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DMPP and Polymer-Coated Urea Promoted Growth and Increased Yield of Greenhouse Tomatoes

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Abstract: Improvements in nitrogen (N) use efficiency reduce stress on the environment and improve tomato production. A two-year trial was conducted in greenhouse tomatoes with a split-plot design, in which one factor was the N application rate (150 kg·ha^{-1}, N1; 200 kg·ha^{-1}, N2; and 250 kg·ha^{-1}, N3) and two other factors were the type of urea applied (urea, T1; slow-release (polymer-coated) urea, T2, and nitrification inhibitors (3,4-dimethylpyrazole phosphate, DMPP) + urea, T3); no N fertilizer was applied in the control. The effects of the nitrogen (N) application rate and type of urea applied on the root morphology indexes, growth indexes, photosynthetic parameters, yield (Y), water use efficiency (WUE), and nitrogen agronomic efficiency (NAE) of greenhouse tomatoes were investigated. The results show that an appropriate N application rate (200 kg·ha^{-1}) can improve tomato growth and net photosynthetic rate (P_n). With T3, the Y and WUE of greenhouse tomatoes first increased and then decreased as the N application rate increased, but with T1 and T2, the Y and WUE increased as the N application rate increased. The NAE of greenhouse tomatoes was significantly lower with N3 than with N2. The root growth, plant growth, P_n, Y, WUE, and NAE of the tomatoes were improved with T2 and T3 compared to T1. These findings can be used to promote N conservation and increase the Y of facility agriculture crops.

Keywords: facility agriculture; nitrogen application rate; roots morphology index; urea type; yield

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1. Introduction

Tomatoes (*Solanum lycopersicum* L.) are popular for their richness in vitamins, amino acids, organic acids, and other nutrients [1,2]. As of 2020, 5.05 million hectares of land are used for tomato cultivation, which accounts for 8.67% of the total vegetable cultivation area [3]. Meanwhile, excessive nitrogen (N) is often applied to greenhouse tomatoes during production to increase yields, and this increases the risk of N leaching and various environmental problems [4]. For the sustainable development of agriculture, a major goal is to find ways to produce increases in the yields (Y) of greenhouse tomatoes by applying less N and improving the N use efficiency (NUE) of crops.

Many studies have examined the effects of different N application rates on greenhouse tomatoes. Cheng et al. (2021) [5] evaluated the effect of N application rate on tomato Y, water use efficiency (WUE), and tomato quality, and found that Y was significantly increased by 59.9% when N was applied at 236–354 kg·ha^{-1} compared with the control. The results of Du et al. (2017) [6] indicate that the optimal N application rate was 250 kg·ha^{-1} for maximizing the Y and WUE of greenhouse tomatoes, and the optimal N application rate was 150 kg·ha^{-1} for maximizing NUE in Northwestern China. Li et al. (2020) [7] studied the Y, WUE, and NUE of tomatoes with different water and N management regimes in greenhouses, and found that the optimal water and N application rate was 70% ET and 150 kg·ha^{-1}, respectively. Previous studies have shown that the optimal N application rate for greenhouse tomatoes varies depending on the experimental objective and external factors. Many crops are sensitive to various environmental variables that can alter the N requirements of crops. The supply of N itself affects the external environment, and the interactions between the two can affect the growth of crops. Many experiments have been conducted to identify optimal N management strategies by altering several variables such as the type of N fertilizer [8,9] and the method of N application [10–12].

Urea is used as a conventional chemical N fertilizer, supplying 67% of the total N in China's agriculture [13,14]. Meanwhile, the high risk due to N leaching, volatilization and N_2O emissions of N in urea has also been heavily addressed as a global issue, challenging the global environmental sustainability [15,16]. Nitrification inhibitors (NIs) and slow-release urea are efficient methods for conserving urea and reducing N losses. NIs inhibit the activity of nitrifying bacteria in the soil, which can slow the rate of conversion of NH_4^+-N to NO_3^--N in the soil [17], reduce the leaching loss of nitrate N, and improve NUE [18–20]. 3,4-Dimethylpyrazole phosphate (DMPP) is one of the most effective commercial NIs because long-lasting inhibitory effects can be achieved at low application rates; it is also non-toxic and environmentally friendly [21,22]. Sergio Menéndez et al. (2012) [23] found that DMPP shows improved N_2O emissions reduction performance in cold and wet conditions. An analysis of 111 datasets by Gilsanz et al. (2016) [24] revealed that DMPP and dicyandiamide (DCD) have similar inhibitory effects. Slow-release urea adapts to crop needs by controlling nutrient release, reducing unnecessary N loss during the early stage of fertilization, increasing the supply of N at the peak stage of N demand [25–27], and reducing the labor input associated with top dressing application [28]. Polymer-coated urea (PCU) is a commonly used slow-release urea fertilizer; the growth and yield of tomatoes are higher with PCU application compared to conventional urea application [8]. Qu et al. (2020) [29] studied the effects of applying blends of PCU and conventional urea on the growth of greenhouse tomatoes, and the results indicate that a urea/PCU ratio of 3:7 was optimal for reducing the N application rate and increasing the Y and quality of tomatoes. Similarly, PCU has a strong N supply capacity in the production of other crops, such as rice [30,31], maize [32], cotton [33], etc. Therefore, the application of slow-release fertilizer or NIs allows the amount of N fertilizer applied to be reduced and improves NUE, which enhances crop yields. However, few studies have compared the effects of PCU and DMPP on greenhouse tomatoes. There is thus a need to study the effects of different urea types and N application rates on the growth of greenhouse tomatoes.

Here, the effects of different urea types and N application rates on the root morphology, plant height (PH), stem diameter (SD), leaf area index (LAI), photosynthetic characteristics, WUE, nitrogen agronomic efficiency (NAE), and Y of greenhouse tomatoes with drip irrigation and plastic film mulching were examined. The aims of this study were to improve integrated water and fertilizer technology and provide information that could aid future studies focused on improving the yield of facility agricultural crops and N conservation.

2. Materials and Methods

The experiment was conducted from 6 April 2020 to 30 July 2020 and from 21 March 2021 to 5 July 2021 in a greenhouse (85 m long × 15 m wide) of the Modern Agricultural Science and Technology Exhibition Center of Xi'an City, Xi'an, China (34°03′ N, 108°52′ E; 435 m). The site had a temperate continental monsoon climate with a mean annual temperature of 13.3 °C, and the maximum number of annual sunshine hours was 2230 h. The soil was classified as sandy loam (International Classification) and consisted of 13.7% clay (<2 μm), 22.7% silt (2~20 μm) and 63.6% sand (20~2000 μm) at a depth of 0~0.4 m. The average bulk density of the 1 m soil layer was 1.53 $g\cdot cm^{-3}$, the water holding capacity of the soil was 25.40%, and the depth of the groundwater table was greater than 30 m. The initial soil nutrient contents were 9.46 and 9.73 $g\cdot kg^{-1}$ organic matter, 6.58 and 6.49 $g\cdot kg^{-1}$ total phosphorus (P), 3.18 and 3.35 $g\cdot kg^{-1}$ total potassium (K), 0.86 and 0.91 $g\cdot kg^{-1}$ total N, 72.33 and 68.47 mg·kg^{-1} available N, 89.94 and 83.49 mg·kg^{-1} available P, and 67.31 and 70.08 mg·kg^{-1} available K before transplanting in 2020 and 2021, respectively.

2.1. Field Management

The tomato variety "Mingzhu" (Danjiangkou Kaixin Seed Industry Co., Ltd., Danjiangkou, China) is a tomato hybrid with a pink, hard, and round fruit that matures early and shows indeterminate growth. Each plot (3.4 m × 1.8 m) contained a raised ridge (1.1 m in width) with walkways (0.7 m) in between adjacent plots. To prevent the horizontal infiltration and movement of soil moisture, a 1.0 m-deep plastic film was buried in the walkways. Two drip irrigation tubes were installed on each ridge with a nozzle spacing of 20 cm. Tomatoes were planted on a ridge with a row spacing of 50 cm and a plant spacing of 30 cm (Figure 1). A small weather station (FT-QC8, Shandong Wanxiang Technology Co., Ltd., Weifang, China) was installed in the middle of the greenhouse, which could automatically record temperature, relative humidity and photoactive radiation every 30 min. The average temperature, daily photosynthetically active radiation and relative humidity of the greenhouse during the growing season were 24.76 (2020) and 24.02 °C (2021), 19.72 (2020) and 18.23 (2021) mol·m^{-2}·d^{-1}, and 62.32 (2020) and 68.71% (2021), respectively.

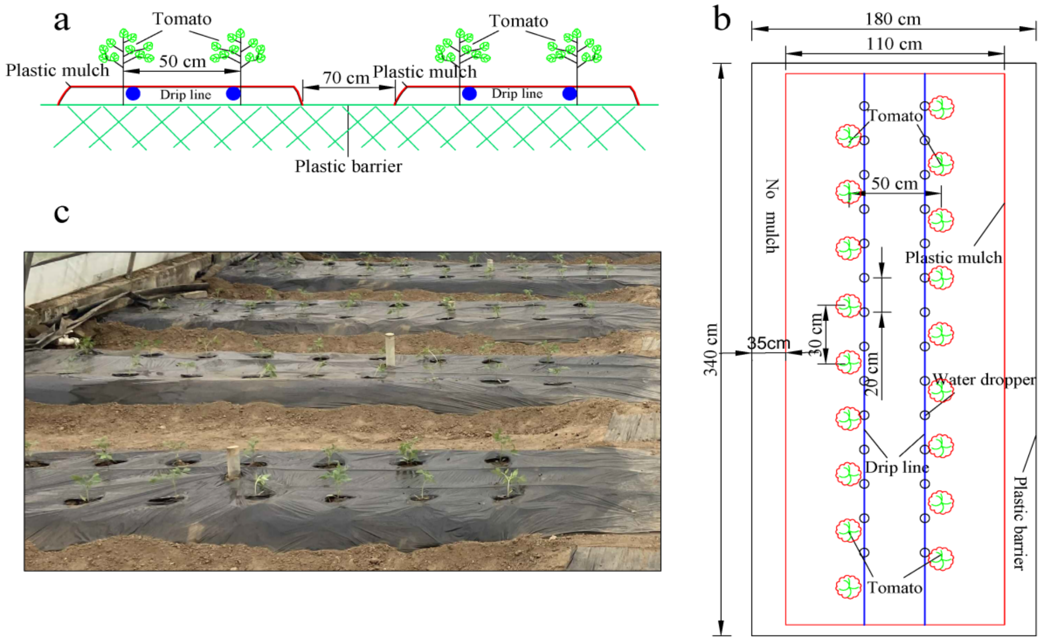

Figure 1. (**a**) Section map of tomato planting, drip-line arrangements, and planting plot; (**b**) the planform for tomato planting and drip-line arrangements in a planting plot; (**c**) field figure of tomato experiments in greenhouses.

Four clusters of each plant were reserved, and field management measures such as irrigation and pesticide applications were the same for all treatments. The source of the irrigation water was groundwater. To ensure the survival rate of transplanting seedlings, the first irrigation was carried out on the day of transplanting. The first irrigation amount (I1) was based on local tomato planting experience. The subsequent irrigation amount (I2) was controlled based on the cumulative evaporation from a 20 cm diameter pan (E_{pan}) [34]. In 2020, tomatoes were planted on April 6, and the irrigation treatment began on 13 April 2020 and ended on 22 July 2020. In 2021, tomatoes were planted on 21 March 2021, and the irrigation treatment began on 28 March 2021 and ended on 28 June 2021. The irrigation amounts in 2020 and 2021 were 274 and 268 mm, respectively.

2.2. Experimental Design

Urea type and N application rate were the two factors in the experiment; the details of the experimental design are shown in Table 1.

Table 1. Test factors and experimental design.

Treatment	Urea Type	Nitrogen Application Rate (kg·ha^{-1})
CK	-	0
N1T1	Urea	150
N2T2	Urea	200
N3T2	Urea	250
N1T2	PCU	150
N2T2	PCU	200
N3T2	PCU	250
N1T3	DMPP + urea	150
N2T3	DMPP + urea	200
N3T3	DMPP + urea	250

The experiment was conducted in a split-block design consisting of 10 treatments with three replicates per treatment (i.e., a total of 30 plots). Before transplanting, 1500 kg·ha^{-1} of organic fertilizer (organic content $\geq$ 45%, NPK $\geq$ 5%, fermentation fertilizer of cattle and sheep excreta), 180 kg·P_2O_5·ha^{-1} (calcium superphosphate, P_2O_5 $\geq$ 46%) and 120 kg·K_2O·ha^{-1} (potassium sulfate, K_2O $\geq$ 51%) were applied as basic fertilizer. According to Zhou et al. [35], tomato plants are sensitive to N 15–60 days after pollination; thus, N application within this window can improve the growth of the tomato plants and the quality of the tomato fruit. The date and amount of N fertilizer application are shown in Table 2. The three levels of N application were 150 (N1), 200 (N2), and 250 kg·ha^{-1} (N3). The three urea types were T1, wherein urea was injected into the drip line during irrigation; T2, wherein PCU (Shandong Olang Biotechnology Co., Ltd., Linyi, China) was buried at a soil depth of 20 cm before tomatoes were transplanted; and T3, wherein urea + DMPP was injected into the drip line during irrigation (DMPP is 1% of N dosage, Henan Shenyu Biotechnology Co., Ltd., Jiaozuo, China). The fertilizer was evenly mixed into the water flow with the hydraulic fertilizer applicator. No N fertilizer was applied in the control group (CK).

Table 2. Fertilization (kg·ha^{-1}) records over the experimental period.

N Application Rate (kg·ha^{-1})	Days after Transplanting							
	24 d	34 d	44 d	54 d	64 d	79 d	94 d	Total
N1	15.00	26.25	26.25	26.25	26.25	15.00	15.00	150
N2	20.00	35.00	35.00	35.00	35.00	20.00	20.00	200
N3	25.00	43.75	43.75	43.75	43.75	25.00	25.00	250

2.3. Sampling and Measurements

The crop evapotranspiration (ET, mm) was calculated using the following water balance Equation (1) [36]:

$$ET = P + I + U - D - R - \Delta W \quad (1)$$

where P is the effective precipitation (mm), I is the irrigation amount (I = I_1 + I_2, mm), U is the water movement from the deep soil into the root zone (mm), D is the amount of downward drainage out of the 1 m soil profile (mm), R is the surface runoff (mm), and ΔW is the variation in the amount of water storage in the 1 m soil profile (mm), given as in Equation (2) [36]:

$$\Delta W = 1000 \times h \times (\theta_0 - \theta_1) \quad (2)$$

where θ_0 and θ_1 are the average soil water content before transplanting and after harvest in the 1 m soil profile (cm^3 cm^{-3}), respectively. The soil water contents θ_0 and θ_1 were measured by the drying method. The soil was collected at a depth of 100 cm and a soil interval of 20 cm in each plot three times.

The experiment was conducted in a greenhouse with drip irrigation on flat terrain, and I was small; hence, P = 0, D = 0, and R = 0. The groundwater table was below 5.0 m, and the crop roots were unable to absorb and utilize the groundwater. Thus, the underground water recharge was negligible, U = 0.

The WUE was calculated by Equation (3) [35]:

$$\mathrm{WUE} = \mathrm{Y}/(10000 \times \mathrm{ET}/1000) \tag{3}$$

where WUE is the crop water use efficiency ($kg{\cdot}m^{-3}$) and Y is the grain yield of crops ($kg{\cdot}ha^{-1}$).

Nitrogen agronomic efficiency (NAE) was calculated by Equation (4) [37]:

$$\mathrm{NAE} = (\mathrm{Y} - \mathrm{Y_c})/\mathrm{N} \tag{4}$$

where N is the nitrogen fertilizer (urea) application rate ($kg{\cdot}kg^{-1}$) and Y_c is the yield of tomatoes with the CK (N0) treatment in $kg{\cdot}ha^{-1}$.

During the mature period, four tomatoes were randomly selected from each plot to determine the number of fruits per plant. The quality of mature tomatoes was measured using an electronic scale. After the Y per plant was obtained, the Y per hectare was calculated. Malformed fruit, rotten fruit and cracked fruit were defined as rejected fruit and were not counted in the marketable yield (Y_m).

One hundred days after the tomatoes were transplanted, three tomato plants along with the soil surrounding each plant (typically 0.4 m in depth and 0.2 m in diameter) were randomly extracted. The samples were placed in a 150-mesh sieve, and the roots were washed. The roots were then scanned by an Epson Chops V700 scanner, and WinRHIZO Pro software was used to obtain the total root length (RL), total surface area (RS), total root volume (RV), total number of root tips (RT), and number of root branches (RB). The root activity (RA) of the tomatoes was determined by the triphenyltetrazolium chloride method.

The PH, SD, and LAI of three randomly selected greenhouse tomato plants from each plot were measured 28, 56, 76 and 100 d after planting. The PH was measured using a ruler, the SD was measured using vernier calipers, and the LAI was measured using an AccuParlP-80 canopy analyzer (Decagon Devices, Inc., Pullman, WA, USA).

The instantaneous transpiration rate (T_r) and net photosynthetic rate (P_n) of tomato leaves in the greenhouse were measured using an LI-6400 portable photosynthesis system (LI-COR, Lincoln, NE, USA). Three healthy plants from each plot and three healthy leaves from each plant were selected for measurement. Measurements were taken 30, 60, and 100 d after transplantation. The instantaneous water use efficiency (WUE_L) was calculated using Equation (5) [35]:

$$\mathrm{WUE_L} = \mathrm{P_n}/\mathrm{T_r}, \tag{5}$$

where WUE_L is the water use efficiency of leaves ($mmol{\cdot}CO_2{\cdot}mol^{-1}{\cdot}H_2O$), P_n is the net photosynthetic rate ($\mu mol{\cdot}CO_2{\cdot}m^{-2}{\cdot}s^{-1}$), and T_r is the instantaneous transpiration rate ($mmol{\cdot}H_2O{\cdot}m^{-2}{\cdot}s^{-1}$).

2.4. Data Analysis

SPSS (Statistical Product and Service Solutions) software (version 22.0, IBM Corporation, Armonk, NY, USA) was used to conduct statistical analyses. Student's *t*-test was used to compare the CK with the other nine treatments, followed by a Univariate Analysis of Variance for separating the mean values and detecting differences (Duncan's test) between means. OriginPro2019 (Origin Lab Corporation, Northampton, MA, USA) was used to build graphs and fit linear. Data are presented as average ± standard error in graphs unless otherwise noted. The main abbreviations in the text are defined in Abbreviation part.

3. Results

3.1. Root Morphological Indexes

The effect of urea type on the root morphological indicators of greenhouse tomatoes (RL, RS, RV, RT, RB, and RA) was weak (Table 3). RL, RT, and RB were highest with T1, followed by T2 and T3, whereas RS, RV, and RA were highest in T3, followed by T1 and T2. The N application rate had a significant effect on the aforementioned root indicators of greenhouse tomatoes. The RL, RS, RV, RT, RB, and RA first increased and then decreased as the N application rate increased. The RL, RS, RV, RT, RB, and RA were 24.00 and 22.47, 31.69 and 29.45, 37.32 and 37.72, 20.92 and 22.03, 22.21 and 21.45, and 36.83 and 33.37% higher in 2020 and 2021, respectively, with N2 compared to CK.

3.2. Growth

3.2.1. Plant Height

The PH of greenhouse tomatoes gradually increased with growth, and a slight decrease in PH was observed in the later stage of tomato growth (Table 4). After 56 d of planting, there were significant differences in the PH of greenhouse tomatoes among treatments, and both the N application rate and urea type had significant effects on PH. The PH of tomatoes was highest with N2T3 (76 d), and the PH of N2T3 and N3T2 was 31.71 and 23.81% as well as 37.68 and 33.77% in 2020 and 2021, respectively, compared to CK.

3.2.2. Stem Diameter

The SD of greenhouse tomatoes changed little after increasing gradually with the advance of the growth period (Table 5). N application rate and urea type had significant effects on the SD of greenhouse tomatoes 56 d after transplanting, but the interaction between these two variables had a weak effect on SD. The SD of greenhouse tomatoes was highest with T3, followed by T2 and T1. The SD of greenhouse tomatoes was 10.14 and 9.86% (56 d), 14.80 and 8.05% (76 d), and 10.32 and 7.74% (100 d) higher in 2020 and 2021, respectively, with T3 compared to CK. The SD of tomatoes increased at 56 d and decreased at 76 and 100 d as the N application rate increased; however, no significant differences between N2 and N3 were observed. The SD of tomatoes was 13.78 and 7.79% (76 d) as well as 10.55 and 8.14% (100 d) higher in 2020 and 2021, respectively, with N2 compared to CK.

3.2.3. Leaf Area Index

The LAI of greenhouse tomatoes first increased with growth and decreased slightly after topping (Table 6). After 56 d of planting, there were significant differences in the LAI of greenhouse tomatoes among treatments, and both the type of urea and the rate of N application had significant effects on the LAI. The LAI of greenhouse tomatoes was highest with T3, followed by T2 and T1. The LAI of tomatoes was 10.99 and 10.88% (56 d), 14.08 and 14.85% (76 d), and 9.62 and 14.40% (100 d) higher in 2020 and 2021, respectively, with T3 compared to CK; the LAI of greenhouse tomatoes increased at 56 d and first increased and then decreased at 76 and 100 d as the N application rate increased; however, there was no significant difference in the LAI between N2 and N3. The LAI was 11.73 and 13.68% (76 d) and 7.77 and 13.12% (100 d) higher in 2020 and 2021, respectively, with N2 compared to CK.

Table 3. Response of tomato total root length (RL, cm·plant^{-1}), total surface area (RS, cm^2·plant^{-1}), total root volume (RV, cm^3·plant^{-1}), total number of root tips (RT), number of root branches (RB) and root activity (RA, mg·g^{-1}·h^{-1}) to different urea types and N application rates in the greenhouse.

Year	Main Effect	RL	RS	RV	RT	RB	RA
2020	CK	304.76 ± 8.67	92.98 ± 2.83	2.31 ± 0.06	629.77 ± 13.40	1540.76 ± 37.95	1.64 ± 0.05
	N1T1	361.16 ± 14.24 **	110.39 ± 4.35 **	2.61 ± 0.10 *	711.19 ± 15.11 **	1812.87 ± 55.35 **	2.07 ± 0.10 **
	N2T1	393.25 ± 17.57 **	122.17 ± 4.00 *	3.15 ± 0.09 **	781.42 ± 15.04 **	1939.77 ± 65.56 **	2.27 ± 0.13 **
	N3T1	378.91 ± 14.89 **	110.42 ± 4.77 **	2.96 ± 0.10 **	747.32 ± 46.70 *	1832.67 ± 42.69 **	2.24 ± 0.08 **
	N1T2	348.83 ± 10.85 **	109.31 ± 5.72 *	2.65 ± 0.08 *	696.95 ± 13.49 **	1736.38 ± 45.50 **	2.08 ± 0.12 **
	N2T2	365.40 ± 13.61 **	117.79 ± 4.05 **	3.08 ± 0.12 **	750.34 ± 23.07 **	1856.61 ± 24.80 **	2.19 ± 0.13 **
	N3T2	369.46 ± 12.22 **	106.06 ± 6.34 *	3.03 ± 0.10 **	723.68 ± 11.89 *	1879.48 ± 28.61 **	2.24 ± 0.07 **
	N1T3	355.32 ± 13.59 **	112.88 ± 6.74 **	2.92 ± 0.15 **	709.54 ± 19.91 *	1758.32 ± 29.64 **	2.08 ± 0.07 **
	N2T3	375.13 ± 8.25 **	127.38 ± 6.12 **	3.30 ± 0.08 **	752.81 ± 14.22 **	1852.67 ± 25.41 **	2.26 ± 0.13 **
	N3T3	356.76 ± 12.63 **	114.35 ± 4.57 **	3.07 ± 0.09 **	728.55 ± 14.33 **	1742.98 ± 30.22 **	2.22 ± 0.07 **
	T						
	T1	377.77 ± 9.05	114.33 ± 2.66	2.91 ± 0.07	746.64 ± 17.38	1861.77 ± 32.58	2.19 ± 0.05
	T2	361.23 ± 7.03	111.05 ± 3.18	2.92 ± 0.07	723.66 ± 10.29	1824.16 ± 22.60	2.17 ± 0.06
	T3	362.40 ± 6.74	118.20 ± 3.50	3.10 ± 0.07	730.30 ± 9.72	1784.66 ± 18.45	2.20 ± 0.06
	N						
	N1	355.10 ± 7.27	110.86 ± 3.17 B	2.72 ± 0.07 B	705.89 ± 9.18 B	1769.19 ± 25.62 B	2.08 ± 0.06
	N2	377.93 ± 7.92	122.44 ± 2.78 A	3.18 ± 0.06 A	761.52 ± 10.30 A	1883.01 ± 25.14 A	2.24 ± 0.07
	N3	368.38 ± 7.59	110.27 ± 3.01 B	3.02 ± 0.06 A	733.18 ± 16.22 AB	1818.38 ± 22.09 AB	2.24 ± 0.04
				F-value (*p*-value)			
	T	1.44 (0.244)	1.38 (0.258)	3.17 (0.048)	0.88 (0.419)	2.65 (0.077)	0.04 (0.962)
	N	2.22 (0.116)	5.07 (0.009)	14.64 (<0.001)	4.87 (0.008)	5.82 (0.005)	2.46 (0.093)
	T × N	0.30 (0.879)	0.09 (0.984)	0.46 (0.765)	0.10 (0.982)	1.29 (0.284)	0.07 (0.990)
2021	CK	308.47 ± 9.24	102.64 ± 9.29	2.30 ± 0.06	622.09 ± 12.91	1497.52 ± 36.40	1.66 ± 0.08
	N1T1	357.10 ± 17.93 **	118.18 ± 12.67 *	2.60 ± 0.10 *	728.64 ± 22.42 **	1729.91 ± 26.10 **	2.03 ± 0.05 *
	N2T1	388.53 ± 11.07 **	127.82 ± 14.02 **	3.13 ± 0.09 **	781.36 ± 20.05 **	1884.54 ± 41.40 **	2.22 ± 0.07 **
	N3T1	366.96 ± 11.53 **	118.20 ± 13.92 *	2.94 ± 0.10 **	735.97 ± 13.78 **	1803.87 ± 49.23 **	2.16 ± 0.09 **
	N1T2	344.60 ± 16.17 *	119.29 ± 6.13 **	2.61 ± 0.12 *	692.14 ± 22.06 **	1705.97 ± 45.36 **	2.03 ± 0.06 *
	N2T2	369.11 ± 10.29 **	134.57 ± 13.29 **	3.09 ± 0.11 **	755.39 ± 21.81 **	1775.19 ± 23.26 **	2.12 ± 0.07 **
	N3T2	351.94 ± 8.43 **	125.77 ± 15.84 **	2.81 ± 0.14 **	720.96 ± 38.18 **	1787.14 ± 34.10 **	2.19 ± 0.08 **
	N1T3	348.73 ± 14.85 *	120.34 ± 15.79 **	2.77 ± 0.14 **	698.91 ± 19.17 **	1706.13 ± 28.41 **	2.14 ± 0.11 **
	N2T3	375.73 ± 7.63 **	136.21 ± 15.22 **	3.29 ± 0.21 **	740.59 ± 13.68 **	1796.55 ± 24.35 **	2.31 ± 0.08 **
	N3T3	350.12 ± 12.20 **	126.13 ± 11.29 **	3.05 ± 0.17 **	717.23 ± 13.79 **	1691.43 ± 28.96 **	2.20 ± 0.11 **

Table 3. *Cont.*

Year	Main Effect	RL	RS	RV	RT	RB	RA
2021	T						
	T1	370.86 ± 8.11	121.40 ± 2.66	2.89 ± 0.07	748.65 ± 11.54	1806.10 ± 25.45 a	2.14 ± 0.04
	T2	355.22 ± 7.00	126.54 ± 2.61	2.84 ± 0.08	722.83 ± 16.55	1756.10 ± 20.86 ab	2.11 ± 0.04
	T3	358.19 ± 7.06	127.56 ± 2.93	3.04 ± 0.10	718.91 ± 9.36	1731.37 ± 17.68 b	2.21 ± 0.06
	N						
	N1	350.14 ± 9.14 B	119.27 ± 2.26 B	2.66 ± 0.07 B	706.56 ± 12.20 B	1714.00 ± 19.20 B	2.07 ± 0.04
	N2	377.79 ± 5.65 A	132.87 ± 2.72 A	3.17 ± 0.08 A	759.11 ± 10.96 A	1818.76 ± 19.45 A	2.22 ± 0.04
	N3	356.34 ± 6.20 AB	123.37 ± 2.65 B	2.93 ± 0.08 A	724.72 ± 13.82 AB	1760.81 ± 23.41 AB	2.18 ± 0.05
				F-value (p-value)			
	T	1.29 (0.281)	1.63 (0.203)	1.77 (0.178)	1.66 (0.198)	3.62 (0.032)	1.22 (0.300)
	N	3.94 (0.024)	7.27 (0.001)	10.65 (<0.001)	4.52 (0.014)	6.87 (0.002)	2.68 (0.076)
	T × N	0.05 (0.995)	0.21 (0.934)	0.08 (0.989)	0.12 (0.973)	1.20 (0.319)	0.35 (0.846)

The data are all average ± standard error (the number of samples for each treatment is 9) in the table, different letters within a column indicate significant differences among all treatments, lowercase letters indicate differences between urea types, and capital letters indicate differences between N application rates; * ($p < 0.05$) and ** ($p < 0.01$) indicate the mean values that significantly differed from the control with Student's *t*-test. T: urea type (urea, T1; polymer-coated urea, T2; DMPP + urea, T3); N: nitrogen application rate (150 kg·ha^{-1}, T1; 200 kg·ha^{-1}, T2; 250 kg·ha^{-1}, T3).

3.3. Photosynthetic Parameters

3.3.1. Net Photosynthetic Rate

The P_n of greenhouse tomatoes in all the treatments first increased and then decreased with the advance of the growth period (Table 7). Little change in the P_n of greenhouse tomatoes at 30 d after transplanting in 2020 and 2021 was observed among the different treatments; thus, there were no significant differences in P_n among the treatments. At 60 d after transplanting, the P_n of greenhouse tomatoes increased as the N application rate increased, and it was highest in T3, followed by T2 and T1. The P_n of greenhouse tomatoes was highest with N3T3, which was 25.54 and 24.59 $\mu mol \cdot CO_2 \cdot m^{-2} \cdot s^{-1}$ in 2020 and 2021, respectively. At 100 d after transplanting, P_n increased as the N application rate increased with T1 and T2 when the N application rate was less than N2. When the N application rate was greater than N2, P_n increased slightly or even decreased. There were no significant differences in P_n between N2 and N3; with T3, P_n first increased and then decreased as the N application rate increased. P_n was significantly lower with N3T3 than with N2T3. P_n was highest with N2T3, and it was 39.35 and 50.69% higher in 2020 and 2021, respectively, with N2T3 compared to CK.

Table 4. Response of tomato plant height (PH, cm) to different urea types and N application rates in the greenhouse.

Year	Main Effect	Days after Transplanting			
		28 d	56 d	76 d	100 d
2020	CK	43.28 ± 1.26	89.5 ± 3.35	111.21 ± 3.44	115.26 ± 2.10
	N1T1	44.35 ± 1.43	92.02 ± 2.77	121.42 ± 3.30 *	118.75 ± 2.22
	N2T1	43.18 ± 1.23	102.19 ± 2.42 *	129.55 ± 2.03 **	129.14 ± 2.15 **
	N3T1	43.55 ± 0.39	102.86 ± 3.95 *	134.19 ± 1.28 **	130.51 ± 2.35 **
	N1T2	41.69 ± 1.15	93.22 ± 2.00	120.34 ± 3.08 *	118.15 ± 3.25
	N2T2	42.49 ± 0.66	102.71 ± 2.39 *	129.24 ± 2.66 **	124.43 ± 3.70
	N3T2	42.91 ± 1.35	104.55 ± 2.11 **	137.69 ± 3.16 **	129.43 ± 4.26 **
	N1T3	42.64 ± 0.74	102.43 ± 2.65 *	132.92 ± 3.34 **	132.61 ± 3.25 **
	N2T3	43.58 ± 0.67	108.62 ± 2.54 **	146.47 ± 3.82 **	146.99 ± 4.67 **
	N3T3	42.30 ± 1.04	112.47 ± 3.06 **	135.44 ± 5.04 **	141.17 ± 5.29 **
	T				
	T1	43.69 ± 0.62	99.03 ± 1.98 b	128.39 ± 1.67 b	126.13 ± 1.61 b
	T2	42.36 ± 0.61	100.16 ± 1.55 b	129.09 ± 2.16 b	124.01 ± 2.27 b
	T3	42.84 ± 0.47	107.84 ± 1.73 a	138.28 ± 2.56 a	140.26 ± 2.74 a
	N				
	N1	42.89 ± 0.67	95.89 ± 1.66 B	124.89 ± 2.12 B	123.17 ± 2.09 B
	N2	43.08 ± 0.50	104.51 ± 1.48 A	135.09 ± 2.27 A	133.52 ± 2.78 A
	N3	42.92 ± 0.57	106.63 ± 1.92 A	135.77 ± 1.97 A	133.70 ± 2.52 A
			F-value (*p*-value)		
	T	1.31 (0.277)	9.38 (<0.001)	8.71 (<0.001)	17.89 (<0.001)
	N	0.03 (0.970)	13.21 (<0.001)	10.63 (<0.001)	8.33 (0.001)
	T × N	0.56 (0.694)	0.17 (0.952)	2.75 (0.035)	0.633 (0.640)
2021	CK	44.55 ± 1.36	87.43 ± 2.78	107.4 ± 1.72	112.36 ± 2.44
	N1T1	42.79 ± 0.72	89.71 ± 1.41	120.02 ± 1.78 **	118.26 ± 2.64
	N2T1	43.70 ± 1.27	98.60 ± 1.78 **	126.18 ± 1.07 **	123.10 ± 3.91 *
	N3T1	43.51 ± 1.02	101.45 ± 2.93 **	130.59 ± 3.36 **	124.48 ± 2.14 **
	N1T2	46.43 ± 0.88	99.04 ± 2.18 **	134.81 ± 2.02 **	129.59 ± 2.58 **
	N2T2	45.47 ± 1.62	109.22 ± 0.98 **	140.44 ± 3.59 **	139.90 ± 3.30 **
	N3T2	44.90 ± 1.36	111.43 ± 3.03 **	143.67 ± 4.20 **	140.49 ± 2.90 **
	N1T3	43.11 ± 1.64	94.26 ± 1.98	132.46 ± 2.95 **	131.30 ± 3.07 **
	N2T3	45.11 ± 1.14	108.92 ± 2.32 **	147.87 ± 2.16 **	144.94 ± 2.55 **
	N3T3	44.82 ± 1.13	110.72 ± 1.99 **	137.29 ± 2.07 **	134.15 ± 3.18 **
	T				
	T1	43.33 ± 0.58	96.59 ± 1.54 b	125.60 ± 1.52 b	121.95 ± 1.74 b
	T2	45.60 ± 0.74	106.56 ± 1.63 a	139.64 ± 2.01 a	136.66 ± 1.90 a
	T3	44.35 ± 0.75	104.63 ± 1.86 a	139.21 ± 1.84 a	136.79 ± 2.00 a

Table 4. *Cont.*

Year	Main Effect	Days after Transplanting			
		28 d	56 d	76 d	100 d
2021	N				
	N1	44.11 ± 0.72	94.34 ± 1.29 B	129.10 ± 1.80 B	126.38 ± 1.91 B
	N2	44.76 ± 0.77	105.58 ± 1.38 A	138.17 ± 2.24 A	135.98 ± 2.59 A
	N3	44.41 ± 0.66	107.87 ± 1.74 A	137.18 ± 2.12 A	133.04 ± 2.01 A
			F-value (*p*-value)		
	T	2.55 (0.086)	18.04 (<0.001)	25.41 (<0.001)	24.95 (<0.001)
	N	0.21 (0.813)	33.79 (<0.001)	9.89 (<0.001)	8.28 (0.001)
	T × N	0.55 (0.698)	0.58 (0.682)	2.40 (0.058)	1.57 (0.192)

The data are all average ± standard error (the number of samples for each treatment is 9) in the table, different letters within a column indicate significant differences among all treatments, lowercase letters indicate differences between urea types, and capital letters indicate differences between N application rates; * ($p < 0.05$) and ** ($p < 0.01$) indicate the mean values that significantly differed from the control with Student's *t*-test. T: urea type (urea, T1; polymer-coated urea, T2; DMPP + urea, T3); N: nitrogen application rate (150 kg·ha^{-1}, T1; 200 kg·ha^{-1}, T2; 250 kg·ha^{-1}, T3).

Table 5. Response of tomato stem diameter (SD, mm) to different urea types and N application rates in the greenhouse.

Year	Main Effect	Days after Transplanting			
		28 d	56 d	76 d	100 d
2020	CK	7.75 ± 0.22	9.85 ± 0.27	11.32 ± 0.14	11.70 ± 0.38
	N1T1	7.14 ± 0.29	9.96 ± 0.24	11.82 ± 0.31	11.76 ± 0.34
	N2T1	7.58 ± 0.30	10.54 ± 0.28	12.45 ± 0.18 **	12.52 ± 0.38
	N3T1	7.55 ± 0.19	10.50 ± 0.25	12.46 ± 0.26 **	12.63 ± 0.16
	N1T2	7.39 ± 0.30	10.14 ± 0.24	12.02 ± 0.35	12.24 ± 0.14
	N2T2	7.28 ± 0.28	11.06 ± 0.24 *	12.75 ± 0.28 **	12.94 ± 0.21 *
	N3T2	7.65 ± 0.22	11.33 ± 0.25 **	12.82 ± 0.30 **	12.64 ± 0.28
	N1T3	7.04 ± 0.28	9.99 ± 0.25	12.28 ± 0.20 **	12.46 ± 0.22
	N2T3	7.41 ± 0.34	10.94 ± 0.48	13.44 ± 0.29 **	13.36 ± 0.17 **
	N3T3	7.63 ± 0.33	11.13 ± 0.29 **	13.27 ± 0.39 **	12.92 ± 0.39
	T				
	T1	7.42 ± 0.15	10.33 ± 0.15 b	12.24 ± 0.15 b	12.31 ± 0.19 b
	T2	7.44 ± 0.15	10.84 ± 0.17 a	12.53 ± 0.19 ab	12.61 ± 0.13 ab
	T3	7.36 ± 0.18	10.69 ± 0.22 ab	13.00 ± 0.20 a	12.91 ± 0.17 a
	N				
	N1	7.19 ± 0.16	10.03 ± 0.14 B	12.04 ± 0.17 B	12.15 ± 0.15 B
	N2	7.42 ± 0.17	10.85 ± 0.19 A	12.88 ± 0.16 A	12.94 ± 0.16 A
	N3	7.61 ± 0.14	10.99 ± 0.15 A	12.85 ± 0.19 A	12.73 ± 0.16 A
			F-value (*p*-value)		
	T	0.06 (0.938)	2.45 (0.094)	5.12 (0.008)	3.80 (0.027)
	N	1.64 (0.201)	9.55 (<0.001)	8.20 (0.001)	6.83 (0.002)
	T × N	0.32 (0.862)	0.40 (0.810)	0.24 (0.914)	0.36 (0.837)
2021	CK	7.69 ± 0.31	9.92 ± 0.29	11.57 ± 0.36	11.51 ± 0.20
	N1T1	7.51 ± 0.27	9.72 ± 0.43	11.68 ± 0.32	11.33 ± 0.16
	N2T1	8.39 ± 0.30	10.36 ± 0.29	12.00 ± 0.21	12.04 ± 0.20
	N3T1	7.95 ± 0.30	10.44 ± 0.68	12.12 ± 0.23	12.15 ± 0.32
	N1T2	7.55 ± 0.36	10.10 ± 0.24	12.22 ± 0.46	12.19 ± 0.21 *
	N2T2	7.61 ± 0.31	10.98 ± 0.18 **	12.77 ± 0.34 *	12.67 ± 0.21 **
	N3T2	7.31 ± 0.16	11.10 ± 0.32 **	12.50 ± 0.29 *	12.63 ± 0.26 **
	N1T3	8.06 ± 0.17	10.32 ± 0.18	12.17 ± 0.36	12.19 ± 0.47
	N2T3	7.72 ± 0.25	10.92 ± 0.34 **	12.64 ± 0.35	12.63 ± 0.24 **
	N3T3	7.62 ± 0.31	11.44 ± 0.36 **	12.77 ± 0.20 *	12.39 ± 0.28 *

Table 5. *Cont.*

Year	Main Effect	Days after Transplanting			
		28 d	56 d	76 d	100 d
2021	T				
	T1	7.95 ± 0.18	10.17 ± 0.28 b	11.93 ± 0.15 b	11.84 ± 0.15 b
	T2	7.49 ± 0.16	10.73 ± 0.17 ab	12.50 ± 0.20 ab	12.50 ± 0.13 a
	T3	7.80 ± 0.14	10.89 ± 0.19 a	12.52 ± 0.18 a	12.40 ± 0.20 a
	N				
	N1	7.71 ± 0.16	10.05 ± 0.18 B	12.02 ± 0.22	11.90 ± 0.19 B
	N2	7.91 ± 0.17	10.75 ± 0.16 A	12.47 ± 0.18	12.45 ± 0.13 A
	N3	7.63 ± 0.16	10.99 ± 0.28 A	12.46 ± 0.15	12.39 ± 0.16 A
			F-value (*p*-value)		
	T	2.13 (0.127)	3.16 (0.048)	3.32 (0.042)	5.03 (0.009)
	N	0.80 (0.455)	5.39 (0.007)	1.93 (0.153)	3.59 (0.033)
	T × N	1.36 (0.256)	0.15 (0.961)	0.16 (0.960)	0.33 (0.859)

The data are all average ± standard error (the number of samples for each treatment is 9) in the table, different letters within a column indicate significant differences among all treatments, lowercase letters indicate differences between urea types, and capital letters indicate differences between N application rates; * ($p < 0.05$) and ** ($p < 0.01$) indicate the mean values that significantly differed from the control with Student's *t*-test. T: urea type (urea, T1; polymer-coated urea, T2; DMPP + urea, T3); N: nitrogen application rate (150 kg·ha^{-1}, T1; 200 kg·ha^{-1}, T2; 250 kg·ha^{-1}, T3).

Table 6. Response of tomato leaf area index (LAI, m^2·m^{-2}) to different urea types and N application rates in the greenhouse.

Year	Main Effect	Days after Transplanting			
		28 d	56 d	76 d	100 d
2020	CK	1.01 ± 0.05	3.06 ± 0.11	6.33 ± 0.11	6.24 ± 0.17
	N1T1	1.06 ± 0.07	3.09 ± 0.08	6.53 ± 0.15	6.24 ± 0.21
	N2T1	1.02 ± 0.03	3.25 ± 0.11	6.97 ± 0.10	6.61 ± 0.17
	N3T1	1.06 ± 0.10	3.32 ± 0.04 *	6.78 ± 0.13 *	6.40 ± 0.18
	N1T2	1.03 ± 0.07	3.16 ± 0.08	6.63 ± 0.09	6.34 ± 0.18
	N2T2	1.08 ± 0.06	3.27 ± 0.12	6.84 ± 0.18	6.62 ± 0.28
	N3T2	1.05 ± 0.04	3.31 ± 0.09 *	6.88 ± 0.13 *	6.54 ± 0.22
	N1T3	0.95 ± 0.06	3.20 ± 0.15	7.05 ± 0.13 **	6.71 ± 0.22
	N2T3	1.01 ± 0.07	3.43 ± 0.10 *	7.42 ± 0.15 **	6.93 ± 0.21 *
	N3T3	1.03 ± 0.04	3.56 ± 0.13 *	7.21 ± 0.18 **	6.86 ± 0.20 *
	T				
	T1	1.04 ± 0.04	3.22 ± 0.05	6.76 ± 0.08 b	6.42 ± 0.11 b
	T2	1.06 ± 0.03	3.25 ± 0.06	6.78 ± 0.08 b	6.50 ± 0.13 b
	T3	1.00 ± 0.03	3.40 ± 0.08	7.23 ± 0.09 a	6.84 ± 0.12 a
	N				
	N1	1.02 ± 0.04	3.15 ± 0.06 B	6.74 ± 0.08 B	6.43 ± 0.12
	N2	1.03 ± 0.03	3.32 ± 0.06 AB	7.08 ± 0.10 A	6.72 ± 0.13
	N3	1.05 ± 0.04	3.40 ± 0.06 A	6.96 ± 0.09 AB	6.60 ± 0.12
			F-value (*p*-value)		
	T	0.65 (0.523)	2.35 (0.102)	10.12 (<0.001)	3.35 (0.041)
	N	0.18 (0.835)	4.28 (0.018)	4.36 (0.016)	1.45 (0.242)
	T × N	0.25 (0.907)	0.25 (0.911)	0.29 (0.885)	0.05 (0.996)
2021	CK	1.07 ± 0.05	3.12 ± 0.10	6.25 ± 0.16	6.05 ± 0.21
	N1T1	1.04 ± 0.03	2.98 ± 0.19	6.57 ± 0.17	6.06 ± 0.17
	N2T1	1.02 ± 0.05	3.17 ± 0.13	6.73 ± 0.12 **	6.54 ± 0.17
	N3T1	1.02 ± 0.03	3.25 ± 0.16	6.81 ± 0.18	6.55 ± 0.24
	N1T2	1.03 ± 0.05	3.22 ± 0.14	6.69 ± 0.20	6.42 ± 0.18
	N2T2	1.06 ± 0.06	3.42 ± 0.15	7.13 ± 0.25 **	6.80 ± 0.23

Table 6. *Cont.*

Year	Main Effect	Days after Transplanting			
		28 d	**56 d**	**76 d**	**100 d**
2021	N3T2	1.02 ± 0.08	3.49 ± 0.17	6.97 ± 0.17	6.78 ± 0.03 **
	N1T3	1.01 ± 0.08	3.39 ± 0.13	6.82 ± 0.20	6.63 ± 0.32
	N2T3	1.05 ± 0.09	3.53 ± 0.13 *	7.46 ± 0.14 **	7.18 ± 0.27 **
	N3T3	1.08 ± 0.07	3.45 ± 0.13 *	7.26 ± 0.37 *	6.94 ± 0.27 **
	T				
	T1	1.03 ± 0.02	3.14 ± 0.09 b	6.71 ± 0.09 b	6.39 ± 0.12 b
	T2	1.03 ± 0.04	3.38 ± 0.09 ab	6.93 ± 0.12 ab	6.67 ± 0.10 a
	T3	1.05 ± 0.05	3.46 ± 0.07 a	7.18 ± 0.15 a	6.92 ± 0.17 a
	N				
	N1	1.03 ± 0.03	3.20 ± 0.09	6.69 ± 0.11 B	6.37 ± 0.14 B
	N2	1.04 ± 0.04	3.37 ± 0.08	7.11 ± 0.12 A	6.84 ± 0.14 A
	N3	1.04 ± 0.04	3.40 ± 0.09	7.02 ± 0.15 AB	6.76 ± 0.12 A
		F-value (*p*-value)			
	T	0.06 (0.944)	3.81 (0.027)	3.80 (0.027)	4.25 (0.018)
	N	0.06 (0.944)	1.63 (0.203)	3.17 (0.048)	3.76 (0.028)
	T × N	0.23 (0.923)	0.19 (0.945)	0.36 (0.839)	0.12 (0.976)

The data are all average ± standard error (the number of samples for each treatment is 9) in the table, different letters within a column indicate significant differences among all treatments, lowercase letters indicate differences between urea types, and capital letters indicate differences between N application rates; * ($p < 0.05$) and ** $p < 0.01$) indicate the mean values that significantly differed from the control with Student's *t*-test. T: urea type (urea, T1; polymer-coated urea, T2; DMPP + urea, T3); N: nitrogen application rate (150 kg·ha^{-1}, T1; 200 kg·ha^{-1}, T2; 250 kg·ha^{-1}, T3).

Table 7. Response of tomato net photosynthetic rate (P_n, μmol CO_2 m^{-2} s^{-1}) to different urea types and N application rates in the greenhouse.

Main Effect	2020			2021		
	30 d	**60 d**	**100 d**	**30 d**	**60 d**	**100 d**
CK	14.87 ± 0.52	17.07 ± 0.46	15.96 ± 0.44	13.95 ± 0.31	15.33 ± 0.47	13.67 ± 0.34
N1T1	14.60 ± 0.29	21.01 ± 0.45 **	17.42 ± 0.46 *	13.85 ± 0.29	20.63 ± 0.90 **	17.01 ± 0.56 **
N2T1	15.38 ± 0.45	22.30 ± 0.65 **	19.73 ± 0.38 **	14.67 ± 0.31	22.14 ± 0.92 **	18.74 ± 0.61 **
N3T1	14.77 ± 0.31	23.10 ± 0.57 **	19.25 ± 0.31 **	14.75 ± 0.30	22.02 ± 1.06 **	19.14 ± 0.59 **
N1T2	14.91 ± 0.34	20.94 ± 1.05 **	17.40 ± 0.59 **	14.45 ± 0.47	21.43 ± 0.45 **	18.78 ± 0.45 **
N2T2	14.40 ± 0.39	22.57 ± 1.00 **	19.28 ± 0.56 **	14.37 ± 0.33	23.07 ± 0.42 **	20.48 ± 0.29 **
N3T2	15.06 ± 0.34	24.54 ± 0.98 **	19.76 ± 0.52 **	14.57 ± 0.62	24.00 ± 0.65 **	20.09 ± 0.44 **
N1T3	14.80 ± 0.40	22.11 ± 0.62 **	18.23 ± 0.73 *	14.24 ± 0.28	21.83 ± 0.98 **	19.02 ± 0.74 **
N2T3	14.82 ± 0.36	24.10 ± 0.64 **	22.24 ± 0.77 **	14.46 ± 0.25	23.53 ± 0.95 **	21.30 ± 0.78 **
N3T3	14.66 ± 0.29	25.54 ± 0.76 **	19.43 ± 0.57 **	13.94 ± 0.28	24.59 ± 0.65 **	18.45 ± 0.67 **
T						
T1	14.92 ± 0.21	22.14 ± 0.36 b	18.80 ± 0.29 b	14.42 ± 0.19	21.60 ± 0.55 b	18.29 ± 0.37 b
T2	14.79 ± 0.20	22.68 ± 0.63 ab	18.81 ± 0.37 b	14.46 ± 0.27	22.83 ± 0.36 ab	19.78 ± 0.26 a
T3	14.76 ± 0.20	23.92 ± 0.47 a	19.96 ± 0.51 a	14.21 ± 0.15	23.31 ± 0.53 a	19.59 ± 0.47 a
N						
N1	14.77 ± 0.19	21.35 ± 0.43 B	17.68 ± 0.34 B	14.18 ± 0.20	21.30 ± 0.46 B	18.27 ± 0.37 B
N2	14.87 ± 0.24	22.99 ± 0.46 A	20.41 ± 0.42 A	14.50 ± 0.17	22.91 ± 0.46 A	20.17 ± 0.39 AB
N3	14.83 ± 0.18	24.39 ± 0.48 A	19.48 ± 0.27 A	14.42 ± 0.25	23.54 ± 0.50 A	19.23 ± 0.34 A
			F-value (*p*-value)			
T	0.17 (0.844)	4.17 (0.019)	4.24 (0.018)	0.41 (0.667)	3.59 (0.033)	5.67 (0.005)
N	0.06 (0.947)	11.61 (<0.001)	18.27 (<0.001)	0.65 (0.527)	6.14 (0.003)	7.82 (0.001)
T × N	1.14 (0.346)	0.33 (0.859)	2.36 (0.061)	0.93 (0.453)	0.25 (0.910)	2.36 (0.061)

The data are all average ± standard error (the number of samples for each treatment is 9) in the table, different letters within a column indicate significant differences among all treatments, lowercase letters indicate differences between urea types, and capital letters indicate differences between N application rates; * ($p < 0.05$) and ** ($p < 0.01$) indicate the mean values that significantly differed from the control with Student's *t*-test. T: urea type (urea, T1; polymer-coated urea, T2; DMPP + urea, T3); N: nitrogen application rate (150 kg·ha^{-1}, T1; 200 kg·ha^{-1}, T2; 250 kg·ha^{-1}, T3).

3.3.2. Water Use Efficiency of Leaves

Table 8 shows the WUE_L of greenhouse tomatoes at each growth stage with different urea types and N application rates. The WUE_L of greenhouse tomatoes was not greatly affected by the urea type and N application rate at 30 d after transplanting in 2020 and 2021, and no significant differences in the WUE_L were observed among treatments. At 60 d after transplanting, WUE_L was highest with T3 followed by T2 and T1. The WUE_L of greenhouse tomatoes was 48.69% and 56.44% higher in 2020 and 2021, respectively, with T3 compared to CK. WUE_L increased as the N application rate increased. The WUE_L of greenhouse tomatoes was 52.76 and 63.72% higher in 2020 and 2021, respectively, with N3 compared to CK. At 100 d after transplanting, the WUE_L was highest with T3, followed by T2 and T1. The WUE_L of greenhouse tomatoes was 26.55% and 34.82% higher in 2020 and 2021, respectively, with T3 compared to CK. The WUE_L of greenhouse tomatoes was 31.95 and 34.78% higher in 2020 and 2021, respectively, with N2 compared to CK.

Table 8. Response of tomato water use efficiency of leaves (WUE_L, mmol CO_2 $mol^{-1}{\cdot}H_2O$) to different urea types and N application rates in the greenhouse.

Main Effect	2020			2021		
	30 d	60 d	100 d	30 d	60 d	100 d
CK	2.14 ± 0.08	1.59 ± 0.05	1.87 ± 0.06	1.97 ± 0.04	1.47 ± 0.06	1.90 ± 0.04
N1T1	1.99 ± 0.07	1.98 ± 0.07 **	2.09 ± 0.07 *	1.90 ± 0.05	1.97 ± 0.09 **	2.15 ± 0.11
N2T1	2.15 ± 0.12	2.14 ± 0.12 **	2.47 ± 0.09 **	2.04 ± 0.06	2.20 ± 0.12 **	2.38 ± 0.07 **
N3T1	2.01 ± 0.06	2.25 ± 0.07 **	2.31 ± 0.06 **	2.02 ± 0.05	2.24 ± 0.10 **	2.38 ± 0.09 **
N1T2	2.11 ± 0.11	2.00 ± 0.13 **	2.06 ± 0.08	2.00 ± 0.09	2.10 ± 0.06 **	2.19 ± 0.10 *
N2T2	2.01 ± 0.09	2.25 ± 0.12 **	2.44 ± 0.08 **	2.04 ± 0.07	2.34 ± 0.04 **	2.51 ± 0.09 **
N3T2	2.15 ± 0.06	2.45 ± 0.16 **	2.45 ± 0.07 **	2.02 ± 0.07	2.45 ± 0.07 **	2.51 ± 0.07 **
N1T3	2.09 ± 0.06	2.13 ± 0.06 **	2.26 ± 0.11 **	1.87 ± 0.04	2.06 ± 0.07 **	2.42 ± 0.16 **
N2T3	2.10 ± 0.12	2.38 ± 0.10 **	2.50 ± 0.09 **	1.97 ± 0.06	2.31 ± 0.08 **	2.78 ± 0.21 **
N3T3	2.01 ± 0.09	2.59 ± 0.13 **	2.35 ± 0.05 **	1.93 ± 0.05	2.52 ± 0.14 **	2.46 ± 0.10 **
T						
T1	2.05 ± 0.05	2.12 ± 0.05 b	2.29 ± 0.05	1.99 ± 0.03	2.14 ± 0.06	2.30 ± 0.06 b
T2	2.09 ± 0.05	2.23 ± 0.09 ab	2.32 ± 0.06	2.02 ± 0.04	2.29 ± 0.04	2.40 ± 0.06 ab
T3	2.07 ± 0.05	2.36 ± 0.07 a	2.37 ± 0.05	1.92 ± 0.03	2.29 ± 0.07	2.55 ± 0.10 a
N						
N1	2.06 ± 0.05	2.04 ± 0.05 B	2.13 ± 0.05 B	1.92 ± 0.04	2.04 ± 0.04 B	2.25 ± 0.07 B
N2	2.09 ± 0.06	2.26 ± 0.07 A	2.47 ± 0.05 A	2.02 ± 0.04	2.28 ± 0.05 A	2.55 ± 0.08 A
N3	2.06 ± 0.04	2.43 ± 0.08 A	2.37 ± 0.04 A	1.99 ± 0.04	2.40 ± 0.06 A	2.45 ± 0.05 AB
			F-value (*p*-value)			
T	0.18 (0.833)	3.46 (0.037)	0.79 (0.457)	1.81 (0.171)	2.98 (0.057)	3.41 (0.038)
N	0.11 (0.893)	9.22 (<0.001)	14.50 (<0.001)	1.84 (0.166)	12.06 (<0.001)	4.88 (0.010)
T × N	0.90 (0.467)	0.24 (0.913)	1.02 (0.403)	0.24 (0.915)	0.32 (0.865)	0.66 (0.621)

The data are all average ± standard error (the number of samples for each treatment is 9) in the table, different letters within a column indicate significant differences among all treatments, lowercase letters indicate differences between urea types, and capital letters indicate differences between N application rates; * ($p < 0.05$) and ** ($p < 0.01$) indicate the mean values that significantly differed from the control with Student's *t*-test. T: urea type (urea, T1; polymer-coated urea, T2; DMPP + urea, T3); N: nitrogen application rate (150 kg·ha^{-1}, T1; 200 kg·ha^{-1}, T2; 250 kg·ha^{-1}, T3).

3.4. Yield, Water Use Efficiency and Nitrogen Agronomic Efficiency

3.4.1. Yield and Yield Components

Urea type and N application rate had a significant effect on greenhouse tomato Y and Y_m (Table 9). The Y and Y_m of greenhouse tomatoes in 2020 and 2021 were highest with T3, followed by T2 and T1, at the same N application rate. The Y and Y_m of greenhouse tomatoes increased gradually with T1 and T2 as the N application rate increased, and Y and Y_m first increased and then decreased with T3 as the N application rate increased. The Y and Y_m were highest with N2T3 (99.10 and 91.14 t·ha^{-1}, 99.25 and 90.70 t·ha^{-1} in 2020 and 2021, respectively), and they were 42.53 and 45.47% and 46.73 and 50.02% higher in 2020 and 2021, respectively, with N2T3 compared to CK.

Urea type and N application rate had a significant effect on the amount of fruit in greenhouse tomatoes. The number of fruits was highest with N3T3 in 2020 and 2021, which was 20.44 and 20.22 plant^{-1}, respectively. Compared with CK, the number of fruits increased by 27.75 and 27.25% in 2020 and 2021, respectively. The urea type had no significant effect on the weight of a single fruit in 2020 and 2021, and the N application rate had significant effects on the weight of a single fruit in 2020. The weight of a single greenhouse tomato tended to increase with the increase in N application rate. Compared with CK, the weight of a single fruit was increased by 15.45 and 18.69% with N3 in 2020 and 2021, respectively.

Table 9. Response of tomato yield (Y, t·ha^{-1}), marketable yield (Y_m, t·ha^{-1}), number of fruits (plant^{-1}), and weight of a single fruit (g) to different urea types and N application rates in the greenhouse.

Year	Main Effect	Yield Indicators			
		Yield	Marketable Yield	Fruit Number	Weight of a Single Fruit
2020	CK	69.53 ± 2.06	62.65 ± 2.15	16.00 ± 0.32	148.32 ± 5.09
	N1T1	76.11 ± 1.40 *	69.00 ± 1.37 *	17.44 ± 0.38 *	148.94 ± 3.67
	N2T1	87.14 ± 1.26 **	79.14 ± 1.26 **	18.00 ± 0.14 **	164.78 ± 3.03
	N3T1	90.79 ± 2.03 **	82.37 ± 1.92 **	18.33 ± 0.43 **	169.16 ± 4.75 *
	N1T2	78.13 ± 1.61 *	70.89 ± 1.58 *	17.11 ± 0.37 *	155.99 ± 4.60
	N2T2	91.42 ± 1.34 **	83.15 ± 1.24 **	20.00 ± 0.46 **	156.47 ± 5.03
	N3T2	94.22 ± 2.38 **	87.10 ± 2.30 **	19.33 ± 0.52 **	170.21 ± 6.97 *
	N1T3	91.61 ± 1.80 **	83.58 ± 1.75 **	18.22 ± 0.35 **	171.63 ± 4.87 *
	N2T3	99.10 ± 2.11 **	91.14 ± 2.10 **	20.44 ± 0.58 **	166.38 ± 6.05
	N3T3	95.86 ± 1.29 **	85.55 ± 1.22 **	18.44 ± 0.36 **	174.33 ± 3.90 *
	T				
	T1	84.68 ± 1.38 c	76.84 ± 1.29 c	17.93 ± 0.20 b	160.96 ± 2.61
	T2	87.92 ± 1.63 b	80.38 ± 1.53 b	18.82 ± 0.33 ab	160.89 ± 3.32
	T3	95.52 ± 1.11 a	86.76 ± 1.10 a	19.04 ± 0.30 a	170.78 ± 2.84
	N				
	N1	81.95 ± 1.47 B	74.49 ± 1.41 B	17.59 ± 0.22 B	158.85 ± 2.93 B
	N2	92.56 ± 1.23 A	84.48 ± 1.22 A	19.48 ± 0.30 A	162.54 ± 2.80 AB
	N3	93.62 ± 1.14 A	85.00 ± 1.09 A	18.70 ± 0.26 A	171.23 ± 3.00 A
		F-value (*p*-value)			
	T	20.28 (<0.001)	20.14 (<0.001)	4.51 (0.014)	3.04 (0.054)
	N	31.14 (<0.001)	27.94 (<0.001)	11.75 (<0.001)	3.79 (0.027)
	T × N	4.12 (0.005)	4.01 (0.005)	2.79 (0.033)	1.15 (0.340)
2021	CK	67.64 ± 3.44	60.46 ± 3.21	15.89 ± 0.44	145.21 ± 7.10
	N1T1	75.98 ± 1.64	68.13 ± 1.62	16.33 ± 0.35	159.09 ± 5.25
	N2T1	86.80 ± 2.78 **	78.04 ± 2.81 **	17.33 ± 0.46	171.76 ± 7.59
	N3T1	87.61 ± 2.74 **	79.25 ± 2.88 **	17.89 ± 0.37 **	166.98 ± 5.29 *
	N1T2	81.09 ± 1.16 **	72.79 ± 1.22 *	17.33 ± 0.32	159.78 ± 4.21
	N2T2	94.97 ± 2.82 **	85.79 ± 2.83 **	19.67 ± 0.38 **	164.57 ± 4.92 *
	N3T2	95.73 ± 1.43 **	86.38 ± 1.35 **	19.56 ± 0.48 **	168.05 ± 3.85 **
	N1T3	88.96 ± 1.94 **	81.07 ± 1.96 **	18.56 ± 0.52 **	163.79 ± 3.99 *
	N2T3	99.25 ± 2.44 **	90.70 ± 2.35 **	20.22 ± 0.40 **	167.45 ± 4.90 *
	N3T3	97.18 ± 1.53 **	87.36 ± 1.54 **	18.00 ± 0.46 **	182.01 ± 5.29 **
	T				
	T1	83.46 ± 1.63 b	75.14 ± 1.63 b	17.19 ± 0.24 b	165.95 ± 3.52
	T2	90.59 ± 1.57 a	81.65 ± 1.52 a	18.85 ± 0.29 a	164.13 ± 2.48
	T3	95.13 ± 1.33 a	86.38 ± 1.29 a	18.93 ± 0.30 a	171.08 ± 2.96
	N				
	N1	82.01 ± 1.27 B	74.00 ± 1.28 B	17.41 ± 0.27 B	160.89 ± 2.53
	N2	93.67 ± 1.73 A	84.85 ± 1.73 A	19.07 ± 0.31 A	167.93 ± 3.33
	N3	93.50 ± 1.29 A	84.33 ± 1.29 A	18.48 ± 0.27 A	172.35 ± 2.93

Table 9. *Cont.*

Year	Main Effect	Yield Indicators			
		Yield	Marketable Yield	Fruit Number	Weight of a Single Fruit
		F-value (p-value)			
2021	T	15.80 (<0.001)	15.42 (<0.001)	12.32 (<0.001)	1.11 (0.336)
	N	21.32 (<0.001)	18.16 (<0.001)	9.08 (<0.001)	2.85 (0.065)
	T × N	0.76 (0.552)	0.63 (0.642)	3.29 (0.016)	0.72 (0.580)

The data are all average ± standard error (the number of samples for each treatment is 12) in the table, different letters within a column indicate significant differences among all treatments, lowercase letters indicate differences between urea types, and capital letters indicate differences between N application rates; * ($p < 0.05$) and ** ($p < 0.01$) indicate the mean values that significantly differed from the control with Student's t-test. T: urea type (urea, T1; polymer-coated urea, T2; DMPP + urea, T3); N: nitrogen application rate (150 kg·ha^{-1}, T1; 200 kg·ha^{-1}, T2; 250 kg·ha^{-1}, T3).

3.4.2. Water Use Efficiency and Nitrogen Agronomic Efficiency

The urea type and N application rate had a significant effect on the greenhouse tomato WUE and NAE (Table 10). The patterns of WUE were similar to those for Y. The WUE was highest with N2T3 (31.57 and 32.34 kg·m^{-3} in 2020 and 2021, respectively), and it was 35.90 and 40.36% higher in 2020 and 2021, respectively, with N2T3 compared to CK. The NAE was highest with T3, followed by T2 and T1, at the same N application rate. NAE first increased and then decreased as the N application rate increased. The NAE was highest with N2T3 (147.90 kg·kg^{-1} and 158.06 kg·kg^{-1} in 2020 and 2021, respectively), and it was 2.36 and 1.84 times higher in 2020 and 2021, respectively, with N2T3 compared to N1T1.

Table 10. Response of water use efficiency (WUE, kg·m^{-3}) and nitrogen agronomic efficiency (NAE, kg·kg^{-1}) of tomatoes to different urea types and N application rates in the greenhouse.

Main Effect	2020		2021	
	WUE	NAE	WUE	NAE
CK	23.23 ± 0.69		23.04 ± 1.17	
N1T1	24.78 ± 0.46	43.89 ± 9.33	25.12 ± 0.54	55.58 ± 10.92
N2T1	28.20 ± 0.41 **	88.09 ± 6.33 **	28.67 ± 0.92 **	95.80 ± 13.88 *
N3T1	28.91 ± 0.65 **	85.05 ± 8.13 **	29.06 ± 0.91 **	79.87 ± 10.97
N1T2	25.88 ± 0.53 *	57.37 ± 10.69	27.42 ± 0.39 *	89.66 ± 7.76
N2T2	29.80 ± 0.44 **	109.47 ± 6.71 **	32.00 ± 0.95 **	136.62 ± 14.09 **
N3T2	29.61 ± 0.41 **	98.76 ± 5.17 **	31.25 ± 0.48 **	112.36 ± 5.74 **
N1T3	29.40 ± 0.58 **	147.21 ± 12.00 **	29.17 ± 0.64 **	142.11 ± 12.92 **
N2T3	31.57 ± 0.67 **	147.90 ± 10.55 **	32.34 ± 0.79 **	158.06 ± 12.19 **
N3T3	31.00 ± 0.77 **	105.32 ± 9.32 **	31.89 ± 0.49 **	118.37 ± 6.12 **
T				
T1	27.30 ± 0.42 c	72.34 ± 5.62 c	27.62 ± 0.54 b	77.08 ± 7.22 c
T2	28.43 ± 0.50 b	90.72 ± 6.46 b	30.22 ± 0.52 a	112.89 ± 6.37 b
T3	30.66 ± 0.35 a	133.46 ± 6.65 a	31.13 ± 0.42 a	139.48 ± 6.82 a
N				
N1	26.69 ± 0.44 B	82.83 ± 9.80 B	27.24 ± 0.41 B	95.78 ± 8.49 B
N2	29.85 ± 0.37 A	115.15 ± 6.15 A	31.00 ± 0.57 A	130.16 ± 8.64 A
N3	29.84 ± 0.38 A	96.39 ± 4.57 B	30.73 ± 0.43 A	103.48 ± 5.17 B
	F-value (p-value)			
T	15.19 (<0.001)	25.41 (<0.001)	14.00 (<0.001)	17.41 (<0.001)
N	24.03 (<0.001)	7.36 (0.001)	19.69 (<0.001)	6.29 (0.003)
T × N	4.18 (0.004)	6.75 (<0.001)	1.02 (0.403)	1.55 (0.196)

The data are all average ± standard error (the number of samples for each treatment is 12) in the table, different letters within a column indicate significant differences among all treatments, lowercase letters indicate differences between urea types, and capital letters indicate differences between N application rates; * ($p < 0.05$) and ** ($p < 0.01$) indicate the mean values that significantly differed from the control with Student's t-test. T: urea type (urea, T1; polymer-coated urea, T2; DMPP + urea, T3); N: nitrogen application rate (150 kg·ha^{-1}, T1; 200 kg·ha^{-1}, T2; 250 kg·ha^{-1}, T3).

4. Discussion

4.1. Root Morphological Indexes

Fertilizers play an important role in the growth and development of crops. Tomatoes absorb water and nutrients in the soil through the root system, perform photosynthesis, and synthesize carbohydrates. N can regulate crop physiological processes and support crop growth [38]; it is thus one of the most important nutrients for supporting crop growth.

Our findings indicate that differences in the root morphological indicators of greenhouse tomatoes with different types of urea were small. RL, RT, and RF were slightly higher with T1 than with T2 and T3. This might be explained by the fact that urea is rapidly hydrolyzed to NO_3^--N in T1; at the same N application rate, greater amounts of NO_3^--N are beneficial to the growth of the lateral roots of plants [39,40]. RS, RV, and RA were higher with T3 than with T1 and T2, which might be related to the development of greenhouse tomatoes. With T3, the N use efficiency was improved due to the effect of DMPP, which promoted the development of the root system of greenhouse tomatoes [41]. The N application rate had a significant effect on the root morphological indicators. An N application rate of N2 improved root growth. The indicators decreased when the N application rate was greater than N2. This might be explained by the fact that the main factors restricting the growth of the root system (e.g., water, P, and K) change as the N application rate increases. In addition, an excessively high concentration of ions might inhibit the development of the root system.

4.2. Growth

The PH of greenhouse tomatoes increased as the N application rate increased 56 d after tomato plants were transplanted, and there were no significant differences in PH between N3 and N2. At 76 d after transplanting, the PH of greenhouse tomatoes was highest with T3, followed by T2 and T1, when the N application rate was less than N2; however, when the N application rate was N3, the PH was highest with T2, followed by T3 and T1, which stems from the high amount of NH_4^+ with T3. The accumulation of ions and the osmotic stress of crops impede the absorption of water and nutrients by crops and thus ultimately inhibit normal crop growth. The SD and LAI of greenhouse tomatoes (56 d after transplanting) increased as the N application rate increased, but there was no significant difference in the SD and LAI between N3 and N2. The SD and LAI of greenhouse tomatoes first increased and then decreased as the N application rate increased at 76 and 100 d after transplanting. Previous studies have shown that high N application rates in the early and middle stages of tomato growth may lead to excessive plant growth, which can result in severe water and fertilizer shortages in the later stages of growth [42,43]; these findings are consistent with the results of this study. Meanwhile, research has found that excessive nitrogen may increase soil pathogens and parasitic nematodes, inhibit root growth, reduce root absorption capacity of water and nutrients, and lead to stunted growth of plant shoots [44].

4.3. Photosynthetic Parameters

The changes in the P_n of greenhouse tomatoes across growth stages varied among the different treatments. At 30 d after transplanting, urea type and N application rate had little effect on the P_n of greenhouse tomatoes, which might stem from the small size and low N demand of greenhouse tomato plants; consequently, the N level of all treatments was sufficient for meeting the growth demands of tomatoes, and no significant differences in P_n were observed among the different treatments. At 60 d after transplanting, the P_n of greenhouse tomatoes increased as the N application rate increased, which is consistent with the findings of Ruiz et al. (2008) [45], and there was no significant difference in P_n observed between N3 and N2. P_n was highest with T1, which might stem from the higher NUE in plants with T2 and T3. At 100 d after transplanting, the net photosynthetic rate of greenhouse tomatoes first increased and then decreased as the N application rate increased. The patterns of change in the P_n among the different urea-type treatments were similar at 60 d after transplanting. The WUE_L is an important parameter for describing water use efficiency at the leaf scale [46]. Patterns of variation in the WUE_L of greenhouse tomatoes with each treatment in this study varied among growth stages. At 30 d after transplanting, there was no significant difference in the WUE_L of greenhouse tomatoes with each treatment, but at 30 d and 60 d after transplanting, the WUE_L first increased and then decreased as the N application rate increased, indicating that an appropriate increase in N application can increase WUE_L; this finding is consistent with the results of Zhou et al. (2020) [35].

4.4. Yield, Water Use Efficiency and Nitrogen Agronomic Efficiency

The Y and Y_m of greenhouse tomatoes with the same N application rate were highest with T3, followed by T2 and T1. Combined with the results of the above analysis, this finding indicates that the application of DMPP + urea in greenhouse tomatoes is superior to PCU application; this might be explained by the high temperature and high humidity in the greenhouse, which affects the release process of PCU and reduces NAE. When the N application rate increased from 0 to 250 kg·ha^{-1}, the Y and Y_m of greenhouse tomatoes did not increase linearly as the N application rate increased, and there was no significant difference between the N2 and N3 treatments with each urea type. The reason may be related to the lower background value of soil K content but high soil N content. Many studies have shown that K is an important factor affecting the yield and quality of tomatoes in greenhouses [47–49]. When the nitrogen application rate is high, the lack of K in soil may be the main factor limiting the accumulation of dry matter in tomato fruit.

There was a significant positive correlation between greenhouse tomato yield, the number of fruits, and the weight of a single fruit (Figure 2). The correlation and significance between Y and the weight of a single fruit were smaller than those between Y and the number of fruits. The results show that the yield of tomatoes was determined by the number of fruits and the weight of a single fruit, and the effect of the number of fruits on yield was greater than that of the average fruit weight on yield.

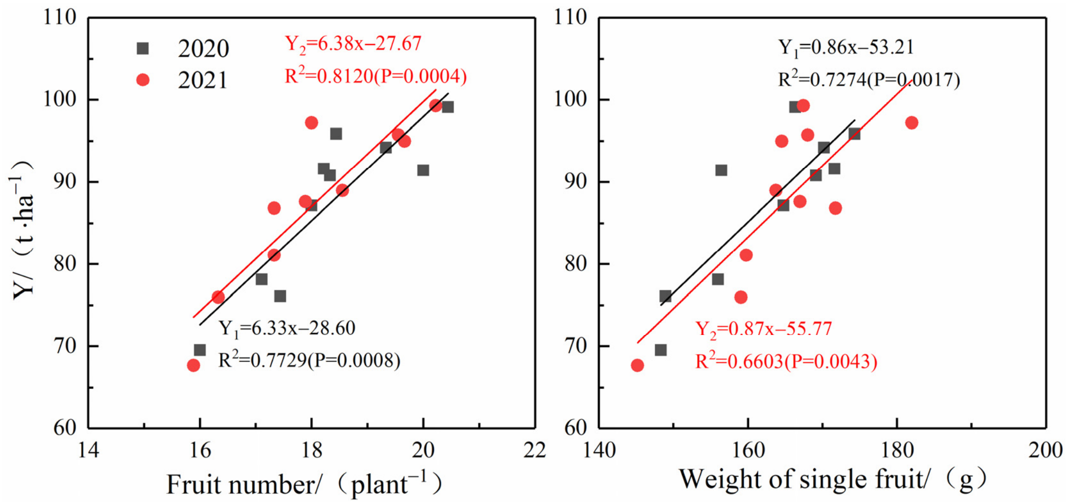

Figure 2. Correlation between yield (Y, t·ha^{-1}), number of fruits (plant^{-1}), and the weight of a single fruit (g) with different urea types and N application rates in the greenhouse. The black line and square dots indicate the result for 2020, the red line and round dot indicate the result for 2021. Y_1 and Y_2 represent estimated yield of greenhouse tomato in 2020 and 2021, respectively.

The pattern of change in the WUE of greenhouse tomatoes was similar to that of Y, indicating that appropriate increases in the N application rate can increase the WUE of greenhouse tomatoes. The NAE of greenhouse tomatoes first increased and then decreased as the N application rate increased. The NAE was significantly lower with N3 than with N2, which might stem from excessive fertilizer application and result in N leaching and volatilization [50,51], increases in the ion concentration in the root zone, increases in osmotic pressure, and inhibition of the absorption of water and nutrients by the roots [52].

5. Conclusions

In this paper, the effects of different urea types and N application rates on the root system, growth characteristics, Y, WUE, and NAE of greenhouse tomatoes with drip irrigation and plastic film mulching were investigated, and the optimal N application strategy for the growth of greenhouse tomatoes was identified. There were two main conclusions. Firstly, the urea type and N application rate had significant effects on the growth of greenhouse tomatoes. The growth indexes of greenhouse tomatoes did not increase linearly as the N application rate increased. The growth indexes of greenhouse tomatoes were slightly increased at 250 kg·ha^{-1} compared with 200 kg·ha^{-1} at the later stage of greenhouse tomato development with urea and polymer-coated urea, but decreased with DMPP + urea treatment. Secondly, moderate N application could increase the Y, WUE, and NAE of greenhouse tomatoes, and excessive N application significantly reduced NAE. According to the analysis, an N application rate of 200 kg·ha^{-1} coupled with DMPP + urea application could increase NAE and Y. The soil texture in this study was sandy loam, and the content of various nutrients (especially K) was low, which affected the utilization efficiency of N to some extent, and research in a wider area is needed to further determine the optimal nitrogen application strategy. In conclusion, the results of our study provide data that will aid further improvements in the N yield of greenhouse tomatoes in northwest China.

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Abbreviations

CK	Control group (0 kg·N·ha^{-1})
DCD	Dicyandiamide
DMPP	3,4-Dimethylpyrazole phosphate
LAI	Leaf area index
N	Nitrogen
NAE	Nitrogen agronomic efficiency
NUE	Nitrogen use efficiency
N1	150 kg·N·ha^{-1}
N2	200 kg·N·ha^{-1}
N3	250 kg·N·ha^{-1}
PCU	Polymer-coated urea
PH	Plant height
P_n	Net photosynthetic rate
RA	Root activity
RB	Number of root branches

RL	The total root length
RS	Total surface area
RT	Total number of root tips
RV	Total root volume
SD	Stem diameter
T1	Urea
T2	Polymer-coated urea
T3	DMPP + urea
WUE	Water use efficiency
WUE_L	Water use efficiency of leaves
Y	Yield
Y_m	Marketable yield

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