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Research paper

Simulating the Winter Wheat Production of Egypt Using WOFOST-PCSE Crop Model

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ABSTRACT

Winter wheat is a critical strategic crop for Egypt's food security. The accurate simulation of its production is therefore fundamental for future planning and evidence-based policy. This study applies the World Food Studies (WOFOST) crop simulation model to estimate winter wheat yield across Lower Egypt (Nile Delta). Following sensitivity analyses to determine the optimal model configuration, WOFOST was calibrated using data from 14 growing seasons (2000–2014) and validated for the period 2015–2020. Model performance, evaluated using relative bias (rbias) and root mean square error (RMSE), showed reasonable agreement with observed yields (RMSE: 0.33–0.39; rbias: 0.4–5.8%). A strong negative correlation was identified between yield and air temperature in the Nile Delta, with Pearson correlation coefficients about 0.8 for mean temperature (Tmean) and -0.7 for both minimum temperature (Tmin) and about 0.66 for maximum temperature (Tmax). Sensitivity experiments imposing temperature perturbations (±0.5°C and ±1.0°C) revealed that a 1.0°C increase in mean daily temperature reduced the total weight of storage organs (TWSO), total above-ground biomass (TAGP), and straw yield (STR) by 5.8–11.4%, 6.22–12.12%, and 6.54–12.76%, respectively, while the harvest index (H_{ind}) increased marginally (0.43–0.81%). Conversely, a 1.0°C cooling increased TWSO, TAGP, and STR by 6.1–11.7%, 6.4–12.92%, and 6.68–14.04%, respectively, accompanied by a slight decrease in H_{ind} (0.27–1.11%). The retrieved results demonstrate the efficacy of the WOFOST model in simulating winter wheat production under variable climatic conditions, supporting its potential application for future climate scenario assessments.

***Keywords**:* Winter wheat; WOFOST-PCSE; Temperature sensitivity; Harvest index; Climate change impact.

A thorough understanding of winter wheat growth and development is essential for improving management efficiency and sustaining production in Egypt, where wheat is a strategic crop. Crop phenology is strongly regulated by temperature and photoperiod, progressing through eleven stages according to Feekes' scale (Fowler, 2018), from germination in mid-November to harvest in April. The reproductive phases—booting, heading, and flowering—are particularly sensitive to environmental stress (Hatfield & Jerry, 2015).

Global warming studies consistently demonstrate that rising temperatures negatively affect wheat productivity. Extreme heat events during flowering and grain filling substantially reduce yield and grain quality (Chandra et al., 2023; Kumar, 2017; Mohanty *et al.,* 2015). These impacts are amplified when combined with drought and elevated CO_2, leading to significant declines in biomass and grain yield (Li *et al.,* 2024; Asseng *et al.,* 2023). Heat stress impairs pollen viability and grain set, while molecular and physiological studies provide insights into thermotolerance mechanisms (Shenoda *et al.,* 2021). Adaptation strategies—including breeding heat-tolerant varieties and optimizing sowing dates and irrigation—have been proposed to mitigate terminal heat stress (Murugesh *et al.,* 2026). In addition, climate risk modeling and geospatial analyses project increasing compound heat–dry hazards under future climate scenarios, supporting strategic adaptation planning (Global Wheat Modeling Consortium, 2026; Zhao & Li, 2024). Experimental and modeling assessments further quantify

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long-term and extreme climate impacts on wheat yields and evaluate mitigation pathways for sustainable production (Chauhdary *et al.,* 2025; Fang *et al.,* 2026).

In this study, the relationship between temperature variables (Tmean, Tmax, Tmin) and winter wheat production in Egypt's Delta region was evaluated using the World Food Studies (WOFOST) crop growth model implemented within the Python Crop Simulation Environment (PCSE) under potential production conditions. The model was calibrated for 2000–2014 and validated for 2015–2020. Production indicators—including TWSO, total aboveground biomass, straw yield, and harvest index—were simulated over 20 growing seasons to assess changes under ±0.5 and ±1 °C temperature scenarios.

MATERIALS AND METHODS

Study area

Egypt lies between latitudes 22°–32° N and longitudes 24°–36° E, bordered by the Mediterranean Sea to the north and the Red Sea to the east. The River Nile, the country's primary irrigation source, flows from south to north and sustains most agricultural activities. According to the Köppen climate classification, Egypt is characterized by a hot desert climate (Köppen, 2011).

This study focuses on the Nile Delta region in northern Egypt (29°37′52″–32°55′49″ E and 29°37′49″–31°41′2″ N), the country's main agricultural zone formed by the branching of the Nile River. The Delta covers approximately 22,000 km² and extends about 240 km along the Mediterranean coast from Alexandria to Port Said, encompassing eight governorates (Elagouz *et al.,* 2020). It represents Egypt's most important agro-climatic and food-producing region. Five key wheat-producing governorates—Sharqia, Kafr El-Sheikh, Behaira, Qalubia, and Gharbia—are examined as individual study sites Fig 1.

Climatically, the Nile Delta is classified as a mid-latitude region with relatively mild and wetter winters compared to the rest of Egypt (Eid *et al.,* 2019). The winter wheat growing season extends from mid-November to late April. During germination in late November, the mean air temperature is approximately 20°C, with maximum temperatures near 26°C and minimum temperatures around 14°C. Temperatures decline during December and January to average values of about 15°C and 13°C, respectively, then gradually increase from February through April (approximately 14°C, 17°C, and 20.5°C). Wind speeds during the growing season remain generally light and show limited monthly variation. These climatic characteristics make the Nile Delta suitable for winter wheat cultivation while also exposing the crop to seasonal temperature fluctuations that may influence growth and yield.

WOFOST model

The World Food Studies (WOFOST) crop model was developed through a collaboration between the Centre for World Food Studies (CWFS) and Wageningen University in the Netherlands. It is a dynamic, mechanistic, and flexible simulation tool that models daily crop growth based on agro-meteorological and soil data for a wide range of crops. WOFOST is designed to calculate the agricultural production potential for specific combinations of crop, soil, and climate (Dewenam *et al.,* 2021, Mishra *et al.,* (2013). Its computational process integrates three core modules: climate, crop, and soil (Hadiya *et al.,* 2018). Using daily meteorological data, the model dynamically simulates crop growth as a function of crop physiology, management practices, and soil conditions. These simulations are performed for three distinct scenarios: potential (non-limiting), water-limited, and nutrient-limited growth. The model incorporates key biophysical and biological processes underlying crop development and yield formation (Li *et al.,* 2024)

Data

Annual winter wheat yield

Annual winter wheat yield data were collected as the mean yield from Agricultural Research Center for Sharqia, Kafr ElSheik, Behaira, Qalubia, and Gharbia.

Basically, the WOFOST requires daily meteorological station data. However, this time scale of data was not available for the sites reported in this study. Instead, the meteorological data were retrieved from a reanalysis product of the National Aeronautics and Space Administration Prediction of Worldwide energy Resources (POWER). The dataset comprises daily values of the following variables: (1) all-sky surface shortwave downward irradiance; (2) mean, minimum, and maximum air temperature measured at 2 m; (3) wind speed at 2 m; and (4) total daily precipitation. A major advantage of the POWER is that it is designed for agrometeorological applications (as in this study), and it is available in horizontal grid spacing of 0.5° x 0.625°. Also, it is based on combination of weather station observation and satellite data. Additionally, POWER is based on the Goddard's Global Modeling and Assimilation Office (GMAO) Modern Era Retrospective-Analysis for Research and Applications (MERRA-2) assimilation model products and GMAO Forward Processing – Instrument Teams (FP-IT) GEOS 5.12.4 near-real time products.

Soil and crop data

The soil file in WOFOST contains information about soil physical characteristics (Boogaard *et al.,* 1998). In Nile delta the soil is very fine so the Environmental/Climate Schema EC5 was used. Crop data file includes the information about crop phenology, assimilation and respiration characteristics, and partitioning of assimilates to plant organs (Boogaard *et al.,* 1998).

Skill score metrics

Three metrics are employed to assess WOFOST performance with different physical configuration and address the best performance of it and the correlation between temperatures and winter wheat yield.

Relative bias (rbias):

Relative bias measures the size of the error in percentage terms and calculates, Equation

$$rBias = \frac{1}{n}\sum_{i=1}^{n}\frac{Y_i - Y_a}{Y_a} \times 100 \tag{1}$$

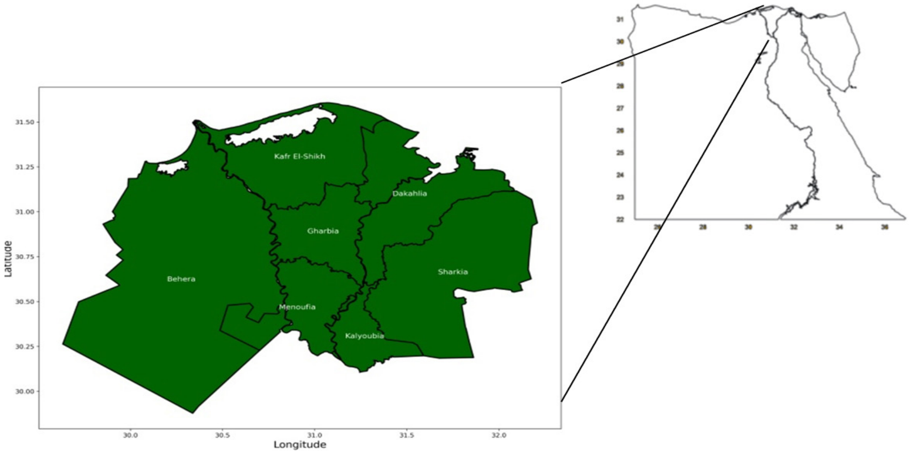

Fig 1: Study sites in the Nile Delta region

where Y_i is the estimated yield and Y_a is the actual yield.

Root Mean Square Error (RMSE)

Root Mean Square Error (RMSE) is the standard deviation of the residuals (prediction errors). Residuals are a measure of how far from the regression line data points are; RMSE is a measure of how spread out these residuals are (Willmott *et al.,* 1985), Equation

$$RMSE = [\sum_{i=1}^{n} (Y_i - Y_a)^2/n]^{1/2} \quad (2)$$

Pearson's Correlation

The Pearson correlation coefficient (named for Karl Pearson) can be used to summarize the strength of the linear relationship between two data samples. The Pearson's correlation coefficient is calculated as the covariance of the two variables divided by the product of the standard deviation of each data sample. It is the normalization of the covariance between the two variables to give an interpretable score.

$$R = \frac{n(\sum xy)-(\sum x)(\sum y)}{\sqrt{[n\sum x^2-(\sum x)^2][n\sum y^2-(\sum y)^2]}} \quad (3),$$

where, R = Pearson Coefficient, n= number of pairs of the stock, $\sum xy$ = sum of products of the paired stocks, $\sum x$ = sum of the x scores, $\sum y$= sum of the y scores, $\sum x^2$ = sum of the squared x scores, $\sum y^2$ = sum of the squared y scores

Relative change in yield

$$\Delta TWSO\ \% = \frac{(y_{es}-y_{ac})}{y_{ac}} * 100 \quad (4)$$

where ΔTWSO is the relative change in production, y_{es} is the estimated yield (Ton/ Fedden), and y_{ac} = actual yield (Ton/ Fedden); one feddan is equal to 4200 m².

Straw Calculation (STR)

$$\text{STR}= TAGP - TWSO \quad (5)$$

where STR is the straw (Ton/Feddan), TAGP is total above ground biomass (Ton/Feddan), and TWSO is crop yield (Ton/Feddan).

Harvest Index

$$H_{Ind} = \frac{TWSO}{TAGP} * 100 \quad (6)$$

where H_{ind} is the harvest index, TWSO is the crop yield (Ton/Feddan), and TAGP is the total above ground biomass (Ton/Feddan).

RESULTS AND DISCUSSION

Calibrating the model's parameters

In the time of experiment, there were no known values of some crop physiological parameters such as TSUM1 (temperature sum from emergence to anthesis stage; in Celsius day), and TSUM2 (temperature sum from anthesis to maturity stage; in Celsius day). Instead, the WOFOST model was trained with different values of TSUM1 and TSUM2 around the default values of WOFOST crop parameters derived from SUCROS87 data set for wheat (Spitters *et al.,* 1989) to obtain the best configuration of the winter wheat yield in the study fields. Data were divided into two periods, 14 seasons from 2001 to 2014 were used to tune the model then 6 seasons from 2015 to 2020 were used to validate it.

WOFOST PCSE was tuned by 14 growing seasons from 2001 to 2014. Such tuning was applied by changing TSUM1 and TSUM2 according to the values reported in Table 1. To quantify the WOFOST performance, different statistical metrics were used, such as relative bias (rbias) and root mean square error (RMSE) between the actual winter wheat yield and the predicted yield from the model were calculated. For most sites, trials 1, 2, and 5 had the least rbias (Table 2) and RMSE (Table 3), which were 0.2-6.27 and 0.21-0.29 respectively. Therefore, we will use the three best trials to detect the most appropriate configuration for the model.

Model validation

The WOFOST model implemented in the Python Crop Simulation Environment (PCSE) was evaluated over six growing seasons from 2015 to 2020 using three parameter configurations (trials 1, 2, and 5). The relative bias (rbias) and root mean square error (RMSE) between the observed and simulated winter wheat yields were computed. Trial 1 demonstrated better performance than

Table 1: Number of trials for WOFOST tuning and TSUM 1 (°C day), TSUM2 (°C day) values for each trial

Trial	TSUM1 (°C day)	TSUM2 (°C day)
1	1200	990
2	1200	1000
3	1200	1100
4	1300	990
5	1300	1000
6	1300	1100
7	1400	990
8	1400	1000
9	1400	1100

Table 2: rbias between actual and simulated yields for each tuning trial

Trial	kafr ElSheik	Garbia	Sharqia	Qalubia	Behaira
1	-1.80	-0.21	6.27	3.20	0.20
2	-1.49	0.12	6.57	3.49	0.50
3	0.90	2.64	9.18	6.03	3.03
4	-1.87	-1.58	2.60	-0.37	-0.78
5	-1.80	-0.21	6.27	3.20	0.20
6	0.58	0.97	5.24	2.20	1.82
7	-5.40	-6.28	-3.45	-6.21	-5.12
8	-5.15	-6.03	-3.20	-5.97	-4.87
9	-3.12	-3.94	-1.07	-3.90	-2.77

Table 3: RMSE between actual and simulated yields for each tuning trial.

	Kafr ElSheik	Garbia	Sharqia	Qalubia	Behaira
1	0.21	0.24	0.29	0.26	0.22
2	0.21	0.24	0.30	0.26	0.22
3	0.22	0.26	0.35	0.30	0.24
4	0.23	0.27	0.26	0.25	0.24
5	0.21	0.24	0.29	0.26	0.22
6	0.23	0.27	0.29	0.27	0.25
7	0.28	0.35	0.31	0.35	0.30
8	0.27	0.35	0.31	0.35	0.30
9	0.25	0.32	0.30	0.33	0.28

Trials 2 and 5 in terms of rbias, as shown in Tables 4 and 5. Based on these results, the WOFOST-PCSE model with TSUM1 = 1200 °C·day and TSUM2 = 990 °C·day is recommended for simulating winter wheat production in the Nile Delta, Egypt.

Table 4: rbias between actual and simulated yield of different validation trials

Trial	Kafr ElSheik	Garbia	Sharqia	Qalubia	Behaira
1	2.86	5.8	0.39	0.89	3.72
2	3.18	6.14	0.67	1.17	4.01
5	3.68	4.82	-2.4	-1.9	3.13

Table 5: RMSE between actual and simulated yields for each validation trial.

Trial	Kafr ElSheik	Garbia	Sharqia	Qalubia	Behaira
1	0.39	0.37	0.36	0.35	0.33
2	0.39	0.37	0.36	0.35	0.33
5	0.4	0.37	0.36	0.35	0.34

Table 6: Mean crop duration, TWSO (Ton Feddon^{-1}), TAGP (Ton Feddon^{-1}), STR (Ton Feddon^{-1}), and Hind (%) in some sites of the Delta governments during 2000-2020.

	Crop Duration (Day)	TWSO (Ton Fadden^{-1})	TAGP (Ton Fadden^{1})	STR (Ton Fadden^{-1})	Hind%
Behaira	143	2.89	6	3.11	48.17
Garbia	143	2.87	6.02	3.15	47.68
Kafr ElSheik	143	2.69	5.53	2.85	48.57
Qalubia	143	2.86	6.16	3.30	46.43
Sharqia	143	2.86	6.15	3.30	46.44

Effect of temperature on yield performance of wheat

Fig. 2 represents pooled regression analysis combining all relative yield data, defined as $(Y-\bar{Y})/\bar{Y}$, where Y is the annual wheat yield and $\bar{Y}$ is the long-term mean yield across all locations and growing seasons with seasonal mean temperature (Tmean), minimum temperature (Tmin), and maximum temperature (Tmax), it also includes the relationship between temperature and wheat yield using linear regression analysis. A strong negative correlation, about -0.8 for Tmean, about 0.7 for Tmin, and 0.66 for Tmax, was observed. Given that when, there is no deficiency in soil minerals or nitrogen, soil moisture relative yield decrease with respect to the mean yield of the period 2000-2020 years as the temperature increases. The regression analysis showed that Tmean and Tmin had the strongest effect on relative yield, as indicated by the steepest negative slope −14, while Tmax had the weakest influence with slope −7. This noted behavior agrees with the results reported by (Prasad *et al.,* 2008; Shenoda *et al.,* 2021; Gyawali *et al.,* 2021; Khan *et al.,* 2021; Zhang *et al.,* 2023).

To further understand the effect of mean temperature on TAGP, TWSO, STR, and H_{ind}, We conducted a hypothetical experiment in terms of inducing an incremental change in the daily mean air temperature of +0.5, +1.0, -0.5, and -1.0 °C. In the Delta region, wheat has mean number of days in the agricultural season (crop duration) of 143 day, TWSO, TAGP, and STR (during the period 2000-2020) were as follows: 2.68-2.89, 5.5-6.16, and 2.8-3.3 ton/Feddan respectively, and harvest index, a measurement of crop yield: harvest index ranged from 46.4 to 48.5%, Table 6.

When mean daily air temperature increased by +0.5 °C, crop duration decreased 4 days (139-140 day) and relative change (Δ) in TWSO, TAGP, and STR -5.3 to -6.5, -5.9 to -6.8 and 6.3 to -7.1% respectively but H_{ind} increased by 0.22 to 0.57%. When mean air temperature changed by +1.0 °C, crop duration decreased by another 3 days (136 day) whereas the decrease in ΔTWSO, ΔTAGP, and ΔSTR nearly doubled 10.4-12.9, 11.5-13.3, and 12.5-13.7 % respectively) and H_{ind} increased by 0.41-1.24%.

When the temperature decreased by -0.5°C, the duration

Table 7: Mean crop duration (day), **Δ**TWSO (%), **Δ**TAGP (%), Δ STR (%), and ΔHind (%) in some sites of the Delta government

	ΔTmean (°C)	Crop Duration (Day)	ΔTWSO (%)	ΔTAGP (%)	ΔSTR(%)	ΔHind(%)
Behaira	0.5	139	-6.1	-6.3	-6.5	0.222
	1	136	-11.9	-12.2	-12.5	0.411
	-0.5	147	6.3	6.5	6.7	-0.189
	-1	151	12.4	13.1	13.8	-0.679
Garbia	0.5	139	-5.8	-6.2	-6.5	0.432
	1	136	-11.4	-12.1	-12.6	0.7
	-0.5	147	6.2	6.4	6.6	-0.191
	-1	150	12.1	13	13.8	-0.772
Kafr ElSheik	0.5	139	-6.5	-6.8	-7.1	0.35
	1	136	-12.9	-13.3	-13.7	0.484
	-0.5	147	7	7.1	7.3	-0.128
	-1	150	13.9	14.5	15.1	-0.558
Qalubia	0.5	140	-5.3	-5.9	-6.3	0.566
	1	136	-10.4	-11.5	-12.5	1.236
	-0.5	147	5.5	6	6.4	-0.429
	-1	151	10	12	13.7	-1.77
Sharqia	0.5	140	-5.3	-5.9	-6.3	0.562
	1	136	-10.4	-11.5	-12.5	1.225
	-0.5	147	5.5	6	6.4	-0.426
	-1	151	10.1	12	13.8	-1.761

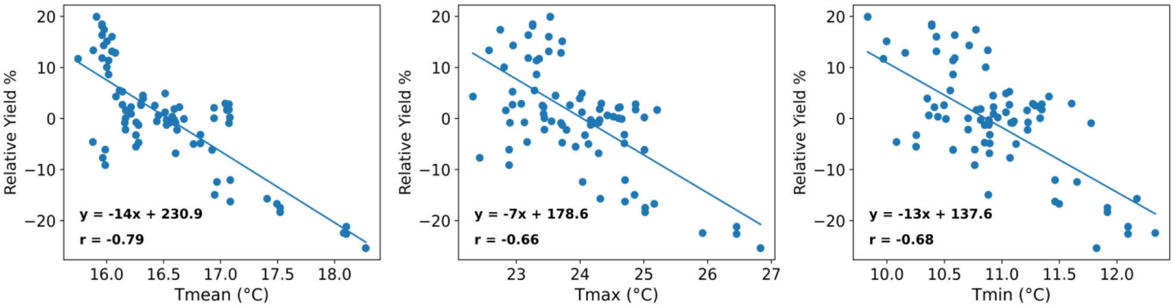

Fig. 2: Pooled regression analysis combining all relative yield data across all locations and growing seasons with Tmean, Tmax, and Tmin.

increased to 147 day and ΔTWSO, ΔTAGP, and ΔSTR increased by 5.5-7, 6-7.1, and 6.4-7.3 % respectively but ΔH_{ind} decreased by 0.13-0.43 %, Table 7. Finally when mean daily air temperature decreased by -1.0 °C, the duration increased to 150-151 day and ΔTWSO, ΔTAGP, and ΔSTR increased by 10-13.9, 12-14.5, and 13.7-15.1 % respectively but ΔH_{ind} decreased by 0.56-1.77%.

CONCLUSION

Winter wheat is a strategic crop in Egypt, and understanding its response to temperature variability is essential under changing climate conditions. In this study, the WOFOST-PCSE crop model was calibrated and validated for five Nile Delta governorates using optimized crop parameters (TSUM1 = 1200 °C days and TSUM2 = 990 °C days). The model showed good performance in simulating grain yield, with RMSE values ranging from 0.33 to 0.39 and relative bias between 0.39 and 5.8%.

Regression analysis between temperature and relative yield indicated a consistent negative relationship across all locations, with slopes ranging from approximately −7 to −14 depending on the temperature indicator. Mean temperature (Tmean) and minimum temperature (Tmin) showed the strongest impact (slope ≈ −14), while maximum temperature (Tmax ≈ −7) had the weakest effect. Similarly, Pearson correlation coefficients confirmed this pattern, with strong negative correlations for Tmean (r = -0.8), Tmin (r = -0.7), and Tmax (r = -0.66).

Sensitivity experiments showed that increasing mean daily air temperature by +0.5 to +1.0 °C reduced grain yield, biomass, and storage organ weight, whereas cooling scenarios produced the opposite effect. These findings confirm the sensitivity of winter wheat productivity to warming conditions and support the applicability of the calibrated WOFOST model for climate impact assessment in the Nile Delta. Future work will incorporate multiple reanalysis and climate datasets (e.g., CMIP5/6 outputs) to evaluate uncertainty and assess wheat yield responses under future climate change scenarios.

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