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Environmental factors affecting tomato growth for industrial processing in the Brazilian Savannah of Goiás State

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ABSTRACT. This study investigates the meteorological variables exerting the most significant influence on the growth and productivity of four tomato hybrids cultivated for industrial processing in the Brazilian Savannah of Goiás State. Data on morphological and meteorological variables were collected in five locations (Hidrolândia, Itaberaí, Palmeiras de Goiás, Piracanjuba, and Silvânia) during the year 2020. Morphological characteristics assessed included plant height, number of branches, and leaf area index (LAI). Meteorological variables considered were average air temperature, global solar irradiance, thermal sum, and soil water availability. Pearson correlations, canonical correlations, and multivariate Stepwise regression were employed to analyze the relationships between morphological and meteorological variables. The study revealed that soil water availability significantly impacts tomato crop development, indicating the need for improved irrigation management. Adequate irrigation management contributed to an 86.1% increase in plant height and a 79.7% boost in leaf area index, while average air temperature influenced a 34% increase in the number of branches. In conclusion, proper irrigation management is crucial for enhancing tomato crop growth and development and optimizing water use.

Keywords: *Solanum lycopersicum*; irrigation; multiple regression; canonical correlation.

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Introduction

Tomato production is highly influenced by environmental factors and can exhibit variations in growth and development due to genotypic traits and local weather conditions (Rocco & Morabito, 2016). Solar radiation, air temperature (Pathak & Stoddard, 2018), and water availability (Mesquita et al., 2019a; Mesquita et al., 2019b) are among the primary variables affecting crop growth and development.

Solar radiation plays a pivotal role in crop development by enhancing photosynthesis through increased evapotranspiration. To maximize tomato plant growth, solar radiation should exceed 8.4 MJ m^{-2} day^{-1} (Silva et al., 2020). Elevated radiation use efficiency contributes to increased productivity (Yang et al., 2019). However, excessive solar radiation intensity negatively impacts plant growth and development by saturating upper canopy leaves, leading to reduced crop stature and leaf area (Lopez-Marin, Galvez, & Gonzalez, 2011; Ilic, Milenkovic, Sunic, & Fallik, 2015; Holzman, Carmona, Rivas, & Niclòs, 2018; Yang et al., 2019). Excess radiation also accelerates leaf senescence and reduces leaf protection of fruit against radiation, affecting both yield and fruit quality (Goto, Yabuta, Ssenyonga, Tamaru, & Sakagami, 2021).

In this context, air temperature also significantly affects tomato growth and development, altering crop phenology (Pathak & Stoddard, 2018). It influences growth rate, cycle length, developmental stages, and crop yield (Floss, 2011). Tomato cultivation requires specific environmental conditions, with an optimal average air temperature of 21°C. Temperatures below 10°C and above 34°C hinder development (Palaretti, Mantovani, Silva, & Cecon, 2012).

Moreover, tomatoes have a high water requirement, with up to 436 mm needed during the growing cycle (Alves Junior et al., 2021). Water deficits and excess water significantly impact productivity and quality (Mesquita et al., 2019a; Mesquita et al., 2019b). Water deficit during flowering can result in plant death. In the vegetative growth phase, moderate water deficit stimulates root growth, while in the reproductive phase, it leads to flower abortion and smaller fruit. Excess water in both phases causes root deoxygenation, plant death, disease susceptibility, and nutrient leaching (Silva et al., 2020).

Plant growth and productivity depend on various biotic and abiotic factors, with meteorological elements playing a prominent role (Schwerz, 2018). Statistical techniques, such as Stepwise regression, are employed to analyze the effects of weather elements on crops. This method evaluates the significance and correlation coefficients between dependent and independent variables, determining their inclusion or exclusion from regression equations (Fiorentin, Corte, Sanqueta, & Behling, 2015).

Predicting productivity using crop models helps approximate agricultural systems, estimating growth and development based on climatic, soil, and crop management variables. These results aid in decision-making to reduce productivity losses and support hybrid selection for each growing season (Sentelhas & Battisti, 2015).

This study hypothesizes that air temperature primarily influences the growth and productivity of industrial tomatoes. It aims to quantify the impact of weather variables on tomato growth across various locations in the Brazilian Savannah of Goiás. Canonical correlations between morphological characters and weather variables are examined, along with multiple linear regression models for each character individually.

Material and methods

This study was conducted across five tomato production areas dedicated to industrial processing from March 2020 to September 2021. The cultivation sites were as follows: Hidrolândia: Located at 17°02'30" S, -49°06'35" W, with an altitude of 914 m; Itaberaí: Positioned at 16°01'37" S, -49°43'20" W, and an altitude of 701 m; Palmeiras de Goiás: Situated at 16°41'12" S, -49°53'52" W, with an altitude of 596 m; Piracanjuba: Found at 17°24'05" S, -48°51'58" W, and an altitude of 740 m; Silvânia: Located at 16°45'46" S, -48°39'35" W, and an altitude of 999 m.

According to the Köppen climate classification, these areas have an Aw climate type, characterized by a tropical climate with a dry season in winter (Figure 1). The average annual air temperature ranges from 0 to 38°C, with accumulated rainfall ranging from 1,400 to 1,900 mm (Alvares, Stape, Sentelhas, Gonçalves, & Sparovek, 2013). The soil in all locations is classified as dystrophic Latosol (Embrapa, 2006), characterized by high clay concentration (33 - 46%) up to a depth of 50 cm, with an average soil density ranging from 1.2 to 1.4 g cm^{-3} up to the same depth (Table 1).

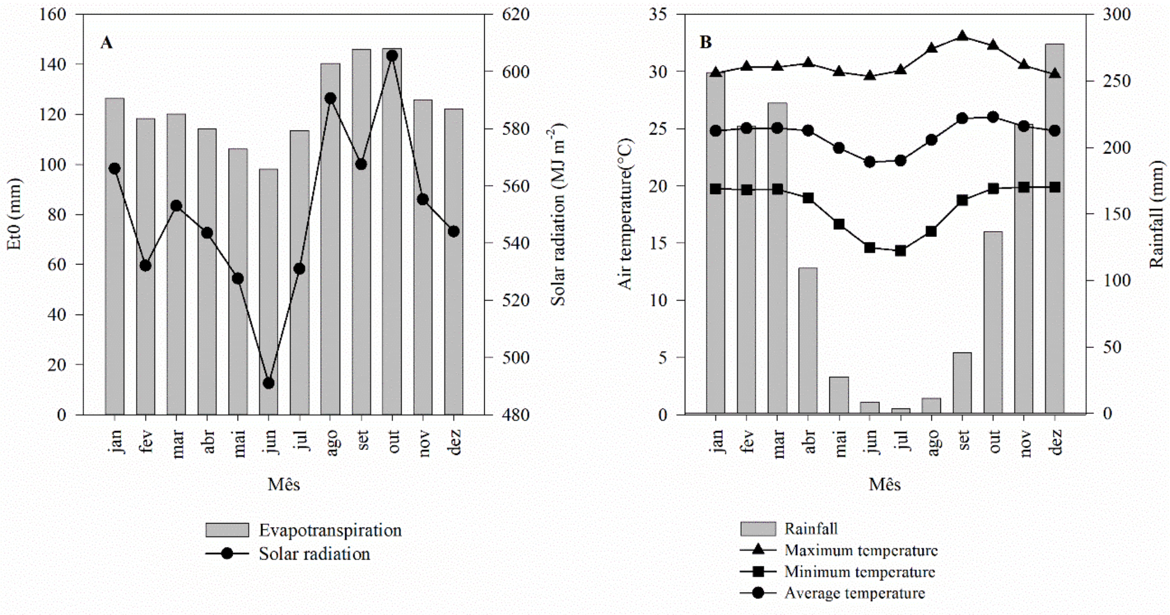

Figure 1. Climatological normals for the state of Goiás, Brazil, with monthly accumulated evapotranspiration (mm) and solar radiation (MJ m^{-2}) (A); accumulated rainfall (mm) and average, maximum, and minimum temperatures (°C) (B).

The tomato hybrids used in this study were H-1301, HM-7885, CVR-2909, and N-901. Transplanting was conducted on the following dates: Palmeiras de Goiás: March 15; Hidrolândia: March 25; Piracanjuba: May 15; Silvânia: May 20; Itaberaí: May 23.

Seedlings were transplanted at 45 days of age. Planting involved tilling the area to a depth of 0.15 m, with double rows spaced 0.60 x 1.20 m and plants placed at 0.37 m intervals, resulting in a population of 30,000 plants per hectare.

Table 1. Average soil physical characteristics up to 50 cm depth, in Hidrolândia, Itaberaí, Palmeiras de Goiás, Piracanjuba, and Silvânia, Goiás State, Brazil.

Locality	Sand (%)	Silt (%)	Clay (%)	Density (g cm^{-3})
Hidrolândia	55.8	5.8	38.4	1.4
Itaberaí	50.9	15.7	33.4	1.3
Palmeiras de Goiás	38.8	14.3	46.9	1.2
Piracanjuba	57.4	7.6	35.0	1.3
Silvânia	44.8	16.4	38.8	1.2

Biometric evaluations were performed every 14 days, involving the collection of 10 plants from each location. These plants were placed in plastic bags and transported to the laboratory of the Department of Biosystems Engineering at the Federal University of Goiás. During each collection, measurements of leaf area, plant height, and the number of branches were taken, as these parameters are key determinants of tomato productivity (Agbna et al., 2017). Leaf area was measured using ImageJ™ software, which involved photographing the leaves and processing the images for area determination (Zárate-Salazar, Santos, Santos, & Isla, 2018; Silva et al., 2018).

Meteorological data, including global solar irradiance, air temperature (minimum, average, and maximum), relative humidity, wind speed, and rainfall, were obtained from automatic meteorological stations (Metos™) installed at each site, approximately 50 meters from the cultivation area. Irrigation data were collected using automatic rain gauges within each cultivation area, equipped with Novus™ dataloggers, and set to record at 10-minute intervals.

All aspects of irrigation, fertilization, and phytosanitary management adhered to standard protocols employed by the producers, ensuring that the research did not interfere with crop management practices. This approach allowed for an accurate assessment of the actual effects of irrigation management in extensive commercial areas.

The daily thermal sum was calculated based on a lower basal temperature (Tb) of 10°C and an upper basal temperature (TB) of 34°C, consistent with values used by Pivetta, Tazzo, Maass, Streck, and Heldwein (2007) and Palaretti et al. (2012). The Degree Days (GDi) were determined using the following equations (Ometto, 1981):

For days when TB > TM > Tm > Tb:

$$GD_i = Tm - Tb$$

When TB > TM > Tb > Tm:

$$GD_i = \frac{(TM - Tb)^2}{2(TM - Tm)}$$

When Tb > TM:

$$GD_i = 0$$

When TM > TB > Tm > Tb:

$$GD_i = \frac{2.(TM - Tm) . (Tm - Tb) + (TM - Tm)^2 - (TM - TB)}{2.(TM - Tm)}$$

When TM > TB > Tb > Tm:

$$GD_i = \frac{1}{2} . \frac{(TM - Tb)^2 - (TM - TB)^2}{(TM - Tm)}$$

where: GDi is the sum of degree days of the day in °C; TM and Tm are the maximum and minimum temperatures of the day in °C, respectively; and Tb and TB are lower and upper basal temperatures, respectively.

Statistical analysis was carried out using Statistical Analysis System software, version 9.0 (SAS, 2002). Initially, tests were conducted to assess the statistical assumptions of normality, linearity, and multicollinearity ($p < 0.05$). Pearson coefficients were calculated for all variables. The chi-square test was used to determine whether there was evidence to reject H0 (Cruz, 2013). Subsequently, linear regression analysis was performed using the Stepwise method ($p \leq 0.15$), identifying the contribution of each variable to the character based on the partial determination coefficient. In this analysis, meteorological variables were considered independent input variables, while morphological characters were considered dependent variables. All interactions between meteorological variables and morphological characters were tested.

Results and discussion

Multicollinearity tests indicated that only the variables of plant height, number of branches, and leaf area index were selected as morphological variables, while accumulated thermal sum, average temperature, accumulated solar radiation, and water availability (rainfall plus irrigation) were chosen as meteorological variables.

Average temperatures ranged from 21 to 21.8°C across sites (Figure 2), falling within the optimal range of 18.5 to 29.5°C for tomato growth (Ayenan et al. 2019). Accumulated solar radiation ranged from 1,858.6 to 2,122.8 MJ m^{-2} $cycle^{-1}$ (Figure 3), while the accumulated heat sum ranged from 1,398 to 1,467.6 degree days (Figure 3), consistent with findings by Alves Junior et al. (2021) between 1,127.1 and 1,605 degree days. Water availability during the cycle varied from 308.9 to 448 mm (Figure 2), directly impacting plant growth, as evident in the correlation index between morphological and meteorological variables (Table 2). Alves Junior et al. (2021) reported an average water consumption of 351 mm during the industrial tomato crop cycle in the study region.

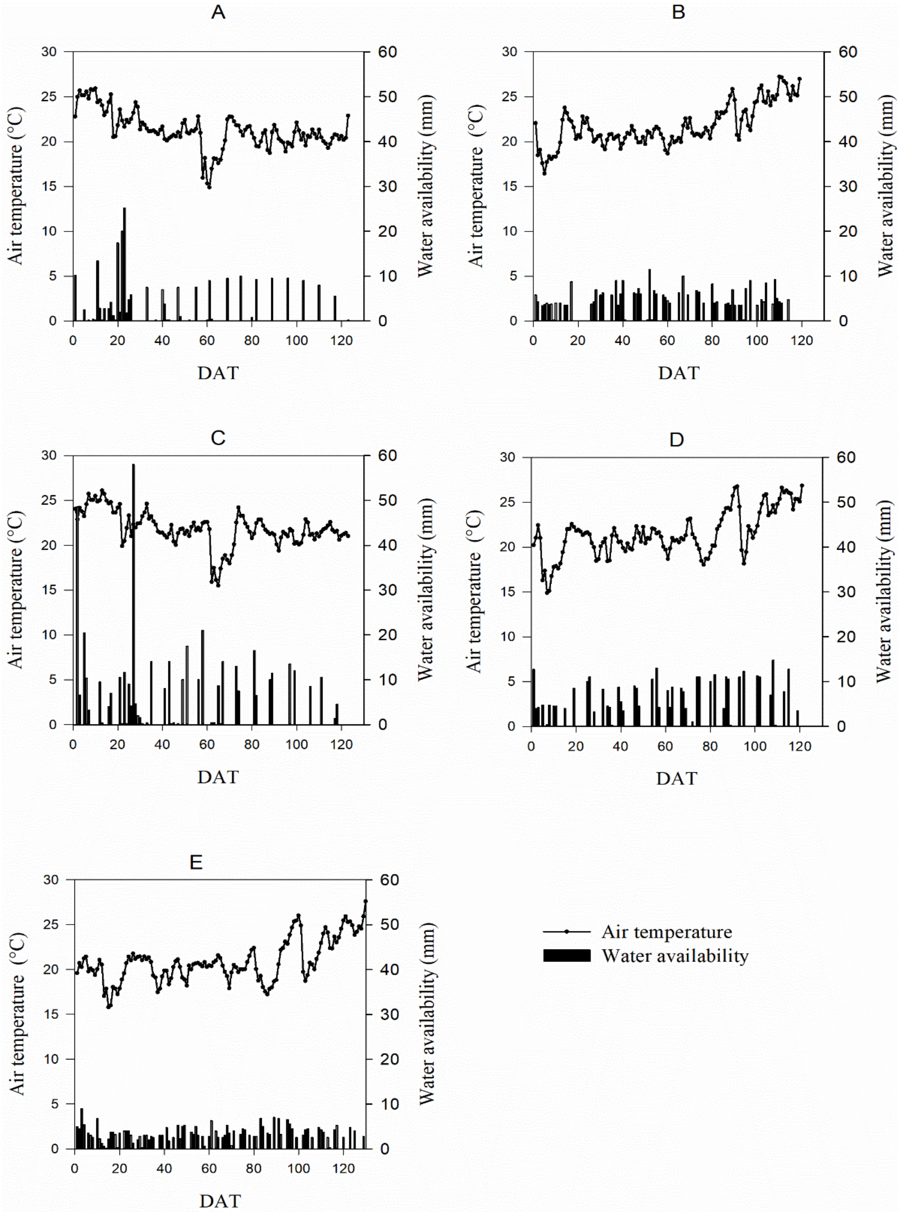

Figure 2. Average air temperature and water availability (rainfall and irrigation) during the tomato crop cycle in days after transplanting (DAT) in Hidrolândia (A), Itaberaí (B), Palmeiras de Goiás (C), Piracanjuba (D) and Silvânia (E), Goiás State, Brazil.

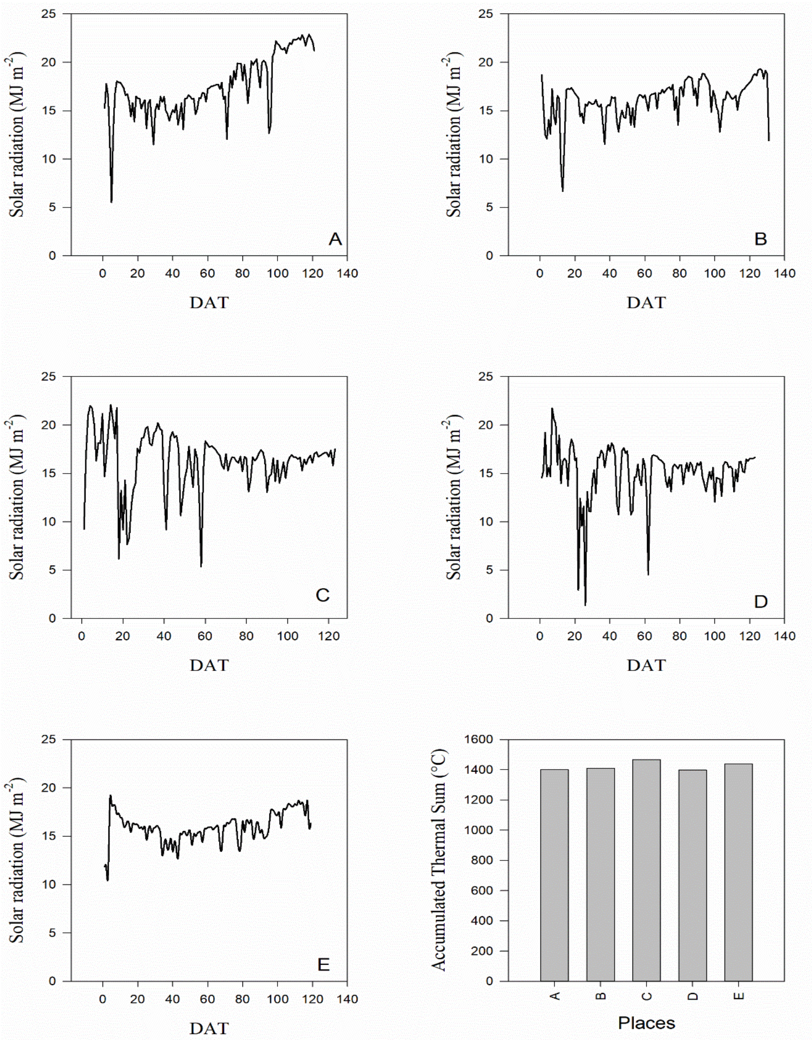

Figure 3. Solar radiation and accumulated thermal sum during the tomato crop cycle in days after transplanting (DAT) in Hidrolândia (A), Itaberaí (B), Palmeiras de Goiás (C), Piracanjuba (D), and Silvânia (E), Goiás State, Brazil.

In Pearson's correlation analysis (Table 2), the meteorological variable with the highest correlation with the morphological variables influencing tomato yield is water availability, showing a correlation of 0.74 with plant height and leaf area index (LAI). This finding aligns with studies by Zhang et al. (2020), Mesquita et al. (2019a), and Mesquita et al. (2019b), which demonstrated a direct relationship between water availability and plant height and leaf area index. The application of different soil moisture tensions and water availability levels reduced plant growth parameters in the morphological variables analyzed by up to 30%, directly affecting productivity when higher soil moisture tensions were applied, indicating lower water availability.

Table 2. Pearson's correlation between plant morphological traits and meteorological variables, for industrial tomatoes in the Brazilian Savannah of Goiás State.

Variable		Correlation	Correlation Degree	p-values
Plant height	ATS	0.43	Regular	0.001**
	Tmen	0.41	Regular	0.002**
	Rad	-0.47	Regular	0.002**
	water	0.74	Strong	0**
Number of branches	ATS	0.16	Weak	0.254
	Tmen	0.05	Weak	0.711
	Rad	-0.06	Weak	0.690
	water	0.20	Weak	0.152
LAI	ATS	0.38	Regular	0.005**
	Tmen	0.27	Weak	0.049
	Rad	-0.18	Weak	0.207
	water	0.74	Strong	0**

ATS = accumulated thermal sum; Tmen = mean air temperature; Rad = solar radiation; Water = water availability; LAI = leaf area index.

Canonical correlation analysis (Table 3) revealed a significant effect for the first canonical pair with a coefficient of 0.91, demonstrating the association between weather variables and morphological characters. Weather variable modifications directly influenced morphological characters and subsequently impacted productivity. In the first canonical pair, the leaf area index exhibited the highest absolute value (0.95), indicating a positive relationship with water availability, accumulated thermal sum, and average air temperature in order of importance, and a negative relationship with accumulated solar radiation during the cycle.

Table 3. Canonical loadings for key determinants of tomato productivity for industrial processing in the Brazilian Savannah of Goiás State.

Variable	Group I		
	1º*	2º	3º
Plant height	0.89	0.42	0.16
Number of branches	0.37	-0.02	0.93
LAI	0.95	-0.30	0.07
		Group II	
ATS	0.47	0.22	0.14
Tmen	0.42	0.52	-0.74
Rad	-0.37	-0.90	0.22
Water	0.90	0.18	-0.37
r	0.91	0.50	0.28
GL	12	6	2

*Canonical pair significant by chi-square test at 5%; LAI = leaf area index; ATS = accumulated thermal sum; Tmen = mean air temperature; Rad = solar radiation; Water = water availability. r = determination coefficient; GL = degrees of freedom.

In the Stepwise regression method, the water variable was the first to be selected and contributed the most to the models, while solar radiation had the lowest participation and contribution. This aligns with findings by Zhang et al. (2020) and Agbna et al. (2017), emphasizing the significant impact of water supply on crop growth, particularly in terms of plant height, which subsequently influences productivity. Greater plant height was associated with higher fruit productivity in the study.

The equations generated by Stepwise regressions indicate that tomato productivity for industrial processing is influenced by a combination of variables (Table 4). This observation is consistent with studies by Schwerz et al. (2018) and Knapp et al. (2021), which also found that a set of weather variables collectively determines crop growth and development.

Table 4. Regression models for the morphological traits plant height, number of branches, and leaf area index, determinants of tomato productivity for industrial processing in the Brazilian Savannah of Goiás State.

Variable	Regression equation	R^2	Contribution
Plant height	0.040418 * (1.52892 * water – 1.08441 * Tmen – 0.6167 * Rad – 0.51209 * ATS)	0.97	Water = 86.1% Tmen = 5.2% Rad = 1.8% ATS = 4.5%
Number of branches	0.04258 * (0.9414 * water – 0.75563 * Tmen)	0.6	Water = 25.5% Tmen = 34.5%
LAI	0.0071 * (1.73621 * water – 0.89096 * Tmen – 0.43313 * ATS)	0.98	Water = 79.7% Tmen = 12.1% ATS = 6.5%

ATS = accumulated thermal sum; Tmen = mean air temperature; Rad = solar radiation; Water = water availability; LAI = leaf area index.

From the results of Pearson's correlation analysis (Table 2), canonical correlations (Table 3), and Stepwise regression (Table 4), it can be concluded that water availability is the primary variable influencing the development and productivity of tomatoes for industrial processing in the conditions of the Brazilian Savannah of Goiás. Correct irrigation management is responsible for an 86.1% increase in plant height and a 79.7% boost in leaf area index, highlighting the critical importance of precise irrigation management in optimizing crop growth. These findings are consistent with studies by Mesquita et al. (2019a) and Agele, Iremiren, and Ojeniyi (2011), which emphasize the impact of water availability on leaf area and plant height, underscoring the necessity of proper irrigation management to enhance productivity and water use efficiency.

Conclusion

The findings of this study have refuted the initial hypothesis that air temperature is the primary variable influencing the growth of tomatoes for industrial processing. Instead, they underscore the paramount importance of accurate irrigation management in tomato cultivation for industrial processing. Adequate water supply significantly enhances plant growth, accounting for 86.2% of the variance in plant height and 79.6% in leaf area index. In contrast, the influence of other meteorological variables during the crop establishment phase was found to be relatively low. This highlights that the predominant factor affecting crop growth and development is the often incorrect irrigation practices employed by producers.

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