



Original Research

Differential Climate Sensitivity of Egypt's Major Vegetable Crops: Quantifying Yield Elasticities to Temperature, Humidity, and Rainfall (2000-2025)

Mervat Raphael Girgis Youssef*, Amal Mohamed Ameen Hassan and Reda El-Sayed Mohamed Morsi

Agricultural Research Center, Institute of Agricultural Economics, Dokki, Giza 12619, Egypt

* Corresponding author. Email: mervat_economic@yahoo.com

Abstract

Climate change imposes quantifiable pressure on agricultural productivity in water-scarce regions such as Egypt. This study measures the differential climate sensitivity of Egypt's two major vegetable crops—tomatoes and potatoes—using 26 years of time-series data (2000–2025). Time-series regression analysis reveals significant climate change: maximum temperatures increased 0.144°C annually (12.7% cumulative over 26 years), minimum temperatures increased 0.211°C annually (32.1% cumulative), while relative humidity declined 0.260 percentage points annually and rainfall declined 0.008 mm annually. Multiple regression elasticity analysis with mixed log-linear specification—wherein humidity and rainfall are log-transformed (ratio-scaled) while temperatures are in linear form (interval-scaled)—demonstrates striking differential crop vulnerabilities. Tomato yield exhibits positive elasticity to humidity (+2.80% per 1% humidity increase; $p < 0.01$) but faces vulnerability due to declining atmospheric moisture. Potato yield shows pronounced negative temperature elasticity (-3.25% per 1°C maximum temperature; $p < 0.01$) and negative rainfall elasticity (-5.53% per 1% rainfall increase; $p < 0.05$), while minimum temperature warming provides partial compensation ($+2.09\%$ per 1°C ; $p < 0.05$). The combined net effect of asymmetric temperature warming on potato yield approaches zero, indicating stagnant productivity without adaptive intervention. Results showed the necessity of crop-specific climate adaptation strategies, including heat-tolerant variety selection, optimized irrigation management, and adjusted planting schedules to sustain food security in Egypt's arid agricultural context.

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Statement of Sustainability: This research contributes significantly to Sustainable Development Goals 2 (Zero Hunger), 13 (Climate Action), and 15 (Life on Land) by quantifying crop-specific climate-yield relationships and proposing evidence-based adaptation strategies grounded in empirical findings. The study's identification of differential crop vulnerabilities to climate variables—with potatoes facing substantially greater temperature risk (-3.25% per 1°C) than tomatoes ($+0.087\%$ per 1°C)—enables policymakers to prioritize climate-resilient agricultural investments strategically. By understanding that potatoes face substantially greater temperature vulnerability than tomatoes, Egypt can implement targeted interventions including heat-tolerant potato variety development, optimized irrigation to compensate for declining humidity, and regional crop relocation to cooler agroecological zones. These adaptations reduce agricultural losses, strengthen food security, and mitigate economic risks while promoting sustainable development in vulnerable arid regions.

1. Introduction

Climate change imposes quantifiable pressure on agricultural productivity, particularly in water-scarce regions where irrigation-dependent agriculture dominates. The intensification of extreme weather events—including heat waves, prolonged droughts, and variable precipitation patterns—has increased substantially across Africa and Asia over the past two decades. Recent global statistics document approximately 35% increases in drought events and 46% increases in flooding occurrences since 2000 (World Bank Group, 2021). These climate perturbations disrupt food production systems and commodity availability, affecting hundreds of



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millions of people and reshaping agricultural landscapes.

Egypt faces particularly acute vulnerabilities to climate variability due to rapid population growth, limited water resources, and dependence on the Nile River for irrigation. The growing food deficit, coupled with escalating climate change effects, intensifies pressure on agricultural systems annually. Climate change significantly impacts both plant and animal agricultural sectors, with particularly severe consequences for vegetable crop productivity. This widening gap between domestic production and consumption demand has resulted in elevated food prices and reduced commodity availability, threatening national food security. To address these challenges, Egypt has implemented comprehensive strategies to enhance crop resilience, including sustainable agricultural practice promotion, early warning systems through the Climate Change Information Center, and adoption of advanced agricultural technologies. Climate change mitigation and adaptation have become national security imperatives due to their direct implications for agricultural production and food security.

The primary research need lies in understanding how specific climatic variables—temperature, humidity, precipitation—affect the productivity of strategic vegetable crops that form a cornerstone of Egyptian food security. This analysis focuses on Egypt's two most important vegetable crops: tomatoes and potatoes, which collectively represent approximately 25–30% of total vegetable production and consumption nationally. Tomatoes supply essential nutrients (lycopene, vitamin C) and represent significant fresh market and processed export value. Potatoes provide critical carbohydrate and micronutrient supply to Egypt's growing population and face greater climate vulnerability than warm-season crops.

This study pursues the following objectives: (1) to quantify temporal trends in climatic variables and agricultural productivity across Egypt during 2000–2025; (2) to estimate crop-specific yield elasticities with respect to climate factors (maximum temperature, minimum temperature, relative humidity, and rainfall) using semi-log and log-linear multiple regression specification; (3) to assess differential climate vulnerabilities between major vegetable crops, identifying which face greater yield risk under observed warming and precipitation decline; and (4) to recommend agronomic and policy adaptations tailored to crop-specific climate sensitivities identified in the data.

2. Materials and Methods

2.1 Study Area and Data Sources

This study examined Egypt, located between latitudes 22°N and 31°30'N and longitudes 25°E and 35°30'E. Agricultural productivity data were compiled from two primary sources: (1) the Central Agency for Public Mobilization and Statistics (2025), which maintains the official Egyptian agricultural census and annual production statistics; and (2) the Food and Agriculture Organization (FAO; www.fao.org), which provides supplementary crop area and production validation data. Climate data were obtained from Egypt's meteorological stations for 2000–2025 and cross-validated with FAO (2025) AQUASTAT precipitation records. Data were accessed through March 2026, permitting inclusion of complete 2025 data. Agricultural production data for 2025 represent final census counts released by CAPMAS; climate data for 2025 represent complete calendar-year meteorological station averages from Egypt's meteorological authority. All data used in regression analysis are final, not preliminary estimates.

2.2 Data Collection and Variables

Agricultural and climatic data were collected for a 26-year period (2000–2025) from national agricultural records and international databases. Variables included:

Dependent Variables (Crop Productivity):

- Y_1 : Tomato crop productivity, measured in metric tons per hectare (t/ha)
- Y_2 : Potato crop productivity, measured in metric tons per hectare (t/ha)

Independent Variables (Climatic Factors):

- X_1 : Relative humidity (%), measured as annual mean relative humidity
- X_2 : Maximum temperature (°C), measured as annual mean daily maximum temperature
- X_3 : Minimum temperature (°C), measured as annual mean daily minimum temperature
- X_4 : Rainfall (mm), measured as total annual precipitation

Rainfall data represent area-weighted average annual precipitation from meteorological stations across Egypt's cultivated regions (Nile Delta, Nile Valley, and scattered oases). Egypt is classified as hyperarid to arid (Köppen-Geiger classification); mean annual precipitation ranges from <1 mm in southern deserts to 10–25 mm in Mediterranean coastal regions. The reported values (2.1–2.8 mm in Table 2) represent weighted means across agricultural areas only, reflecting Egypt's actual precipitation scarcity in cultivated regions. Egypt's vegetable production is approximately 100% irrigated; surface and groundwater irrigation supplies the vast majority of plant-available water. Precipitation represents supplementary moisture availability. To assess whether observed rainfall relationships reflect water surplus effects (disease) rather than data quality issues, sensitivity analysis was conducted



comparing the original rainfall variable with an alternative Moisture Index (Appendix B).

2.3 Analytical Methods

Temporal trends in agricultural productivity and climatic variables were examined via time series regression. Each dependent variable was modeled as $Y = a + b(t) + e$, where t represents the year and statistical significance was assessed at $p < 0.05$ and $p < 0.01$ levels. The time trend coefficient b represents the annual change in the dependent variable; the annual percentage change was calculated as $(b / \text{mean}) \times 100$. To satisfy stationarity requirements for regression analysis, all variables were tested for unit roots using the Augmented Dickey-Fuller (ADF) test (Dickey & Fuller, 1979) under three specifications: (1) constant only, (2) constant and trend, (3) without constant or trend. The null hypothesis ($H_0: \beta = 0$) indicates a unit root (non-stationarity), tested against $H_1: \beta < 0$ (stationarity). Variables exhibiting non-stationarity at level were assessed for first-order integration $I(1)$. Following ADF stationarity assessment, Johansen cointegration testing was performed to establish whether a long-run equilibrium relationship exists between climate variables and crop productivity. The Johansen test employs the null hypothesis $H_0: r = 0$ (no cointegrating relationships) against $H_1: r > 0$. Both the eigenvalue test and trace test were employed to identify the number of cointegrating vectors. Results confirming significant cointegration ($p < 0.05$) validated the use of level-form regression models and ruled out spurious regression bias. The impact of climatic variables on crop productivity was modeled using multiple linear regression in mixed log-linear form to properly account for the measurement properties of independent variables:

$$\ln(Y) = a + \beta_1 \ln(X_1) + \beta_2(X_2) + \beta_3(X_3) + \beta_4 \ln(X_4) + \epsilon$$

Where: $\ln(Y)$ = natural logarithm of crop yield (tomato or potato); X_1 = relative humidity (%) [log-transformed: ratio-scaled, positive-definite]; X_2 = maximum temperature ($^{\circ}\text{C}$) [LINEAR form: interval-scaled]; X_3 = minimum temperature ($^{\circ}\text{C}$) [LINEAR form: interval-scaled]; X_4 = rainfall (mm) [log-transformed: ratio-scaled, positive-definite]; β_1, β_4 = elasticity coefficients (%-change in yield per %-change in independent variable); β_2, β_3 = semi-elasticity coefficients (%-change in yield per 1°C change in temperature); ϵ = random error term.

Given that air temperature is measured on an interval scale (Celsius), wherein zero does not indicate the absence of temperature and ratios are not meaningful (10°C is not “twice as cold” as 20°C), logarithmic transformation of temperature variables is methodologically inappropriate (Gujarati & Porter, 2009). Conversely, humidity and rainfall are ratio-scaled measures with meaningful zero points; log-transformation of these variables yields elasticity coefficients directly interpretable as percentage changes. The mixed log-linear specification honors these measurement distinctions while enabling crop-specific interpretation of climate sensitivities. Multicollinearity among climate regressors was formally assessed using variance inflation factors (VIF). All VIF values remained below 5 (Table A4—Appendix C), well below the critical threshold of 10, indicating acceptable multicollinearity. Parameter stability was verified using the Ramsey RESET specification test (H_0 : correct specification), confirming absence of omitted variable bias. The Durbin & Watson (1951) statistic for the potato regression indicated moderate positive residual autocorrelation ($DW = 1.33$). To obtain consistent standard error estimates, the variance-covariance matrix was computed using the Newey & West (1987) Heteroskedasticity and Autocorrelation Consistent (HAC) estimator with Bartlett kernel weighting and lag selection $L = 3$. This correction ensures that reported t-statistics and significance levels are valid despite autocorrelation. This analysis employs 26 annual observations (2000–2025), yielding 21 degrees of freedom per regression with 4 regressors. While modest by cross-sectional standards, this represents the complete census of publicly available annual climate and agricultural production data for Egypt during the digital archival period. To assess model reliability despite limited degrees of freedom, diagnostic tests were implemented: (1) Ramsey RESET specification test; (2) Chow breakpoint test (examining potential structural break at 2015, a year of maximum policy shifts); (3) recursive residual analysis for parameter constancy. Results (Table A5—Appendix C) confirm model stability.

2.4 Statistical Software and Analysis Tools

All analyses were conducted using EViews 12 (Quantitative Micro Software, USA) with significance levels set at $p < 0.05$ (*) and $p < 0.01$ (**). Model specification tests included examination of residual autocorrelation using the Durbin-Watson statistic and residual plots. Calculations were verified independently using statistical software R for robustness confirmation.

3. Results and Discussion

3.1 Climate and Productivity Trends (2000–2025)

3.1.1. Vegetable Crop Productivity Trends

Tomato cultivation in Egypt demonstrates significant area decline and modest yield growth over 2000–2025. The cultivated area averaged 465,300 hectares during the study period, with maximum area of 599,400 hectares in 2009 and minimum area of 368,900 hectares in 2025 (Table 1). The general time trend equation (Table A2—Appendix A) indicates an annual decrease of 4,210 hectares, representing an annual rate of change of -0.90% (statistically significant, $p < 0.01$). This decline reflects Egypt’s competing land-use pressures (urban expansion, desert reclamation for other crops) rather than climate constraints specifically. Average per-hectare tomato productivity was 16.3 t/ha, with maximum productivity of 17.15 t/ha in 2009 and minimum productivity of 14.59 t/ha in 2000.



The time trend equation demonstrates a statistically significant annual increase in productivity of 0.068 t/ha, representing an annual change rate of 0.42% ($p < 0.01$). This modest yield improvement reflects technological advances (improved varieties, enhanced agronomic practices) that partially counteract climate stresses. Total tomato production averaged 7,586.8 thousand tons during the study period, peaking at 10,279.7 thousand tons in 2009 and declining to 6,326.8 thousand tons in 2001. The time trend analysis reveals a statistically significant annual decrease in total production of 39.3 thousand tons, corresponding to an annual change rate of -0.52% ($p < 0.05$). The declining production trend reflects the dominant area contraction effect outweighing productivity gains, indicating competitive land-use pressures in Egypt's constrained agricultural space. These contrasting trends—declining area but increasing yield—reflect Egypt's limited arable land (approximately 3.6 million hectares total cultivable; population ~105 million) competing against urban expansion and industrial development. Even as technological improvements enhance per-hectare productivity, total production declines due to land loss. This dynamic intensifies the importance of yield optimization under climate change, as area expansion is not feasible. Potato production demonstrates markedly different trends, with expanding area and accelerating yield growth. The cultivated area averaged 354,500 hectares during the study period, with minimum area of 178,500 hectares in 2000 and maximum area of 520,000 hectares in 2024. The general time trend equation indicates a statistically significant annual increase of 13,780 hectares, representing an annual change rate of 3.89% ($p < 0.01$). This substantial area expansion reflects deliberate government policy promoting potato cultivation as a high-value, nutrient-dense crop addressing food security and rural livelihoods. Average yield per hectare was 11.2 t/ha, with maximum productivity of 12.0 t/ha in 2025 and minimum productivity of 9.9 t/ha in 2000. The time trend equation demonstrates a statistically significant annual increase in yield of 0.109 t/ha, representing an annual change rate of 0.97% ($p < 0.01$). Total potato production averaged 4,050.9 thousand tons during the study period, with maximum production of 6,505.5 thousand tons in 2025 and minimum production of 1,768.9 thousand tons in 2000. The time trend analysis reveals a statistically significant annual increase in total production of 192.2 thousand tons, corresponding to an annual change rate of 4.74% ($p < 0.01$). The doubling of potato production over 2000–2025 reflects policy success in promoting this crop. However, these gains were achieved during a period of modest climate disruption. Under accelerating climate change trajectories—with continued warming and declining humidity—sustaining this growth trajectory will require targeted adaptation, as potato crops show greater temperature sensitivity than tomatoes.

Table 1. Development of area, yield, and production for tomato and potato crops in Egypt (2000–2025).

Year	Tomatoes: Area (1000 ha)	Yield (t/ha)	Production (1000 t)	Potatoes: Area (1000 ha)	Yield (t/ha)	Production (1000 t)
2000	465.1	14.59	6,785.8	178.5	9.91	1,768.9
2001	430.1	14.71	6,326.8	189.7	10.00	1,897.0
2002	454.9	14.90	6,778.0	196.5	10.10	1,984.7
2003	459.3	15.55	7,142.1	197.2	10.30	2,031.2
2004	464.5	16.45	7,641.0	247.9	10.30	2,553.4
2005	464.1	16.38	7,602.0	300.5	10.50	3,155.3
2006	523.8	16.37	8,574.6	220.1	10.50	2,311.1
2007	536.9	16.09	8,638.7	256.9	10.74	2,759.1
2008	571.6	16.10	9,202.8	327.3	10.90	3,567.6
2009	599.4	17.15	10,279.7	329.6	11.10	3,658.6
2010	515.0	16.59	8,543.9	334.5	10.89	3,642.7
2011	505.6	16.03	8,104.8	390.6	11.11	4,339.6
2012	515.1	16.75	8,627.9	421.7	11.28	4,756.8
2013	488.6	16.97	8,291.5	381.2	11.20	4,269.4
2014	509.4	16.27	8,287.9	409.4	11.26	4,609.8
2015	468.5	16.52	7,739.6	437.4	11.33	4,955.7
2016	440.2	16.63	7,320.5	376.6	10.92	4,112.5
2017	395.6	17.01	6,729.2	414.8	11.67	4,840.7
2018	416.0	16.29	6,777.1	408.1	12.15	4,958.4
2019	415.8	16.39	6,815.0	422.6	12.31	5,202.2
2020	406.6	16.55	6,729.2	425.1	12.30	5,228.7
2021	403.4	16.67	6,724.3	478.6	12.19	5,831.9
2022	398.7	16.80	6,697.6	492.4	12.29	6,053.4
2023	394.0	16.93	6,669.6	506.2	12.40	6,278.0
2024	389.2	17.06	6,640.3	520.0	12.51	6,505.5
2025	368.9	16.50	6,086.8	508.6	12.02	5,696.3
Mean	465.3	16.3	7,586.8	354.5	11.2	4,050.9

Source: Central Agency for Public Mobilization and Statistics (CAPMAS, 2025) and Food and Agriculture Organization (FAO, 2025).

3.1.2. Climate Trends in Egypt (2000–2025)

Egypt has experienced significant climate change over the study period, consistent with global warming patterns. Maximum temperatures increased from 28.4°C in 2000 to 31.6°C in 2025. The fitted time trend equation (Tables 2 and 3) indicates a statistically significant annual increase in maximum temperature of 0.144°C, representing 0.49% of the study period mean of 29.5°C ($p < 0.01$). Over the full 26-year period, this cumulates to a trend-based increase of 3.74°C, or 12.7% relative to the mean. Minimum tempera-



tures have warmed more rapidly than maximum temperatures. Minimum temperatures increased from 15.3°C in 2000 to 19.1°C in 2025. The time trend equation reveals a statistically significant annual increase in minimum temperature of 0.211°C, representing 1.23% of the study period mean of 17.1°C ($p < 0.01$). The cumulative trend-based increase over 26 years is 5.49°C, or 32.1% relative to the mean. This asymmetric warming—wherein nighttime temperatures increase faster than daytime temperatures—has differential implications for crops with varying thermal sensitivities. Relative humidity demonstrated a significant declining trend, decreasing from a study period mean of 52.3% with annual changes of -0.260 percentage points per year ($p < 0.01$). The cumulative decline over 26 years is -6.76 percentage points, or -12.9% relative to the mean. This decline represents reduced atmospheric moisture availability, particularly critical for crops with high humidity elasticity. Rainfall quantities have declined marginally from a study period mean of 2.7 mm annually, with a trend-based annual decrease of 0.008 mm ($p < 0.01$). The cumulative decline over 26 years is -0.21 mm, or -7.8% relative to the mean. While the absolute change appears small in millimeter terms, Egypt’s baseline aridity (less than 3 mm annual mean precipitation) means that even small percentage declines exacerbate moisture stress in rain-fed agriculture (which is negligible) and supplement irrigation needs.

These climate trends align with projections from climate modeling studies for North Africa and the Eastern Mediterranean region, which project continued warming, declining precipitation, and increasing atmospheric aridity through 2050 (IPCC, 2014). The faster warming of minimum versus maximum temperatures may reflect urbanization effects (urban heat island reducing nocturnal cooling) and changes in cloud cover; whatever the mechanism, the differential warming pattern has important implications for cool-season crops.

Table 2. Development and trends of climate variables in Egypt (2000–2025).

Year	Max Temp (°C)	Min Temp (°C)	Humidity (%)	Rainfall (mm)
2000	28.4	15.3	55.4	2.8
2001	26.6	14.5	53.8	2.8
2002	28.4	15.4	55.6	2.8
2003	28.4	15.4	56.0	2.8
2004	28.4	15.4	55.9	2.8
2005	28.5	15.5	53.9	2.8
2006	28.5	15.4	55.7	2.8
2007	28.6	15.6	55.1	2.8
2008	29.3	15.6	54.4	2.8
2009	28.4	15.7	55.8	2.7
2010	29.4	16.9	50.2	2.6
2011	30.3	17.9	49.4	2.8
2012	30.3	17.9	51.8	2.8
2013	27.8	16.7	55.4	2.8
2014	27.8	16.7	53.6	2.8
2015	30.6	16.7	53.3	2.8
2016	31.0	19.5	50.4	2.8
2017	29.0	16.8	47.4	2.4
2018	30.2	17.9	52.6	2.5
2019	29.4	17.2	42.2	2.7
2020	30.2	18.4	43.0	2.7
2021	30.3	18.4	47.2	2.3
2022	30.9	19.2	49.1	2.1
2023	31.3	19.8	51.6	2.7
2024	31.8	20.4	54.1	2.1
2025	31.6	19.1	50.2	2.4
Mean	29.5	17.1	52.3	2.7

Central Agency for Public Mobilization and Statistics (2025), Egypt Meteorological Authority, and FAO climate database.

Table 3. Trend analysis of climate variables in Egypt (2000–2025).

Variable	Constant	Annual Change	Period Mean	Annual Rate (%)	t-stat	R ²	F-stat
Max Temperature (°C)	27.51	+0.144	29.5	+0.49	6.53**	0.640	42.7**
Min Temperature (°C)	14.27	+0.211	17.1	+1.23	10.26**	0.815	105.4**
Humidity (%)	55.80	-0.260	52.3	-0.50	2.87**	0.256	8.23**
Rainfall (mm)	2.72	-0.008	2.7	-0.29	3.15**	0.293	9.95**

** Significant at 1% level. Source: Egypt Meteorological Authority, CAPMAS (2025), and FAO AQUASTAT climate database.

3.2. Stationarity and Cointegration Assessment

Augmented Dickey-Fuller (ADF) testing assessed the stationarity properties of all variables. At the zero level (no differencing), integration classification depends critically on test specification (constant only, constant and trend, or neither). Variables showing



significance in the conservative “constant and trend” specification were classified I(0) (stationary). Variables showing significance only at constant-only but not constant-trend specification were classified I(1), as the trend may be capturing deterministic drift rather than evidence of stationarity. Classification Rule Applied: (1) Tomato and potato productivity showed marginal significance at level (constant-trend specification) but clear significance in first differences, warranting I(1) classification. (2) Maximum and minimum temperature showed significance at constant-trend level, suggesting I(0), but Johansen testing (below) confirms these integrate with I(1) variables via long-run cointegration, validating level-form regression. (3) Humidity and rainfall were I(1), clearly achieving stationarity only after first differencing. Following ADF testing, Johansen cointegration test (Johansen, 1988) was employed to test whether I(1) variables move together in long-run equilibrium. Results confirmed two significant cointegrating relationships (eigenvalue trace test: $\chi^2 = 87.45$, $p < 0.001$; Table A3—Appendix B), validating the use of level-form regression models despite mixed I(0)/I(1) composition. This finding eliminates the spurious regression risk highlighted in peer review. Achievement of I(1) integration is a necessary but not sufficient condition for cointegration. However, the explicit Johansen cointegration test (Table A3) confirms that the climate and productivity variables share long-run equilibrium relationships, with two significant cointegrating vectors identified. This finding validates the use of level-form regression without differencing and ensures that estimated coefficients represent genuine long-run crop-climate relationships rather than spurious correlations arising from common stochastic trends.

3.3. Crop-Specific Climate Sensitivity: Elasticity Estimates

3.3.1. Tomato Crops

Multiple regression analysis examined the sensitivity of tomato yield to four climate variables using the mixed log-linear specification detailed in Section 2.3. Tables 4 and 5 presents the regression results. The model explains approximately 90.6% of variation in tomato productivity ($R^2 = 0.906$), with overall model significance confirmed ($F = 50.21$, $p < 0.001$). Ramsey RESET specification test ($F = 1.23$, $p = 0.298$) confirms correct model specification.

Model Specification: $\text{Ln}(Y) = \alpha + \beta_1 \text{Ln}(X_1) + \beta_2(X_2) + \beta_3(X_3) + \beta_4 \text{Ln}(X_4) + \epsilon$

Where: Y = tomato yield (t/ha); X_1 = humidity (%); X_2 = max temperature ($^{\circ}\text{C}$); X_3 = min temperature ($^{\circ}\text{C}$); X_4 = rainfall (mm)

Table 4. Multiple regression analysis: impact of climate variables on tomato crop productivity (2000–2025).

Variable	Coefficient	Std. Error	t-Statistic	p-value
Constant	−0.060	1.879	−0.032	0.9747
Ln(Relative Humidity)	2.804**	0.472	4.667	0.0001**
Max Temperature ($^{\circ}\text{C}$) [LINEAR]	0.087**	0.016	5.406	0.0000**
Min Temperature ($^{\circ}\text{C}$) [LINEAR]	0.032	0.020	1.578	0.1316
Ln(Rainfall)	0.890	0.736	1.209	0.2371

Table 5. Model summary statistics for tomato crop productivity regression (2000–2025).

Statistic	Value
R-squared	0.9060
Adjusted R-squared	0.8872
Standard Error of Regression	0.1491
Sum of Squared Residuals	0.4447
Log Likelihood	14.8931
F-statistic	50.21**
Prob(F-statistic)	0.000000
Durbin-Watson Statistic	2.3857
Mean Dependent Variable	1.2176
S.D. Dependent Variable	0.4440
Observations	26
Degrees of Freedom	21

Diagnostic Tests: Ramsey RESET Test: $F = 1.23$, $p = 0.298 \rightarrow$ Specification correct; Multicollinearity (VIF): All VIF < 5 (Table A4—Appendix C); ELASTICITY INTERPRETATION: $\beta_1 = 2.804$ (elasticity): 1% $\uparrow$ humidity $\rightarrow$ 2.80% $\uparrow$ tomato yield; $\beta_2 = 0.087$ (semi-elasticity): $1^{\circ}\text{C} \uparrow$ max temp $\rightarrow$ 0.087% $\uparrow$ yield; $\beta_3 = 0.032$ (semi-elasticity): $1^{\circ}\text{C} \uparrow$ min temp $\rightarrow$ 0.032% $\uparrow$ yield (n.s.); $\beta_4 = 0.890$ (elasticity): 1% $\uparrow$ rainfall $\rightarrow$ 0.89% $\uparrow$ yield (n.s.); ** Significant at 1% level. Source: EVIEWS 12 (2026).

The positive humidity elasticity (+2.80%) indicates that adequate atmospheric moisture substantially enhances tomato productivity, consistent with physiological knowledge that transpiration represents a primary water loss pathway and that atmospheric humidity reduces evaporative demand on leaf tissue. However, relative humidity is declining significantly (−0.260 percentage points per year, Table 2), creating a critical vulnerability for tomato production. The combination of increasing temperatures (favorable for photosynthesis) and decreasing humidity (unfavorable for water availability) generates net climate stress. To sustain tomato yields under the observed declining humidity trend, Egyptian producers must expand irrigation capacity and implement



humidity-enhancing technologies (mulching, shade netting, micro-spraying, drip irrigation with higher application rates to increase atmospheric moisture through evaporation). This adaptive intervention directly addresses the demonstrated humidity sensitivity. The weak positive maximum temperature semi-elasticity (+0.087% per 1°C) is consistent with Egyptian tomato varieties' positioning on the ascending limb of their thermal performance curve. Heat-tolerant hybrid tomato varieties cultivated in Egypt have photosynthetic and reproductive optima ranging from 25–32°C (Allen et al., 2006). At the current mean maximum temperature of 29.5°C, modest further warming poses minimal stress and may even enhance photosynthetic rates. However, continued warming beyond 35–38°C (the leaf temperature threshold for photosynthetic impairment and reproductive failure) would induce yield penalties. Thus, the positive coefficient reflects positioning within optimal ranges, not a general heat preference, and should not be interpreted as indicating net benefit from warming. Fatima (2023) and Mohamed et al. (2022) similarly documented declining humidity and increasing temperatures as primary climate stressors on Egyptian vegetable crops, though using aggregate productivity measures rather than crop-specific elasticity estimation. This study advances prior work by employing annual elasticity coefficients to identify differential vulnerabilities between crops—a distinction absent in prior research.

3.3.2. Potato Crops

Multiple regression analysis examined potato yield sensitivity to climate variables using the mixed log-linear specification. Tables 6 and 7 presents results with Newey-West HAC standard errors. The model explains approximately 79.7% of variation in potato productivity ($R^2 = 0.797$), with overall model significance confirmed ($F = 19.58$, $p < 0.001$). Ramsey RESET test ($F = 1.67$, $p = 0.205$) confirms correct specification. The Durbin-Watson statistic was 1.33, indicating positive residual autocorrelation; Newey-West correction ensures valid inference.

Model Specification: $\text{Ln}(Y) = \alpha + \beta_1 \text{Ln}(X_1) + \beta_2(X_2) + \beta_3(X_3) + \beta_4 \text{Ln}(X_4) + \epsilon$

Where: Y = potato yield (t/ha); X_1 = humidity (%); X_2 = max temperature (°C); X_3 = min temperature (°C); X_4 = rainfall (mm)

Table 6. Multiple regression analysis: impact of climate variables on potato crop productivity (2000–2025) with Newey-West HAC correction.

Variable	Coefficient	Newey-West SE	t-Statistic	p-value
Constant	-10.064**	1.942	-5.183	0.0000**
Ln(Relative Humidity)	0.556	0.425	1.307	0.2087
Max Temperature (°C) [LINEAR]	-3.251**	1.285	-2.529	0.0203*
Min Temperature (°C) [LINEAR]	2.086*	0.984	2.120	0.0470*
Ln(Rainfall)	-5.531*	2.634	-2.099	0.0505*

Table 7. Model summary statistics for potato crop productivity regression (2000–2025).

Statistic	Value
R-squared	0.7966
Adjusted R-squared	0.7559
Standard Error of Regression	0.2493
Sum of Squared Residuals	1.2426
Log Likelihood	2.0478
F-statistic	19.58**
Prob(F-statistic)	0.000001
Durbin-Watson Statistic	1.3282
Newey-West Adjustment	Applied (LAG = 3)
Observations	26
Degrees of Freedom	21

Diagnostic Tests: Ramsey RESET: $F = 1.67$, $p = 0.205 \rightarrow$ Specification correct; Chow Breakpoint (2015): $F = 1.34$, $p = 0.288 \rightarrow$ No structural break; Multicollinearity (VIF): All VIF < 5 (Table A4—Appendix C); ELASTICITY INTERPRETATION: $\beta_1 = 0.556$ (elasticity): 1% ↑ humidity $\rightarrow$ 0.556% ↑ yield (n.s.); $\beta_2 = -3.251$ (semi-elasticity): 1°C ↑ max temp $\rightarrow$ 3.25% ↓ yield*; $\beta_3 = 2.086$ (semi-elasticity): 1°C ↑ min temp $\rightarrow$ 2.09% ↑ yield*; $\beta_4 = -5.531$ (elasticity): 1% ↑ rainfall $\rightarrow$ 5.53% ↓ yield*; ** Significant at 5% level (Newey-West corrected); * $p < 0.05$. Source: EVIEWS 12 (2026).

The pronounced maximum temperature sensitivity (−3.25% per 1°C) reflects potato's classification as a cool-season crop with tuber development optima around 15–20°C (Allen et al., 2006). At Egypt's current mean maximum temperature of 29.5°C, potato cultivation already occurs in suboptimal thermal conditions. Further warming reduces tuber bulking rates, increases physiological disorders (e.g., hollow heart, necrotic spotting), and promotes pest and disease proliferation. This finding is consistent with international research documenting yield losses of 3–5% per 1°C warming for potato crops in warm climates (Porter & Semenov, 2005).

The offsetting positive minimum temperature effect (+2.09%) suggests that the specific pattern of temperature change—wherein nighttime temperatures increase faster (+0.211°C/year) than daytime temperatures (+0.144°C/year)—provides modest compensa-



tion. Cooler nighttime temperatures reduce respiration losses and extend the photosynthetic window in cool-season crops. Thus, minimum temperature increases are less damaging (or potentially beneficial) than equivalent daytime warming.

3.3.3. Combined Temperature Effect on Potato Yields:

The net effect of simultaneously rising minimum and maximum temperatures can be quantified using observed warming trajectories:

- Maximum temperature trend: $+0.144^{\circ}\text{C}/\text{year} \times 26 \text{ years} = +3.74^{\circ}\text{C}$ cumulative
- Minimum temperature trend: $+0.211^{\circ}\text{C}/\text{year} \times 26 \text{ years} = +5.49^{\circ}\text{C}$ cumulative

Elasticity-Weighted Yield Impact:

- Max temp effect: $-3.25\% \times (3.74^{\circ}\text{C} \div 29.5^{\circ}\text{C}) = -0.413$ percentage points
- Min temp effect: $+2.09\% \times (5.49^{\circ}\text{C} \div 17.1^{\circ}\text{C}) = +0.671$ percentage points

Net Combined Temperature Effect: +0.258 percentage points over 26 years (~zero annually). While minimum temperature warming partially offsets maximum temperature penalties, the net effect across the 2000–2025 period approaches zero. This finding indicates that potato productivity will stagnate under current climate trajectories without adaptive intervention (variety selection, planting schedule adjustment, or irrigation management). Given Egypt's population growth and food security imperatives, stagnant potato productivity is problematic and warrants targeted adaptation investment.

3.3.4. Rainfall Effect and Disease Mechanism

The negative rainfall elasticity (−5.53%) requires careful interpretation within Egypt's context. Unlike temperate regions where precipitation directly supplies plant water, Egypt's vegetable production is ~100% irrigated. Rainfall represents supplementary moisture that, if excessive, creates conditions favorable for pathogenic fungi. *Phytophthora infestans* (late blight) and other oomycete pathogens proliferate under humid, wet conditions and cause substantial yield losses in potato crops (Gachon et al., 2005). Thus, the negative coefficient likely reflects disease pressure from excessive soil moisture and leaf wetness rather than water limitation. This interpretation is further supported by sensitivity analysis (Appendix B), which confirms the negative moisture elasticity across alternative moisture index specifications. Rainfall data validity: The reported values (2.1–2.8 mm annual mean) reflect Egypt's actual hyperarid to arid climate. These values are consistent with Egypt Meteorological Authority records and FAO AQUASTAT precipitation data for Egypt's cultivated regions (mean ~2–3 mm for Nile Valley agricultural zones). Desert regions receive <1 mm; Mediterranean coastal areas receive 10–25 mm. The agricultural-area-weighted average is ~2.7 mm. Sensitivity analysis comparing original rainfall with alternative moisture indices yielded consistent results (Appendix B), confirming that the negative elasticity is robust and reflects genuine biological mechanisms rather than data artifacts. Findings regarding potato temperature sensitivity align with international research (Allen et al., 2006) and Egyptian assessments by Wael & Gweily (2023), who noted yield reductions in cool-season crops under warming. The negative rainfall elasticity for potatoes has precedent in Mediterranean region studies (Gachon et al., 2005) and Egyptian horticultural observations, suggesting that disease pressure rather than water scarcity drives yield losses in wet conditions. Rababa & Al-Khatib (2025) focused on field crops in coastal Matrouh Governorate; this extension to irrigation-dependent vegetable crops in the Nile Delta and Valley expands regional coverage and strengthens understanding of climate-yield relationships across Egypt's diverse agroecological zones.

3.4. Food Security and Climate Vulnerability

The differential climate sensitivities identified in this study have profound implications for Egypt's food security. Tomato and potato crops are not equally vulnerable to observed climate change; instead, they face divergent challenges requiring crop-specific policy responses. Tomato crops exhibit relatively modest temperature sensitivity (+0.087% per 1°C maximum temperature) but pronounced humidity sensitivity (+2.80% per 1% humidity). Under current climate trajectories characterized by warming and declining humidity, tomato production faces humidity-driven stress despite manageable temperature trends. The declining relative humidity (−0.260 percentage points annually) is a direct threat to tomato productivity if irrigation systems are not expanded to compensate through enhanced water application and moisture-management technologies. Potato crops face substantially greater climate vulnerability. The strong maximum temperature sensitivity (−3.25% per 1°C) creates acute risk in a warming climate. While the offsetting minimum temperature effect (+2.09%) provides partial compensation, the net combined effect is approximately zero—indicating that potato yields will stagnate unless adaptive measures are implemented. Given Egypt's rapid population growth (estimated to reach 130+ million by 2035), stagnant potato productivity threatens food security. Potatoes are critical staple crops providing affordable carbohydrates and micronutrients to lower-income populations; they have lower price elasticity of demand than tomatoes, meaning that production shortfalls directly reduce nutritional access rather than shifting consumption to alternative crops. Furthermore, the negative rainfall elasticity for potatoes (−5.53%) indicates disease vulnerability under wet conditions. Egypt's irrigation expansion, while necessary for crop water supply, may inadvertently promote late blight and other fungal diseases through increased soil moisture and atmospheric humidity. Disease management through drainage, fungicide application, and variety selection becomes increasingly critical under climate change. Egypt's food security strategy must therefore prioritize



climate-resilient potato production, allocating research and development resources to heat-tolerant variety development, disease-resistant germplasm, and adaptive management practices. Tomato production can likely sustain current productivity through irrigation optimization addressing declining humidity. Potato production requires more fundamental adaptation including variety replacement and possibly regional relocation to cooler agroecological zones (Upper Egypt mountain regions, Mediterranean coast) to exploit natural temperature variation within the country.

4. Adaptation Strategies

4.1. Water Management and Irrigation Optimization

Given that tomato yield exhibits strong humidity elasticity (+2.80% per 1% humidity increase) while relative humidity is declining (−0.260 percentage points annually), irrigation systems must be optimized to maintain soil moisture and atmospheric humidity within critical growth stages. Deficit irrigation strategies, micro-spraying, mulching, and high-frequency drip-line systems are recommended to capitalize on this demonstrated humidity sensitivity. These technologies maintain soil water availability while increasing atmospheric moisture through controlled evaporation. For potato crops, irrigation must balance adequate moisture supply with drainage to prevent waterlogging, particularly during the critical tuber-filling phase (45–75 days post-emergence). The negative rainfall elasticity (−5.53%) indicates that excess soil moisture promotes fungal disease; controlled irrigation timing and improved field drainage reduce pathogenic pressure while sustaining productivity.

4.2. Crop Variety Selection and Breeding Priorities

The contrasting temperature sensitivities identified in this study should guide breeding and variety selection priorities at national and farm levels. Tomato cultivation uses varieties already positioned near their thermal optimum (positive coefficient +0.087%/°C reflects optimal range positioning). Breeding efforts should focus on humidity and drought tolerance traits, including reduced stomatal conductance, improved root depth, and epicuticular wax accumulation to reduce transpiration under low-humidity stress. Conversely, potato cultivation faces pronounced temperature vulnerability (−3.25% per 1°C), requiring urgent development of heat-tolerant cultivars. International germplasm exchange with breeding programs in warmer regions (India, Sub-Saharan Africa, Southeast Asia) should be prioritized to identify and introgress heat-tolerance traits into Egyptian potato germplasm. Public-sector breeding programs (Agricultural Research Center, universities) should allocate resources toward marker-assisted selection for temperature resilience, capitalizing on modern genomic technologies.

4.3. Temporal Optimization: Adjusted Planting Schedules

The asymmetric temperature change pattern—wherein minimum temperature warming (+0.211°C/year) exceeds maximum temperature warming (+0.144°C/year)—can be leveraged through adjusted planting schedules. For potatoes, early-season planting (August–September for winter harvest) allows crop maturation and harvest before peak summer maximum temperatures are reached (June–July). This strategy directly exploits the positive minimum temperature elasticity (+2.09%) while minimizing exposure to the harmful maximum temperature effect (−3.25%). Conversely, tomato planting can be extended into warmer periods (spring and summer plantings in addition to winter plantings) to leverage the modest positive temperature response and longer growing seasons under warming. These scheduling adjustments require coordination with water availability from irrigation infrastructure and labor availability, but represent low-cost adaptation strategies immediately implementable by farmers.

4.4. Regional Diversification and Agroecological Zoning

Climate vulnerability is not spatially uniform within Egypt. Temperature variation across Egyptian agroecological zones ranges from ~18°C mean annual temperature in cooler Mediterranean coastal regions to >30°C in Delta and Valley zones. This natural variability can be leveraged through regional crop diversification. Potato production, facing greater temperature vulnerability, can be concentrated in cooler regions (Mediterranean coast, Upper Egypt mountain areas, oasis regions at higher elevations) where natural temperature conditions are more favorable for tuber development. Tomato production, with modest thermal requirements, can expand in warmer Delta regions and in protected cultivation systems in other zones. This regional optimization requires data on crop water requirements versus regional water availability, soil suitability, and market access—analyses beyond this study's scope but warranting urgent policy-research partnerships.

4.5. Policy Integration and Food Security Planning

Climate-informed agricultural planning must incorporate these crop-specific vulnerabilities into national food security policy. Potato production, facing greater climate vulnerability (net combined effect near zero despite adaptation options), warrants priority investment in heat-tolerant variety development, disease-management research, and farmer training on adaptive agronomic practices. Climate risk insurance mechanisms linked to yield losses should be developed to protect vulnerable farmers from climate-induced crop failures. Similarly, tomato production insurance should address humidity-driven productivity declines. These risk-management instruments require partnerships between government (Ministry of Agriculture, risk-pooling institutions)



and private-sector agricultural insurance providers, but represent critical food security infrastructure in a warming climate. Regional crop diversification strategies and trans-regional trade coordination can enhance food availability resilience by distributing production across agroecological zones facing differential climate risks.

5. Conclusions

This study quantifies climate-yield relationships for Egypt's two major vegetable crops during 2000–2025. Time-series analysis reveals significant climate change: maximum temperature increased 0.144°C annually (12.7% cumulative), minimum temperature increased 0.211°C annually (32.1% cumulative), while relative humidity declined 0.26 percentage points annually and rainfall declined 0.008 mm annually. Multiple regression elasticity analysis with mixed log-linear specification identified striking differential vulnerabilities: tomato crops exhibit positive response to humidity (+2.80%) but face vulnerability due to declining atmospheric moisture; potato crops demonstrate pronounced temperature sensitivity (−3.25% per 1°C maximum temperature). The combined net effect of asymmetric temperature warming on potato yields approaches zero over the study period, indicating that productive capacity will stagnate without adaptation. Potatoes face substantially greater climate risk than tomatoes under observed trends, warranting priority policy attention and investment in climate-resilient agricultural practices. Evidence-based adaptation strategies must be crop-specific: potatoes require heat-tolerant varieties and optimized planting schedules to minimize peak-heat exposure, while tomatoes require enhanced irrigation to maintain humidity under declining precipitation. Both crops require improved water-use efficiency and disease management. These findings support SDG 2 (Food Security) and SDG 13 (Climate Action) in Egypt's arid agricultural context.

Author Contributions

Mervat Raphael Girgis Youssef: Conceptualization, study design, methodology, data collection, statistical analysis, writing—original draft, writing—review and editing, and supervision; Amal Mohamed Ameen Hassan: Data collection, data curation, database compilation, time-series data preparation, descriptive analysis, data validation, and writing—review and editing; Reda El-Sayed Mohamed Morsi: Climate data analysis, statistical analysis, regression modeling, interpretation of results, writing—methodology, writing—review and editing.

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Declarations

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