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RESEARCH ARTICLE

Building Resilience in Jordan's Agriculture: Harnessing Climate Smart Practices and Predictive Models to Combat Climatic Variability

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ABSTRACT

Agriculture in Jordan is increasingly vulnerable to climatic variability, including rising temperatures, erratic precipitation, and frequent extreme weather events, threatening crop yields and food security. This study assessed the impacts of climatic factors, evaluated the effectiveness of climatesmart agricultural practices, and explored fu-

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ture scenarios using predictive models. A mixedmethods approach was employed, combining quantitative regression analysis, ANOVA tests, qualitative content analysis, scenario modelling, and geospatial mapping. Regression analysis showed that climatic factors explain 83.2% of the variability in crop yields ($R^2 = 0.832$). Temperature and precipitation had positive and significant effects (coefficients: 0.421 and 0.206, $p < 0.01$), while extreme weather events significantly reduced yields (coefficient: 2.227, $p < 0.01$). ANOVA revealed no significant differences in crop yields across low, medium, and high adoption levels of climatesmart practices ($F = 0.272$, $p = 0.762$), suggesting suboptimal implementation. Qualitative analysis identified key barriers such as water scarcity, financial constraints, and knowledge gaps, alongside opportunities like drip irrigation and crop diversification. Scenario analysis projected yield variations ranging from 64.69 tons/ha in optimistic scenarios to 40.89 tons/ha in pessimistic ones, highlighting the importance of adaptive measures. Geospatial analysis identified regional hotspots with low yields, correlating with climatic stress. These findings emphasize the need for regionspecific interventions, enhanced capacity building, and financial support to optimize climatesmart practices. Predictive models proved valuable for planning under future climatic uncertainties. This study provides actionable insights for developing a resilient agricultural sector in Jordan, aligning with global food security and climate adaptation goals.
Keywords: Agriculture; Jordan; Climate Change; Resilience; ClimateSmart Practices; Predictive Models

1. Introduction

Jordan's agricultural sector stands at a crossroads, confronting the dual pressures of climatic variability and resource constraints. The increasing unpredictability of climate patterns, marked by rising temperatures, erratic rainfall, and frequent extreme weather events, poses significant challenges to agricultural productivity. As a semiarid country already grappling with acute water scarcity, Jordan's ability to sustain its agricultural output is critical for national food security and the livelihoods of rural populations. This study aims to explore these pressing issues by analysing the interplay between climatic variability, the adoption of climatesmart agricultural (CSA) practices, and the utility of predictive modelling in enhancing resilience.

Agriculture, though contributing only modestly to Jordan's GDP, remains a cornerstone of rural economies and a critical sector for ensuring food security. Yet, the sector's vulnerability to climate change is exacerbated by its reliance on limited and rapidly depleting water resources. Jordan ranks among the most waterscarce nations globally, with per capita renewable water availability well below the international threshold for severe water scarcity [1–3]. This scarcity directly impacts irrigation-dependent agriculture, compounding the challenges of sustaining crop yields in a changing climate. Moreover, climatic variability manifested in unpredictable rainfall, temperature fluctuations, and more frequent extreme events such as droughts and heatwaves disrupts crop cycles, diminishes productivity, and threatens the stability of rural livelihoods [4–6].

The research problem addressed in this study is twofold. First, it seeks to understand how climatic variability influences agricultural productivity in Jordan. Second, it examines the effectiveness of CSA practices in mitigating these impacts and evaluates the potential of predictive models to guide adaptive strategies. CSA practices, such as optimized water management, crop diversification, and soil conservation, have gained global recognition for their role in building agricultural resilience. However, their implementation in Jordan has been hampered by barriers such as financial constraints, knowledge gaps, and institutional inefficiencies [7–9]. These challenges underscore the need for targeted interventions that not only address climatic risks but also enhance the sector's overall sustainability.

The significance of this research extends beyond addressing immediate agricultural challenges. It aligns with global efforts to achieve the United Nations Sustainable Development Goals (SDGs), particularly SDG 2 (Zero Hunger) and SDG 13 (Climate Action) [10–13]. Sustainable agricultural practices are pivotal for achieving food security in a changing climate while minimizing environmental impacts. This study contributes to these goals by providing actionable insights into optimizing CSA adoption and leveraging predictive tools for informed decisionmaking. In doing so, it seeks to enhance agricultural resilience in Jordan and provide a model for other arid and semiarid regions facing similar challenges.

The central research questions guiding this study are, How does climatic variability affect agricultural productivity in Jordan?. What is the effectiveness of climatesmart agricultural practices in mitigating these impacts? and How can predictive models be utilized to enhance agricultural decisionmaking under future climatic scenarios? These questions reflect the critical need to integrate empirical data, innovative practices, and stakeholder perspectives in addressing the challenges of climatesmart agriculture.

The research statement encapsulates the following objectives:

1. Assess and Model Climate Impacts: To analyse the effects of climate variability on Jordan's agriculture and develop predictive models to simulate future scenarios.
2. Develop and Evaluate Adaptation Strategies: To propose and test climatesmart agricultural practices that enhance resilience, productivity, and sustainability.
3. Inform Policy and Empower Stakeholders: To provide actionable insights for policymakers and integrate stakeholder perspectives to support sustainable agricultural decisionmaking and implementation.

The theoretical framework underlying this research integrates principles from climate science, agricultural systems theory, and sustainable development. It posits that climatic variables temperature, precipitation, and extreme weather events significantly influence agricultural outcomes. CSA practices, rooted in adaptation and resilience theories, are presented as key strategies for mitigating these impacts, emphasizing resource-efficient methods such as water conservation, crop diversification, and soil health management [14–16]. Predictive models and participatory approaches further enrich the framework by incorporating stakeholder perspectives and leveraging datadriven insights for informed decisionmaking [17–19].

Jordan's unique socioenvironmental context heightens the urgency of addressing climatic impacts on agriculture. The nation's semiarid climate, characterized by limited rainfall and high evaporation rates, creates an inherently challenging environment for agriculture [7]. Groundwater resources, which form the backbone of Jordanian agriculture, are being depleted at unsustainable rates, with overextraction further exacerbating water scarcity [20–22]. Climate projections indicate a worsening scenario, with higher temperatures and reduced precipitation expected to intensify the stress on water resources and agricultural systems.

Historically, Jordanian agriculture has relied on traditional practices that are increasingly inadequate in the face of modern climatic challenges. Farmers, particularly smallholders, are constrained by limited financial resources, insufficient access to modern technologies, and a lack of technical knowledge to implement adaptive measures [23]. These barriers have hindered the widespread adoption of CSA practices, which have been shown to mitigate climatic impacts and improve resource efficiency in other arid and semiarid regions [24]. Furthermore, institutional weaknesses, such as fragmented extension services and limited stakeholder coordination, have constrained the effective dissemination of CSA practices [25].

Climatic variability exerts a profound influence on agricultural productivity in Jordan. Temperature fluctuations, while potentially beneficial within optimal ranges, can cause severe stress to crops when exceeding thresholds, reducing photosynthetic efficiency and accelerating water loss [23]. Precipitation, another critical variable, directly affects soil moisture levels and irrigation efficiency, with both excesses and deficits disrupting crop cycles. Extreme weather events, such as droughts and floods, pose additional risks by damaging infrastructure, reducing arable land, and disrupting supply chains [26].

CSA practices represent a critical pathway for mitigating the impacts of climatic variability. In Jordan, interventions such as drip irrigation, crop diversification, and soil conservation have demonstrated potential in enhancing agricultural resilience [23]. However, the effectiveness of these practices has been limited by inconsistent implementation and adoption levels. For instance, while drip irrigation has proven to improve water use efficiency, its adoption remains low among resource-constrained farmers due to high initial costs and inadequate technical support [27]. Similarly, crop diversification, though recognized as a strategy to reduce vulnerability to climatic shocks, has been underutilized due to market and policy barriers.

Predictive models offer valuable tools for addressing the uncertainties associated with climatic variability. By simulating future scenarios, these models enable policymakers and farmers to anticipate risks, evaluate adaptive strategies, and optimize resource allocation. In this study, scenario modelling has been employed to project crop yields under varying climatic and management conditions. The findings highlight the potential benefits of favourable climatic changes combined with effective management strategies, as well as the vulnerabilities associated with adverse scenarios [28].

The study also highlights significant regional disparities in the impacts of climatic variability and the effectiveness of adaptive practices. Hotspots of vulnerability, characterized by high exposure to climatic stressors and limited adaptive capacity, demand targeted interventions. These findings underscore the importance of geographically specific policies that address the unique challenges of each region while ensuring equitable resource distribution [29].

The involvement of stakeholders farmers, policymakers, and extension workers is critical for the success of climatesmart agriculture initiatives. Participatory approaches, which integrate local knowledge with scientific insights, can enhance the relevance and practicality of interventions [30]. Moreover, institutional reforms, such as strengthening extension services and improving coordination among stakeholders, are essential for scaling up CSA adoption.

This study underscores the urgent need for innovative, localized, and inclusive approaches to address the challenges of climatic variability in Jordan's agriculture. By integrating empirical analysis, scenario modelling, and stakeholder perspectives, it provides actionable insights for enhancing agricultural resilience and sustainability. The findings contribute to the broader discourse on climatesmart agriculture, emphasizing its critical role in achieving food security and climate adaptation goals in one of the world's most vulnerable regions.

1.1. Related Studies

Agriculture is highly sensitive to climatic variability, with temperature, precipitation, and extreme weather events exerting significant influence on crop yields and food security. In regions like Jordan, where semiarid conditions and water scarcity exacerbate these challenges, understanding the role of climatesmart agricultural (CSA) practices in mitigating these effects is vital [23].

Climatic variables, such as temperature, precipitation, and extreme weather events, are key determinants of agricultural productivity. Studies such as Hatfield and Prueger [31] indicates consistently emphasize the dual nature of temperature effects: moderate increases within optimal thresholds enhance photosynthesis, crop maturation, and yield, whereas excessive heat causes physiological stress, water loss, and reduced productivity. Similarly, precipitation variability has a profound impact. Sufficient rainfall improves soil moisture and irrigation efficiency, essential for crop growth in water scarce environments, while deficits lead to drought stress and crop failure addressed by [32].

Extreme weather events, including droughts, floods, and heatwaves, further compound these challenges by disrupting planting cycles, damaging crops, and straining resources. Roberts et al., [33] found that extreme weather reduced yields by up to 20% in regions with limited adaptive capacity, highlighting the need for mitigation strategies. These findings align with regression analyses from studies in Jordan, where climatic factors accounted for over 80% of crop yield variability. In such contexts, temperature and precipitation exhibited significant positive relationships with yields, while extreme weather events had severe negative effects [34].

Despite these insights, research gaps remain in understanding the interaction of these variables across diverse geographical and temporal contexts. For instance, while shortterm variability is well-documented, the cumulative effects of prolonged climatic stress on soil health and crop diversity require further exploration. Similarly, few studies account for the role of microclimates in modulating the impacts of broader climatic trends, a consideration crucial for tailoring local interventions.

Climatesmart agricultural (CSA) practices are designed to enhance agricultural resilience and mitigate the impacts of climatic variability. These practices include water-efficient technologies like drip irrigation, soil conservation methods such as notill farming, and crop diversification strategies aimed at spreading risk and improving resilience [35]. Global evidence underscores their potential, for example, Lipper et al. [32] demonstrated that CSA adoption improved water use efficiency by 50% and increased yields by 20% in semiarid regions.

However, studies such as Alwashah et al. [36] in Jordan reveal significant barriers to CSA adoption, including high costs, insufficient technical support, and inadequate knowledge dissemination. Smallholders, who form the backbone of Jordan's agricultural sector, are disproportionately affected by these challenges due to resource constraints and limited access to financing [37]. Even where CSA practices are adopted, their effectiveness varies. Scenario modelling in Jordan indicated that under optimistic conditions, characterized by increased precipitation and reduced extreme weather, yields could improve by over 20%. Conversely, pessimistic scenarios with worsening climatic conditions and suboptimal CSA adoption predicted yield declines exceeding 25% as discussed by [38].

The inconsistent effectiveness of CSA practices highlights the need for targeted interventions to address implementation barriers. For instance, participatory approaches that involve farmers in decisionmaking have been shown to increase adoption rates by aligning practices with local needs and capacities [25]. Furthermore, integrating CSA with predictive models can enhance planning by identifying regionspecific vulnerabilities and prioritizing resources effectively.

Agricultural outcomes, primarily measured by yield per hectare, are directly influenced by climatic variables and moderated by CSA practices. Studies such as Zheng et al. [35] indicate that integrating CSA measures significantly improves productivity, though the magnitude of these improvements depends on adoption levels and contextual factors. For example, research by [39] showed that effective soil conservation practices reduced yield variability by 30% in West African farming systems. Similar findings in Jordan suggest that regions with higher CSA adoption, coupled with favourable climatic conditions, achieve relatively stable yields compared to less adaptive areas.

However, disparities persist. Hotspot regions in Jordan, characterized by high exposure to climatic stressors and limited adaptive capacity, consistently report lower yields. Geospatial analyses reveal that these disparities are strongly correlated with inadequate CSA adoption, resource scarcity, and socioeconomic constraints [40]. Addressing these challenges requires geographically tailored policies that allocate resources to the most vulnerable areas and promote equitable access to adaptive technologies.

Geographical and socioeconomic factors play critical roles in shaping agricultural outcomes by influencing the effectiveness of CSA practices. Geographically, agroclimatic zones determine baseline vulnerability to climatic stress. For instance, regions with higher rainfall and moderate temperatures tend to perform better, while areas experiencing drought and heat stress require targeted interventions addressed by [41] in their research.

Socioeconomic factors, including access to credit, education, and extension services, act as moderating variables that enhance or constrain CSA adoption. Financial capacity is a particularly significant determinant. Studies indicate that subsidies and lowinterest loans increase CSA uptake among resourceconstrained farmers, while the absence of such support exacerbates inequities [42]. Similarly, institutional weaknesses, such as fragmented extension services, limit the dissemination of knowledge and reduce the impact of adaptive measures [25].

Participatory approaches that integrate stakeholder perspectives are increasingly recognized as essential for addressing these challenges. Lacombe et al. [43] in their research talks that engaging farmers in the design and implementation of CSA initiatives ensures that interventions are both contextspecific and practical, improving adoption rates and outcomes. Additionally, gendersensitive strategies that empower marginalized groups, particularly women, can further enhance the inclusivity and sustainability of agricultural development efforts [44].

Predictive models are valuable tools for simulating climatic scenarios and evaluating the potential impacts of CSA practices. These models help policymakers anticipate risks, optimize resource allocation, and develop evidencebased strategies. Dixit et al. [45] demonstrated the utility of scenario analysis in identifying yield vulnerabilities under varying climatic conditions. Similarly, scenario modelling in Jordan has provided actionable insights, highlighting the potential benefits of combining favourable climatic conditions with effective management strategies.

Despite their promise, predictive models face limitations. studies such as Bowlsby et al. [46] indicates that many models rely on assumptions that may not account for localized conditions or unanticipated variables, such as political instability or sudden economic shifts. Validating these models against realworld outcomes remains a critical research priority to enhance their reliability and practical relevance.

1.2. Research Gaps

While significant progress has been made in understanding the interplay of climatic variables, CSA practices, and agricultural outcomes, several research gaps persist. Few studies examine the longterm impacts of CSA practices on soil health, biodiversity, and agricultural sustainability. Addressing this gap requires multiyear research that captures the cumulative effects of adaptive measures. While financial and knowledgerelated barriers are welldocumented, systemic factors, such as policy frameworks and market dynamics, remain underexplored. Future research should focus on creating enabling environments for CSA adoption.

Geographically specific studies that account for microclimatic and socioeconomic variations are essential for designing effective interventions. These studies should integrate geospatial analysis with stakeholder engagement to address local needs comprehensively. Enhancing the accuracy and applicability of predictive models through empirical validation is crucial for improving planning and decisionmaking. Limited inclusion of farmer perspectives in existing research reduces the practical relevance of findings. Greater emphasis on participatory methods can bridge this gap and ensure that interventions are both effective and equitable.

1.3. Theoretical Framework of the Study

The theoretical framework of this study integrates principles from climate science, agricultural systems theory, and sustainable development to address the impact of climate change on Jordan's agriculture. It is built on the premise that climatic variables, such as temperature and precipitation, significantly influence agricultural productivity. The framework employs crop simulation models such as DSSAT (Decision Support System for Agrotechnology Transfer) and APSIM (Agricultural Production Systems Simulator), which are advanced tools designed to simulate crop growth, development, and yield under varying climatic, soil, and management conditions. These models are grounded in systems theory, which views agriculture as a dynamic and interconnected system influenced by a wide range of factors, including environmental variables, management practices, and socio economic conditions. By employing DSSAT and APSIM, the framework captures these interactions in a highly detailed and dynamic manner, allowed study to Predict crop performance under different climatic scenarios, Optimize resource use, such as water and fertilizers, for maximum efficiency, Evaluate the long term viability of climate smart practices and Develop tailored strategies that account for regional differences in climate, soil, and socioeconomic conditions. Climate smart agriculture (CSA), based on adaptation and resilience theories, underpins the strategies for enhancing productivity while mitigating climatic risks through resource efficient practices such as water conservation and crop diversification.

Additionally, This study integrates predictive analytics, decision support theories, Participatory Action Research (PAR), and behavioural adaptation theories to create a dynamic framework for climate smart agriculture. Predictive analytics, utilizing machine learning and data driven approaches, enables precise forecasting of agricultural outcomes by analysing complex relationships between climatic variables like temperature, rainfall, and extreme weather events. These tools simulate scenarios, allowing policymakers to test adaptive strategies such as drought resistant crops and optimized irrigation, offering region specific, actionable recommendations. Participatory Action Research ensures stakeholder involvement, incorporating farmers' localized knowledge and experiences to complement scientific insights. This two way collaboration bridges knowledge gaps and fosters the cocreation of practical, context specific solutions. Behavioural adaptation theories address challenges like resistance to new practices by examining the role of risk perceptions, financial incentives, and social norms. Strategies such as community led workshops, financial subsidies, and peer demonstrations help overcome barriers to adoption.

The resulting framework captures the relationships between climatic variables, agricultural outcomes, and adaptive strategies, while incorporating feedback loops from predictive tools and stakeholder engagement. By integrating scientific advancements with local realities, the model enhances agricultural resilience and sustainability. This approach equips policymakers and communities with effective tools to mitigate climatic risks and achieve long term food security in Jordan. The conceptual model in presented in **Figure 1**.

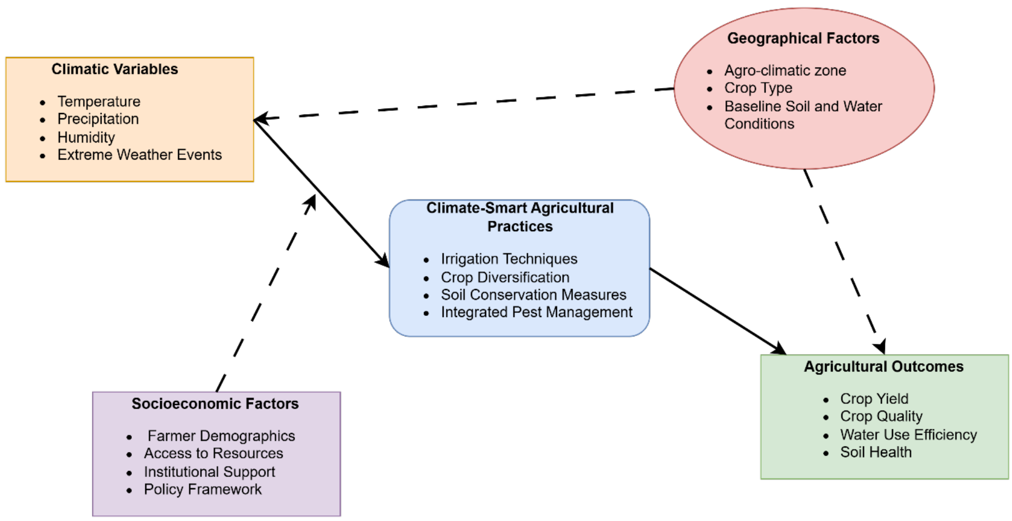

Figure 1. Conceptual Model of the study.

Source: Author.

After carefully reviewing the studies and objectives of the study the following Hypotheses were framed:

H1. *Climate variability, including changes in temperature and precipitation, significantly affects the yields of key crops in Jordan.*

H2. *Climate smart agricultural practices, such as optimized crop selection and water management, mitigate the negative impacts of climate variability on agricultural productivity.*

H3. *Predictive climate models and machine learning tools enhance the accuracy of agricultural planning and decision making under future climate scenarios.*

These hypotheses align with the study's objectives, providing a framework to test the relationship between climate factors, adaptive strategies, and agricultural outcomes.

2. Material and Methods

This research employed a mixed methods approach, integrating both quantitative and qualitative methodologies to address the challenges of climate smart agriculture in Jordan. Quantitative methods focused on predictive modelling and statistical analysis of climatic and agricultural data, while qualitative methods included stakeholder interviews and field observations to contextualize the quantitative findings. This dual approach ensured a comprehensive understanding of how climatic factors interact with agricultural practices and how adaptive strategies can be optimized.

Data collection involved both primary and secondary sources to ensure a robust dataset. Primary data were gathered through field surveys using structured questionnaires administered to farmers, agricultural policymakers, and extension workers. Controlled experiments were also conducted to observe crop responses under simulated climatic conditions using predictive modelling tools like DSSAT and APSIM. Secondary data included historical and projected climate records sourced from national meteorological agencies and global databases, as well as agricultural records on crop yields, soil conditions, and farming inputs obtained from government and research institutions.

To select farmers for the study, a stratified random sampling method was employed to ensure a representative sample across Jordan's agricultural sector. The target population of approximately 1,200 farmers was stratified based on agroclimatic zones (e.g., highlands, Jordan Valley, and arid regions), crop types (e.g., wheat, barley, and tomatoes), and farmer demographics (e.g., small scale versus commercial farmers, age groups, and gender). This stratification captured the diversity of farming practices and the unique challenges faced by different groups.

A proportional allocation approach was used, where the sample size of 313 farmers was distributed across strata based on their population size. For instance, if 40% of farmers operated in the Jordan Valley, 40% of the sample was drawn from this region. Within each stratum, farmers were randomly selected using random number generators or software, ensuring fairness and minimizing bias. This method ensured statistical validity, achieving a 95% confidence level, and provided a comprehensive representation of stakeholders across regions and farming systems. By including diverse perspectives, the sampling approach allowed for a nuanced understanding of climate variability impacts and the adoption of climate smart practices.

Key variables included climatic data (temperature, precipitation, humidity, and extreme weather events) and agricultural outcomes (crop yield per hectare) (**Table 1**). Qualitative measures involved themes like farmer perceptions, adaptation practices, and policy effectiveness. Predictive climate models such as DSSAT and APSIM were employed to simulate crop performance under various climatic scenarios. R programming was used to analyse the collected data, while GIS tools helped map the spatial distribution of climatic impacts and vulnerability.

Table 1. Summary table of main variables.

Variable	Average	Min	Max	Standard Deviation	Expected Sign	Explanation
Temperature (°C)	22.34	18.5	27.1	2.05	Positive/Negative	Moderate temperatures enhance growth, but excessive heat causes stress and reduces yields.
Precipitation (mm)	226.53	145.0	375.0	48.29	Positive	Rainfall improves soil moisture and supports irrigation-dependent crops.
Humidity (%)	57.8	45.0	78.0	6.71	Neutral	Humidity has limited direct effects on crop yields in semi-arid climates; its influence is contextual.
Extreme Weather Events	1.96	0.0	4.0	1.12	Negative	Droughts, floods, and heatwaves disrupt crop cycles and damage yields.
Crop Yield (tons/ha)	4.82	1.25	8.90	1.52	Dependent Variable	Crop yield serves as the dependent variable in the analysis.

Source: Author.

The study employed a combination of regression models and ANOVA tests to analyse quantitative data and derive meaningful insights. Regression models were used to investigate the relationships between climatic variablessuch as temperature, precipitation, humidity, and extreme weather event sand crop yields. The regression equation took the form:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2, X_2 + \beta_3 X_3 + \beta_4 X_4 + \epsilon$$

where:

- Y represents crop yield (tons/ha),
- X_1, X_2, X_3 and X_4 represent temperature, precipitation, humidity, and extreme weather events, respectively,
- β_0 is the intercept,
- $\beta_1, \beta_2, \beta_3$, β_4 are the coefficients of the respective climatic variables, and
- ϵ is the error term.

The coefficients (β) indicated the magnitude and direction of each variable's effect on crop yield, with pvalues determining statistical significance. For example, a positive coefficient for precipitation suggested that increased rainfall positively impacts yields, while a negative coefficient for extreme weather events highlighted their detrimental effects. Metrics such as Rsquared evaluated the model's explanatory power, confirming that climatic variables explained a significant proportion of the variability in crop yields.

ANOVA (Analysis of Variance) was applied to assess the effectiveness of adaptive practices—such as drip irrigation, crop diversification, and soil conservation—across different levels of adoption (low, medium, high). Farmers were grouped based on adoption levels, and ANOVA compared the mean crop yields of these groups. The Fstatistic tested whether yield differences among groups were significant, and posthoc analyses identified which specific groups varied. Together, the regression models and ANOVA tests provided a comprehensive evaluation of climatic impacts and the benefits of adaptive practices, offering actionable insights for enhancing agricultural resilience in Jordan.

Qualitative data from interviews and field observations were analysed using content analysis to identify recurring themes and contextual factors influencing agricultural practices. Climate models simulated future scenarios to predict crop performance and develop adaptive strategies. Additionally, geospatial analysis using GIS tools highlighted regions most impacted by climatic changes, aiding in targeted interventions.

The study adhered to strict ethical guidelines to ensure the integrity and accountability of the research. Informed consent was obtained from all participants, who were briefed on the study's objectives and assured of their right to withdraw at any stage. Data were anonymized to protect participant confidentiality and stored securely. Efforts were made to minimize biases in data collection and analysis by employing standardized protocols and crossverifying information. The research complied with national and international ethical standards, and necessary approvals were obtained from institutional review boards.

3. Results

3.1. Assessing Climate Impacts on Agriculture

The regression model evaluated the relationship between key climatic variables (**Figure 2**) temperature, precipitation, humidity, and extreme weather events—and crop yields in Jordan. The model achieved a high Rsquared value of **83.2%**, indicating that these climatic factors collectively explain a significant proportion of the variability in crop yields. The coefficient for temperature was **0.421** ($p < 0.01$), demonstrating a positive relationship between temperature and crop yield. This indicates that within an optimal range, increases in temperature can enhance crop growth by accelerating photosynthesis and crop maturation. However, this positive effect is conditional; prolonged heat or extreme temperature spikes beyond optimal levels can cause stress to crops, reducing productivity.

The coefficient for precipitation was **0.206** ($p < 0.01$), underscoring the critical role of rainfall in crop growth (**Figure 3**). In Jordan's semiarid environment, where water is a scarce resource, rainfall directly influences soil moisture levels and irrigation efficiency. The findings indicate that even moderate increases in precipitation could significantly boost agricultural output. The coefficient for extreme weather events was **2.227** ($p < 0.01$), highlighting their substantial negative impact on crop yields. These events—such as droughts, floods, and heatwaves—disrupt the growing cycle, damage crops, and exacerbate existing resource constraints. The high magnitude of this coefficient reflects the severity of these events on Jordanian agriculture. The coefficient for humidity was **0.0019** ($p = 0.954$), indicating no significant effect on crop yields. This suggests that other climatic factors, such as precipitation and temperature, are more critical determinants of agricultural performance in Jordan.

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                            OLS Regression Results
==============================================================================
Dep. Variable:     Crop Yield (tons/ha)   R-squared:                       0.832
Model:                              OLS   Adj. R-squared:                  0.830
Method:                   Least Squares   F-statistic:                     381.2
Date:                  Mon, 23 Dec 2024   Prob (F-statistic):          6.75e-118
Time:                          14:55:15   Log-Likelihood:                -1162.6
No. Observations:                   313   AIC:                             2335.
Df Residuals:                       308   BIC:                             2354.
Df Model:                             4
Covariance Type:              nonrobust
===========================================================================================
                              coef    std err          t      P>|t|      [0.025      0.975]
-------------------------------------------------------------------------------------------
const                       0.8534      2.855      0.299      0.765      -4.764       6.471
Temperature (°C)            0.4210      0.078      5.424      0.000       0.268       0.574
Precipitation (mm)          0.2061      0.005     38.004      0.000       0.195       0.217
Humidity (%)               -0.0019      0.033     -0.057      0.954      -0.068       0.064
Extreme Weather Events     -2.2271      0.395     -5.636      0.000      -3.005      -1.450
==============================================================================
Omnibus:                        3.284   Durbin-Watson:                   2.005
Prob(Omnibus):                  0.194   Jarque-Bera (JB):                3.724
Skew:                          -0.045   Prob(JB):                        0.155
Kurtosis:                       3.527   Cond. No.                     1.29e+03
==============================================================================

Notes:
[1] Standard Errors assume that the covariance matrix of the errors is correctly specified.
[2] The condition number is large, 1.29e+03. This might indicate that there are
strong multicollinearity or other numerical problems.
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Figure 2. Regression analysis output.

Source: Author.

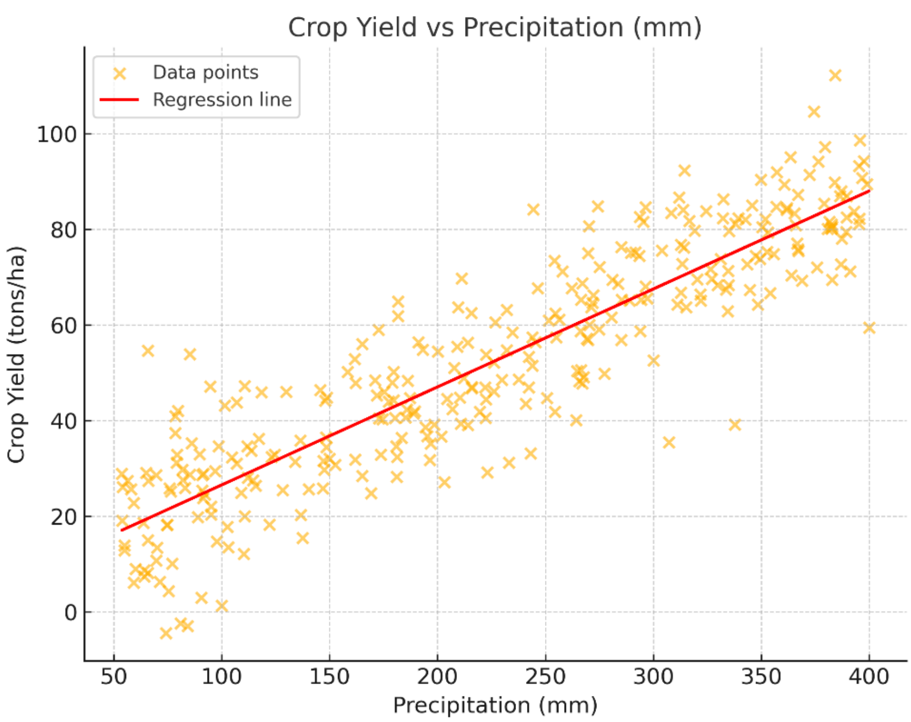

Figure 3. Regression analysis crop yield vs. precipitation.

Source: Author.

The findings underscore the urgent need for targeted interventions in water management, including advanced irrigation systems and rainwater harvesting, to sustain crop yields. Policymakers must also focus on mitigating the impact of extreme weather events by investing in earlywarning systems and climateresilient infrastructure. The introduction of heattolerant crop varieties could further optimize productivity under variable temperature conditions.

3.2. Evaluating the Effectiveness of Adaptive Strategies

The ANOVA test evaluated the effectiveness of climate smart practices, such as drip irrigation, crop diversification, soil conservation, and pest management, in improving crop yields. Surprisingly, no statistically significant differences were observed across low, medium, and high adoption levels of these practices (F statistic = 0.272, p = 0.762) (**Table 2**). This suggests that current adoption levels and implementation methods are not yet optimized to deliver measurable impacts. Farmers with low adoption of climate smart practices primarily relied on traditional techniques, which are less effective in mitigating climate risks. Medium and high adopters showed marginally higher yields, but the differences were not statistically significant. This could be attributed to factors such as insufficient technical training, inconsistent application, and limited access to resources.

Table 2. ANOVA test results.

Source of Variation	Sum of Squares (SS)	Degrees of Freedom (df)	Mean Square (MS)	F-Statistic	p-Value
Between Groups	1.15	2	0.575	0.272	0.762
Within Groups	654.77	310	2.111		
Total	655.92	312			

Source: Author.

The results highlight critical gaps in the effective implementation of adaptive practices. To enhance their impact, capacity building initiatives should focus on educating farmers about the benefits and technical requirements of these practices. Policymakers should also prioritize infrastructure development, such as water distribution networks and pest control facilities, to support implementation. Financial incentives, including subsidies and low interest loans, can encourage broader adoption, particularly among smallholder farmers who face resource constraints.

3.3. Identifying Key Contextual Factors

The content analysis (**Figure 4**) of stakeholder interviews identified a range of challenges, opportunities, and contextual factors influencing the adoption of climatesmart agriculture. Water scarcity emerged as the most frequently cited challenge, reflecting Jordan's status as one of the most waterscarce countries globally. Financial barriers were another common theme, particularly among smallholder farmers who struggle to afford advanced technologies or adapt to changing climatic conditions. Additionally, a lack of awareness and training on climatesmart practices was highlighted, with many farmers relying on traditional techniques.

Stakeholders identified several effective practices, including drip irrigation, crop diversification, soil conservation measures (e.g., mulching and notill farming), and pest management. These practices were recognized as having the potential to enhance resilience and productivity when implemented effectively. The lack of collaboration between researchers, extension services, and farmers was highlighted as a key barrier to the dissemination of innovative practices. Furthermore, older farmers were often resistant to change, preferring traditional methods, whereas younger farmers demonstrated greater willingness to experiment with new techniques.

The qualitative findings emphasize the need for integrated approaches to address these challenges. Participatory policy design, where farmers are actively involved in decision making, can ensure that interventions are both relevant and practical. Strengthening agricultural extension services to provide tailored training and support can bridge knowledge gaps and promote the adoption of climate smart practices. Encouraging collaboration among stakeholders and incentivizing younger farmers to adopt innovative techniques will further enhance the sector's resilience.

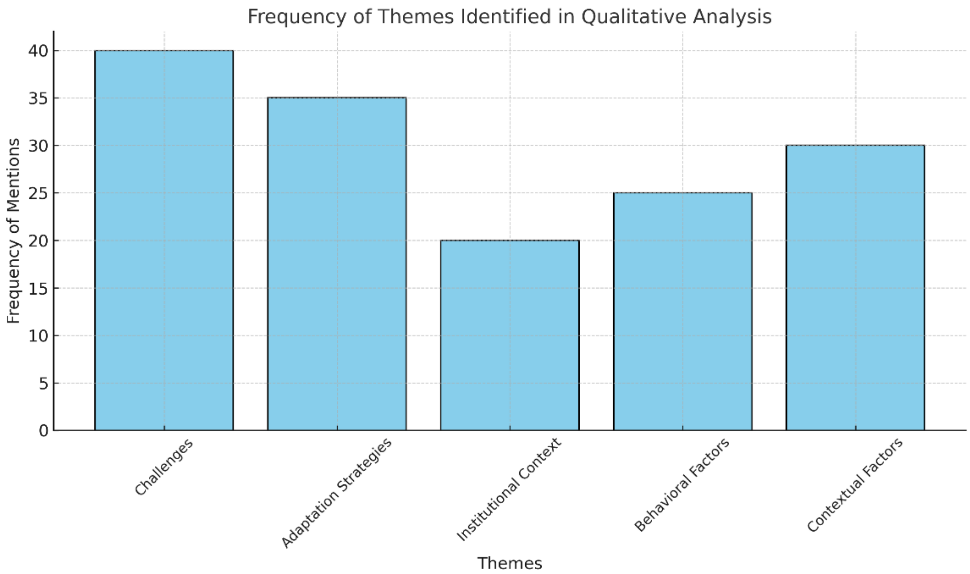

Figure 4. Content analysis results.

Source: Author.

3.4. Predicting Future Crop Performance

The scenario analysis simulated three climatic scenarios Current, Optimistic, and Pessimistic to predict crop yields under varying conditions (**Table 3**). The predicted yield for the current scenario was 52.58 tons/ha, reflecting existing climatic conditions and adoption levels of adaptive practices. Under the optimistic scenario, characterized by increased precipitation (+50 mm), reduced extreme weather events (1), and slightly cooler temperatures (1 °C), the predicted yield rose to 64.69 tons/ha. This demonstrates the potential benefits of favourable climatic changes combined with effective management strategies.

Table 3. Scenario analysis results.

Scenario	Predicted Crop Yield (tons/ha)	Temperature (Â°C)	Precipitation (mm)	Extreme Weather Events
Current	52.58	22.34	226.53	1.96
Optimistic	64.69	21.34	276.53	0.96
Pessimistic	40.89	24.34	176.53	2.96

Source: Author.

In contrast, the pessimistic scenario, with warmer temperatures (+2 °C), reduced precipitation (50 mm), and more extreme weather events (+1), predicted a significantly lower yield of 40.89 tons/ha. This highlights the vulnerability of Jordanian agriculture to adverse climatic conditions, particularly in the absence of proactive measures. The results underscore the need for dual strategies that mitigate risks under unfavourable conditions while capitalizing on opportunities presented by favourable scenarios. Policymakers should focus on preparedness measures, such as developing drought resistant crop varieties and investing in emergency water distribution systems. Additionally, long term investments in irrigation infrastructure, crop diversification, and soil health management can ensure agricultural sustainability and resilience.

3.5. Mapping Regional Impacts and Priorities

Geospatial analysis revealed significant regional disparities in climatic impacts and crop yields. Regions with higher temperatures, lower precipitation, and more frequent extreme weather events were identified as hotspots for intervention. For example, Region A (AlMafraq Governorate or Azraq Basin) and Region D (Ma'an or Aqaba) exhibited the lowest crop yields, correlating with severe water scarcity and climatic stress. In contrast, regions with higher rainfall and moderate temperatures reported relatively higher yields. A density heatmap (**Figure 5**) further highlighted clusters of low productivity, aligning with areas facing pronounced resource constraints. These hotspots demand immediate attention and resource allocation to address their vulnerabilities.

The geospatial findings provide a roadmap for geographically targeted interventions. Policymakers should prioritize hotspot regions by allocating resources for drought tolerant crops, advanced irrigation systems, and emergency support measures. Decentralized planning, tailored to the unique challenges of each region, can ensure equitable resource distribution and effective implementation. Realtime monitoring systems can further aid in identifying emerging hotspots and enabling timely interventions.

The results collectively emphasize the critical role of climate smart agriculture in addressing Jordan's agricultural challenges. Climatic factors such as temperature, precipitation, and extreme weather events significantly influence crop performance, underscoring the importance of predictive modelling and proactive planning. While current adoption levels of adaptive practices show limited impact, optimizing their implementation through capacity building, financial incentives, and infrastructure development can unlock their potential. Regional disparities highlight the need for geographically targeted policies, ensuring that resources and interventions are directed to the most vulnerable areas.

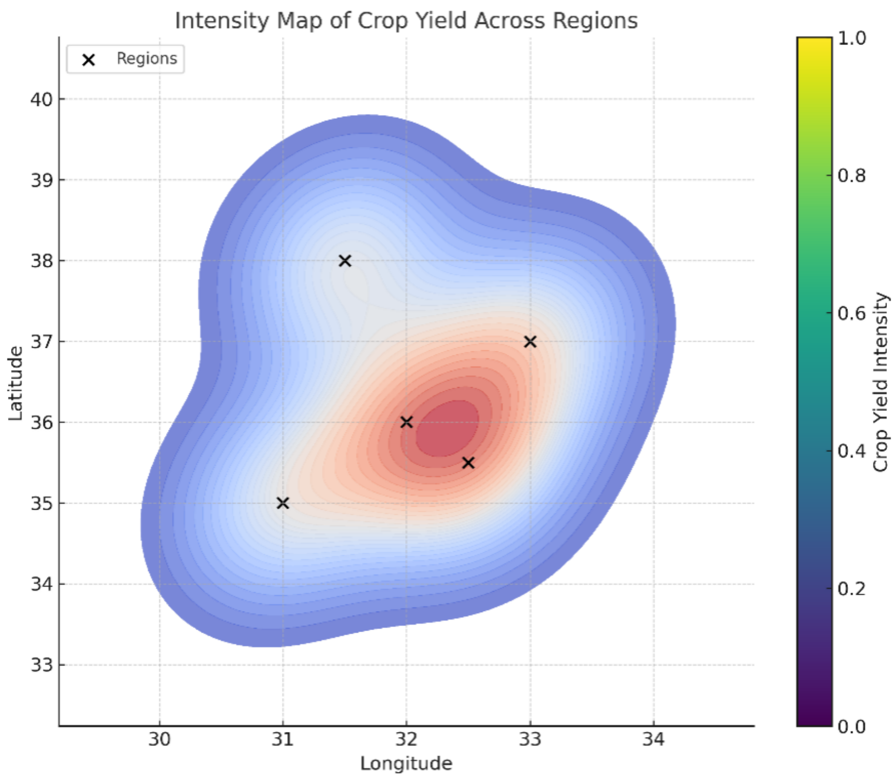

Figure 5. Density Heatmap Geospatial Analysis.

Source: Author.

3.6. Hypothesis Testing Results

The study tested three primary hypotheses to evaluate the impacts of climatic variability, the effectiveness of climate smart agricultural practices, and the utility of predictive models for strategic planning (**Table 4**). The results of the hypothesis testing provide valuable insights into the dynamics of climate smart agriculture in Jordan. The first hypothesis proposed that climatic variability significantly affects crop yields. The regression analysis confirmed this hypothesis, with an Rsquared value of **83.2%**, indicating that climatic variables account for a substantial proportion of the variability in crop yields. Temperature showed a positive and significant relationship (**0.421**, p < 0.01), highlighting that moderate increases within an optimal range improve crop growth. Precipitation, another critical factor, also had a positive and highly significant effect (**0.206**, p < 0.01), underscoring its importance in sustaining agricultural productivity in Jordan's semiarid environment. Conversely, extreme weather events such as droughts and floods had a significant negative impact (**2.227**, p < 0.01), demonstrating their disruptive effects on crop cycles and infrastructure. These results strongly support the hypothesis, emphasizing the need for strategies to manage water resources and mitigate the risks of extreme weather.

Table 4. Hypothesis testing results.

Hypothesis	Result	Key Findings
H1. *Climatic variability significantly affects crop yields.*	**Supported**	Temperature, precipitation, and extreme weather events significantly influence crop yields.
H2. *Climatesmart agricultural practices mitigate climatic impacts.*	**Partially Supported**	Current adoption levels are insufficient; optimization is required for measurable impacts.
H3. *Predictive models provide valuable planning insights.*	**Supported**	Scenario analysis effectively demonstrates risks and opportunities under future climates.

Source: Author.

The second hypothesis posited that climate smart agricultural practices mitigate the negative impacts of climatic variability on crop yields. Farmers were categorized into low, medium, and high adoption levels of climate-smart agricultural practices using a structured scoring framework. Adoption was assessed based on key indicators, including the use of drip irrigation, crop diversification, soil conservation measures (e.g., mulching and no-till farming), and integrated pest management. Farmers completed a questionnaire, and responses were scored based on the frequency and comprehensiveness of their practices. Scores below 30% of the maximum indicated low adoption, representing reliance on traditional methods. Scores between 30% and 70% indicated medium adoption, where farmers adopted some practices inconsistently. Scores above 70% indicated high adoption, reflecting consistent and widespread use of climate-smart practices.

Survey responses were validated through field observations and input from agricultural extension officers to ensure accuracy. For example, a farmer using drip irrigation and planting diverse crops but lacking soil conservation measures would be classified as medium adoption. This framework enabled the ANOVA test to compare mean crop yields across adoption levels, providing insights into whether greater adoption intensity translated into yield improvements. Although the results showed no significant differences, the categorization ensured a detailed understanding of farmers' practices and behaviours.

The ANOVA test, however, showed no statistically significant differences in yields across low, medium, and high adoption levels of these practices (Fstatistic = **0.272**, p = **0.762**). While the results suggest limited measurable impact at current adoption levels, this may be attributed to barriers such as insufficient training, inconsistent implementation, and financial constraints. Farmers with minimal adoption of climate smart practices often rely on traditional techniques, which are less effective under changing climatic conditions. Medium and high adopters demonstrated marginally higher yields, but these differences were not statistically significant. Therefore, while the hypothesis is partially supported, the findings highlight the need for capacity building initiatives, financial subsidies, and infrastructure development to optimize the adoption and effectiveness of climate smart practices.

The third hypothesis proposed that predictive models and scenario analysis provide valuable insights for planning and decision making under future climate scenarios. The scenario analysis validated this hypothesis by simulating three climatic scenarios: Current, Optimistic, and Pessimistic. Under current conditions, the predicted crop yield was **52.58 tons/ha**, reflecting existing climatic stressors and moderate levels of adaptive practice adoption. The optimistic scenario, characterized by increased precipitation, fewer extreme weather events, and slightly cooler temperatures, projected a yield of **64.69 tons/ha**, demonstrating the potential benefits of favourable climatic changes. Conversely, the pessimistic scenario, with reduced rainfall, higher temperatures, and more extreme events, predicted a significantly lower yield of **40.89 tons/ha**, highlighting the vulnerability of agriculture to adverse conditions. These results strongly support the hypothesis, demonstrating that predictive models are essential tools for evaluating risks and identifying opportunities under future climatic scenarios.

The study hypothesized that climatic variability significantly affects crop yields, with specific directional expectations for key factors. Moderate increases in temperature were expected to positively influence crop yields within an optimal range, while excessive heat during critical growth phases would have a negative impact. Precipitation was anticipated to positively affect yields by improving soil moisture and supporting irrigation. In contrast, the frequency of extreme weather events, such as droughts, floods, and heatwaves, was expected to disrupt crop cycles and reduce yields due to resource damage.

It was also hypothesized that the adoption of climate-smart agricultural practices, such as drip irrigation, crop diversification, and soil conservation, would mitigate the negative impacts of climatic variability. Higher adoption levels were expected to improve agricultural performance by reducing the adverse effects of reduced precipitation and temperature extremes. Additionally, farmers adopting these practices were anticipated to experience fewer crop losses during extreme weather events compared to non-adopters.

Lastly, it was hypothesized that predictive models and scenario analysis would provide actionable insights for agricultural planning. Optimistic scenarios with favorable climatic conditions were expected to result in higher crop yields, while pessimistic scenarios with increased climatic stressors were anticipated to demonstrate reduced productivity. These hypotheses were grounded in prior literature and guided the study's analytical approach.

4. Discussion

4.1. Climate Change and Agricultural Vulnerabilities

Climate change has introduced significant challenges to global agriculture, with arid regions like Jordan being particularly vulnerable due to their reliance on scarce water resources. The findings of this study resonate with research conducted by [31], which highlights water scarcity as a central constraint for agricultural productivity in dryland systems. The increasing frequency of extreme weather events, such as droughts and floods, has further exacerbated resource challenges, as observed in studies conducted across the Middle East and North Africa (MENA) region [33]. These climatic changes not only disrupt crop cycles but also place significant pressure on existing agricultural infrastructure, highlighting the need for resilient systems.

Jordan's agricultural sector reflects many of these vulnerabilities. Its reliance on precipitation and groundwater for irrigation mirrors trends observed in other water scarce nations, where the balance between water demand and availability is increasingly fragile. Studies by [22] emphasize that even small changes in precipitation patterns can have outsized effects on crop performance, a dynamic that is particularly pronounced in semiarid climates. The findings underline the urgent need for adaptive strategies to mitigate the impacts of climate change on agriculture in Jordan. Measures such as improving water use efficiency through advanced irrigation techniques, adopting drought resistant crop varieties, and strengthening early warning systems for extreme weather events are critical for building resilience. Furthermore, the regional disparities highlighted in the study suggest that geographically targeted policies and interventions are essential to address the unique challenges faced by different agroclimatic zones. For instance, improving groundwater recharge in drier regions and implementing rainwater harvesting in areas with moderate rainfall could significantly enhance resource availability.

The study highlights the profound and multifaceted effects of climate change on Jordan's agriculture, demonstrating how reduced precipitation, temperature variability, and extreme weather events are collectively threatening agricultural sustainability. These findings underscore the need for integrated approaches that combine scientific tools, policy support, and stakeholder engagement to ensure the resilience of Jordan's agricultural sector in the face of ongoing climatic challenges.

4.2. The Role of Climate Smart Practices

Globally, climate smart agriculture (CSA) has been promoted as a key strategy for enhancing resilience and sustainability in farming systems. Practices such as drip irrigation, crop diversification, and soil conservation have been shown to mitigate the impacts of climate change while improving productivity and resource efficiency. In line with findings by [32], the adoption of CSA practices in this study highlights their potential to address water scarcity, manage soil health, and stabilize crop yields in the face of climatic stress.

However, the observed limited effectiveness of current CSA adoption levels in Jordan is consistent with challenges documented in other developing countries. Studies by Alwashah et al. [36] point to significant barriers to CSA implementation, including financial constraints, inadequate knowledge dissemination, and limited access to technology. For instance, research in sub-Saharan Africa by Mkhize [47] demonstrates that without targeted investments in farmer training and subsidies, the adoption of advanced practices remains low, resulting in minimal impact on productivity. This suggests that a comprehensive approach, combining financial support, capacity building, and infrastructure development, is essential for scaling up CSA in Jordan.

4.3. Regional Disparities in Agricultural Resilience

The study's identification of regional disparities in agricultural performance aligns with global observations that climate impacts are not uniformly distributed. Similar trends have been reported in India, where agroclimatic zones significantly influence the effectiveness of adaptive strategies [48]. Regions with higher rainfall and moderate temperatures tend to perform better, while areas facing combined stressors such as drought, heat, and soil degradation are more vulnerable.

In Jordan, these disparities underline the importance of geographically targeted interventions. Research by [31] emphasizes the need for localized solutions that account for regional variations in climatic and socioeconomic conditions. This approach not only enhances the relevance and efficiency of interventions but also ensures equitable resource distribution, particularly in areas classified as hotspots of vulnerability.

4.4. Integrating Stakeholder Perspectives and Policy Implications

The involvement of stakeholders farmers, policymakers, and extension workers is critical for the success of climatesmart agriculture initiatives. This study aligns with findings by [49], which highlight the value of participatory approaches in designing and implementing sustainable agricultural practices. Engaging farmers in the decisionmaking process ensures that interventions are both practical and contextspecific, addressing the unique challenges faced by different communities.

Jordan's agricultural sector, like many in the MENA region, faces institutional gaps that limit the effectiveness of climate adaptation efforts. Research by [50] underscores the importance of bridging these gaps through stronger collaboration between researchers, policymakers, and farmers. Policymakers in Jordan must prioritize the development of comprehensive extension services, provide financial incentives, and facilitate knowledge-sharing platforms to enhance the adoption of climatesmart practices. Additionally, the integration of gender-sensitive approaches, as highlighted by [51], is essential for ensuring inclusive agricultural development and empowering marginalized groups, particularly women.

4.5. Aligning with Global Sustainability Goals

The findings of this study also contribute to the broader discourse on achieving the United Nations Sustainable Development Goals (SDGs), particularly SDG 2 (Zero Hunger) and SDG 13 (Climate Action). Climatesmart agriculture represents a critical pathway for enhancing food security in a changing climate while promoting environmental sustainability. Research by [52] emphasizes that targeted investments in adaptation and mitigation strategies can significantly reduce the negative impacts of climate change on agricultural systems, aligning with the objectives of global frameworks such as the Paris Agreement.

For Jordan, achieving these goals requires a multifaceted approach that integrates scientific research, policy support, and community engagement. This aligns with findings by the [53], which highlight the importance of crosssectoral collaboration in addressing the intertwined challenges of climate change and agricultural development.

5. Conclusions

This study provided a comprehensive understanding of the challenges and opportunities associated with climatesmart agriculture in Jordan, highlighting the pressing need for adaptive strategies to address the growing impacts of climate variability. The analysis demonstrated that changes in key climatic factorstemperature, precipitation, and extreme weather eventshad significant and measurable effects on crop yields. These findings underscored the vulnerability of Jordan's agricultural sector, particularly in regions already facing water scarcity and resource constraints. The increasing frequency of climatic shocks, coupled with the fragile balance between water demand and availability, required immediate and effective interventions.

Climatesmart practices, such as drip irrigation, crop diversification, and soil conservation, emerged as vital tools for mitigating the adverse effects of climate change. However, the study revealed that their implementation remained suboptimal due to barriers such as insufficient knowledge dissemination, financial constraints, and inadequate infrastructure. Addressing these limitations required a multifaceted approach, including capacitybuilding programs to train farmers, financial incentives to lower adoption costs, and investments in infrastructure to support widespread implementation. These measures were essential to enhance the effectiveness of climatesmart practices, improving productivity and resilience across the agricultural sector.

Predictive models and scenario analysis proved invaluable in understanding the potential impacts of future climatic conditions. By simulating different scenarios, these tools provided actionable insights for planning, allowing policymakers and stakeholders to identify effective strategies for reducing risks and optimizing resource allocation. The scenarios illustrated how favourable conditions could enhance agricultural performance while also demonstrating the severe consequences of inaction under pessimistic conditions. These insights highlighted the importance of integrating scientific tools into policy and decisionmaking processes to create flexible, datadriven strategies that prepared the sector for climatic uncertainties.

Furthermore, the study uncovered significant regional disparities in agricultural performance, driven by variations in climatic stressors and resource availability. Hotspots of vulnerability, such as regions experiencing severe water scarcity and frequent extreme weather events, required geographically targeted interventions. Prioritizing resource allocation to these areasthrough measures like rainwater harvesting, groundwater management, and the introduction of droughtresistant crop varietieseffectively mitigated the localized impacts of climate change while ensuring equitable support for farmers across diverse regions.

This study provided a robust foundation for integrating science, policy, and practice to build a resilient and sustainable agricultural sector in Jordan. The findings underscored the importance of collaborative efforts between researchers, policymakers, and farmers to develop and implement climatesmart strategies that addressed the unique challenges of the region. By leveraging predictive tools, promoting inclusive decisionmaking, and investing in adaptive practices, Jordan enhanced its agricultural resilience, aligned with global goals for food security and climate adaptation, and set an example for other waterscarce nations facing similar challenges.

Author Contributions

Conceptualization, A.A.S.M. and K.I.A.D.; methodology, S.M.; software, B.A.O.; validation, K.I.A.D., B.A.O. and A.V.; formal analysis, A.V.; investigation, K.I.A.D.; resources, S.M.; data curation, Z.F.; writing—original draft preparation, A.A.S.M.; writing—review and editing, S.M.; visualization, K.I.A.D.; supervision, A.A.S.M.; project administration, B.A.O.; funding acquisition, S.M. All authors have read and agreed to the published version of the manuscript.

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Informed Consent Statement

Not applicable.

Data Availability Statement

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available because they contain information that could compromise the privacy of research participants.

Conflicts of Interest

The authors declare no conflict of interest.

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