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Climate-Resilient Agriculture in Algeria: A Territorial Analysis of Crop Diversification and Water Management Strategies

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ABSTRACT

Climate change presents significant challenges to Algerian agriculture, marked by rising temperatures, erratic rainfall, and increasing water scarcity. This study evaluates the effects of these shifts on crop yields, rural livelihoods, and water resources, while examining vegetable diversification as a potential adaptation strategy. A mixed-methods approach integrates long-term climatic and agricultural data (1922-2023) with 100 semi-structured interviews conducted in Mitidja, Oued Souf, and Sidi Bel Abbès. Quantitative findings reveal that cereal yields have declined by up to 45% during drought years, with 85% of farmers reporting losses directly linked to weather variability. Although vegetable production is on the rise, it faces persistent constraints such as water shortages, soil degradation, and rising input costs. While Algeria's policy framework promotes climate-smart agriculture, its on-the-ground implementation remains limited—85% of surveyed farmers cite challenges including inadequate funding, restricted credit access, and insufficient technical support. A SWOT analysis identifies key strengths, such as political will, market potential, and institutional partnerships, alongside major threats, including limited irrigation infrastructure, high production costs, and ongoing climate risks. Vegetable diversification, supported by 80% of farmers, emerges as a viable pathway for adaptation—provided it is underpinned by efficient irrigation systems, improved soil management, and climate-resilient infrastructure. The study concludes with recommendations for strengthening agricultural resilience through targeted green finance, locally driven innovations, and better alignment between national policies and successful regional initiatives to enhance food security and adaptive capacity.

1. INTRODUCTION

Earth's climate is undergoing rapid and unprecedented changes, marked by rising temperatures, shifting precipitation patterns, and more frequent and intense extreme weather events. These transformations are primarily driven by anthropogenic greenhouse gas (GHG) emissions and represent a significant threat to ecosystems, economies, and societies worldwide [1]. Developing countries are particularly vulnerable, as limited adaptive capacity and greater exposure to climate risks amplify the adverse impacts of these changes [2, 3].

Adaptation strategies are thus critical, especially in regions where climate change consequences are most pronounced. Among the sectors at greatest risk is agriculture, which is central to global food security and rural livelihoods. Climate change threatens agriculture through shortened growing seasons, increased water scarcity, and accelerated soil degradation—disruptions that can destabilize food systems, particularly in climate-sensitive regions such as the Mediterranean basin [4, 5].

The Mediterranean is recognized as one of the world's major climate change hotspots. Its unique combination of ecological fragility, chronic water stress, and high population density contributes to heightened vulnerability and makes it a focal point for climate adaptation efforts [6]. Algeria, as a key Mediterranean country, exemplifies many of the climate challenges facing the region. Over the 20th century, the national average temperature increased by approximately 1.75°C—more than twice the global average rise of 0.74°C—accompanied by a 10-20% decline in precipitation, particularly in the northern and central regions [7]. These climatic changes are driven in part by large-scale atmospheric patterns such as the Mediterranean Oscillation and the North Atlantic Oscillation [8], and are projected to intensify by 2030, placing additional pressure on Algeria's already limited water and natural resources. In response, Algeria has shown a formal commitment to climate action by ratifying key international agreements, including the United Nations Framework Convention on Climate Change (UNFCCC) in 1993, the Kyoto Protocol in 2005, and the Paris Agreement in 2016. Domestically, institutional responses have included the creation of the National Agency for Climate Change (ANCC) in 2005 and the Directorate of Climate Change (DCC) in 2016. Despite these efforts, as with many developing countries, financial and institutional constraints continue to hinder the implementation and scalability of effective adaptation measures—particularly in the vulnerable agricultural sector [9]. Understanding the structure of Algeria's agricultural sector is essential for assessing its vulnerability to climate change. As of 2019, the country's agricultural land covered approximately 44 million hectares—representing 18.5% of the national territory. However, only 15% of this area is irrigated, leaving the vast majority of agricultural production dependent on increasingly unpredictable rainfall patterns. Moreover, 76% of Algeria's 1,023,799 agricultural holdings are smaller than 20 hectares, making them particularly susceptible to climate-related risks such as reduced precipitation and elevated temperatures. Structural challenges further exacerbate the sector's exposure to climate stress. These include fragmented land ownership, underdeveloped irrigation systems, and the continued encroachment of urban development on arable land. Despite these obstacles, Algeria's agricultural sector has demonstrated resilience and remains a contributor to economic growth. Nonetheless, transitioning toward climate-smart agricultural practices is critical to enhancing long-term sustainability and food security under evolving climate conditions [10, 11].

This study explores the impact of climate change on Algerian agriculture, with particular emphasis on vegetable diversification as an adaptation strategy. To ensure a comprehensive evaluation, it integrates multiple data sources—including historical climate records, agricultural statistics, and qualitative insights from interviews with farmers and government officials—offering a holistic perspective on the challenges facing Algerian agriculture and ongoing adaptation efforts. The study pursues three main objectives: (1) to assess the impact of climate change on cereal and vegetable production; (2) to evaluate the sustainability of diversification strategies in terms of food security and water resource management; and (3) to identify policy measures that can strengthen the climate resilience of Algeria's agricultural sector. Through this analysis, the research aims to provide valuable insights into Algeria's adaptation strategies and support the development of informed, long-term responses to climate-related challenges.

2. MATERIALS AND METHODS

2.1 Study area

Algeria, located in North-western Africa along the Mediterranean coast, features a wide range of climates—from fertile northern plains to the vast Sahara Desert, which covers 87% of the country (Figure 1). This geographic diversity presents both challenges and opportunities for agriculture, a key sector for food security and economic development.

Algeria's climate is highly variable, comprising five distinct bioclimatic zones (Table 1, Figure 2).

The northern coastal areas, such as the Algiers Mitidja Plain, receive relatively high rainfall and support intensive agriculture. In contrast, much of the country is arid or semi-arid, with erratic rainfall patterns. This variability highlights the need for effective water management, especially in arid regions like Oued Souf, where agriculture depends largely on groundwater.

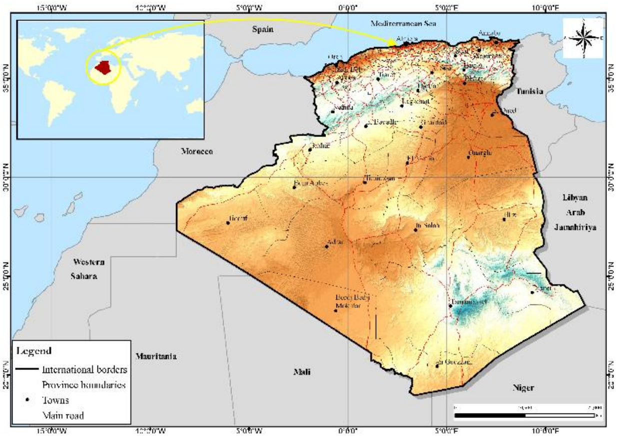

Figure 1. Situation of the study area

Table 1. Bioclimatic zones in Algeria [12]

Bioclimate	Rainfall (mm)	Area (ha)	% of Total Area
Humid	>900	958,773	0.40
Sub-humid	800-900	3,401,128	1.43
Semi-arid	300-600	9,814,985	4.12
Arid	100-300	11,232,270	4.72
Saharien	<100	212,766,944	89.33

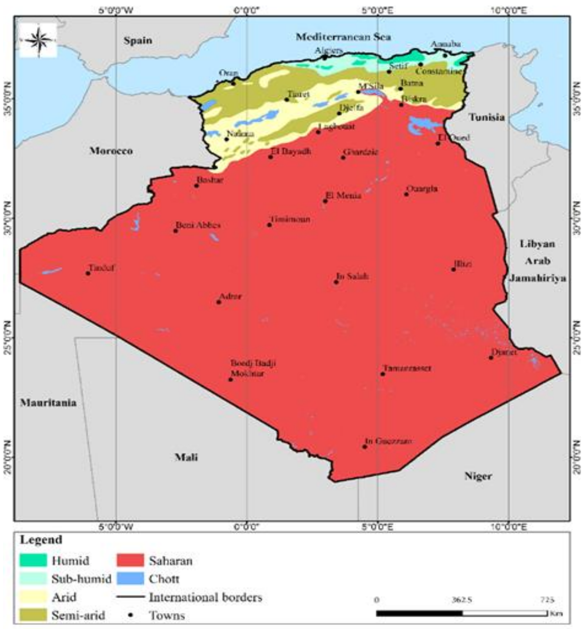

Figure 2. Bioclimatic zones in Algeria

Temperature and precipitation in Algeria vary widely, with the north experiencing a Mediterranean climate and the south characterized by arid conditions. In Algiers, average temperatures range from 10°C in January to 25.5°C in summer, moderated by the Mediterranean Sea. Water scarcity remains a major concern, with renewable resources at only 450 m³ per capita annually—well below the FAO's 1,000 m³ threshold. Semi-arid regions like Sidi Bel Abbès also struggle with erratic rainfall, further affecting agricultural productivity.

2.2 Data collection and analysis

This study uses a mixed-methods approach, combining quantitative and qualitative data to assess the effects of climate change on Algeria's agricultural systems. Integrating both types of data allows for a comprehensive analysis of sectoral vulnerabilities, capturing statistical trends alongside stakeholder insights into adaptation measures.

2.2.1 Data collection

Quantitative data include historical climate records (1922-2012) from the National Agency for Hydraulic Resources (ANRH) and agricultural statistics (2000-2023) from the Ministry of Agriculture and Rural Development (MADR), the National Office of Statistics (ONS), and FAOSTAT. Additional indicators on water stress and regional needs were sourced from reports by the World Bank, ANRH, and the National Climate Plan (NCP). Climate projections were drawn from the IPCC Sixth Assessment Report (2023).

Qualitative data were gathered between July and November 2023 through 100 semi-structured interviews with 90 farmers and 10 government officials. The study sites were purposively selected to represent Algeria's main and contrasting agro-ecological zones, allowing for a comparative analysis of climate vulnerabilities and adaptation pathways. The three selected regions are:

Mitidja Plain, representing a humid Mediterranean system;

Oued Souf, representing a hyper-arid Saharan oasis system; and

Sidi Bel Abbès, representing a semi-arid steppe system.

This purposive sampling strategy enables a comprehensive analysis of diverse adaptation strategies across Algeria. The full interview guide is available in Appendix 1.

2.2.2 Qualitative data analysis

The 100 semi-structured interviews were analyzed using NVivo 14, following a rigorous thematic analysis to ensure transparency and reproducibility.

Coding Framework Development: A hybrid deductive-inductive approach was used. Initial coding was guided by predefined themes from the interview protocol (e.g., *climate risks*, *adaptation strategies*), followed by open coding by two researchers, who independently generated 198 initial codes. This process surfaced emergent themes such as *farmer-led innovation*. These codes were grouped into 19 sub-themes and then consolidated into six main analytical categories:

1) Perceptions of Climate Risk
2) Adaptation Practices
3) Institutional Challenges
4) Water Resource Management
5) Innovation and Knowledge Systems
6) Policy Implementation Gaps

Inter-Coder Reliability (ICR) and Consensus: The entire dataset was double-coded. NVivo's coding comparison tool showed a 77% initial agreement rate (152 of 198 codes matched). Discrepancies were resolved through collaborative discussion, resulting in a unified coding framework. This consensus-based process enhances the rigor and credibility of qualitative research.

Triangulation and Validation: To enhance the validity of the thematic findings, results were triangulated with quantitative data and key national policy documents, including the NADP, PRAR, and Plan Felaha. This cross-referencing ensured that interpretations were grounded in both empirical evidence and the broader policy context.

2.2.3 Quantitative statistical analysis

To validate observed trends, inferential statistical tests were conducted at a 5% significance level ($\alpha = .05$). A multiple linear regression model assessed the effects of temperature and rainfall on cereal yields. A one-way ANOVA tested for significant differences in mean yields across the three study regions. Additionally, a two-sample t-test compared average yields before (2017-2019) and after (2021) the 2020 drought to evaluate its impact.

3. RESULTS AND DISCUSSION

3.1 Climate change impacts on Algerian agriculture

Algerian agriculture is highly vulnerable to climate change. Rising temperatures and erratic rainfall threaten crop yields, water availability, and overall productivity. Higher temperatures reduce yields and promote pest outbreaks, while unpredictable rainfall increases the risk of crop failure and long-term decline in output. These effects are compounded by the sector's heavy reliance on already strained water resources.

Interviews from all three regions revealed unanimous concern over declining water availability and quality (100% of farmers). Agriculture consumed 65% of Algeria's water in 2000 (6.074 billion m^3), dropping to two-thirds of total use by 2015 (4.15 billion m^3) [7]. In groundwater-dependent areas like Oued Souf, farmers reported falling water tables—one noting, *"Water is our biggest worry. The groundwater levels are dropping every year."*

Droughts further exacerbate these challenges. The severe 2020 drought affected over 80% of farmland, cutting wheat yields by 45% and barley by 35% [13], with farmers reporting significant economic losses. Rising temperatures also disrupt crop cycles, even for arid-adapted species like date palms. While irrigated land expanded from 0.985 million hectares in 2010 to 1.5 million in 2021 (Figure 3)—increasing from 11% to 17% of the Utilized Agricultural Area (UAA)—this growth has not been sufficient to offset water scarcity. Rainfed cereal crops remain particularly vulnerable to rainfall variability.

Interviews showed that 85% of farmers observed cereal yield declines due to erratic rainfall. Projections [14] indicate a further 12% drop in cereal output in 2023, resulting in a 20% deficit compared to historical averages, mainly due to rainfall shortages during key growth stages. These findings align with the study of Bouznit et al. [15], which emphasizes the strong correlation between rainfall patterns and cereal yields, underscoring the vulnerability of rainfed agriculture to climate variability.

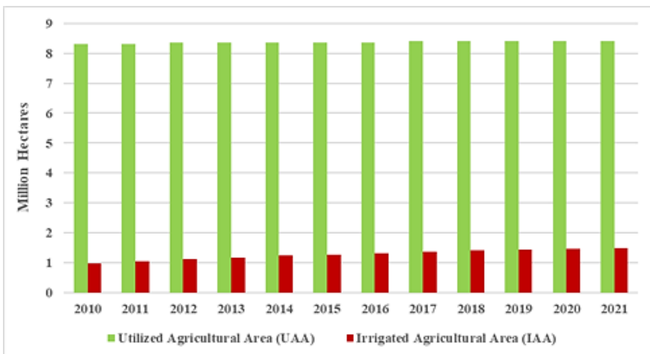

Figure 3. Evolution of utilized and irrigated agricultural areas in Algeria (2010-2021)

Algeria's heavy reliance on cereal imports exacerbates its food security challenges. Domestic cereal production consistently falls short of the country's annual demand of 8,000,000 t, positioning Algeria as the world's seventh-largest cereal importer. Wheat imports alone average 7,500,000 t per year, costing approximately $2.1 billion. Government officials have emphasized the urgent need to reduce this dependence, particularly in light of the sharp decline in per capita arable land—from 0.56 hectares in 1970 to just 0.19 hectares in 2020 [16]. In response, both farmers and policymakers increasingly view vegetable diversification as a viable adaptation strategy. By promoting water-efficient crop varieties, this approach holds promise for reducing import dependency, improving food security, and strengthening Algeria's resilience to climate change.

3.2 Southern agricultural development and trade balance

Southern Algeria has experienced notable agricultural growth, even as the northern regions face increasing climate-related challenges. This progress is largely attributed to the expansion of irrigated agricultural areas (IAA). Between 2011 and 2021, these areas increased by 106,000 hectares, reaching a total of 356,000 hectares—now accounting for 23.75% of Algeria's irrigated land. This expansion is underpinned by the growing water potential of the Saharan Northern Aquifer System (SASS), projected to reach 6.1 billion m³ annually by 2050 [17]. Such development is critical for boosting the production of vegetables, cereals, and red meat by an estimated 30%, thereby contributing to national food security amidst climate pressures. However, interviews with government officials underscore persistent challenges, particularly in market access and long-term sustainability. Farmers in the south have also expressed concerns over inconsistent water supply, which hampers both agricultural output and the adoption of sustainable farming practices.

Despite notable crop expansion—such as date palms (165,000 hectares), cereals (82,000 hectares), and vegetables (93,000 hectares, 41% of which are potatoes)- effective water management remains a central obstacle. Algeria's agricultural trade deficit, estimated at $9.5 billion in 2022, reflects the country's heavy dependence on food imports. Imports accounted for 83% of this deficit, driven by population growth and rising demand that domestic production struggles to satisfy [16]. This dependency carries significant implications for Algeria's economic trajectory. As Asogwa and Azu [18] indicated, agricultural export performance can have a substantial positive impact on economic growth, particularly within economically integrated regions. Their research suggests that policies such as monetary unification, improved infrastructure connectivity, and trade policy reforms could enhance intra-African trade and, in turn, stimulate economic growth in countries like Algeria. Since 2000, national food expenditures have nearly tripled, underscoring Algeria's growing dependence on imports. Strengthening domestic agricultural production—particularly of high-demand vegetables—is essential to reducing this reliance and advancing agricultural sustainability in the face of increasing climate risks. In summary, while agricultural development in southern Algeria has made important contributions to national food security, significant challenges remain. Addressing water scarcity, expanding market access, and adopting policies that facilitate agricultural trade are critical steps toward unlocking the full potential of the southern agricultural regions and building long-term resilience against climate change.

3.3 Opportunities and challenges of vegetable diversification

3.3.1 Government policies and production growth

Algeria has made notable progress in vegetable diversification, particularly in the cultivation of potatoes and other fresh vegetables. This advancement has been largely driven by targeted government policies aimed at enhancing food security and fostering economic resilience. Key national initiatives—such as the National Agricultural Development Program (NADP, 2000-2010), the Agricultural and Rural Renewal Policy (PRAR, 2010-2014), and Plan Felaha (2014-2020)—have prioritized the expansion of irrigation infrastructure, the provision of subsidies, and support for large-scale agricultural enterprises. These measures were designed to reduce Algeria's reliance on food imports while promoting sustainable rural development.

As a result, fresh vegetable production increased by 125.2% between 2000 and 2010, followed by an additional 69.3% growth by 2021, reaching over 14,600,000 t. Potato production alone expanded by 234.1% from 2000 to 2010. However, a modest decline of 2.1% from 2010 to 2021 suggests emerging constraints and the need for continued policy intervention. These trends highlight the strategic role of vegetable diversification in enhancing food self-sufficiency, generating rural employment, and contributing to broader agricultural development objectives (see Table 2).

Despite notable progress, sustaining Algeria's vegetable diversification efforts over the long term will require comprehensive strategies centered on effective water management, market stability, continued government support, and investment in agricultural infrastructure. Diversification is increasingly recognized as a key strategy for climate adaptation, particularly in water-scarce and environmentally vulnerable regions.

Table 2. Agricultural production (in t) [19, 20]

Product	2000	2010	2021	Growth (2000-2010%)	Growth (2010-2021%)
Cereals	1,952,925	4,002,112	2,764,825.8	105	-30.9
Dry Vegetables	21,864	72,345	98,442.3	230.7	36.1
Fresh Vegetables	3,837,416	8,640,443	14,627,564.2	125.2	69.3
Potatoes	1,333,465	4,452,126.2	4,360,414.8	234.1	-2.1
Grapes	1,881,390	4,025,920	6,299,622	114.0	56.5
Olives	1,919,260	3,112,520	704,619.5	62.2	-77.4
Citrus fruits	5,194,590	7,881,110	1,513,447	51.7	-80.8
Dates	4,184,270	6,447,410	1,188,803	54.1	-81.6
Milk (1,000 L)	1,594,000	2,632,911	3,287,673	65.2	25
Industrial Crops	4,290,500	7,776,900	2,397,739.2	81.3	-69.2

For instance, Sudarma et al. [21] found that chili farmers in Bali, Indonesia, successfully employed diversification—along with modified planting schedules and improved irrigation practices—to mitigate the adverse effects of climate change on crop yields and incomes. This case highlights the potential for similar approaches to strengthen climate resilience within Algeria's agricultural sector.

3.3.2 Market challenges

While vegetable diversification offers clear benefits for food security and rural development, Algeria continues to face significant market-related challenges that limit the economic potential of this strategy. Interviews with farmers indicate that 80% perceive restricted market access and high price volatility as major barriers. Although domestic demand for fresh vegetables is projected to reach approximately US$66 billion by 2025 [22], Algeria's vegetable exports remain limited—averaging only 4,000 t annually.

Several structural constraints contribute to this gap. Underdeveloped market infrastructure, combined with high transportation and logistics costs, leads to increased post-harvest losses and reduces the competitiveness of Algerian produce in both domestic and international markets. These inefficiencies also perpetuate Algeria's dependence on fresh vegetable imports, estimated at 300,000-400,000 t per year. This import reliance not only undermines local production efforts but also exposes consumers to global price fluctuations. Addressing these systemic challenges through improved infrastructure, market systems, and trade facilitation is essential for strengthening Algeria's agricultural self-sufficiency and maximizing the benefits of vegetable diversification.

3.3.3 Environmental sustainability concerns

Despite the expansion of vegetable production in Algeria, significant concerns remain regarding environmental sustainability, particularly in relation to water resource management. In 2020, agricultural activities in the Mitidja region accounted for 63.8% of the area's renewable water consumption [23], and national agricultural water withdrawals now exceed global averages, with the water stress index reaching 138% [24]. In highly arid zones such as Sidi Bel Abbès, all surveyed farmers reported experiencing acute water scarcity. Intensive agricultural practices further exacerbate environmental degradation. Fertilizer consumption increased from 135,220 t in 2000 to 195,100 t in 2021 [24], while the widespread adoption of monoculture has contributed to soil degradation. In Oued Souf, for example, land is frequently abandoned after just 3-5 years of intensive potato cultivation due to soil nutrient depletion [25]. Moreover, the use of high-salinity water for irrigation has negatively affected crop yields, particularly in areas such as the Sidi Okba oasis [26]. The area under vegetable cultivation expanded by 180,000 hectares between 2000 and 2010, and by an additional 84,000 hectares from 2010 to 2021 [19, 20], intensifying pressure on both water and soil resources. While some environmentally friendly practices—such as drip irrigation and organic manure application—have been adopted in regions like Mitidja and Oued Souf [23, 25], 90% of interviewed farmers emphasized the urgent need for improved water access and the wider adoption of modern irrigation technologies. Ensuring the long-term environmental sustainability of vegetable production systems is therefore critical to the future of Algeria's agricultural sector.

3.4 Agriculture and greenhouse gas emissions

GHG emissions from Algeria's agricultural sector have increased markedly in recent decades, rising by 74.3% from 11,230.85 ktCO_2eq in 1990 to 19,575.24 ktCO_2eq in 2020 (Ministry of Environment and Renewable Energies, 2023). This rise has been primarily driven by methane (CH_4) emissions from livestock and nitrous oxide (N_2O) emissions related to fertilizer use and soil management. CH_4 emissions increased by 68.5% due to the intensification of livestock production, while N_2O emissions grew by 85.5% as a result of expanded synthetic fertilizer application and soil disturbance.

Although emissions directly attributable to vegetable diversification have not been systematically quantified, many farmers have demonstrated growing interest in adopting agroecological practices to mitigate their environmental footprint. These practices may include crop rotation, organic fertilization, and integrated pest management. Future research comparing the emissions profiles of vegetable versus cereal production could provide valuable insights into the role of diversification in supporting low-carbon and climate-resilient agricultural systems in Algeria.

3.5 Effects of climate change on water resources

Algeria's water security crisis is intensifying under the effects of climate change, with significant implications for agricultural sustainability. Between 2010 and 2020, the country experienced a 17.5% decline in freshwater availability, while the national water stress index reached a critical level of 138% (Figure 4) [27]. These figures indicate that water demand far exceeds the available renewable supply, placing substantial pressure on agricultural systems.

Qualitative data from farmer interviews reveal widespread concern regarding the deteriorating availability and quality of water resources. Many respondents cited increasing difficulty in accessing water for irrigation, as well as growing variability in supply. Long-term climatological data spanning 1922 to 2012 further underscore these concerns. Time-series analysis shows a significant decline in annual precipitation in Algeria's central and northwestern regions (Figures 5(a) and 5(c)), while the northeast exhibits more inter-decadal variability than a persistent long-term decline (Figure 5(b)) [28]. This trend of aridification is geographically confirmed by a clear northward retreat of the 200 mm and 300 mm isohyets over the last decades (Figure 6). Furthermore, the rainfall deficit is most pronounced in these same central and western areas, which are classified as having "High" to "Extreme" deficits (Appendix 2). This persistent decline has had a cascading impact on the recharge rates of aquifers and the levels of surface water in major hydrological basins. Reduced recharge and heightened evapotranspiration are exacerbating groundwater depletion and threatening the long-term viability of irrigated agriculture, especially in already water-scarce regions.

Drought conditions have critically strained key aquifers, particularly in the Oranie-Chott-Chergui and Chelif-Zahrez regions, resulting in significant water deficits. Similarly, surface water reservoirs have been adversely affected.

Long-term data shows that dam recharge in western Algeria has declined by 62.6% compared to the pre-1976 average (Table 3). The recent consequences of this deficit are visible in the highly variable and often critically low annual water inputs between 2000 and 2020 (Figure 7). This situation further exacerbates water scarcity and limits the availability of irrigation resources.

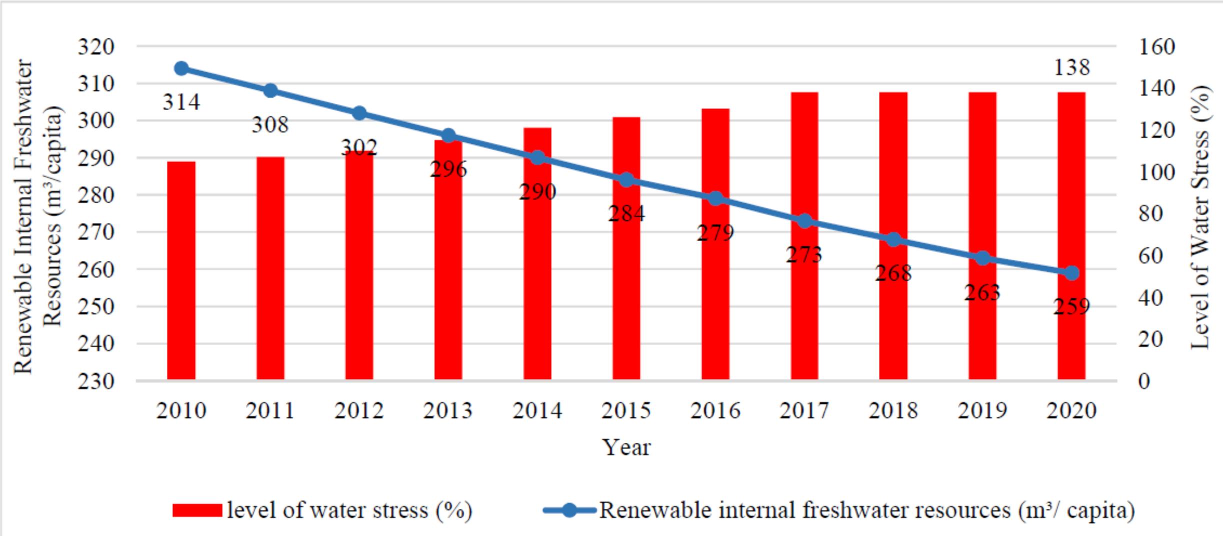

Figure 4. Evolution of water stress indicator and freshwater availability per capita in Algeria (2010-2020)
Source: Authors, based on data [29]

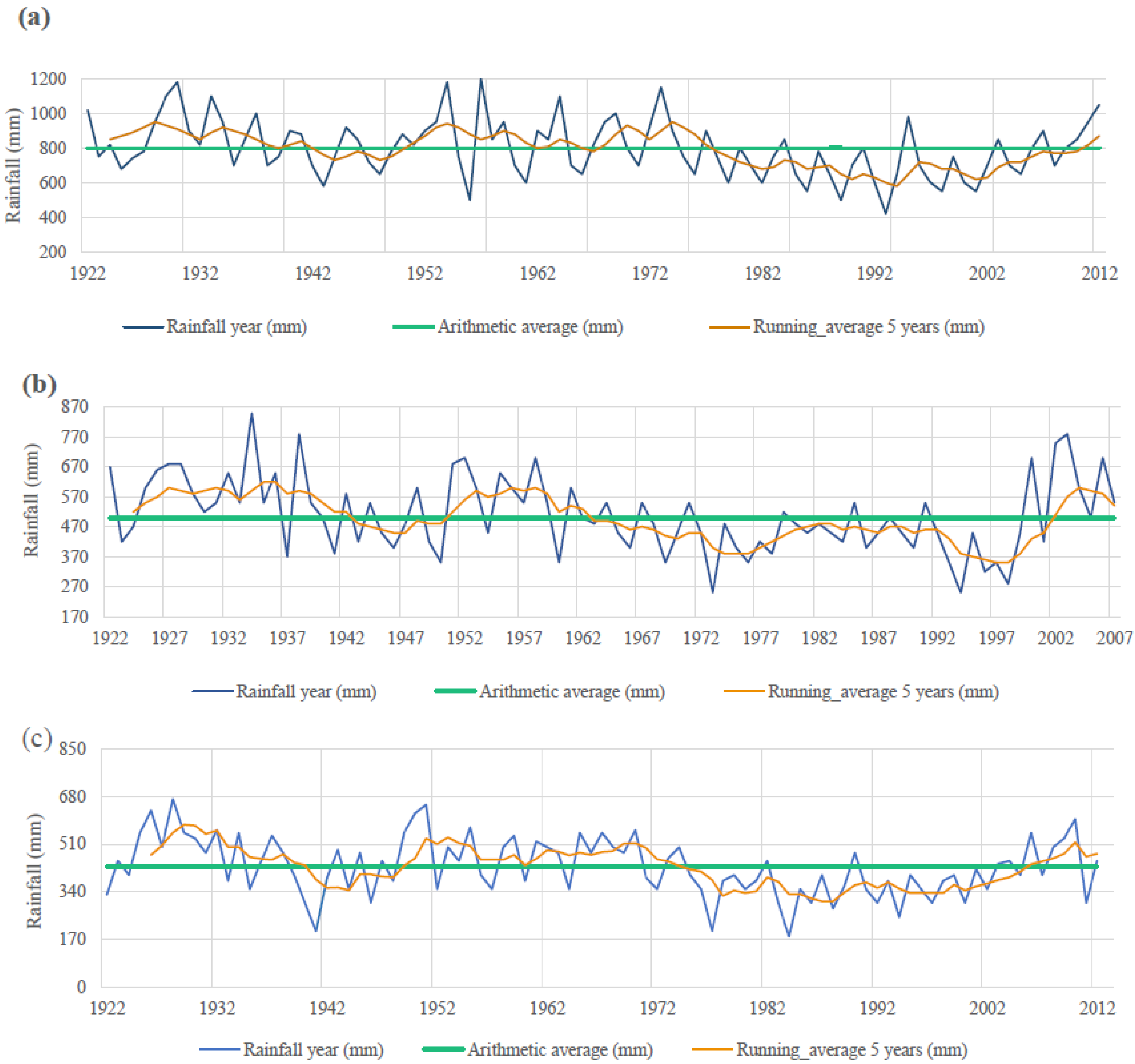

Figure 5. Evolution of annual rainfall at three meteorological stations in Algeria: (a) Algiers (1922-2012), (b) Constantine (1922-2007), and (c) Oran (1922-2012)

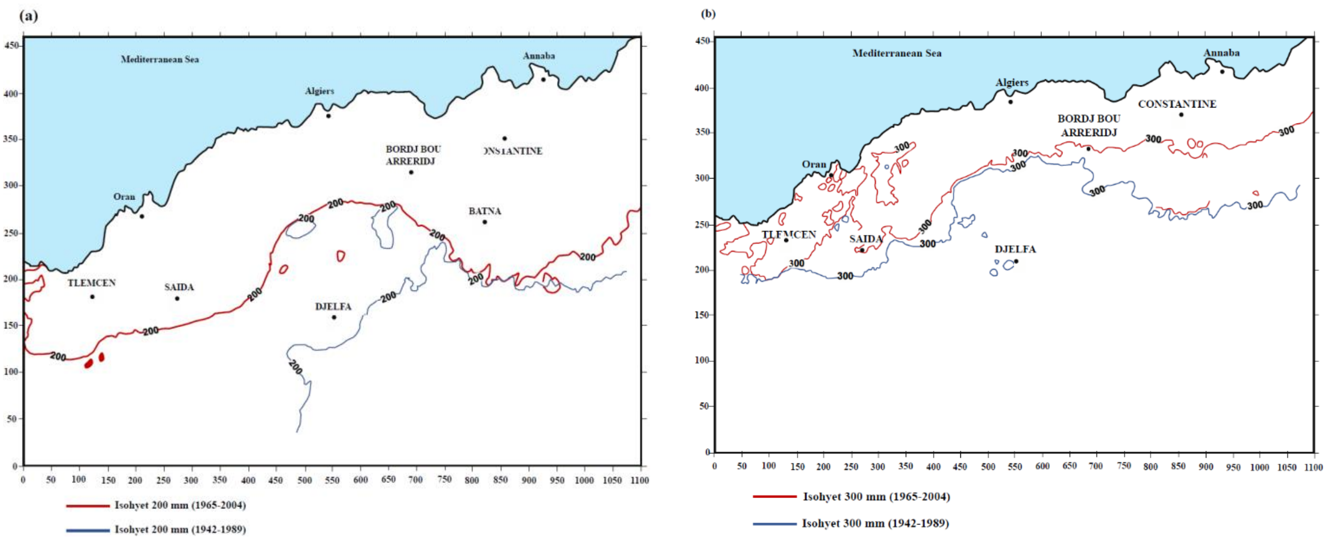

Figure 6. Evolution of 200 mm and 300 mm isohyets in Algeria

Table 3. Average water inputs by zone [12]

Dams	Average Annual Rainfall (mm)		Rainfall Reduction %	Average Annual Recharge (hm^3)		Recharge Decrease %
	Before 1976	After 1976		Before 1976	After 1976	
West	474.6	364.8	23.1	73.8	27.6	62.6
Center	581.1	470.9	19.0	84.9	52.6	38.0
East	742.7	647	12.9	90.1	69.2	23.2

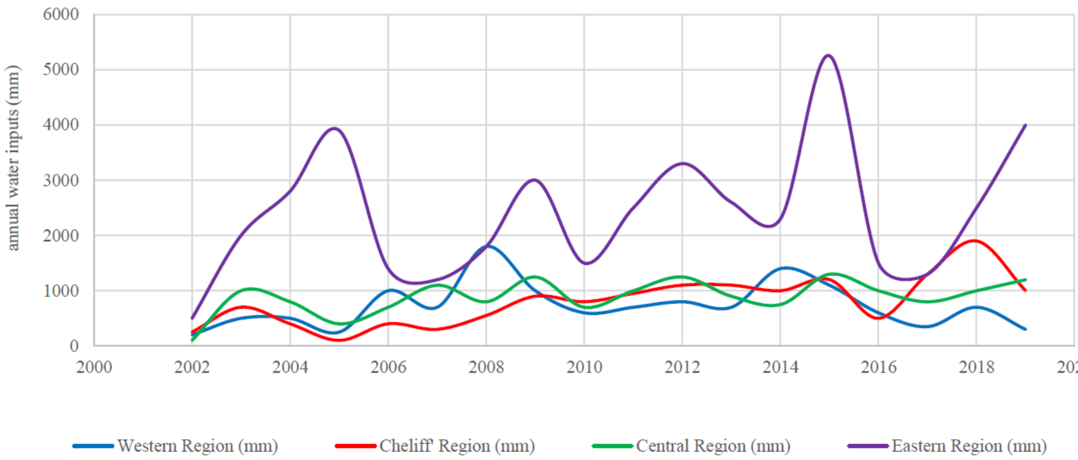

Figure 7. Evolution of annual water inputs (mm) by region in Algeria (2000-2020)

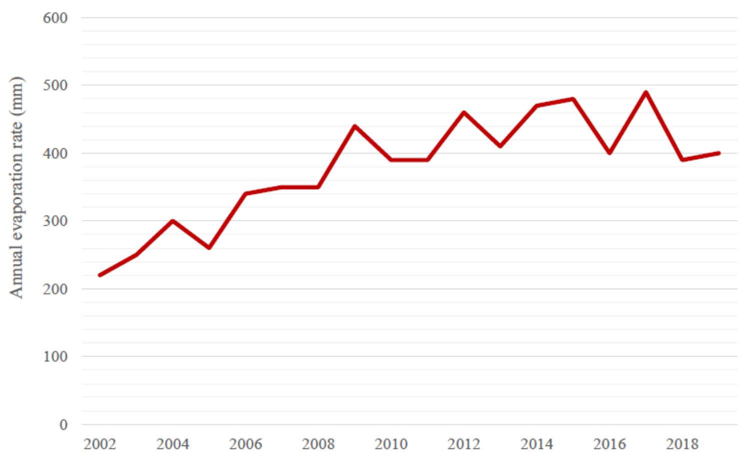

Figure 8. Evolution of annual evaporation rate in Algeria (2002-2018)

Aquifer overexploitation in Algeria has reached critical levels, driven by escalating water demand for agriculture and domestic use. This is evidenced by a severe decline in aquifer recharge since 1976, reaching as high as -73.7% in key agricultural areas like Sidi Bel Abbes and Mascara (Table 4) [12]. This groundwater depletion is compounded by climate change, with a clear trend of increasing annual evaporation rates observed between 2002 and 2018 (Figure 8). These combined pressures are particularly acute in the Mediterranean Slope and Endorheic watersheds (Figure 9), which host the majority of the country's agricultural activities. The urgency of this situation is strongly felt by farmers, with 87% of those surveyed supporting increased government investment in modern irrigation infrastructure and water-saving technologies to ensure the sustainability of their production.

Table 4. Aquifer recharge before and after 1976 [12]

Aquifer	Inputs/Contributions before 1976 (millions m^3)	Inputs/Contributions after 1976 (millions m^3)	Decrease (%)
Maghnia	171	81.2	- 52.5
Soumam	724	395.8	- 45.3
Sidi Bel Abbés	136.7	35.9	- 73.7
Mascara	73	19.2	- 73.7
Mitidja	730	461.9	- 36.7
Mostaganem	34	11.3	- 66.8
Zahrez	78	57	- 26.9
Ain Ouessara	117	38.5	- 67.1
Chott Chergui	367	305.5	- 16.8

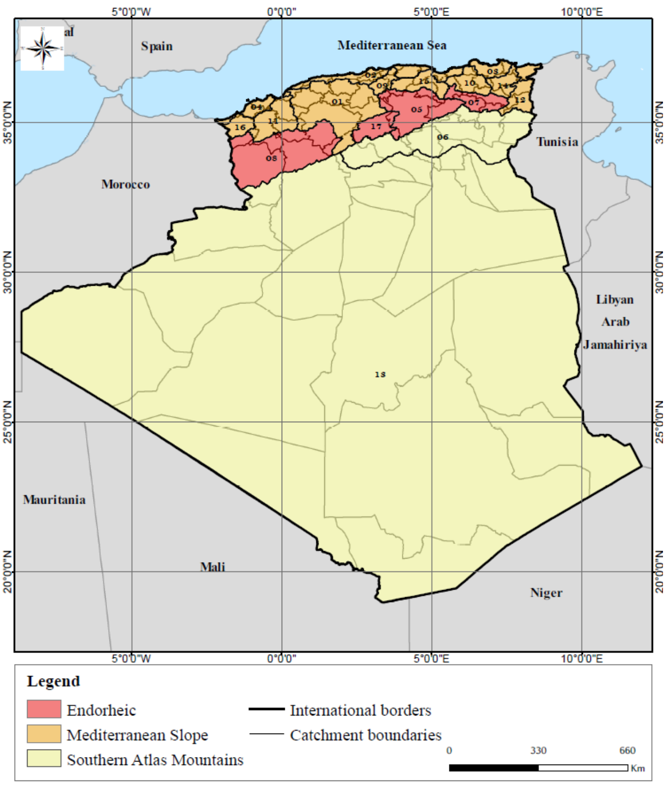

Figure 9. Map of Algerian catchment basins

3.6 Empirical statistical validation of climate and regional yield effects

To strengthen the empirical foundation of the study's findings, a series of statistical analyses were conducted focusing on cereal yields, given their critical importance to national food security and the availability of consistent long-term data. The analysis covers the period from 2010 to 2023, coinciding with the implementation of Algeria's recent agricultural renewal policies, such as the PRAR.

A multiple linear regression model was first employed to quantify the effects of temperature and rainfall on cereal yields. This model demonstrated strong predictive capability, explaining 80% of the variance in yields ($R^2 = 0.80$, $F(2, 39) = 78.71$, $p < 0.001$). The results suggest a potential multicollinearity between temperature and rainfall, indicating that their combined influence on yields is more substantial than the isolated effect of either variable.

To investigate spatial heterogeneity in vulnerability, a one-way analysis of variance (ANOVA) compared mean cereal yields across three key agricultural regions: Mitidja (M = 2.18 t/ha), Oued Souf (M = 1.38 t/ha), and Sidi Bel Abbès (M = 1.72 t/ha). The differences in mean yields were statistically significant ($F(2, 39) = 19.77$, $p < 0.001$), confirming regional disparities in agricultural performance.

Finally, the system's sensitivity to acute climatic shocks was assessed by examining the impact of the 2020 drought. A two-sample t-test comparing pre-drought (2017–2019) and post-drought (2021-2023) mean yields revealed a significant decline from 1.92 t/ha to 1.36 t/ha ($t(16) = 3.29$, $p = 0.005$), highlighting the lasting negative effect of extreme drought events on cereal production.

Together, these analyses provide a robust, multi-dimensional quantitative validation of the study's central argument: Algerian cereal production is highly sensitive to climatic variables, exhibits significant spatial variability in vulnerability, and is subject to enduring reductions in yield following extreme weather events. These findings underscore the imperative for regionally tailored, resilience-oriented agricultural policies.

3.7 Adaptation strategies and resilience to climate change

In response to escalating climate impacts, Algeria has developed a comprehensive strategy centered on mobilizing water resources and enhancing agricultural resilience.

3.7.1 Water resource mobilization and management

Non-conventional resources (Desalination). To mitigate the effects of declining rainfall, Algeria plans to significantly expand its desalination capacity, increasing coverage from 17% in 2023 to 42% by 2024 and targeting 60% by 2030. This expansion entails growing the number of operational desalination plants from 12 to 23. By reallocating dam water currently used for domestic consumption to agricultural purposes, this strategy has the potential to expand irrigated areas, such as in the Chlef-Maghnia region. However, farmers have expressed concerns regarding the energy intensity of desalination and the environmental impacts of brine discharge, highlighting the importance of integrating sustainable practices within this approach.

Water storage capacity expansion. To bolster agricultural water security, Algeria is constructing four additional dams, which will increase total water storage capacity to approximately 9 billion m³ by 2024. This expanded capacity is particularly vital for sustaining vegetable production in drought-prone areas. Reflecting the critical importance of water availability, 87% of farmers surveyed emphasized the necessity of consistent and reliable access to irrigation water.

Water-efficient irrigation. Water-efficient irrigation methods currently cover 60% of Algeria's irrigated lands, with plans to increase this coverage by 50,000 hectares annually. Financial incentives covering up to 60% of installation costs aim to facilitate wider adoption. This aligns with the views of 95% of surveyed farmers, who called for expanded training and technical support to optimize irrigation system efficiency and ensure sustainable water use.

3.7.2 Key public interventions for climate resilience

Large dams and water transfers. Algeria's extensive network of approximately 80 dams—alongside four additional dams under construction—supports irrigation across 274,000 hectares. Moreover, seven large-scale water transfer systems distribute water to 11 provinces, enabling crop diversification in arid and semi-arid regions. Despite these infrastructural advances, farmers stress the need for greater transparency and equity in water distribution to maximize the benefits of these public investments.

Wastewater reuse. Addressing water scarcity in Algeria's arid regions is critical for sustainable agricultural development. The country currently operates approximately 200 wastewater treatment plants, generating around 942 million m³ of treated wastewater annually. This treated effluent provides an important alternative source of irrigation water, especially in water-stressed areas, and is actively promoted by government authorities as a sustainable and viable solution.

This strategy aligns with international best practices for agricultural water reuse. For instance, Carrión-Mero et al. [30] demonstrated the successful integration of treated wastewater with groundwater resources, combined with artificial aquifer recharge, to support farming in the semi-arid Ayangue commune of Ecuador. Such approaches underscore the potential for treated wastewater to enhance water security and foster sustainable agricultural production.

Localized Irrigation Infrastructure. Algeria's network of 592 small dams and hillside reservoirs plays a vital role in supporting agricultural diversification in rural and mountainous regions. These decentralized water storage systems reflect farmers' strong advocacy for community-centered water management, which enhances local control over scarce water resources.

Groundwater Exploitation. The country's 255 boreholes currently irrigate over one million hectares. However, farmers have voiced concerns about the sustainability of groundwater extraction, emphasizing the urgent need for improved monitoring and regulation to prevent overexploitation and salinization of aquifers.

Highland and Southern Valleys Water Projects. Ambitious water transfer initiatives from southern aquifers aim to irrigate approximately 1.56 million hectares by 2030. These projects are expected to bolster crop diversity and strengthen climate resilience in Algeria's highland and southern valley regions.

3.7.3 Farmer-led innovations: A bottom-up approach

Algerian farmers demonstrate notable resilience and adaptability through locally driven innovations. In Oued Souf, for example, farmers have developed an artisanal irrigation pivot system—an affordable and effective technology now adopted widely across the Sahara and beyond—highlighting the critical role of indigenous knowledge in addressing water scarcity.

Traditional water management techniques are also experiencing a revival. Communities in Tilouline and Aougrout (Adrar) are restoring ancient foggara systems—underground channels designed for water conservation [31]. These combined traditional and modern approaches significantly enhance resilience in arid environments.

Farmers in Ras El Ma (Sidi Bel Abbès) integrate crop and livestock production to diversify income sources, while those in Aougrout are experimenting with drought-resistant crops such as cucumbers. In Oued Souf, foggara systems are being integrated with modern irrigation technologies to improve sustainability [32]. Furthermore, southern farmers have adopted Canarian-style greenhouses, which provide protection against high temperatures and strong winds, exemplifying the adoption of climate-resilient agricultural technologies [33].

3.7.4 Leveraging public-private partnerships for farmer-led climate adaptation

Public-private partnerships (PPPs) play a crucial role in bridging the climate finance gap and advancing grassroots adaptation initiatives in Algeria. By mobilizing private sector resources, expertise, and technical training, PPPs effectively complement constrained public funding and accelerate the adoption of climate-resilient agricultural practices.

A prominent example is the collaboration in Oued Souf between Algerian and Dutch institutions, which introduced water-saving subsurface fertigation technology to promote sustainable potato production [34]. This initiative provided farmers with advanced equipment, technical support, and data-driven insights, reducing investment risks while significantly enhancing water use efficiency and crop yields.

Such partnerships not only alleviate funding constraints but also facilitate critical knowledge transfer, empowering farming communities with sustainable practices essential for long-term resilience. Engaging the private sector broadens access to innovative technologies and expertise, thereby strengthening Algeria's agricultural climate resilience. Future efforts to develop scalable PPP models and explore alternative financing mechanisms hold promise for incentivizing private investment in climate-smart agriculture, contributing to a sustainable and resilient agricultural future.

3.8 Algerian agricultural plans and policies for climate resilience

A comprehensive assessment of Algeria's climate resilience strategies requires a regional lens, as neighboring countries contend with similar agro-climatic challenges. In Tunisia, for example, two decades of conservation agriculture have yielded a 21% increase in wheat yields alongside marked improvements in soil health under semi-arid conditions [35]. Morocco's "Green Generation" initiative provides a strong policy framework for scaling such sustainable practices.

Empirical studies from semi-arid Moroccan regions confirm that no-till systems can enhance soil organic carbon stocks by up to 30% compared to conventional tillage methods [36, 37]. Meanwhile, Egypt's Desert Research Center has pioneered advanced geostatistical techniques for managing soil salinity and monitoring water quality—innovations with significant relevance to Algeria's Saharan zones [38, 39].

These regional examples underscore a crucial insight: technical interventions such as no-till agriculture and precision irrigation only deliver substantial, sustained benefits when integrated within comprehensive public policies. These include institutional incentives, capacity-building initiatives, and farmer engagement.

Within this context of regional best practices, Algeria has also enacted a series of targeted national policies to enhance agricultural climate resilience. The National Agricultural Development Program (NADP, 2000-2010) prioritized modernization and diversification by boosting productivity, improving rural livelihoods, and promoting sustainable practices, particularly through expanded irrigation and agricultural research. The National Plan of Action and Adaptation to Climate Change (NPA-ACC, 2003-2013) focused on reducing GHG emissions, advancing water-efficient irrigation, and enhancing climate knowledge to better manage water variability.

Subsequent efforts continued with the Agricultural and Rural Renewal Policy (PRAR, 2010-2014), aimed at revitalizing rural areas and supporting smallholder farmers. The Felaha Plan (2014-2020) further reinforced food security and modernization, emphasizing productivity, water management, and sustainable land use. Recognizing water's pivotal role, the National Water Strategy (NWS, 2016-2025) seeks to optimize water use, promote climate-resilient crop varieties, and adjust agricultural calendars to evolving climate conditions.

These initiatives converge in the National Climate Plan [12], which integrates adaptation and mitigation efforts across sectors, with a particular focus on climate-smart agriculture. This framework is aligned with Algeria's Nationally Determined Contributions (NDCs) under the UNFCCC, underscoring the country's commitment to food security and climate resilience [40].

Although Algeria's agricultural policies articulate ambitious climate resilience goals, significant barriers hinder their effective implementation. Interviews with farmers and officials reveal that 85% of respondents perceive a disconnect between policy objectives and practical support, citing limited financial resources, restricted credit access, and insufficient assistance for adopting sustainable practices. The high costs associated with climate-smart technologies—such as resilient seed varieties and advanced irrigation systems—further exacerbate challenges, particularly in regions like Sidi Bel Abbès, where farmers report these tools remain financially inaccessible despite their proven benefits. Studies by Ariom et al. [41] and Aidat et al. [42] emphasize the necessity of decentralized funding mechanisms to effectively support local adoption. Moreover, the predominant focus on intensive agricultural models that prioritize short-term yield gains risks compromising long-term sustainability, as highlighted by Boudedja et al. [43].

Bridging this implementation gap requires expanded financial access to adaptation technologies and enhanced agricultural training—a need underscored by 90% of interviewed officials who stress the importance of strengthening capacity among farmers and agricultural professionals.

3.9 SWOT analysis: Assessing vegetable diversification for climate adaptation

To evaluate vegetable diversification as a viable climate adaptation strategy, a SWOT analysis was conducted. This assessment integrates data, policy reviews, and insights from farmers and officials, highlighting key strengths, weaknesses, opportunities, and threats shaping Algeria's adaptation landscape (Table 5).

Table 5. SWOT analysis of Algeria's strategy for vegetable diversification as a climate adaptation measure

Strengths	Weaknesses	Opportunities	Threats
Strong Government Commitment: Policies like NADP, NCP, and NWS lay a foundation for vegetable diversification.	Implementation and Financial Gaps: Inadequate funding and restricted access to agricultural credit significantly hinder the widespread adoption of climate-smart agricultural practices, underscoring the need for improved financial mechanisms and institutional support.	Public-Private Partnerships: PPPs can bridge funding gaps, draw investment, and advance climate-smart practices, as demonstrated by a subsurface fertigation project in Oued Souf that enhanced water efficiency in vegetable farming.	Exacerbated Water Scarcity: Climate change is projected to intensify water scarcity, placing additional stress on agricultural production-particularly for water-intensive crops-as increasing irrigation demands, declining rainfall, and elevated temperatures further diminish already limited water resources.
Traditional Knowledge Integration: Use of "foggara" systems can support resilience when combined with new tech.	Lack of Training and Technology Access: Approximately 95% of farmers report insufficient training in sustainable and water-efficient agricultural practices, highlighting a critical gap in capacity-building efforts.	International Climate Finance and Collaboration: Algeria has the opportunity to leverage international climate finance mechanisms and strategic partnerships to advance the development of climate-smart agriculture and accelerate the adoption of resilient vegetable production systems.	Increased Climate Hazards: Droughts, floods, and heatwaves pose escalating risks to vegetable production and food security.
Market Potential: Reducing food import reliance by expanding local vegetable production could boost food security.	Soil Degradation from Intensification: Intensive practices, such as potato farming in Oued Souf, threaten soil health.	Strategic Diversification for Resilience: Climate-adapted vegetables for arid areas, supported by 80% of farmers, can enhance adaptability.	

The SWOT analysis underscores Algeria's commitment to climate adaptation, yet identifies several impediments to progress, including financial limitations, insufficient training, high technology costs, and a decentralized funding structure. Additionally, the environmental risks associated with intensive farming practices further complicate efforts. However, public-private partnerships and international climate finance emerge as potential avenues to support the transition to climate-smart agriculture. By tackling water scarcity and implementing focused policies and strategic partnerships, vegetable diversification could be developed into a sustainable and effective adaptation strategy for Algeria.

4. CONCLUSIONS

Climate change presents a formidable threat to Algerian agriculture, exacerbating food insecurity through heightened water scarcity, extreme weather events, and diminishing crop yields. This study reveals a significant gap between Algeria's national adaptation strategies, as outlined in its Nationally Determined Contributions (NDCs), and the realities faced at the ground level. Key barriers to effective adaptation include financial limitations, inadequate access to agricultural credit, and continued reliance on intensive, resource-dependent farming systems that undermine long-term sustainability.

To overcome these challenges, it is imperative to adopt urgent and innovative approaches, such as green bonds, enhanced public-private partnerships, and expanded access to international climate finance. Vegetable diversification stands out as a promising strategy for building agricultural resilience; however, its success hinges on the development of sustainable infrastructure and the implementation of context-specific strategies tailored to Algeria's diverse agro-ecological regions. In addition to providing qualitative and descriptive insights, this study strengthens its analytical framework through rigorous inferential statistical methods applied to data spanning from 2010 to 2023. A multiple linear regression analysis confirmed the substantial combined effect of climatic variables on cereal yields, while one-way ANOVA testing highlighted significant regional disparities in productivity.

Moreover, a t-test revealed a statistically significant decline in yields following the 2020 drought, offering robust evidence of the enduring negative impacts of extreme weather events. These empirical results underscore the critical role of both climatic variability and regional factors in shaping agricultural outcomes and emphasize the need for these considerations to inform future adaptation policies.

Despite the valuable contributions of this study, several limitations must be acknowledged. Firstly, the analysis primarily focuses on selected regions that, while representative of Algeria's major agro-climatic zones, may not fully capture the country's national diversity. Secondly, the assessment of policy effectiveness is constrained by the lack of comprehensive long-term performance data. Finally, while some of the study's findings may be relevant to broader North African contexts, caution should be exercised when generalizing them beyond Algeria.

These limitations suggest important avenues for future research. Large-scale quantitative assessments and comparative case studies—especially those examining the differences between irrigated and rain-fed systems—are crucial to gaining a deeper understanding of the barriers to effective adaptation. Furthermore, the longitudinal monitoring of key interventions, such as water governance reforms and input subsidy programs, could provide valuable insights into the factors that drive both effective and equitable climate resilience. These efforts are essential to bridging the gap between policy and practice, and ensuring a sustainable future for Algerian agriculture in the face of escalating climate challenges.

4.1 Recommendations

To enhance Algeria's agricultural resilience in the face of climate change, the following actions are recommended:

Expand Water-Efficient Irrigation: Promote the widespread adoption of drip irrigation systems, supported by subsidies, targeted training programs, and green bond financing. This initiative should be integrated into Algeria's updated Nationally Determined Contributions (NDCs) to ensure long-term sustainability.

Promote Integrated Soil Management: Address the growing issue of soil degradation through strategic investments in research, farmer education, and organic input subsidies. Public-private partnerships should be leveraged to encourage the adoption of sustainable soil management practices across diverse agricultural systems.

Invest in Climate-Resilient Infrastructure: Prioritize the development of rainwater harvesting systems, the modernization of irrigation infrastructure, and the enhancement of weather forecasting capabilities. These efforts should be supported through international climate finance mechanisms, such as green bonds and the Green Climate Fund (GCF), to ensure their scalability and long-term impact.

Support Farmer-Led Innovation: Recognize and integrate local agricultural practices, such as the artisanal pivot and foggara systems, into national climate adaptation strategies. Providing both financial and technical support for these farmer-driven innovations will foster grassroots-level adaptation and enhance resilience.

Scale Successful Regional Initiatives: Build on the successful vegetable diversification and water management strategies implemented in regions like Mitidja and Sidi Bel Abbes. Expanding these practices nationwide will strengthen food security and enhance climate resilience across Algeria's agricultural sectors.

These targeted interventions are critical to fostering a sustainable and resilient agricultural sector in Algeria. By addressing the challenges of climate change, they will bolster food security and support the livelihoods of rural communities in the face of an increasingly unpredictable climate.

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APPENDIX

Appendix 1. Semi-structured interview Questions:

This appendix details the semi-structured interview questions used in this research. Separate interview protocols were developed for farmers and government officials to explore their respective experiences and perspectives on climate change adaptation and agricultural development.

Part 1: Government Official Interviews

(1) Perceptions of Climate Risks. Could you describe the specific impacts of climate change that you have observed on cereal and vegetable production in your region? Can you provide concrete examples?

What are the main challenges related to water availability and quality that your region is facing due to climate change? How are these challenges affecting agriculture?

In your opinion, what are the most significant socio-economic consequences of climate change for farmers and food security in Algeria?

(2) National Plans and Policies. To what extent is vegetable crop diversification considered in national climate change adaptation plans (such as the NADP, PRAR, Plan Felaha)?

What are the key strategies implemented by the government to promote sustainability and resilience in agriculture in the face of climate change?

Could you describe the specific measures taken by the government to improve water management and foster climate change adaptation in the agricultural sector?

(3) Adaptation Measures. What are the current government initiatives that support vegetable crop diversification in Algeria?

How does the government encourage the adoption of sustainable agricultural practices, such as agroecology and conservation agriculture?

Are there any research and development programs to develop drought- and disease-resistant crop varieties? If so, could you tell us more about them?

What measures are being taken to improve access to irrigation and water for farmers, especially in drought-prone regions?

(4) Future Strategies. What is the government's vision for a resilient and sustainable agricultural sector in the face of climate change in Algeria?

What role does vegetable crop diversification play in this long-term vision?

What are the main investments needed in research, technology, and infrastructure to strengthen the resilience of the agricultural sector?

What policies and incentives could be implemented to encourage farmers to adopt sustainable agricultural practices?

Part 2. Farmer Interviews

(1) Experiences of Climate Change Impacts. Could you describe the specific climate changes you have observed on your farm in recent years? How have these changes affected your agricultural production, particularly for cereals and vegetables?

Have you noticed any changes in the availability or quality of water for irrigation? If so, what are these changes and how are they impacting you?

What are the main challenges you face in maintaining your livelihood and ensuring the viability of your farm in the face of climate change?

(2) Current Adaptation Practices. What adaptation strategies have you implemented on your farm to cope with climate change?

Have you adopted vegetable crop diversification? If so, what are your motivations, the benefits you have observed, and the challenges you have encountered?

Do you use sustainable agricultural practices, such as agroecology or conservation agriculture? If so, which ones and what benefits do you derive from them?

Do you have access to new technologies or improved crop varieties to adapt to climate change? If so, which ones and how do you use them?

(3) Challenges and Barriers to Adaptation. What are the main obstacles you face in adapting to climate change and diversifying your crops?

What are the specific difficulties related to access to water and irrigation in your region?

Do you feel there is a lack of support or training to address the challenges of climate change?

Are there any policies or regulations that hinder your ability to adapt?

(4) Needs and Recommendations. What kind of support would be most helpful to you in building greater resilience on your farm and adopting sustainable agricultural practices?

What concrete recommendations would you make to the government or other institutions to improve climate change adaptation in the agricultural sector?

Appendix 2. Figure of rainfall deficit index in Algeria (created by the authors using ArcGIS 10.8 software, based on rainfall data [12]).