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Relationship between the Dynamic Characteristics of Tomato Plant Height and Leaf Area Index with Yield, under Aerated Drip Irrigation and Nitrogen Application in Greenhouses

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Abstract: The current study was undertaken to investigate the dynamic characteristics of the tomato crop, such as its plant height and leaf area index (*LAI*), based on the effective cumulative temperature. This was assessed under aerated drip irrigation (ADI) conditions and the application of a specific nitrogen (N) dose, and their relationship with the yield of the crop was formulated. The study was conducted in a greenhouse located in Zhengzhou, Henan province, China. The assessment conditions were the two irrigation methods, ADI and conventional drip irrigation (CK), and the three N application rates, i.e., 0, 140, and 210 kg ha^{-1}. The logistic and Richards models were used to fit dynamic equations for plant height and *LAI* under the different treatments to quantify the characteristic parameters and understand their relationship with yield. The results revealed that the growth of the tomato plant fitted well with the logistic and Richards model at $R^2 > 0.98$ ($p < 0.01$), regardless of the treatments. ADI and N application were found to significantly increase the maximum growth rate and average growth rate over the rapid growth period based on the tomato plant height and *LAI*. They were also noted to reduce the effective cumulative temperature at which plant height entered the rapid growth period ($p < 0.05$), thereby increasing the time spent in the nutritional growth phase. This is an essential precursor for the better development of subsequent reproductive organs. Tomato yields also confirm it: the highest yield of 85.87 t ha^{-1} was obtained with 210 kg N ha^{-1} for the ADI treatment, with an increase of 13.8%, 12.2%, and 39.6% compared to the CK–210 kg N ha^{-1}, ADI–140 kg N ha^{-1}, and ADI–0 kg N ha^{-1} treatments, respectively ($p < 0.05$). Grey correlation analysis showed that the characteristic parameters closely related to yield were all from the ADI and N application treatments. Furthermore, it was observed that the effective cumulative temperature and the maximum growth rate of the *LAI* at which the *LAI* entered the slow growth phase were the key growth characteristic parameters affecting tomato yield. This study provides a scientific basis for regulating the growth dynamics and yield of vegetables in greenhouse facilities under ADI and N application.

Keywords: irrigation; effective cumulative temperature; growth characteristics; logistic model; Richards model; grey correlation analysis

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1. Introduction

In recent years, facility agriculture has been a major pillar of the agriculture sector, and its rapid development has provided new vitality for agricultural production [1]. However, long-term cultivation, high-intensive management, and the water–heat–gas imbalance have led to significant changes in the soil microenvironment of the cultivated area. Groundwater pollution, fertility imbalance, and soil quality degradation have seriously affected soil productivity and are the bottlenecks that limit the sustainable development of facility agriculture [2]. Tomatoes are a widely grown cash crop in all regions of the world, and are usually produced in greenhouses. However, conventional irrigation methods often

cause soil saturation in the root zone of the crop, which greatly reduces the permeability and oxygen content of the soil [3]. This results in soil hypoxia, which causes stunted root growth and development, delayed uptake of nutrients from the soil, and increased leaching of fertilizers [4]. Intensive tillage practices and short crop rotations have degraded the soil quality, thereby decreasing crop productivity in many parts of the world [5,6]. As an extension of traditional irrigation, aerated drip irrigation (ADI) produces microbubbles that have a large surface area, longer retention time in the liquid, and the ability to deliver oxygen continuously to water [7,8]. Nitrogen (N) is a vital nutrient that influences plant growth, as well as the quality and quantity of the produce [9]. By delivering oxygenated water and nitrogen fertilizer to the root zone of the crop, soil hypoxia can be alleviated, resulting in improved soil fertility [10,11] and providing a better microenvironment for the growth and development of the crop. Therefore, the effective combination of ADI and N fertilizer application is critical to ensure good crop growth for a high and stable yield.

The plant stalk is a channel for transporting water, nutrients, and organic matter. The apical dominance effect causes the stalk to grow upward while also promoting the uniform distribution of the leaves, thereby facilitating the absorption and utilization of light energy. Plant height is one of the major agronomic traits that are used to characterize the stalks of the crops. An excessive increase or decrease in plant height is not a conducive characteristic for the accumulation of photosynthetic products and significantly affects the yield [12]. The leaf area index (*LAI*) is a vital indicator that is needed to characterize the variation in leaf area in crop populations and for crop growth simulation. Its magnitude is closely related to the yield level [13]. Effective cumulative temperature (ECT) is a vital meteorological factor that affects crop growth and development. It is usually used to quantify the combined effect of air temperature and the representative temperature on crop growth, thereby eliminating the ineffective cumulative temperature, which does not affect crop growth and development. The effective cumulative temperature more objectively and accurately describes the thermal requirements of crop growth, which is more scientifically meaningful than crop growth simulation with fertility days as a step unit [14–17]. The current quantitative description of crop growth dynamics is mainly performed using non-linear functions. The sigmoid curve, a typical non-linear model class, is often used to quantitatively model the plant height, leaf area index, dry matter mass, and nitrogen fertilizer application [7,18–20]. The logistic [21] and Richards models [22] are sigmoid non-linear models commonly used in growth analysis and have been used for the growth modeling of many crops, such as tomato [23,24], pepper [25], pumpkin [26], winter wheat, and summer maize [15]. Fang et al. reported that logistic models are closer to predicting tomato growth and adjusting field work schedules to improve the efficiency of the greenhouse production of tomatoes compared to Gompertz models [17]. However, no study has been reported on the relationship between the dynamic characteristics of plant height and *LAI*, which are important growth indicators affecting tomato yield, and the effective cumulative temperature under the synergistic effect of ADI and N application. In the current investigation, we simulated the relationship between plant height, *LAI*, and yield under ADI and N application conditions, using effective cumulative temperature as the independent variable.

The objectives of the current study were to: (a) apply the logistic and Richards models in tomato, for modeling the dynamics of plant height and *LAI* under ADI and N application, (b) work out the regression equations of the characteristic parameters of plant height and *LAI* with the yield, to clarify the key characteristic parameters affecting tomato yield, and (c) utilize the effective cumulative temperature to predict the growth dynamics of the plant height and *LAI* in tomato, to provide a scientific basis for quantitative analysis of the crop growth dynamics.

2. Materials and Methods

2.1. Experimental Site

Field experiments were conducted on tomato in a solar greenhouse from 15 September 2021 to 12 January 2022 at the Agricultural High-Efficiency Water Use Test Site of the North China University of Water Resources and Electric Power at Zhengzhou, located in Henan Province (China, 34°47′ N, 113°46′ E, altitude 110.4 m). The study area belongs to a temperate continental climate with a long-term annual mean air temperature of 17.1 °C. The annual mean precipitation is 630 mm, 2400 annual sunshine hours, and 220 d frost-free period. The solar greenhouse is a ridge-type structure that spans 9.6 m and has a bay of 4 m, for a total area of 537.6 m^2. As is common for the area, the greenhouse is configured east–west to trap maximize solar radiation. It is equipped with a meteorological observation station inside the greenhouse, which eliminates any interference from natural rainfall. The temperature and humidity during the tomato growing period inside the greenhouse are presented in Figure 1.

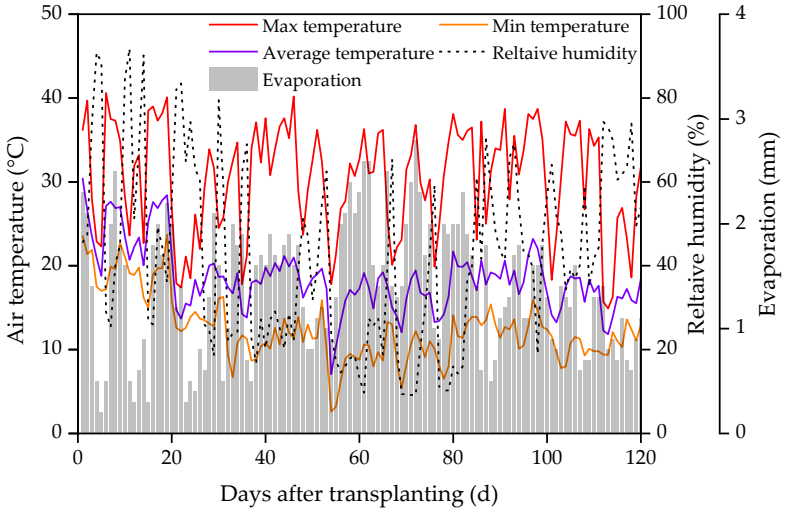


Figure 1. Daily evaporation, daily air temperature (including daily maximum, minimum, and average), and daily relative humidity (RH) during the growing season of greenhouse tomato.

The soil type is clay soil. At the 0–20 cm soil depths, the organic matter content was 20.14 g kg^{-1}, with a total N of 1.04 g kg^{-1}, total P of 0.93 g kg^{-1}, and a total K of 28.69 g kg^{-1}. The average dry bulk density of soil in the 0–40 cm soil layer was 1.46 g cm^{-3}, pH value was 7.79, and the field capacity was 28.00%. The soil particle composition was as follows: gravel mass fraction, 32.99%; powder particle mass fraction, 34.03%; and clay particle mass fraction, 32.98%.

2.2. Experimental Design

The experiment was laid in a randomized split-plot design; aerated drip irrigation (ADI) and conventional drip irrigation (CK) were randomly assigned to the main plots. Three rates of N application (0, 140, and 210 kg ha^{-1}) were randomly assigned to the subplots within each main plot, including conventional N fertilization (N_2, 210 kg ha^{-1}), 2/3 of conventional N fertilizer (N_1, 140 kg ha^{-1}), and non-N fertilization (N_0, 0 kg ha^{-1}). All the experiments had six treatments and each treatment had three replicate plots. Sources of N, P, and K fertilizers applied in the present study were urea (N $\geq$ 46% by weight), calcium superphosphate ($P_2O_5 \geq 12\%$), and potassium sulfate ($K_2O \geq 51\%$), respectively. Calcium superphosphate and potassium sulfate were broadcast at 150 kg P_2O_5 ha^{-1} and 200 kg K_2O ha^{-1} as the basal fertilizers one day before transplanting for the tomato experiments; 40% of the total nitrogen was supplied as the basal fertilizer in each nitrogen treatment plot; the remaining N fertilizer was supplied in 3 equal amounts at 38, 63, and 81 days after transplanting through a drip irrigation.

The tomato variety used for the experiment was 'Dongsheng 6876'. A ridge was an experimental plot, measuring 4.0 m long and 0.6 m wide, with 33 cm between plants within rows, and accommodating 12 tomato plants (Figure 2a). Just after transplanting, 20 mm water was applied to keep tomato seedlings alive. The soil surface was covered by a polyethylene film. An underground drip irrigation tube (16 mm in diameter, 33 cm between drips) was laid in the center of each cultivation plot, and the buried depth was 15 cm (Figure 2b). The water flow of the drips was 1.2 L h^{-1}, the water supply pressure at the inlet of the pipeline was 0.1 MPa.

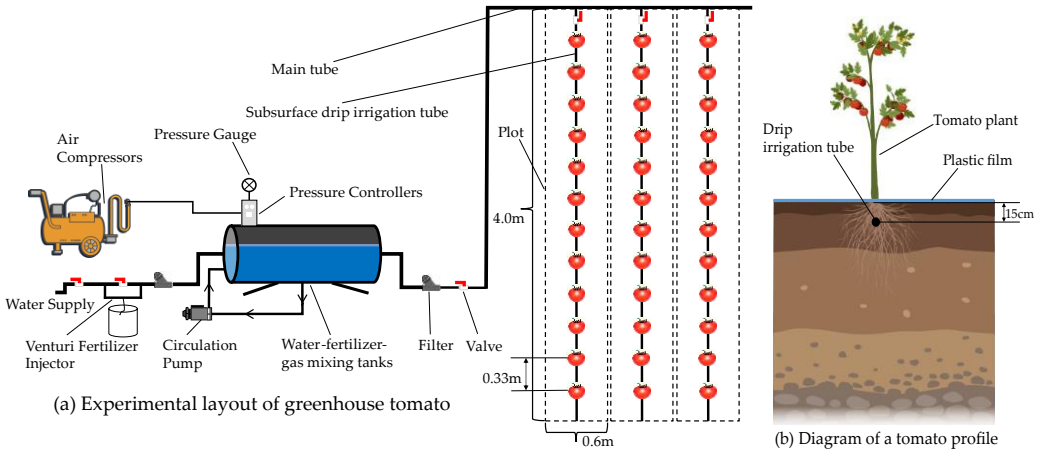


Figure 2. Diagram of experimental layout (**a**) and plant profile (**b**) of greenhouse tomato.

ADI used aerated water by ADI system (Figure 2a), including storage lines, circulation pumps, Mazzei air injector 684, (Mazzei Injector Company, Bakersfield, CA, USA), and other equipment to circulate aeration for 20 min to produce irrigation water with an air void fraction of 15%, while CK used groundwater for irrigation with an independent water supply device. Irrigation occurred once every 7–10 days based on cumulative evaporation between two irrigation intervals in evaporation pan (20 cm in diameter and 9 cm in depth). Each plot was equipped with a flow meter and control valve to control the water volume. The total irrigation amount and irrigation time for the crop growing season were 155.8 mm and 13 time, respectively.

2.3. Plant Height and Leaf Area Index (LAI)

Six plants of uniform growth were randomly marked in each experimental plot, and plant height and leaf area were measured every 10 days from the 15th day after transplanting by a straightedge. Then leaf area was derived by summing the rectangular area of each leaf multiplied by a reduction coefficient [27]. Leaf area index (*LAI*) refers to the leaf area of tomato plants per unit area. The equation is as follows:

$$LAI = 0.64(L \cdot W_m)/(S_l \cdot S_r) \quad (1)$$

where L and W_m are the leaf length (cm) and leaf maximum width (cm), S_l and S_r are the row spacing (cm) and plant spacing (cm), and 0.64 is the reduction coefficient.

2.4. Shoot Biomass and Yield of Tomato

At the fruit harvesting stage, three uniform plant samples were randomly selected from each plot. Plant samples were cut on the ground to obtain the aboveground dry matter (i.e., stems, leaves, and fruits) and underground dry matter (i.e., root). Samples were then placed in an oven at 105 °C for 30 min to deactivate enzymes, followed by 75 °C until a constant dry weight was reached. Aboveground dry matter accumulation is the sum of stem, leaf, and fruit weights [28].

At the fruit maturity stage, we generally select tomato plants that are uniform in growth and free from pests and diseases throughout the whole plot. Eight plants were marked to determine yield in each plot; the single fruit weight and the number of fruits per plant were also recorded for yield calculation.

2.5. Model Description and Application

The logistic model and Richards model were used to quantify the relationship between effective cumulative temperature and greenhouse tomato plant height and *LAI* under ADI.

2.5.1. Effective Cumulative Temperature

The meteorological data for this experiment were obtained from an automatic weather station located in the greenhouse. The following formula was used to calculate the effective cumulative temperature:

$$ECT_i = \sum_{k=1}^{i} \left[\frac{T_{\min} + T_{\max}}{2} - T_b \right] \quad (2)$$

where ECT_i is the effective cumulative temperature from 1 day to i day after transplanting (°C d), $T_{\max}$ and $T_{\min}$ are the daily maximum and minimum temperature values (°C), respectively, and T_b is the base temperature of 10 °C for greenhouse tomato [29].

2.5.2. Logistic Model

Non-linear regression fitting of tomato plant height and *LAI* using a logistic model, respectively. The expressions are as follows [15]:

$$Y = \frac{a}{(1 + b \cdot \exp(-k \cdot x))} \quad (3)$$

where Y is the plant height or *LAI* of tomato, a is the maximum plant height or *LAI* in tomato, t is the effective cumulative temperature (°C d), and b and k are constants.

Characteristic parameters of the logistic model are calculated as follows:

$$v_1 = \frac{ka}{4} \quad (4)$$

$$v_2 = \frac{a}{\sqrt{3}(t_3 - t_2)} \quad (5)$$

$$t_1 = \frac{\ln b}{k} \quad (6)$$

$$t_2 = \frac{1}{k} \ln \frac{b}{2+\sqrt{3}} \quad (7)$$

$$t_3 = \frac{1}{k} \ln \frac{b}{2-\sqrt{3}} \quad (8)$$

where v_1 and v_2 are the maximum growth rate and average growth rate during the rapid growth stage (cm °C $^{-1}$ d^{-1} for plant height, and cm^2 cm^{-2} °C $^{-1}$ d^{-1} for *LAI*), respectively, t_1 (°C d) is the effective cumulative temperature when growth rate reaches the maximum value, and t_2 and t_3 (°C d) are the start and end time nodes of the rapid growth period, respectively. In terms of growth stages, 0~t_2 is the gradual growth stage, t_2~t_3 is the rapid growth stage, t_3~∞ is the slow growth stage.

2.5.3. Richards Model

The Richards model is a four-parameter non-linear equation; the equation is as follows:

$$Y = A/(1 + \exp(B - Cx))^{1/D} \quad (9)$$

where Y is the plant height or *LAI* of tomato, A is the maximum plant height or *LAI* in tomato, x is the effective cumulative temperature (°C d), and B, C, and D are parameters.

The characteristic parameters of the Richards model are calculated as follows:

$$Rmax = AC(D+1)^{-(1+1/D)} \tag{10}$$

$$Ravg = AC/(2D+4) \tag{11}$$

$$x_1 = (B - \ln D)/C \tag{12}$$

$$x_2 = \ln\left(\frac{3\exp(B) - \exp(B)\sqrt{D^2+6D+5} + D\exp(B)}{2D}\right)/C \tag{13}$$

$$x_3 = \ln\left(\frac{3\exp(B) + \exp(B)\sqrt{D^2+6D+5} + D\exp(B)}{2D}\right)/C \tag{14}$$

where *Rmax* and *Ravg* are the maximum growth rate and average growth rate during the rapid growth stage (cm °C $^{-1}$ d^{-1} for plant height, cm^2 cm^{-2} °C $^{-1}$ d^{-1} for *LAI*), respectively, x_1 (°C d) is the effective cumulative temperature when growth rate reaches the maximum value, and x_2 and x_3 (°C d) are the start and end time nodes of the rapid growth period, respectively.

2.6. Grey Correlation Analysis

Grey correlation analysis is a quantitative description and comparison of the development of and change in a system. In this study, the yield of tomato was used as the reference series (X_0) and growth characteristic parameters as the comparison series (X_i). The relative relationships between yield and growth characteristic parameters of tomato could be clarified through grey system correlation analysis. The correlation coefficient can be calculated using the following Formula [30]:

$$\xi_i(k) = \frac{(\Delta X_{\min} + \rho\Delta_{\max})}{\Delta X_{i(k)} + \rho\Delta X_{\max}} \tag{15}$$

where $\Delta X_{\min}$ and $\Delta X_{\max}$ are the minimum and maximum absolute differences of all comparison sequences at each time, respectively. $\Delta X_{i(k)}$ is the absolute difference between the two comparison sequences at time k, and ρ is resolution coefficient, taken as 0.5.

The degree of relevance is calculated as follows [30]:

$$r_i = \frac{1}{n}\sum_{k=1}^{n}\xi_i(k) \tag{16}$$

where r_i is the degree of association between subsequence i and parent sequence 0, and n is the length of the comparison sequence.

2.7. Statistical Analysis

All data were analyzed using Excel 2019 (Microsoft Corp., Redmond, WA, USA). The fitting of the logistic model and Richards model was performed with Curve Expert Professional. data analysis with SPSS 22.0 software (SPSS Inc., Chicago, IL, USA). The significance of differences among treatments were tested by two-way analyses of variance (ANOVAs), and the means were compared by Duncan's multiple range tests at a significant level of p = 0.05. Correlation analysis and grey correlation analysis were completed using SPSS 22.0. The figures were generated using Origin 2022 and PowerPoint 2019 (Origin Lab Corp., Microsoft Corp., Redmond, WA, USA). R^2, *nRMSE*, and *EF* were also used to evaluate the performance of the proposed model.

$$R^2 = \left[\frac{\sum_{i=1}^{n}(S_i - \overline{S})(P_i - \overline{P})}{\sqrt{\sum_{i=1}^{n}(S_i - \overline{S})^2}\sqrt{\sum_{i=1}^{n}(P_i - \overline{P})^2}}\right] \tag{17}$$

$$nRMSE = \frac{RMSE}{\overline{S}} \times 100\% \quad (18)$$

$$EF = 1.0 - \frac{\sum_{i=1}^{n} (S_i - P_i)^2}{\sum_{i=1}^{n} (S_i - \overline{S})^2} \quad (19)$$

where S_i and P_i ($i = 1, 2, \ldots, n$) are the observed and predicted data, respectively, and $\overline{S}$ and $\overline{P}$ are the respective mean values. n is the number of observations. A better performance of the fitted procedure will have $R^2 \approx EF \approx 1$ and $nRMSE \approx 0$ [31–33].

3. Results

3.1. Plant Height and LAI

The 'S'–shaped dynamic changes in the tomato plant height and leaf area index (*LAI*) with effective cumulative temperature under different treatments are shown in Figure 3. Under ADI, the maximum plant height of tomatoes was 1.1%, 3.4%, and 4.7% higher than that of the CK treatments for N_0, N_1, and N_2, respectively. Moreover, the maximum *LAI* of the crop in the N_0, N_1 and N_2 treatments with ADI was an average of 3.71 cm^2 cm^{-2}, which was 7.2% higher than that of the CK in the N_0, N_1, and N_2 treatments.

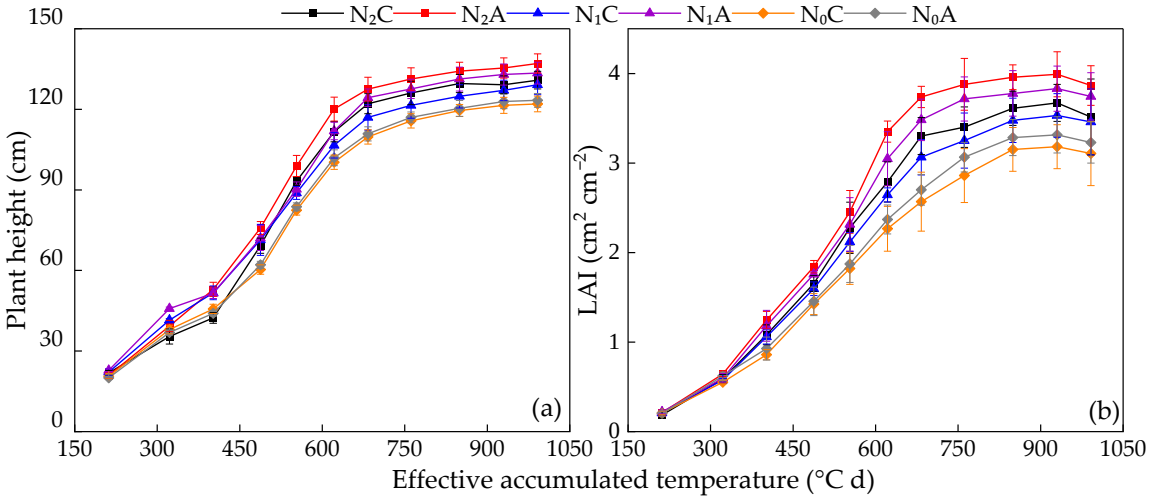


Figure 3. Dynamic changes in tomato plant height (**a**) and *LAI* (**b**) with effective accumulated temperature under different treatments.

The plant height and *LAI* of tomatoes were found to be increased by varying degrees in response to the different N fertilizer management practices. Under the two irrigation methods, the plant height and *LAI* of tomato were found to be generally increased with increasing nitrogen application rate, reaching a maximum under N_2A and N_2C treatments, respectively.

3.2. Fitting of Equation Based on Logistic and Richards Models

The fitting parameters of the logistic model and Richards model for tomato plant height and *LAI* dynamics under different treatments are shown in Table 1. Using the logistic model, with the effective cumulative temperature as the independent variable, the fitted R^2 values of the plant height and *LAI* under the different treatment conditions were 0.987–0.994 and 0.993–0.998, respectively, at extremely significant levels ($p < 0.01$). The logistic model for the plant height and *LAI* exhibited the largest range of variation for parameter '*b*' with a CV of 0.30 and 0.35, respectively, and the smallest range of variation was observed for parameter '*a*' with a CV of 0.04 and 0.08, respectively.

Using the Richards model, the fitted R^2 values for plant height and *LAI* under the different treatment conditions were greater than 0.996 and 0.997 ($p < 0.01$). The Richards model for the plant height and *LAI* varied the most for parameter '*D*' with a CV of 0.17 and 0.44, respectively, while parameter '*A*' varied the least with a CV of 0.04 and 0.07, respectively.

Table 1. Fitting parameters of logistic and Richards models for plant height and *LAI* dynamics under different treatments.

Index	Treatments	Parameters of Logistic Model			R^2	Parameters of Richards Model				R^2
		a	b	k		A	B	C	D	
Plant height	N_0C	127.37 ± 2.77	29.89 ± 2.28	0.007 ± 0.001	0.989 **	120.86 ± 2.74	11.46 ± 1.70	0.018 ± 0.001	4.54 ± 0.15	0.997 **
	N_0A	128.00 ± 2.62	34.62 ± 2.09	0.008 ± 0.001	0.990 **	122.08 ± 1.98	10.80 ± 1.16	0.017 ± 0.001	4.08 ± 0.14	0.997 **
	N_1C	132.11 ± 3.59	27.05 ± 2.20	0.007 ± 0.001	0.994 **	126.90 ± 1.68	9.04 ± 1.34	0.015 ± 0.001	3.61 ± 0.12	0.998 **
	N_1A	139.31 ± 3.22	27.21 ± 2.79	0.007 ± 0.001	0.987 **	132.14 ± 2.10	13.93 ± 1.48	0.021 ± 0.001	5.85 ± 0.17	0.996 **
	N_2C	135.67 ± 2.25	53.49 ± 2.11	0.009 ± 0.001	0.988 **	130.35 ± 2.51	11.98 ± 1.37	0.019 ± 0.001	4.16 ± 0.16	0.997 **
	N_2A	139.51 ± 2.45	46.11 ± 2.88	0.009 ± 0.001	0.992 **	134.67 ± 2.06	11.66 ± 1.25	0.019 ± 0.001	4.23 ± 0.16	0.999 **
	Coefficient of variation, *CV*	0.04	0.30	0.13		0.04	0.14	0.11	0.17	
LAI	N_0C	3.26 ± 0.18	78.26 ± 2.01	0.008 ± 0.001	0.998 **	3.24 ± 0.11	4.77 ± 0.15	0.009 ± 0.001	1.14 ± 0.17	0.998 **
	N_0A	3.41 ± 0.12	77.73 ± 2.08	0.008 ± 0.001	0.997 **	3.35 ± 0.13	6.26 ± 0.17	0.011 ± 0.001	1.65 ± 0.09	0.998 **
	N_1C	3.58 ± 0.19	102.44 ± 1.75	0.009 ± 0.001	0.998 **	3.55 ± 0.11	5.80 ± 0.14	0.010 ± 0.001	1.39 ± 0.10	0.999 **
	N_1A	3.89 ± 0.21	146.26 ± 1.56	0.010 ± 0.001	0.996 **	3.81 ± 0.10	9.24 ± 0.15	0.015 ± 0.001	2.40 ± 0.11	0.998 **
	N_2C	3.68 ± 0.19	138.11 ± 2.01	0.010 ± 0.001	0.996 **	3.63 ± 0.08	7.11 ± 0.15	0.013 ± 0.001	1.71 ± 0.13	0.997 **
	N_2A	4.05 ± 0.21	183.77 ± 3.59	0.011 ± 0.001	0.993 **	3.94 ± 0.14	12.93 ± 0.68	0.021 ± 0.001	3.48 ± 0.12	0.997 **
	Coefficient of variation, *CV*	0.08	0.35	0.13		0.07	0.39	0.33	0.44	

Note: N_0, N_1, and N_2 indicates N fertilization rate of 0, 140, and 210 kg ha^{-1}; A represents the aerated drip irrigation method, and C represents the conventional drip irrigation methods; ** identify significant differences at $p < 0.01$.

The *r*, *nRMSE*, and *EF* for the observed and the simulated plant height by the logistic model were 0.993, 6.22%, and 0.779, while the *r*, *nRMSE*, and *EF* for the observed and the simulated *LAI* were 0.998, 4.53%, and 0.918. The *r*, *nRMSE*, and *EF* for the observed and the simulated plant height by the Richards model were 0.998, 2.68%, and 0.958, while the *r*, *nRMSE*, and *EF* for the observed and the simulated *LAI* were 0.998, 4.53% and 0.920 (Figure 4). The results show that the logistic and Richards models can accurately simulate the variation in plant height and *LAI* with effective cumulative temperature and can be relied on to further analyze the effect of different treatments on the growth process of the plant height and *LAI* in tomato.

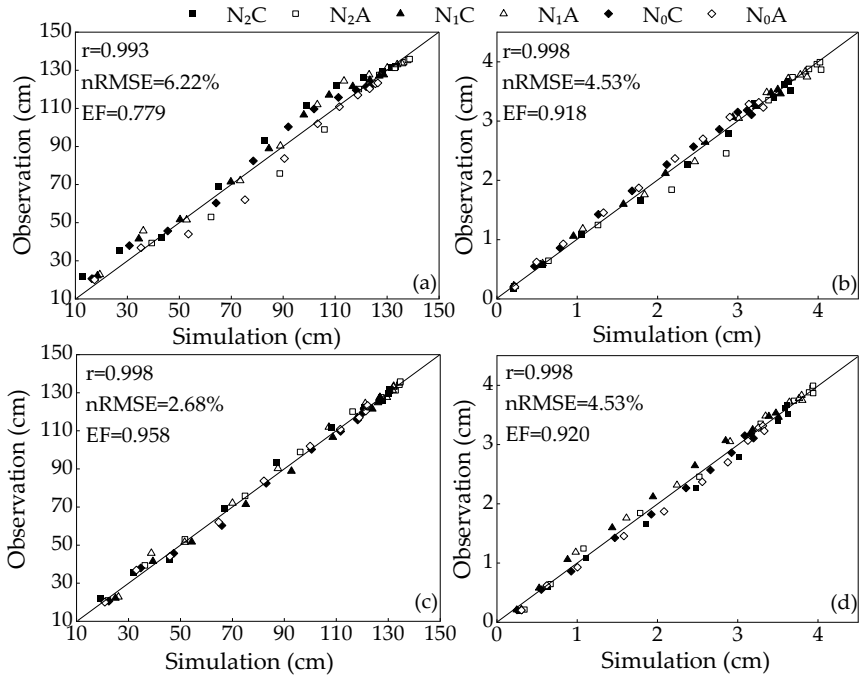


Figure 4. Observed and simulated values of tomato plant height and *LAI* of logistic (**a**,**b**) and Richards models (**c**,**d**) under different treatments.

3.3. Characteristic Parameters Plant Height of Tomato

The characteristic parameters under different treatments in the logistic model are shown in Table 2. At 0, 140, and 210 kg N ha^{-1}, the Hv_1 and Hv_2 of tomato under ADI were higher than in CK treatments. In particular, the Hv_1 and Hv_2 of N_0A treatment were increased by 14.8% and 15.4%, respectively, over the N_0C treatments, and the Ht_1 of N_0A treatment was reduced by 42.3 °C d compared to the N_0C treatments, both at a significant level ($p < 0.05$). Under CK, the Hv_1 and Hv_2 of tomato were significantly increased by 36.8% and 37.4%, respectively, at N_2 treatment compared to that of N_0 treatment, whereas under ADI, the Hv_1 and Hv_2 of tomato were significantly ($p < 0.05$) increased by 22.7% and 22.2%, respectively, at N_2 treatment over that of N_0 treatment.

The analysis of the characteristic parameters of the Richards model (Table 2) shows that the *HRmax*, Hx_2, and Hx_3 of tomato under ADI was significantly higher ($p < 0.05$) than that of the respective treatments under CK at 140 kg N ha^{-1}. Under CK, at N_2 treatment, the *HRmax* of tomato was significantly ($p < 0.05$) increased by 20.0% and 20.5% compared to that of N_1 and N_0 treatments, respectively. Under ADI, the *HRmax* of tomato at N_2 and N_1 treatments were significantly ($p < 0.05$) increased by 20.8% and 6.6%, respectively, over the N_0 treatment.

The *HRmax* and *HRavg* of tomato were found to be increased with the improvement in the N application level under both the irrigation methods, reaching a maximum of 0.331 and 0.205 cm $(°C\ d)^{-1}$, respectively, at N_2A. Under CK treatments, the difference between Hx_2 and Hx_3 of tomato was not significant. However, the Hx_2 and Hx_3 of tomato were initially increased and later decreased, with the improvement in N application level under ADI treatments reaching a minimum of 434.7 and 640.9 °C d, respectively, at 210 kg N ha^{-1}. Conventional N application (210 kg N ha^{-1}) required a lower cumulative temperature to reach the critical period of tomato growth under ADI.

3.4. Characteristic Parameters of LAI

The characteristic parameters of the logistic model under different treatments are shown in Table 3. At 140 and 210 kg N ha^{-1}, the Lv_1 and Lv_2 of tomato under ADI were significantly higher than those of the corresponding treatments under CK, while the Lt_3 of tomato reduced at a significant level ($p < 0.05$). Under ADI, the Lv_2 of tomato at 140 and 210 kg N ha^{-1} was significantly increased by 50.0% and 66.7%, respectively, over the 0 kg N ha^{-1}. The Lv_1 of tomato was increased with the improvement in the N application level, while the Lt_1, Lt_2, and Lt_3 of tomato decreased with the improvement in the N application level.

The analysis of the characteristic parameters of the Richards model (Table 3) shows that under ADI treatments, the *LRmax*, and *LRavg* of tomato at 140 and 210 kg N ha^{-1} levels were significantly higher ($p < 0.05$) than those of CK, while significantly ($p < 0.05$) increasing the Hx_1 of tomato from 505.7 °C d at N_2C treatment to 556.3 °C d at N_2A treatment. Notably, the Ht_3 of tomato was initially increased but later decreased with the improvement in the N application level under both of the irrigation methods.

3.5. Dry Matter Accumulation and Yield of Tomato

The accumulation of dry weight in tomato under different treatments increased gradually but consistently (Figure 5). The dry weight accumulation increased to varying degrees in response to the ADI and N fertilizer application treatments. The aboveground dry weight at the fruit mature stage with ADI was 4.2%, 9.3%, and 6.0% higher than that of the CK treatments at the 0, 140, and 210 kg N ha^{-1} levels, respectively ($p < 0.05$). Compared with the CK treatments, the aboveground dry weight at the fruit expanding stage with ADI was significantly ($p < 0.05$) increased by 10.9% and 13.8% in the 140 and 210 kg N ha^{-1} treatments, respectively. The underground dry weight of N_2A at the fruit expanding stage and mature stage was, significantly ($p < 0.05$), 1.07–fold higher than in the corresponding N_2C treatments.

Table 2. Characteristic parameters describing plant height dynamic process of tomato under different treatments.

Treatments	Characteristic Parameters of Logistic Model					Characteristic Parameters of Richards Model				
	Ht_1	Ht_2	Ht_3	Hv_1	Hv_2	Hx_1	Hx_2	Hx_3	*HRmax*	*HRavg*
	(°C d)			(cm (°C d)$^{-1}$)		(°C d)			(cm (°C d)$^{-1}$)	
N_0C	485.4 ± 12.0 a	297.2 ± 21.2 a	637.5 ± 11.5 ab	0.223 ± 0.01 d	0.195 ± 0.01 d	552.6 ± 12.6 ab	441.4 ± 11.7 b	663.9 ± 13.4 ab	0.269 ± 0.01 c	0.166 ± 0.02 c
N_0A	443.1 ± 14.5 bc	278.4 ± 11.7 a	607.7 ± 21.7 bc	0.256 ± 0.01 b	0.225 ± 0.01 b	542.3 ± 10.6 ab	438.7 ± 7.4 b	666.5 ± 10.7 ab	0.274 ± 0.01 c	0.171 ± 0.02 bc
N_1C	471.1 ± 21.1 ab	283.0 ± 12.3 a	659.2 ± 14.9 a	0.231 ± 0.01 cd	0.203 ± 0.01 cd	517.1 ± 10.9 c	392.8 ± 8.0 b	641.4 ± 17.1 b	0.270 ± 0.01 c	0.170 ± 0.02 bc
N_1A	471.9 ± 20.9 ab	283.8 ± 9.6 a	660.1 ± 18.2 a	0.244 ± 0.01 bc	0.214 ± 0.01 bc	579.2 ± 14.5 a	476.0 ± 9.2 a	682.4 ± 14.3 a	0.292 ± 0.01 b	0.177 ± 0.02 abc
N_2C	442.2 ± 17.1 bc	295.8 ± 16.2 a	588.5 ± 17.2 cd	0.305 ± 0.02 a	0.268 ± 0.01 a	555.5 ± 9.4 ab	453.0 ± 13.4 b	658.1 ± 14.5 ab	0.324 ± 0.01 a	0.201 ± 0.02 ab
N_2A	425.7 ± 16.4 c	279.3 ± 14.1 a	572.0 ± 17.0 d	0.314 ± 0.01 a	0.275 ± 0.01 a	537.8 ± 12.1 bc	434.7 ± 12.0 b	640.9 ± 14.8 b	0.331 ± 0.01 a	0.205 ± 0.02 a
N	*	ns	**	**	**	**	ns	ns	ns	**
I	*	ns	ns	*	*	*	ns	ns	**	ns
N × I	ns	ns	ns	ns	ns	ns	**	*	**	ns

Note: Ht_1, the accumulated temperature required for the maximum growth rate; Ht_2, the accumulated temperature required to enter the rapid increase period; Ht_3, the accumulated temperature required to enter the slow increase period; Hv_1, the maximum growth rate; Hv_2, the average growth rate during the rapid growth period. Hx_1, the accumulated temperature required for the maximum growth rate; Hx_2, the accumulated temperature required to enter the rapid increase period; Hx_3, the accumulated temperature required to enter the slow increase period; *HRmax*, the maximum growth rate; *HRavg*, the average growth rate during the rapid growth period. The different letters indicate significant differences at 0.05. N and I represent the N application rates and irrigation methods, respectively; N × I represents the effect of the interaction between the amount of N application and the irrigation method; N_0, N_1, and N_2 indicate N fertilization rates of 0, 140, and 210 kg ha^{-1}, respectively; A represents the aerated drip irrigation method, and C represents the conventional drip irrigation methods; * and ** identify significant differences at $p < 0.05$ and $p < 0.01$, respectively, and ns identifies no significant difference.

Table 3. Characteristic parameters describing *LAI* process of tomato under different treatments.

Treatments	Characteristic Parameters of Logistic Model					Characteristic Parameters of Richards Model				
	Lt_1	Lt_2	Lt_3	Lv_1	Lv_2	Lx_1	Lx_2	Lx_3	*LRmax*	*LRavg*
	(°C d)			(cm^2 cm^{-2} °C^{-1} d^{-1})		(°C d)			(cm^2 cm^{-2} °C^{-1} d^{-1})	
N_0C	545.0 ± 14.0 a	380.4 ± 8.4 a	709.6 ± 10.6 a	0.007 ± 0.001 c	0.006 ± 0.001 d	515.4 ± 15.3 c	364.7 ± 13.8 c	666.2 ± 11.0 ab	0.007 ± 0.001 c	0.005 ± 0.001 c
N_0A	544.2 ± 14.6 a	379.5 ± 14.8 a	708.8 ± 15.3 a	0.007 ± 0.001 c	0.006 ± 0.001 d	523.6 ± 13.9 bc	388.4 ± 11.8 bc	658.8 ± 13.0 b	0.008 ± 0.001 c	0.005 ± 0.001 c
N_1C	514.4 ± 14.9 b	368.0 ± 14.1 ab	660.7 ± 16.3 b	0.008 ± 0.001 c	0.007 ± 0.001 cd	547.1 ± 13.4 ab	404.8 ± 12.2 b	689.4 ± 13.5 a	0.008 ± 0.001 c	0.005 ± 0.001 c
N_1A	498.5 ±15.0 bc	366.8 ± 12.0 ab	630.2 ± 13.4 c	0.010 ± 0.001 b	0.009 ± 0.001 ab	557.6 ± 13.7 a	447.6 ± 8.7 a	667.7 ± 11.7 ab	0.010 ± 0.001 b	0.006 ± 0.001 b
N_2C	492.8 ± 15.7 bc	361.1 ± 11.0 ab	624.5 ± 12.2 c	0.009 ± 0.001 b	0.008 ± 0.001 bc	505.7 ± 15.0 c	390.2 ± 12.5 bc	621.1 ± 13.4 c	0.010 ± 0.001 b	0.006 ± 0.001 b
N_2A	474.0 ± 13.6 c	354.3 ± 10.8 b	593.7 ± 8.8 d	0.011 ± 0.001 a	0.010 ± 0.001 a	556.3 ± 10.3 a	468.5 ± 12.8 a	644.1 ± 9.0 bc	0.012 ± 0.001 a	0.008 ± 0.001 a
N	**	*	**	**	**	**	**	**	**	**
I	ns	ns	**	**	**	**	**	ns	**	**
N × I	ns	ns	ns	ns	ns	*	*	*	ns	**

Note: Lt_1, the accumulated temperature required for the maximum growth rate; Lt_2, the accumulated temperature required to enter the rapid increase period; Ht_3, the accumulated temperature required to enter the slow increase period; Lv_1, the maximum growth rate; Hv_2, the average growth rate during the rapid growth period. Lx_1, the accumulated temperature required for the maximum growth rate; Lx_2, the accumulated temperature required to enter the rapid increase period; Lx_3, the accumulated temperature required to enter the slow increase period; *LRmax*, the maximum growth rate; *LRavg*, the average growth rate during the rapid growth period. The different letters indicate significant differences at 0.05. N and I represent the N application rates and irrigation methods, respectively; N × I represents the effect of the interaction between the amount of N application and the irrigation method; N_0, N_1, and N_2 indicate N fertilization rates of 0, 140, and 210 kg ha^{-1}, respectively; A represents the aerated drip irrigation method, and C represents the conventional drip irrigation methods; * and ** identify significant differences at $p < 0.05$ and $p < 0.01$, respectively, and ns identifies no significant difference.

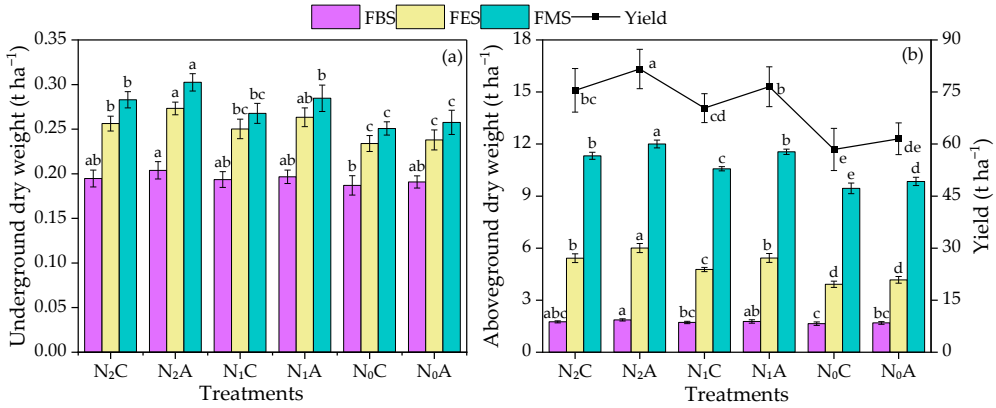


Figure 5. Plant dry matter and yield of tomato under different treatments at different growing stages (**a**) is the underground dry weight of tomato, and (**b**) is the aboveground dry weight and yield of tomato. FBS, FES, and FMS represent the flowering and fruit bearing stage, the fruit expanding stage, and fruit mature stage, respectively. The different letters in the same column indicate significant differences at the level of 0.05.

The yield of tomato was significantly increased by ADI treatments in the 140 and 210 kg N ha^{-1} levels (Figure 5b). Under 140 and 210 kg N ha^{-1} treatments, the yield of tomato under ADI was increased by 11.7% and 13.8% ($p < 0.05$), respectively, compared with the CK treatment. Under the two irrigation methods, the accumulation of dry weight and the yield of tomato were increased with the improvement in the N application level at the three growth stages. The maximum yield was recorded in the N$_2$A treatment at 85.87 t ha^{-1}.

3.6. Grey Correlation Analysis

To evaluate the most suitable growth characteristic parameters under the different treatments, a grey system was established from the logistic and Richards models (Figures 6 and 7). The response index data of the growth characteristic parameters of the model under different treatments were used as the comparison sequence, while the yield of tomato under the different treatments was used as the reference frame. The comparison of the correlation coefficients reveals that under the different irrigation methods (Figure 6a,b), the top three highest-ranked correlations between the growth characteristic parameters of the logistic model and yield were Lv_1, Hv_1, and Lt_3. In comparison, the top three highest-ranked correlations between the characteristic growth parameters and yield for the Richards model were Hx_2, $LRmax$, and Lx_2.

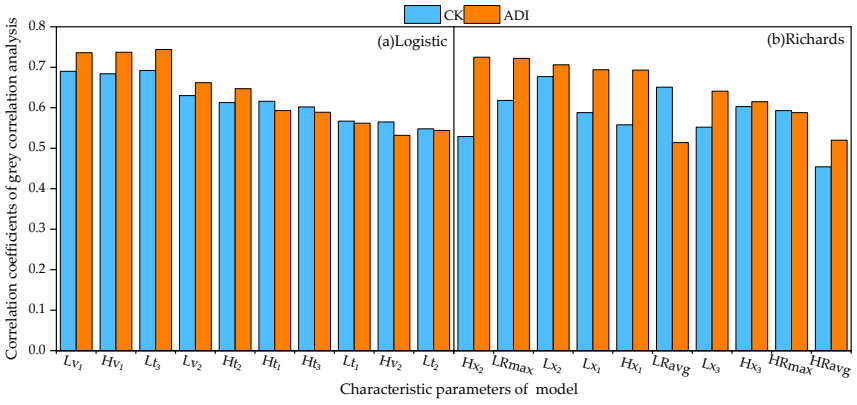


Figure 6. Grey correlation analysis of growth characteristic parameters and yield of tomato under irrigation method treatments. (**a**) is the growth characteristic parameters of Logistic model, and (**b**) is the growth characteristic parameters of Richards model.

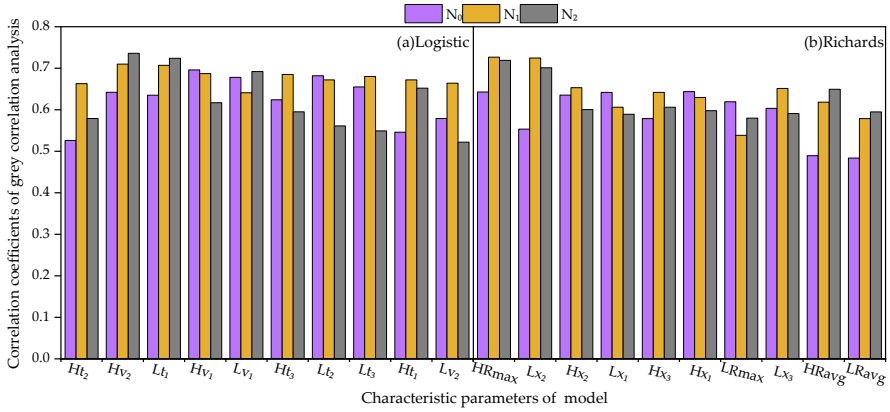


Figure 7. Grey correlation analysis of growth characteristic parameters and yield of tomato under N application rate treatments. N_0, N_1, and N_2 represent 0, 140, and 210 kg ha^{-1} N application rates, respectively. (**a**) is the growth characteristic parameters of Logistic model, and (**b**) is the growth characteristic parameters of Richards model.

The top three parameters with the highest correlation between the two models were from the ADI treatment alone. Under the different N application rates (Figure 7a,b), the growth characteristic parameters of the logistic and Richards models with a correlation above 0.7 with the yield were Hv_2 and Lt_1, and *HRmax* and Lx_2, respectively, and both were obtained from the N_1 and N_2 treatments.

3.7. Relationship between Growth Characteristic Parameters and Yield of Tomato

The correlation analysis between the growth characteristic parameters and the yield is shown in Figure 8. The parameters Hv_1, Hv_2, Lv_1, and Lv_2 were highly significant and positively correlated with the yield (Y), while the parameters Ht_1, Lt_1, Lt_2, and Lt_3 were negatively correlated with the yield ($p < 0.05$, 0.01). The parameters *HRmax*, Lx_2, *LRmax*, and *LRavg* were highly significant and positively correlated with the yield ($p < 0.01$).

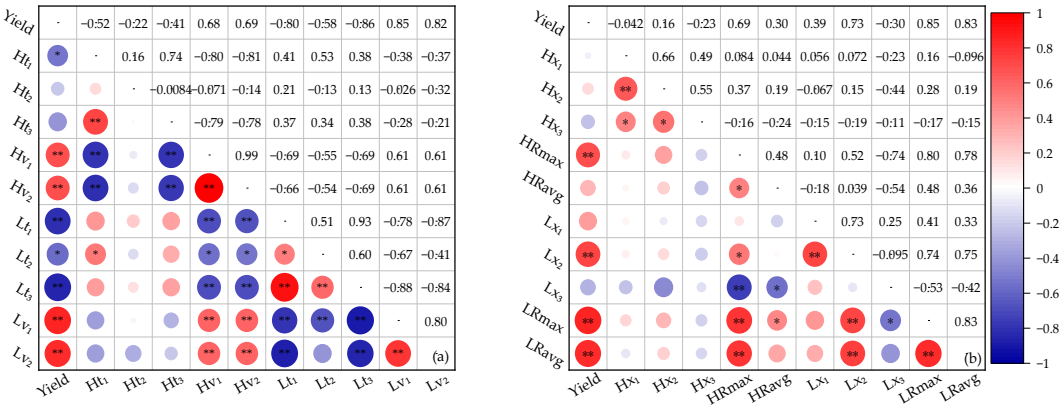


Figure 8. Correlation coefficients between the logistic (**a**) and Richards (**b**) characteristic parameters of model and yield. * and ** identify significant differences at $p < 0.05$ and $p < 0.01$, respectively.

The stepwise regression method was used to establish the optimal regression equation. The growth characteristic parameters were used as independent variables, while the yield of tomato was considered as the dependent variable. According to the corresponding results of the test of significance for the independent variables, Lt_3 was noted to have a significant effect on yield in the logistic model (Table 4). The regression relationship explained 70.2% of the variation in the yield, where the linear equation obtained was $Y = -0.195\ Lt_3 + 198.77$.

In the Richards model, the regression relationship explained 70.2% of the variation in the yield, where the linear equation obtained was Y = 4610.64 *LRmax* + 29.02.

Table 4. Regression coefficient output.

Model	Factors	R^2	Unstandardized Coefficients, B	Standardized Coefficients, Beta	Sig.
Logistic	Constant	0.722	198.77		0.004
	Lt_3		−0.195	−0.859	0.002
Richards	Constant	0.702	29.02		0.001
	LRmax		4610.64	0.848	0.000

4. Discussion

4.1. Model Construction and Analysis of Tomato Plant Height and LAI

Plant height and leaf area are important dynamic indicators of crop growth and development, which are closely related to crop biomass and yield [34]. Soil fertility refers to the ability of the soil to meet the water, nutrient, air, and heat requirements for crop growth and development, which is greatly influenced by soil fertility. Earlier studies have reported that aerated irrigation could improve soil fertility, thereby significantly increasing crop yields [10,35,36]. In the present study, ADI and N application were found to increase the tomato plant height and *LAI* (Figure 3), as was also observed in several other studies [23,37,38].

Cumulative temperature is one of the most important environmental factors that affects crop growth, and has been widely used in crop phenology modeling, agro-meteorological forecasting, and also in the prediction of yield [39]. The study of the quantitative relationship between effective cumulative temperature and crop growth indicators provides a basis for quantitative studies on crop growth dynamics and regulation, and provides essential support for predicting changes in crop yield. Using tomato and aubergine as subjects, and effective cumulative temperature as the independent variable, Hsieh et al. conducted a study in Taiwan to establish the relationship with plant stem thickness using Gompertz, Richards, and logistic models, and reported that the R^2 was greater than 0.70 [24]. Jiao et al. reported that the Gompertz model and logistic model could be used to fit the growth of *A. thaliana* rosette leaves, with $R^2 > 0.86$ [40]. In the present investigation, the logistic and Richards models were used to fit the variety of tomato plant height and *LAI* values with effective cumulative temperature under different treatments, where the R^2 of the fitted equation was above 0.98 for all of the treatments at extremely significant levels (Table 1). In both the models, between the treatments, the measured and simulated values were observed as: *r* being greater than 0.99, *nRMSE* within 10.0%, and *EF* above 0.70 (Figure 4). The logistic and Richards models, based on the effective cumulative temperature, can effectively simulate and predict the dynamic changes in the tomato plant height and leaf area index under the different treatments. The models that are based on effective cumulative temperature are currently applied to a wide range of crops [15,24,41]. However, the response of crop growth indicators to different field management practices, crop varieties, soil quality, and other factors needs further investigation, and the resulting model should be validated using multi-year and multi-location growth data.

4.2. Relationship of Model Characteristic Parameters of Plant Height and LAI of Tomato with Yield

Several biologically significant parameters can be derived from the multi-order derivation of the growth equation, which can be further used to analyze the changes in the crop growth dynamics [34]. In the present study, the logistic and Richards models were used to derive multiple orders for the equations fitted to tomato plant height and *LAI*. The resulting growth process of tomato was divided into three stages, namely, the gradual growth stage, the rapid growth stage, and the slow growth stage. During the process of production, the early transition of the crop leaf area to the fast growth period results in an accelerated rate of the establishment of photosynthetic organs, leading to a greater

accumulation of photosynthetic products. Concurrently, the prolonged duration of the slow growth period is beneficial, as the growth of the nutrient organs is curtailed during this period, whereby most of the photosynthetic products can be utilized for fruit formation. The longer the duration, the better it is for yield improvement [42]. Li et al. used the logistic and Richards models to quantify the dynamic characteristics of the *LAI* and plant height of winter wheat under coupled water and nitrogen conditions, showing that the application of 210 kg N ha^{-1} significantly increased the maximum growth rate of the plant height and *LAI* compared to the treatment without N fertilizer, with a significant reduction in the cumulative temperature required for the maximum growth rate [43]. Xiao et al. found that ADI increased both the maximum growth rate and the average growth rate over the rapid growth period in Pepper by 13.0% and 11.8%, respectively, compared to the CK treatments, which accelerated the formation of the nutrient organs in pepper [44]. The aforementioned results were similar to the findings in the current study.

In our study, we found that N_2 could significantly increase the Hv_1, Lv_1, Hv_2, and Lv_2 compared to N_0 treatment under both irrigation methods (Tables 2 and 3). Under the CK treatments, using the logistic model, the cumulative temperature required for the Ht_1 and Lt_1 decreased with an increasing N application rate. In contrast, the cumulative temperatures required for Hx_1 and Lx_1 in the Richards model did not change significantly (Tables 2 and 3). Different irrigation methods also significantly affected the variation in growth parameters of both models. The Hv_1, Lv_1, Hv_2, Lv_2, and *HRmax*, *LRmax*, *HRavgHRavg*, and *LRavg* were significantly higher under the ADI compared to the CK treatments. However, under the nitrogen application rates (N_2, N_1), the Ht_1, Ht_2, and Ht_3 did not change significantly in the ADI (Tables 2 and 3). Surprisingly, the relevant parameters of the Richards model present a different result. Under ADI, the Ht_2, Ht_3, Lt_2, and Lt_3 tended to initially increase but later decrease with increasing N application, reaching a minimum at the N_2 level. This shows that the N_2 treatment combined with ADI required less cumulative temperature to reach the critical period of growth compared to the N_0 or N_1 treatments. This ensures that the crop continues to grow in the exuberant stage, accumulating more dry matter, thereby contributing to the yield at a later stage, provided that all other external conditions remain the same. This may be due to the fact that ADI increases the oxygen content in the root zone of tomatoes, providing nutrients for root respiration and aerobic soil microorganisms and enzymes, and improves the absorption and use of nutrients by the root system. It also promotes the establishment of the plant canopy structure at an early growing stage, providing sufficient N for crop reproductive growth, thereby improving the N accumulation and its transport to the fruit.

There is an inextricable relationship between crop growth traits and the development of final yield and quality, with crop yield showing an increase with increasing leaf area index within a specific range [45]. Li et al. indicated that the number of grains per square meter in winter wheat was significantly and positively correlated with the mean *LAI*, while the thousand grain quality was significantly and positively correlated with the maximum plant height, where the mean *LAI* played a greater role in determining yield [43]. Song et al. reported that the yield of winter wheat was significantly and positively correlated with the mean and maximum growth rates of the dry matter accumulation process [46]. The present study used correlation and stepwise regression analysis (Figure 8 and Table 4) to find that the model characteristics Lt_3 and *LRmax*, which were significantly correlated with yield, had the most significant effect on yield formation. The grey correlation analysis showed (Figure 6) that the correlation between the parameters Lt_3 and *LRmax*, and yield under aerated drip irrigation was above 0.7. In addition, it was observed (Table 3) that ADI, and N_1 and N_2 applications significantly reduced Lt_3 while significantly increasing *LRmax* compared to the CK and N_0 application treatments. This promoted favorable growth in leaf area, resulting in a positive impact on yield formation. Jo et al. also confirmed that the fruit number increased with the higher *LAI* [13]. In the current scenario, the study of crop dry matter quality and nutrient accumulation using sigmoid curves and their characteristic parameters has become one of the main focuses of crop growth simulation

studies [7,24,47,48]. In this study, only two growth dynamic indicators, i.e., plant height and *LAI*, were simulated and analyzed. In the future, multi-year experiments must be carried out to simulate the dry matter accumulation and nitrogen accumulation of different vegetables at different fertility stages under aerated drip irrigation, using the effective cumulative temperature as the independent variable. This would improve the precise regulation of nitrogen fertilization in vegetables and provide a scientific basis for reasonable prediction of biomass and yield to ultimately achieve increased yield and efficiency.

5. Conclusions

Through this study, it was found that a scientific basis was provided for the dynamic simulation and accurate prediction of greenhouse tomato growth under ADI and N application.

Compared to the CK and 0 kg N ha^{-1} treatment, ADI and N application were found to significantly increase the maximum growth rate and average growth rate over the rapid growth period of the tomato plant height and *LAI*; this also reduced the effective cumulative temperature at which plant height entered the rapid growth period ($p < 0.05$), thereby increasing the time spent in the nutritional growth phase, and this laid the foundation for better development of the subsequent reproductive organs. Tomato yields also confirm it: the highest yield of 85.87 t ha^{-1} was noted in the N_2A treatment, which was increased by 13.8%, 12.2%, and 39.6% ($p < 0.05$), respectively, compared to N_2C, N_1A, and N_0A treatments. Grey correlation analysis showed that the characteristic parameters closely related to yield were all from the ADI and N application treatments. Furthermore, it was observed that the effective cumulative temperature (Lt_3) and the maximum growth rate (*LRmax*) of the *LAI* at which the *LAI* entered the slow growth phase were the key growth characteristic parameters affecting tomato yield.

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