected relationship between policy interventions and community-based adaptations, a crucial part of the ongoing debate on climate change adaptation and resilience in agriculture. The findings of this study contribute to this important conversation, particularly for areas facing similar challenges.

Keywords: agricultural vulnerability; climate change; Tunisia; Tunisian agriculture; agriculture sector

1. Introduction

The results of climate change are not limited to an alteration in the environments of all areas of our world. The evolving weather change has been associated with a billion consequences, different for every area. (Seneviratne et al., 2012). Both central regions —the Middle East and North African countries, as highlighted by the Intergovernmental Panel on Climate Change (2024), are severely hit. These areas suffer from long-term, frequent droughts and have a problem of water supply shortages, etc, due to climate change. Agriculture is at risk due to rising temperatures and more frequent droughts with serious health risks, especially in urban areas where stretches of 90-day-long heat waves (Lange, 2023). However, the climate of this region is remarkable in its own right. It includes myriad examples of complex desert dust feedbacks that complicate all aspects related to radiative budget, along with hints at irregular extreme weather events (Πατλάκας et al., 2024).

In Tunisia, the agricultural sector is a leading force. It is the most hit because this activity is strongly linked to climate change processes and its variability, which affect the ecological system. (Jaouadi et al., 2016). New research serves to compound the existing fears of climate impacts, particularly on agriculture in Tunisia. It shows we can still turn things around if only possible adaptive measures are implemented. Zarrouk et al. (2022) also studied the impact of climatic variability on olive agriculture. They found a strong relationship between temperature deviations and decreasing yield trends (in terms of maximum and minimum temperatures). Similarly, Ben Jat et al. (2023) and Nasr et al. (2021) identified that cereal crops are more vulnerable to climate extremes as they are more likely to be accommodated. Thus, some proactive adaptation options must be recognized for sustainable land management. The effect of retreating dust bowls in East Africa would be to bolster yields, and thus, this is where action should most urgently go if we are catalyzing change from the climate impacts side. In addition, increasing temperature and lower air moisture will reduce fruit harvests and cereals, which are critical for agriculture; in return, it can increase household consumption, thus, more unemployed people (Zouabi, 2021). In addition to this investment-oriented policy, several comprehensive frameworks for climate adaptation with proposals on how they can also enhance resilience and inform decision-making have been developed, focusing on the case of automatic growth green that emphasizes compatibility and social inclusion (Verner, 2013; Verner et al., 2013)

These studies underline more critical concerns regarding productivity and sustainability in the agricultural sector. They also embrace climate-smart strategies to minimize climatic adversities and explore "green" developmental dimensions that may ensure continued profitable farming activities for Tunisia.

This study aims to examine how climate change affects Tunisia's agricultural sector. It will reveal important lessons for adapting and strengthening the sector. The objectives of this research are showcased in the following points;

- To evaluate the impact of climate change on Tunisian agriculture, including changes in weather events, temperature, and precipitation patterns.
- To investigate the strategies and measures adopted by the policymakers to mitigate the adverse effect of climate change on the agriculture sector.
- To examine the resilience of Tunisian agriculture by considering the capacity to recover and adapt to climate change disturbance while maintaining the necessary structure.

2. Methodology

This study covers different domains of climate change impact on Tunisian agriculture, explained by three main categories using integrated mixed methods research design those are (i) Assessment, (ii) Adaptation strategies and their impacts and feedback, and (iii)—resilience building process. The methodological framework comprises three main components: data collection methods and analysis techniques.

2.1. Data collection methods

We use a mixed-methods approach to combine country-level climate indices and yield data with adaptation typologies obtained through thematic micro-analysis to provide insights into ecological, economic, and social dimensions driving resilience. The study's data collection methods have been meticulously chosen to capture the diverse aspects of climate change impacts and adaptation in the Tunisian agricultural sector. This careful selection ensures a comprehensive analysis.

- Primary Data Collection: Primary data were collected through semi-structured interviews with key stakeholders, including local farmers, policymakers, agricultural experts, and representatives from non-governmental organizations. This approach enables collecting in-depth qualitative data on current adaptation practices, perceived challenges, and opportunities for enhancing resilience. The semi-structured nature of the interviews allows for flexibility in exploring respondents' experiences and insights while ensuring coverage of key themes relevant to the study's objectives.

- Secondary Data Collection: Secondary data were obtained from various sources, including climate models, government reports, academic research, and databases such as the World Bank's Climate Change Knowledge Portal and the Intergovernmental Panel on Climate Change (IPCC). These sources provide quantitative data on climate variables (e.g., temperature, precipitation, extreme weather events), agricultural productivity, and socio-economic indicators. Policy documents and reports were also reviewed to understand Tunisia's existing frameworks and strategies for climate adaptation and resilience.

2.2. Data analysis techniques

The study employs a mixed-methods analytical approach to integrate and analyze quantitative and qualitative data. The combination of quantitative and qualitative methods was chosen to capture both the measurable impacts of climate change on agricultural outputs and the more nuanced socio-economic and policy dimensions that affect adaptation and resilience. This multi-faceted approach allows for a deeper understanding of how climate change dynamics manifest at both the local and regional levels in Tunisia and how adaptive capacity can be enhanced. This combination of methods ensures a robust analysis of climate change's multidimensional impacts and the effectiveness of adaptation and resilience strategies.

- Quantitative Analysis: The quantitative component of this research involved analyzing 20 years of historical climate and crop yield data (2000–2020) obtained from government records and international databases such as the World Bank's Climate Change Knowledge Portal. The data were analyzed using regression and time-series analysis, which assessed the relationship between climate variables (e.g., temperature, precipitation) and agricultural productivity. For instance, a multiple regression model was used to quantify the effects of temperature and precipitation on cereal crop yields, controlling for other factors such as irrigation practices and soil quality.

The regression analysis was conducted using ordinary least squares (OLS) to estimate the impact of climate variables on crop yields. The following equation was employed to model the effects of temperature (T) and precipitation (P) on agricultural productivity (Y):

$$Y_t = \beta_0 + \beta_1 T_t + \beta_2 P_t + \epsilon_t$$

Where:

1) Y_t = agricultural yield at time t,
2) T_t = average temperature at time t,
3) P_t = average precipitation at time t,
4) ϵt = error term.

Autoregressive integrated moving average (ARIMA) models were used for time-series analysis to examine temporal trends and cyclical temperature and precipitation patterns throughout the study period. Here, we considered it in a longer-term perspective where the time lag enabled us to capture how being under climate variability manifested over prolonged periods onto agro-systems.

- Qualitative Analysis: Qualitative data, such as the transcripts of interviews, were analyzed by a thematic-analytical strategy. Coding captured common themes and patterns across the interview transcripts around adaptation practices, resilience factors, and policy challenges. The thematic analysis enabled the interpretation of the stakeholder's subjective experience and views on climate change adaptation/resilience measures. It can also help to identify gaps and opportunities in existing policy and practice frameworks.
- Integration of Quantitative and Qualitative Findings: This study combines quantitative and qualitative results to triangulate the characteristics of climate change within Tunisian agriculture. By cross-validating across different data sources and methods, this strategy guarantees the robustness of these results. Analyzing climate and yield data statistically alongside thematic insights drawn from stakeholder interviews, this paper sheds light on the intricate web of influence among changes in climatic variables, adoption, readiness stages for various adaptation strategies, and resilience.

2.3. Justification for the methodological choices

The complexity of capturing climate change dynamics in Tunisian agriculture stimulates the combination of a mixed-methods and embedded case study design. Collecting quantitative and qualitative data can enhance this understanding of impacts, adaptation measures, and resilience factors. The semi-structured interviews helped gather in-depth, context-specific information on local adaptation practices and socio-economic issues.

In contrast, the statistical analysis of climate data and agricultural yields offers an objective perspective on how extensive trends in climate impact. The broad research scope exemplifies a comprehensive methodological framework for robust inquiry into the research questions. It provides essential insights for broader discussions surrounding climate change adaptation and resilience in agricultural systems.

3. Impacts

3.1. Impact of climate change on the agriculture sector

The land in Tunisia represents about 5 million hectares of agricultural land. (Hamdan, 2019) Moreover, it dominates the national economy's growth and social and regional development (Benabdelkader et al., 2021). However, the agriculture sector uses around 83% of the water resources. (Benabdallah, 2007). Horchani (2007) states that around 2000 m^3 of water is used for irrigation, with an average consumption of 5000 m^3 per hectare per year. Climate change has brought droughts and sometimes heavy rainfall, which has affected the overall production of agricultural land in Tunisia. (Skuras and Psaltopoulos, 2012).

The agriculture sector in Tunisia constitutes a significant contributor to economic growth since it contributes about 35% of production, 20% of exports, and around 27%

of employment opportunities (Qadir et al., 2003). This sector also helps reduce the migration of rural populations towards urban areas as it provides income to farmers (Holliday, 2007).

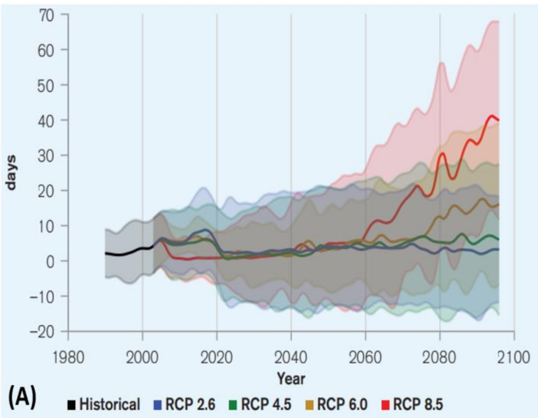
Tunisia’s agriculture’s main harvest is olive oil, citrus fruits, dates, and dates. (Ben Dhiab et al., 2017) Olive trees play an integral role in the economy, contributing about 60% of the total exports; the number of trees was estimated to be around 60 million. (Mansour et al., 2018) The planting of olive trees depends on the region and can be adjusted according to the predicted annual rainfall. History shows that harvesting olive trees was the main activity of the rural population. Because of this, Tunisia ranked as the biggest producer and exporter of olive oil. (Fernández-Lobato et al., 2022). According to Ben Nasr et al. (2021), Climate change in Tunisia has a vulnerable impact on water resources, agrosystems, and ecosystems, especially in the olive oil and cereals sectors. This study focused on the impact and adaptation of climate change on the agriculture sector to assess resilience to future climate change.

The change in extremes in the climate determines the impact and vulnerability of the condition. As stated by Radović and Iglesias (2019), the increased frequency of extreme weather events caused by the climate would result in applying risk management techniques, which can contribute to coping with these events. It adapts strategies to the extent to which changes are weakly vulnerable and significant in size. The impacts of climate change in the Tunisian region are as outlined below.

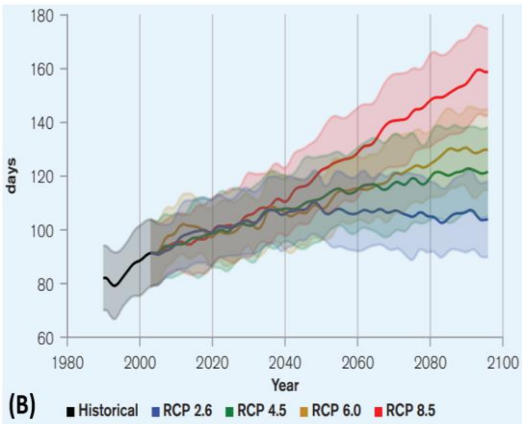
3.2. Impact on weather events

This urgency is further substantiated by the worsening types of weather-related disasters in Tunisia, which lead to more direct impacts on the national economy with pronounced heat waves, dust storms, and heavier flooding events. Healthwise, the rising temperature in Tunisia is also causing health problems under high temperatures (Nouioui et al., 2016).

Figure 1a depicts the projected heat index during the daytime, which is expected to rise to 35 foby090 by mid-century and continue to increase until the end of the century. **Figure 1b** illustrates the Tropical Night graph, showing a projected increase in nighttime temperatures due to varying emission conditions.



(a)



(b)

Figure 1. Extreme weather events in Tunisia **(a)** Days with a high heat index; **(b)** number of topical nights.

Source: World Bank Report (2021a).

3.3. Impact on the temperature

Tunisia ranked 64th among 181 countries in the Climate Risk Countries Report 2019 (Eckstein et al., 2018). **Figure 2** shows the graph of the time series regarding the temperature condition of Tunisia, which exhibited that Tunisia has been vulnerable to climate change and is expected to experience adverse effects in the future due to the increase in the temperature condition, which resulted in the reduced precipitation, increased aridity and rise in the sea-level condition. The environmental implications in Tunisia will not affect agriculture but the livestock, ecosystem, health, and the tourism sector. (Baban et al., 1999). Tunisia has proactively addressed climate change, as evidenced by its National Determination Contribution to the United Nations Framework Convention on Climate Change (UNFCCC) in 2016, a document outlining its commitment to sustainable development and environmental protection. In 2019, Tunisia also showed its commitment to climate by presenting the Third National Communication on Climate submitted at UNFCCC, reflecting efforts made and planned for this fight against climate change (Bleu, 2019). It was observed from the graph that during the last 30 years, the temperature change in the country showed an increase in the annual temperature from 16 °C to 20 °C, with its increase to 32 °C in summers. Whereas, in winter, this temperature drops in between 14 °C to 10 °C.

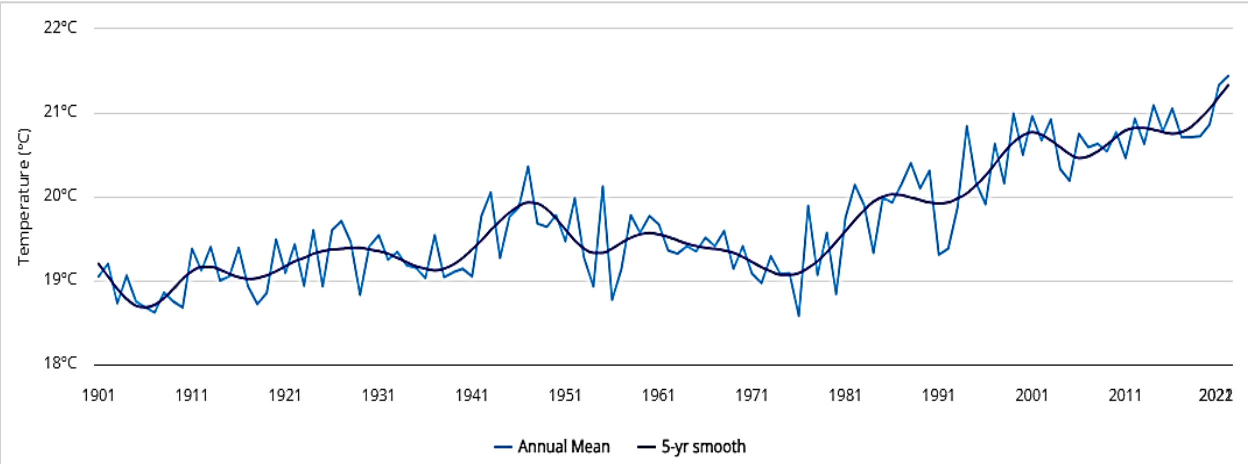


Figure 2. Annual average temperature of Tunisia for 1901–2022. Source: World Bank Report (2021b).

3.4. Impact on precipitation level

Tunisia is a highly arid country that receives little precipitation annually. (Ouessar et al., 2009) Most of Tunisia's rain falls in humid and coastal areas, whereas the southern areas receive little rainfall, about 150 mm per year. (Medhioub et al., 2019). The Tunisian region faces challenges regarding water availability, precipitation pattern changes, and population demand and needs (Ouessar et al., 2021). Precipitation in Tunisia varies according to climate change. **Figure 3** shows a decrease of 3% in precipitation over the past 30 years, which has reduced water availability, increased droughts, and dry spells. In recent years, increased and more vital precipitation has also caused flooding.

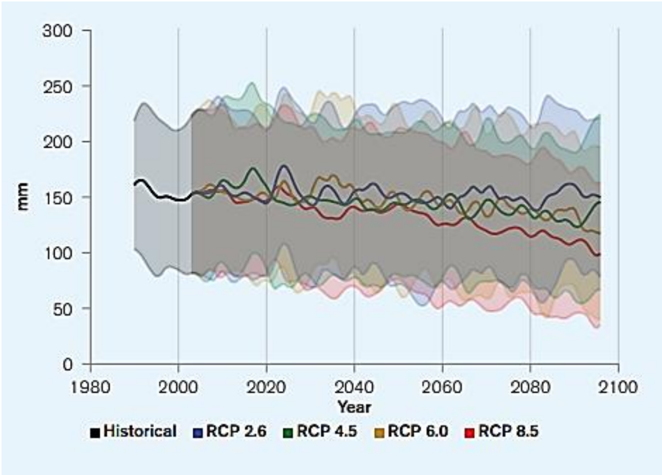


Figure 3. Annual average precipitation in Tunisia from 1980 to 2099. Source: World Bank Report (2021c).

3.5. Quantitative analysis: Results and implications

The quantitative component of this research, which involved analyzing 20 years of historical climate and crop yield data (2000–2020) obtained from government records and international databases such as the World Bank's Climate Change Knowledge Portal, is of significant importance. The data were analyzed using regression and time-series analysis, which assessed the relationship between climate variables (e.g., temperature, precipitation) and agricultural productivity. For instance, a multiple regression model was used to quantify the effects of temperature and precipitation on cereal crop yields, controlling for other factors such as irrigation practices and soil quality.

Table 1 gives the detailed output of the regression model: temperature and precipitation. These results show that temperature, followed by precipitation, was the significant crop yield common in Tunisia. A coefficient of −0.067 for temperature suggests that as the temperature corresponds to everyone ℃, the increase in crop yield decreased by 0.067 tons per ha. These results are supported by a highly significant test statistic at the 1% level ($p < 0.001$), which highlights the dependence on the realized temperature and warming measures on agricultural productivity.

Table 1. Regression analysis of temperature impact on crop yields.

Variable	Coefficient (β)	Standard Error	*t*-Statistic	*p*-Value
Constant	2.143	0.543	3.947	0.001
Temperature (°C)	−0.067	0.012	-5.583	0.000
Precipitation (mm)	0.045	0.021	2.143	0.035
R-squared	0.72	-	-	-

In contrast, the positive sign of the precipitation coefficient (0.045) represents its significant relationship with crop yield, which means that each millimeter increase in rainfall results in 0.045 tons hectare-1 more rice yields. The relationship is statistically significant at a 5 %level ($p = 0.035$), meaning crop productivity will significantly increase for every increased unit of rainfall. The *R*-squared value of the model is 0.72, which means that all temperature and precipitation changes can explain 72 % of crop yield variance in Tunisia, so this model could be considered effective in studying the influence of climate variables on agriculture here.

Implications for Agriculture in Tunisia:

- Negative impact of rising temperatures: As temperatures increase due to climate change, crop yields are likely to decline significantly. However, this finding also presents an opportunity for adaptation strategies, such as developing heat-resistant crop varieties or modifying planting schedules, which could mitigate the adverse effects of higher temperatures and offer hope for maintaining agricultural productivity.
- Positive role of precipitation: Increased rainfall benefits crop productivity, emphasizing the importance of water management strategies in Tunisian agriculture. In areas experiencing water scarcity, efficient irrigation systems (e.g., drip irrigation) and rainwater harvesting could help improve agricultural yields.
- Overall significance: The statistically significant temperature and precipitation results confirm climate variables' strong influence on crop yields. This highlights the need for climate adaptation measures to maintain agricultural sustainability in Tunisia.

4. Adaptation measures to mitigate climate change risk

The government should establish management strategies in Tunisia to enhance the sustainable use of available resources. Water scarcity is a significant problem for farmers that can only be mitigated through new agricultural techniques. (Mansour and Hachicha, 2014) Farmers need proper assistance to adapt to climate change conditions and minimize crop sensitivity. The following measures can mitigate the risk of climate change.

4.1. Renewable energy adoption

Renewable energy is adopting new technologies using the traditional energy released from fossil fuels. (Chel and Kaushik, 2018) Renewable energy can be adopted in various ways, such as solar panels, which convert sunlight into electricity for lighting and heating. (Sardianou and Genoudi, 2013), wind power that helps in the turning of turbine blades for the production of electricity (Makki & Mosly, 2020). Farmers should be encouraged to adopt renewable energy sources, such as solar or wind power, to reduce their reliance on fossil fuels. (Chel and Kaushik, 2011) Using clean energy helps reduce the effect of climate change by lowering greenhouse gas emissions. For instance, solar and wind power, being renewable energy sources, do not produce greenhouse gases during electricity generation, thereby significantly reducing the carbon footprint of agricultural operations.

4.2. Afforestation and reforestation technique

According to Anderegg et al. (2020), Forests are crucial in reducing CO_2, ultimately reducing climate change risk. The afforestation technique involves planting trees without forests, whereas the reforestation technique includes replacing the trees in the deforested areas. (Zomer et al., 2008). According to UNFCCC (2002), Reporting afforestation and reforestation are the activities accepted at the COP-7 conference, known as the Marrakech Accords. This technique would enhance the carbon sequestration and biodiversity in the ecosystem. (Yamagata and Alexandrov, 2001). The afforestation and reforestation technique will also provide the farmers with the added security of livelihood by offering an alternate means of opportunity for production (Bond et al., 2020).

4.3. Carbon captures and storage process

The carbon capture and storage process involve capturing the CO_2 emitted by burning coal in power stations, compressing it, and storing it deep underground. This prevents CO_2 from entering the atmosphere, reducing the greenhouse effect and mitigating climate change. (Benson and Orr, 2008). This gas will be trapped under the impermeable rock layer, preventing it from returning. (Saraf and Bera, 2021). According to Suvantoc (2013), the process involves three steps, which include pre-combustion (conversion of fossil fuel into CO_2 and hydrogen gas), post-combustion (capturing of CO_2 from exhaust gases after combustion), and oxy-fuel combustion (burning of fossil fuel in the mixture of oxygen and flue gasses). According to Azar et al. (2006), Implementing this process in the agriculture industries with high carbon emissions will capture CO_2 before it enters the atmosphere and causes climate change.

4.4. Waste recycling process

Waste recycling is an integrated process involving the organic recycling of waste in producing new materials or energy recovery. (Al-Salem et al., 2009) The waste recycling process has become necessary since the growing number of open waste dumps has increased soil pollution due to heavy metal exposure. (Mor et al., 2006). According to Massarutto et al. (2011), the waste recycling process will help in the recovery of energy from the waste materials, reduce greenhouse gas emissions, and contribute to the reduction of methane emissions, mitigating the risk of climate change on agriculture (Adhya et al., 2009) Furthermore; waste recycling helps improve soil structure, sustain soil nutrients, and reduce soil erosion. By recycling organic waste into new materials or energy, farmers can reduce their reliance on chemical fertilizers, which contribute to greenhouse gas emissions, and improve the health and fertility of their soils. (Lal, 2015).

4.5. Financial policies

Lack of financial assistance in agriculture has been observed as a barrier to adopting measures that will lead to agricultural sustainability. (Greiner and Gregg, 2011). New technology requires financial investments that help reduce greenhouse gas emissions, which farmers should adopt to increase profitability. (Rochecouste et al., 2015). The government should implement some financial policies and incentives that encourage the adoption of climate-friendly techniques. According to Batchelder et al. (2006), These incentives include tax credits, financial incentives for farmers, and subsidies. Financial incentives and rewards will help improve the capital structure and positively impact the renewable energy adoption process.

The government and policymakers can significantly mitigate climate change risk and foster sustainable future agricultural growth by adopting such measures.

4.6. Climate-resilient agriculture techniques

Tunisian agriculture faces severe challenges due to the increasing frequency of droughts, rising temperatures, and unpredictable rainfall patterns. According to Skuras and Psaltopoulos (2012), In Tunisia, climate change has caused land abandonment and increased erosion, ultimately decreasing the number of livestock, decreasing water availability, and causing deforestation. Unique adaptations in Tunisian agriculture include the introduction of drought-resistant crop varieties specifically developed to withstand prolonged dry periods and extreme temperatures. This approach is particularly beneficial in arid regions where water scarcity is persistent.

Farmers in Tunisia have been utilizing initiatives like rainwater harvesting and collecting and storing rainfall for irrigation during low-precipitation periods alongside crop innovation to cope with rapidly changing conditions. These strategies are vital in arid regions like southern Tunisia, where rainfall is unpredictable and water is scarce. Farmers have also implemented improved irrigation practices, such as drip irrigation, which optimizes water usage and reduces waste. Delivering water directly to the roots helps maintain soil moisture levels, even during periods of low precipitation.

Another notable adaptation is using renewable energy, particularly solar power, to power irrigation systems. This reduces reliance on fossil fuels and provides a sustainable energy source for agricultural operations. Solar-powered irrigation is particularly effective in remote areas with limited access to electricity. The following are the proposed strategies that help enhance agriculture's resilience to climatic change.

4.7. Diversification of crops

Crop diversification is defined as growing a variety of crops in an area. It can be accomplished by adding new crop species or changing the existing cropping system; thus, integrating crop diversity in the agriculture system would help gain financial benefits. (Lin, 2011). In agriculture, crop diversification is essential in the production process, contributing towards biodiversity, which is an integral part of maintaining the ecosystem and helps promote resilience. (Matson et al., 1997). For instance, alternating crops like pulses, forage seed, and oil seed can be produced to manage the risk of plant disease in cereal crops. (Krupinsky et al., 2002) The example showed that farmers should be encouraged to diversify their variety of crops, which will not only mitigate the risk of climate change on specific crops but also benefit food security and reduce disease vulnerability in agriculture.

Crop diversification in Tunisia is essential for achieving multiple aims, such as food security, poverty alleviation, and sustainable land use (Bouali Guesmi, 2022). The agricultural sector in Tunisia faces challenges related to urbanization and resource management, which can affect the fragility of horticulture if not addressed (Bouali Guesmi et al., 2022). Studies have shown that diversified crop patterns can lead to more efficient use of resources and better risk mitigation in farming systems (Khoufi Sahari et al., 2016; M et al., 2019). In the case of cereal, oilseed, and protein (COP) farms in Tunisia, specialized farms exhibited higher technical efficiency levels than those with mixed cropping systems. Similarly, in the district of Sidi Makhlouf, farming systems were classified into different groups based on their performance and strategies implemented by farmers. These findings suggest that targeted agricultural policies and interventions should be implemented to strengthen the performance of different farm groups and respond to their specific contexts.

4.8. Water management technique

Water management is essential in identifying saving plans and implementing available natural resources for effective agricultural growth. (Qadir et al., 2003) Water management is a way to control water resources to minimize water scarcity and maximize the effective use of water in planting, developing, or distributing. (Pereira et al., 2002). Effective water management practices are drip irrigation or rainwater harvesting to address the water scarcity issues caused by climate change. (Nouri et al., 2019). This practice will help in sustainable agricultural production and improve agricultural efficiency. The water management technique requires various modern techniques, and previous literature has proved that modern techniques that rely on technology would help overcome agricultural drawbacks. (Evans and Sadler, 2008).

Water management techniques in Tunisia include subsurface irrigation systems such as subsurface drip irrigation (SDI) and buried diffusers (BD) (Douh Boutheina et al., 2022). These techniques minimize spatio-temporal losses by increasing water storage in the root zone, reducing evaporation and percolation, and limiting weed growth. Studies have shown that deficit irrigation with 50% of crop evapotranspiration using SDI can increase water use efficiency compared to full irrigation (Mohamed Elleuch et al., 2019). A hybrid approach combining the reciprocal weights method, the analytic hierarchical process, and the Hurwicz criterion method has been developed to evaluate and select the best water resources for different sectors in Tunisia, such as Sfax (Jamel et al. et al. 2017). Remote sensing and Geographic Information System techniques also estimate irrigation water requirements in arid regions like the Regueb watershed (Emna Guermazi et al., 2016). The optimization of water resources management in Tunisia is crucial for sustainable development and involves technical measures, political measures, and the development of an institutional framework (Bouchrika Ali, 2022).

4.9. Agroforestry

Agroforestry practices have been used in the region with higher temperatures, integrating tree production into the agricultural landscape. (Kay et al., 2019). Agroforestry has been considered a suitable practice for sustainable growth for nearly half a century. (Garrity, 2012). As Newaj et al. (2013) stated, Agroforestry has numerous benefits, including carbon reduction, windbreak, increased soil quality, reduced soil erosion, increased resilience, and increased production, which leads to more farmer income. It can be used in both developing and developed countries. (Nair, 1991) In brief, agroforestry would help mitigate many harmful effects of agriculture and provide ecological, economic, productive, and cultural benefits. (Wilson and Lovell, 2016).

4.10. Soil management practices

Soil management practices are obtained to improve the quality of the crops and for sustainable agriculture productivity. (De Corato, 2020) A soil management plan or practice is essential for ensuring soil sustainability during the seedling procedure because without one, the valuable soil and its crops risk being damaged (Powlson et al., 2011). Soil management practices include cover cropping, crop rotation, and reduced tillage, which can enhance soil health and fertility. (Njira and Nabwami, 2013) Healthy soil can withstand extreme climate change conditions and support healthy crop growth. Soil management techniques control the emission of NH_4 and CO_2 gases, which will affect global warming's overall impact on agriculture. (Robertson et al., 2000).

Soil management practices in Tunisia have been the focus of several studies. Different tillage practices were investigated to determine their effects on soil properties. It was found that shallow tillage practices improved the soil's physical and hydraulic properties (Amami et al., 2019). Water erosion is a significant issue in Tunisia, particularly in semi-arid areas. Best management practices, such as crop rotation and organic fertilization, have been studied to control water erosion and improve soil fertility. Results showed that long fallow-chickpea rotation and using olive mill wastewater as organic fertilizer improved soil fertility and increased crop performance (Laajili-Ghezal, 2018). Saline irrigation management is another critical aspect of soil management in Tunisia. Excess salt in the soil affects overall soil health and reduces productivity. Crop rotation effectively maintained and improved soil fertility in saline conditions (Issam et al., 2022). Conservation agriculture, particularly no-tillage, has been promoted to combat soil erosion in Tunisia. Studies have shown that no-tillage practices improve soil resistance to erosion and increase soil microbial activity (Mohamed Annabi, 2023). Overall, these studies provide valuable insights into soil management practices in Tunisia, highlighting the importance of adopting sustainable practices to improve soil health and productivity.

4.11. Early warning information

Early weather warning information contains an integrated system with risk evaluation, coordination, and decision support. (Pulwarty and Sivakumar, 2014). Robust surveillance and early information may impact the evaluation, risk reduction, and prepared disaster strategies. (Rogers and Tsirkunov, 2011) Establishing early warning systems that could provide farmers with on-time information about upcoming weather events is recommended. (Admassu, 2013). This would help farmers make informed decisions and take timely measures to promote agricultural resilience. An adaptative strategy is required to maintain agricultural sustainability. Therefore, the early warning system is one of the adaptation strategies prevailing in the agricultural sector. (Willock et al., 1999) Farmers also believe that early climatic information will lead to the promotion of more success and sustainable growth. (van Ginkel and Biradar, 2021).

4.12. Livestock management practices

Using new technology would enhance the efficiency and livestock management practices in agriculture. (Loyon et al., 2016). According to Asresie et al. (2015), Livestock management in agriculture means raising livestock for farming and agriculture, for instance, using animals to produce wool and leather. Livestock management practices should be implemented, including improved animal husbandry and breeding of resilient livestock. (Berghof et al., 2019). The livestock management projects allow the farmers to be aware of the information regarding trending management practices regarding diseases and veterinary services. (LeBlanc et al., 2006) This practice will also help mitigate climate change's adverse effects on livestock productivity, food security, and poverty reduction. (Rojas-Downing et al., 2017).

Livestock management practices in Tunisia vary across different regions and farming systems. Principal Component Analysis (PCA) and multivariate K-Mean classification were used to analyze a representative sample of sheep farms in Tunisia. Five typical sheep production systems were identified: mixed sheep-cereal, agro-sylvo-pastoral, agro-pastoral, extensive agro-pastoral, and mixed sheep-olive tree systems (Ibidhi et al., 2018). Regarding feeding systems, four categories were identified: rangeland-based, concentrate-based, mixed, and fodder crop and alfalfa-based systems (Amamou et al., 2018). Tunisian dairy farmers have different perceptions of climate change risks and adaptation strategies based on their farm typology. Farmers focus on increasing water capacity for livestock and crop production and improving livestock and housing conditions (H et al., 2022). Conservation Agriculture (CA) has been proposed as a management system to enhance agricultural productivity in Tunisia. However, the adoption and up-scaling of CA have been limited (Nasser et al., 2000). Livestock waste management practices in Tunisia include composting, biogas production, rotator drum composting, and vermicomposting. These methods can enhance farm profitability and reduce the risk of fecal contamination of water and food supplies (S et al., 2022).

By combining all the given strategies, Tunisia can enhance its agricultural production, contribute to efforts to mitigate the adverse effects of climate change, and improve resilience to food security and farmers' livelihoods.

5. Conclusion

This study has identified one of the biggest challenges threatening Tunisian agriculture under climate change regimes. At the same time, it sheds light on different alternatives to face these potential problems by using more flexible strategies for adaptation action plan envelopment. The evidence documents climate variability through increasing temperatures, erratic rainfall, and droughts, which greatly pressure crop production, water resources, and rural lifestyles. These changes are already affecting major agricultural sectors like olives, cereals, and citrus fruits, which are crucial for food security and the country's economy and social stability.

A critical insight from this research is investing in solid infrastructure to help agriculture adapt to these changing conditions. Effective irrigation systems, like subsurface drip irrigation and rainwater harvesting, can help manage scarce water resources more efficiently. Building better water storage and flood control systems can reduce the risk of crop damage during extreme weather events. Shifting to renewable energy sources, such as solar and wind, can lower costs for farmers and reduce dependence on unreliable energy supplies. These infrastructure improvements are essential, not just as technical fixes, but as foundational elements that will help farmers remain productive despite the increasing challenges posed by climate change.

Resilience is about more than infrastructure. However, sound policies and good governance are equally important. The study offers a timely contribution to identifying key actions for policymakers looking into options for supporting the development of new infrastructure in agriculture and climate change adaptation. For instance, promoting public-private partnerships can drive investment and expertise in climate-resilient infrastructure. Additionally, as many other regions worldwide offer subsidies for water-saving technologies or renewable energy, this will incentivize farmers to use more sustainable practices. We also need to look at water management in an integrated way, particularly in those regions where lack of water is already a challenge. Ensuring fair and efficient use of water resources will require coordinated planning that considers the needs of both agriculture and local communities.

Establishing dedicated funds to support climate adaptation projects, such as early warning systems for extreme weather or local disaster preparedness initiatives, will also be necessary.

Strengthening local governance and engaging communities in prior planning for managing these projects can serve sustainable solutions that are adaptive to specific contexts.

In other words, investing in infrastructure with a higher climate resistance is not only economically rewarding for the agricultural sector. Besides, it can help ensure better incomes for farmers and create employment opportunities so that economic activities in rural areas can increase. For instance, solar-powered pumping for irrigation is cheaper and results in the electrification of distant regions, hence economic development. Improved roads and storage facilities can help farmers get their products to market more efficiently, reducing waste and increasing their income potential.

These investments also help promote fairness by ensuring smaller and more vulnerable farmers have the resources to cope with climate impacts. With reliable access to water and storage for every farmer, a community is much more disaster-resilient. Droughts or flooding are opportunities rather than sources of discontinuous stress on the system, leading to unfair, unequal resource distribution.

Although this study has dealt with Tunisia's case, implications could be generalized to other agricultural regions experiencing the same dynamics of climate change. Tunisia's strategies for addressing the problems wrought by climate change can serve as lessons to countries of all sizes and varying climates throughout the Middle East, North Africa (MENA), and Southern Europe, where arid conditions exist. These cross-regional groups meet to discuss the regional climate stress that multiple regions face and strategies for resilience, including water management, crop diversification, and renewable energy.

For example, Algeria and Morocco face similar climate risks, particularly from prolonged droughts and water scarcity, making Tunisia's adoption of advanced irrigation techniques and drought-resistant crops a model worth considering (Haddadi et al., 2022). Similarly, the practices found in this study that build resilience could be applied to Spain and Italy as both countries struggle with increasing temperatures or changing rainfall patterns, challenging their agricultural production.

Climate change presents enormous challenges, but with the right investments in infrastructure, good policies, and community engagement, they can absolutely be solved. This study's findings point to the need for a more coordinated effort to create a future where agriculture can thrive, even under more challenging conditions. Through pragmatic and policy-supported initiatives to couple infrastructure development with tangible solutions emphasizing food security and job protection in rural communities, Tunisia can pave away from a future strewn deeper into the quagmire of unsustainable growth.

Climate change in agriculture cannot be merely reactive, as this only responds to external problems. Agriculture will suffer a lot from climate change, and it requires action to fight against it because being reactive is acting as a respondent, which means only reacting to external problems. That requires vision and thinking that our agricultural practices support resilience and sustainability in the backbones for future generations. In this way, we can hope that the farmers of Tunisia will persevere and prosper in facing these adversities.

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