SOIL STOICHIOMETRIC CHARACTERISTICS OF GREENHOUSE TOMATO REGULATED BY IRRIGATION SYSTEM

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Abstract. The change of soil moisture under new water-saving micro-sprinkling irrigation with plastic film (MSPF) in greenhouse agriculture caused the change of soil nutrients, soil enzyme activity and the process of this is not clear. Therefore, the rhizosphere soil of different irrigation frequency (F, F1: 3d, F2: 5d, F3: 7d) and irrigation amount (I, I1: 0.7 Epan, where Epan is the cumulative evaporation of Φ20 cm standard pan, I2: 1.0 Epan, I3: 1.2 Epan) under MSPF were collected and analyzed to explore the response of soil nutrient, soil enzyme activity and its stoichiometric ratio. The results showed that the soil carbon, nitrogen, phosphorus and enzyme stoichiometric ratio of tomato increased first and then decreased or increased with the decrease of irrigation frequency F and the increase of irrigation amount I. When F was 5 days, the soil carbon and nitrogen limitation could be reduced, and the soil carbon and nitrogen accumulation was better under 1.0 Epan. The F2I2 could significantly increase the yield of tomato and improve the water use efficiency of tomato. Soil total organic carbon / total phosphorus and β-glucosidase / aline phosphatase had good correlation with yield, which could be used as important indicators to evaluate soil nutrient cycling.
Keywords: *irrigation frequency, irrigation amount, soil carbon nitrogen phosphorus, soil enzyme activity, regression analysis*

Introduction

Chemometrics is to explore the balance relationship between energy, material cycle, carbon, nitrogen and phosphorus ecological chemical elements, which can provide innovation for the balance of energy and its elements in the ecosystem (Li et al., 2024). As the basic elements required for plant growth and development, carbon, nitrogen and phosphorus are of great significance in the nutrient cycle of the ecosystem for regulating and driving succession processes (Liu et al., 2021; Lu et al., 2023). At present, chemometrics has been widely used in forest, grassland, food crops and other fields (Fang et al., 2019; Yuan et al., 2020; Feyissa et al., 2022; Lasota et al., 2022). Studies have shown that the C/N and C/P can be used to characterize the growth rate of plants, the utilization efficiency of soil N and P by plants is determined by their ratio, and the nutrient elements that limit productivity can also be indicated by N/P (Zhang et al., 2021; Liao et al., 2024). Soil stoichiometric ratio is an important index for evaluating nutrient adaptation strategies of forest plants (Su and Shangguan, 2021; Shao et al., 2023). Soil stoichiometric ratio is also a dynamic driver of soil organic carbon in grassland and food crops (Fang et al., 2019; Xu et al., 2020). The exploration of soil stoichiometric ratio is of great significance for

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revealing the interaction between soil carbon, nitrogen and phosphorus, regional soil nutrient management and sustainable land use.

Greenhouse agriculture is an important part of vegetable production safety. Its unique management mode (such as frequent tillage, irrigation and fertilization, etc.) is easy to promote soil salinization and nutrient loss and reduce nutrient turnover between crop roots and soil. This process directly or indirectly affects soil carbon, nitrogen, phosphorus and soil enzyme stoichiometry (Li et al., 2019; Liu et al., 2021). Studies have shown that different irrigation amount and fertilization treatments can change the soil enzyme activity, nutrient distribution and the growth status of crop organs in greenhouse agriculture, and then affect the nutrient cycling process and balance characteristics of greenhouse agriculture microsystem (Zapata-Sierra et al., 2021; Islam et al., 2022; Zeyada et al., 2022). As a common facility agricultural vegetable, tomato demand is increasing year by year due to its high nutritional value and great economic benefits for local farmers (Zheng et al., 2013). Ensuring the stable yield of tomato, reducing the waste of water resources and improving the utilization rate of soil nutrients have become the research hotspots of greenhouse agriculture. Irrigation is an important factor to ensure the increase of tomato yield. Irrigation frequency and irrigation amount are two important indexes of irrigation, which determine when to irrigate and how much to irrigate (Liu et al., 2019; Wei et al., 2024). Studies have shown that changes in external factors such as crop irrigation frequency and irrigation amount will affect soil enzymes, carbon, nitrogen and phosphorus and plant leaves and roots nutrients, and plant leaves and roots growth activities provide soil with nutrient sources and conversion driving force (Tangolar et al., 2019; Sałata et al., 2022). With the change of different irrigation frequency and irrigation amount, the nutrient cycle between plants (leaves, roots) and soil will also change (Wang et al., 2016; Zhang et al., 2021). When the soil is short of water, the C/N and C/P values in sugarcane and banana plants will decrease (Long et al., 2018; de Oliveira Filho et al., 2021). Therefore, it is of great significance to explore the characteristics of soil carbon, nitrogen and phosphorus content, enzyme activity and stoichiometric ratio in different irrigation frequency and irrigation amount treatment processes in greenhouse agriculture, to clarify the variation law of element circulation and mutual coupling in greenhouse agriculture ecosystem, and to enrich the ecological stoichiometric theory of terrestrial ecosystem.

As a new water-saving technology in greenhouse agriculture, the MSPF has achieved good results in greenhouse cucumber, celery and watermelon (Xie, 2019; Zeng et al., 2021; Yin et al., 2021). At present, chemometrics is less used in the field of greenhouse agriculture irrigation, especially in the new water-saving technology of MSPF. The change mechanism of tomato rhizosphere soil under MSPF is not clear. At the same time, the correlation between carbon-nitrogen-phosphorus stoichiometric ratio, enzyme stoichiometric ratio and yield of tomato under MSPF is lack of quantitative description. Therefore, in this study, greenhouse tomato in greenhouse agriculture was used as the research object to explore the response of tomato yield and soil stoichiometric ratio to different irrigation frequency and irrigation amount in greenhouse with MSPF. Regression analysis was used to determine the correlation between tomato soil carbon, nitrogen and phosphorus stoichiometric ratio, enzyme stoichiometric ratio and yield of tomato. The purpose of this paper is to provide data support for water-saving and yield-increasing of facility agricultural tomato in Northwest China through greenhouse experiment and target optimization data analysis.

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Materials and Methods

Experimental site and management

The experiment was carried out at Xi 'an Modern Agricultural Science and Technology Exhibition Center (108°52′E, 34° 03′N) in Xi 'an, Shaanxi Province, China. The average annual rainfall in the experimental area was 507.70-719.80 mm, and more than 60 % of the rainfall was concentrated from August to October. The frost-free period is 219-233 d, the annual sunshine hours are up to 2230 h, the annual average wind speed is 2-3 m/s, and the annual average temperature is 13.30 °C. The soil is sandy loam, and the mass fractions of sand, silt, and clay are 63.9%, 29.63%, and 6.47%, respectively. The average bulk density of the 1.0 m soil layer was 1.48 g/cm^3, the water holding capacity of field weight was 27.40%, and the depth of groundwater table on the site exceeded 30 m. The content of total organic carbon (TOC, C), total nitrogen (TN, N), total phosphorus (TP, P) in 0-40 cm soil layer before tomato planting were19.87 g/kg, 1.75 mg/g, 1.46 g/kg, respectively. The C/N, C/P and N/P of greenhouse soil were 11.35, 13.61 and 1.18, respectively.

The greenhouse (85 m long and 15 m wide) was oriented from north to south. The tomato variety ‘Jingfan 401’ (*Solanum lycopersicum*, Jingyan Yinong Seed Sci-tech Co. Ltd., Beijing, China), with a 50 cm row spacing and a 40 cm plant spacing, was planted on a ridge. In this study, tomato is a pink tomato hybrid, medium maturity, unlimited growth type, strong growth, 4-5 fruit per panicle, round fruit, no green shoulder, beautiful sepals, good hardness, storage and transportation. It has Ty1 and Ty3a gene loci against tomato yellow leaf curl virus disease, and Tm2a gene loci against tomato mosaic virus disease. It has good comprehensive resistance to leaf diseases and good heat resistance. The length of the ridge was 3.4 m and the width was 1.2 m. The distance between each plot was 4 m; one 1.0-m deep building waterproof film made up of styrene-butadiene-styrene block copolymer was buried in the middle to prevent the horizontal infiltration and movement of soil moisture, thus avoiding their effect on other plot experiments. In order to ensure the planting density of tomatoes and reduce the uncontrollable factors of the experiment, tomato seed seedlings were carried out in advance in this study. After 30 days of tomato emergence, tomatoes with consistent growth were selected and transplanted to each experimental plot. The field management measures, such as fertilisation, irrigation, and pesticides, were kept similar in all treatments. To ensure the survival of seedlings on the day of planting, the irrigation was unified with reference to the local tomato planting experience. The source of irrigation water in the region was groundwater. The irrigation water originated from groundwater, the pH of which was 6.8, the chemical oxygen demand (COD) was 53.2 mg/L, the anionic surfactant content was 3.2 mg/L, and the chloride content was 0.48 mg/L. In this study, basal fertilizer was applied, and no topdressing was applied after tomato planting. Before transplanting, 1500 kg/ha of organic fertilizer (organic content≥45%, NPK≥5%, fermentation fertilizer of cattle and sheep excreta), 180 kg·CH_4N_2O/ha (urea, N≥46%), 180 kg·P_2O_5/ha (calcium superphosphate, P≥46%) and 120 kg·K_2O/ha (potassium sulfate, K≥51%) were applied as the basic fertilizer. The meteorological data related to tomato growth period are shown in *Figure 1*.

This experiment set two factors of irrigation frequency (F) and irrigation amount (I), and the test scheme is shown in *Table 1*. The F set 3 levels: 3 d (F1), 5 d (F2), 7d (F3). The irrigation amount (I) was controlled based on the pan evaporation method (Epan).

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Different irrigation gradients were achieved by controlling the crop-pan coefficient kcp, and kcp was set at three levels: 0.70 (I1), 1.00 (I2), and 1.20 (I3) (Zhu et al., 2020).

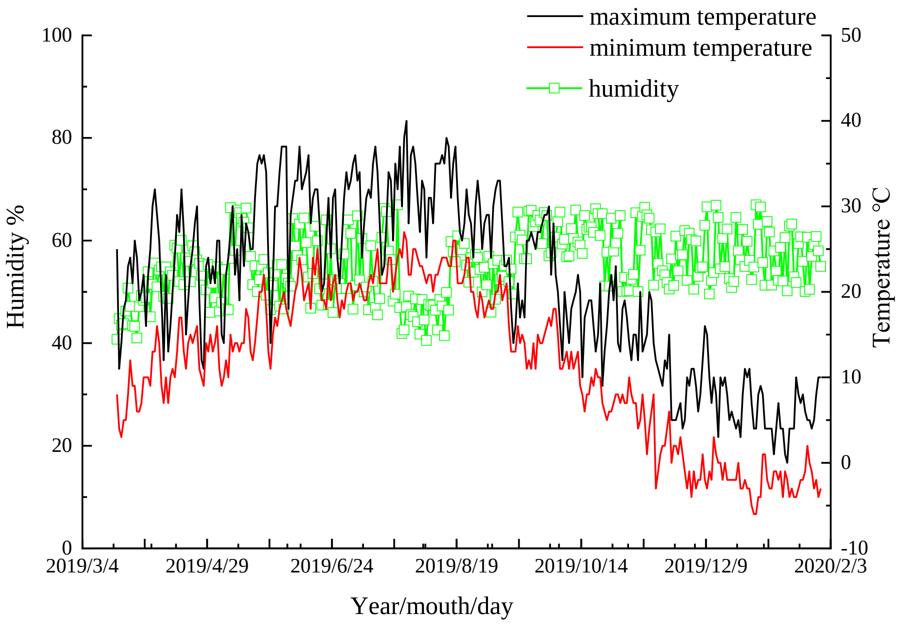

Figure 1. *Meteorological data related to tomato growth period*

Table 1. *Experimental design of F and I*

No.	Treatment	Irrigation frequency day	k_{cp}	Irrigation amount mm		Irrigation frequency times	
				Spring tomato	Autumn tomato	Spring tomato	Autumn tomato
1	F1I1	3	0.70	247.12	152.73	33	47
2	F1I2	3	1.00	353.03	218.19	33	47
3	F1I3	3	1.20	423.64	261.83	33	47
4	F2I1	5	0.70	247.12	152.73	21	28
5	F2I2	5	1.00	353.03	218.19	21	28
6	F2I3	5	1.20	423.64	261.83	21	28
7	F3I1	7	0.70	247.12	152.73	15	20
8	F3I2	7	1.00	353.03	218.19	15	20
9	F3I3	7	1.20	423.64	261.83	15	20

Note: F: irrigation frequency, I: irrigation amount

Spring tomato was planted on March 27, 2019. The irrigation treatment began on April 4, 2019. The irrigation was stopped on July 15, 2019. It was fully harvested on July 25, 2019. Autumn tomato was planted on August 23, 2019. Irrigation began on August 30, 2019. Irrigation was stopped on January 17, 2020, and they were fully harvested on January 30, 2020. The irrigation amount was controlled on the basis of the cumulative evaporation from a 20-cm diameter standard pan (E_{pan}, DY.AM3, Weifang Dayu Hydrology Technology Co., Ltd., Shandong, China) following Liu et al. (2013). The evaporation amount was measured at 08:00 am every 5 d. The irrigation amount was

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evaluated after the measurement. The W of irrigation quota was calculated according to Formula (*Eq.1*), and the irrigation times and amounts were recorded (*Figure 2*).

$$W = A \times E_{pan} \times k_{cp} \quad \text{(Eq.1)}$$

In the formula: E_{pan} represents the evaporation within the interval of two irrigation, basing on the cumulative evaporation from a 20 cm diameter pan (mm); A represents the capillary control area (mm), and k_{cp} represents the crop- pan coefficient (Zhu et al., 2020).

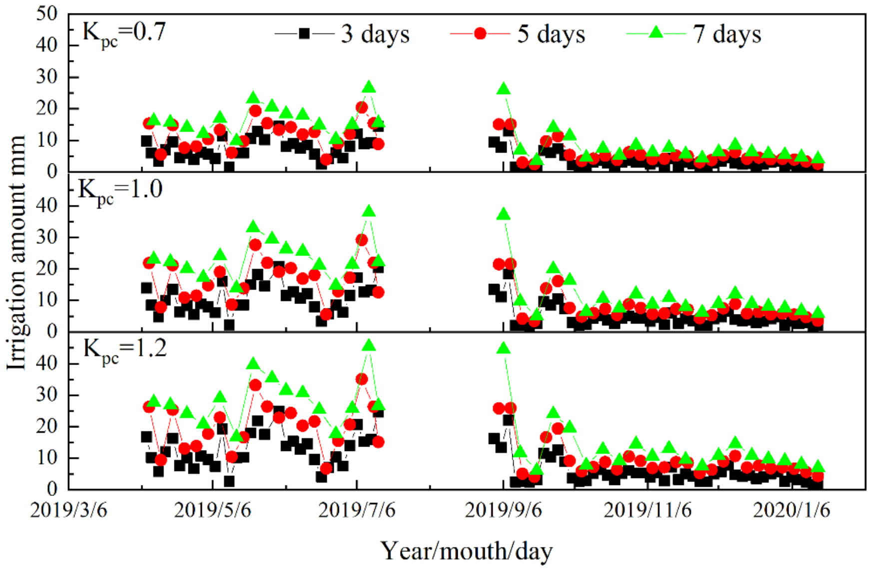

Figure 2. *Tomato growth period irrigation time and irrigation amount. The 3,5,7 indicates that the irrigation frequency is 3 days, 5 days and 7 days respectively*

Measurements and computational methods

Collection, determination and calculation of relevant parameters of soil samples

1) Collection of soil sampling

The soil in this study is rhizosphere soil. The soil was extracted by shaking method (5-25 cm tomato roots were dug out as a whole (*Figure 3*), the loose soil combined with tomato roots was shaken off, and the soil closely combined with tomato roots in greenhouse was brushed slightly with soft brush as the rhizosphere soil of tomato in greenhouse). Three soil samples were randomly selected from each plot, and the samples were taken back to the room and the fresh soil plant residues were removed. The soil samples were divided into two parts, half of which were stored in a refrigerator at -20 °C, and the other half was used for air drying and drying. The determination of soil related indicators was completed within 10 days.

2) Samples determination method

The rhizosphere soil total organic carbon (TOC), soil total nitrogen (TN), soil total phosphorus (TP), soil leucine aminopeptidase activity (LAP), soil β-glucosidase activity (BG), soil alkaline phosphatase activity (AP) and soil N-acetyl-d-glucosaminidase activity (NAG) were measured at 36,72 and 110 days after planting of spring tomato and

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autumn tomato. The TOC was determined using a total organic carbon analyzer (Vario El, ElementarAnalysen Systeme GmbH, Germany) (Chatterjee et al., 2018). The TN was determined by concentrated sulfuric acid digestion, potassium sulfate-copper sulfate catalysis and semi-micro Kjeldahl method (Dang et al., 2022). The TP was digested by $HClO_4$-H_2SO_4 and determined by molybdenum antimony colorimetric method(Zhang et al., 2021). The BG, LAP and NAG were extracted by enzyme-linked immunosorbent assay and determined by microplate reader (RT-6100, Shanghai Precision Instrument Co., Ltd., China) (Puissant et al., 2019). The AP was determined by disodium phenyl phosphate colorimetric method (Wang et al., 2022).

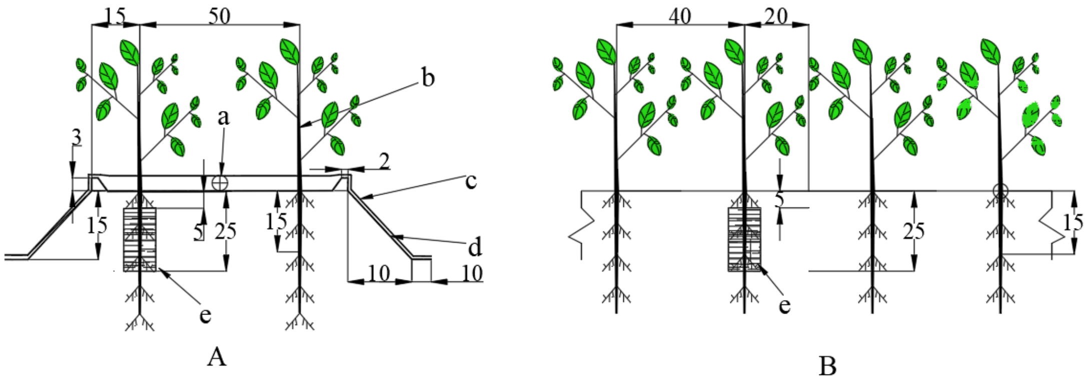

Figure 3. *Schematic diagram of soil sampling and measurement locations (cm). A: the left view section; B: the main view section; a: capillary, b: tomatoes; c: mulch; d: surface; e: rhizosphere soil sampling location*

Among them, C/N represents the stoichiometric ratio of soil TOC to TN. C/P represents the stoichiometric ratio of soil TOC to TP. N/P represents the stoichiometric ratio of soil TN to TP. BG/(LAP+NAG) represents the stoichiometric ratio of soil BG to LAP+NAG. BG/AP represents the stoichiometric ratio of soil BG to AP. (LAP+NAG)/AP represents the stoichiometric ratio of soil LAP+NAG to AP.

Yield and crop water use efficiency (WUE)

1) Four tomato plants were randomly selected, and the mature fruit mass of four tomatoes was weighed by electronic scale with precision of 0.01 g, and the yield per hectare was converted.

2) Time-domain reflectometry soil moisture sensor (TRIME-PICO-IPH, IMKO, Inc., Ettlingen, Germany) was used to measure the soil volume moisture content at different layers of soil (0–10, 10–20, 20–30, 30–40, 40–50, 50–60, 60–70, and 70–80 cm, respectively). It was measured once before and after each growth period. Water consumption (ET_a) and crop water use efficiency (WUE) were calculated by formulas (2) and (3), respectively (Zhang et al., 2021).

$$ET_a = I \pm 1000 \times H \times (\theta_{t1} - \theta_{t2}) \quad \text{(Eq.2)}$$

In the *formula (2)*, ET_a represents crop water consumption during the growth period (mm); I represents the irrigation quota during a certain growth period (mm); H represents

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the depth of the planned wetting layer (H = 0.8 m); θ_{t1} and θ_{t2} represent 80-cm average soil volumetric water contents at times $t1$ and $t2$ (cm^3/cm^3), respectively.

$$WUE = 1000 * Y/ET_a \quad \text{(Eq.3)}$$

In the *formula (3)*, Y indicates crop grain yield (t/hm^2).

Data analysis

The significant difference was analyzed by F test of SPSS22.0 (IBM Crop., Armonk, New York, NY, USA), and the significant level was set to $P<0.05$. The picture was draw by OriginPro2019 (Origin Lab Corporation, Northampton, MA, USA). Regression analysis was used to determine the correlation between tomato soil carbon, nitrogen and phosphorus stoichiometric ratio, enzyme stoichiometric ratio and yield of tomato By Excel 2016 (Microsoft Excel, Microsoft, Washington, USA).

Results

Effects of different treatments on soil carbon, nitrogen and phosphorus contents of greenhouse tomato

It can be seen from *Table 2* that with the advancement of tomato growth period, the TOC of greenhouse spring tomato and autumn tomato soil showed an increasing trend. TN and TP showed a decreasing trend. The F and I had significant effects on soil TOC, TN and TP of spring tomato and autumn tomato ($P\leq 0.05$, the same as below).

With the decrease of F, the soil TOC of spring tomato and autumn tomato under MSPF increased first and then decreased. The soil TOC of F2 treatment was about 5.01% and 8.31% higher than that of F1, and about 11.02% and 14.99% higher than that of F3. With the decrease of F, the soil TN of spring tomato and autumn tomato under MSPF showed an increasing trend. The soil TN of F2 treatment was about 4.40% and 3.38% higher than that of F1, but it was about 1.81% and 2.56% lower than that of F3. With the decrease of F, the soil TP of spring tomato and autumn tomato under MSPF decreased first and then increased. The soil TP of F2 treatment was about 6.46% and 4.81% lower than that of F1, and about 11.87% and 9.38% lower than that of F3.

With the increase of I, the soil TOC of spring tomato and autumn tomato under MSPF increased first and then decreased. The soil TOC of I2 treatment was about 8.48% and 13.40% higher than that of I1, and about 0.52% and 2.26% higher than that of I3. With the increase of I, the soil TN of spring tomato and autumn tomato under MSPF showed a decreasing trend. The soil TN of I2 treatment was about 1.82% and 2.91% lower than I1, but higher than I3 about 3.03% and 2.72%. With the increase of I, the soil TP of spring tomato and autumn tomato under MSPF decreased first and then increased. The soil TP of I2 treatment was about 13.63% and 7.30% lower than that of I1 and I3.

Effects of different treatments on soil enzyme activities of greenhouse tomato

It can be seen *Figure 4* that with the advance of tomato growth period, the activities of soil BG, LAP, NAG and AP of spring tomato and autumn tomato in greenhouse increased first and then decreased. The soil enzyme activity of 72 days after tomato planting in greenhouse was higher than that of 36 and 110 days.

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Table 2. *Effects of different treatments on soil carbon, nitrogen and phosphorus contents of greenhouse tomato*

	Treatment	TOC mg/g			TN mg/g			TP mg/g		
		36d	72d	110d	36d	72d	110d	36d	72d	110d
Spring	F1I1	10.667±0.892bc	12.478±0.626bc	13.8±1.196ab	1.668±0.091abc	1.597±0.115abc	1.558±0.148ab	1.226±0.126a	1.062±0.081ab	0.814±0.07ab
	F1I2	11.467±0.638ab	13.956±0.532ab	14.544±1.269ab	1.622±0.081bc	1.552±0.114bc	1.539±0.12ab	1.15±0.072bc	0.999±0.054b	0.653±0.041bc
	F1I3	11.389±0.896ab	14.1±0.74a	14.556±1.429ab	1.563±0.064c	1.526±0.091c	1.493±0.089b	1.083±0.122cd	0.974±0.064b	0.672±0.058bc
	F2I1	11.278±3.233ab	13.267±1.147bc	14.267±1.679ab	1.711±0.132ab	1.671±0.11ab	1.629±0.196ab	1.235±0.067ab	1.025±0.071b	0.732±0.218bc
	F2I2	12.367±1.573a	14.5±0.776a	15.289±1.13a	1.691±0.067ab	1.638±0.133abc	1.611±0.12ab	0.938±0.167e	0.943±0.162b	0.602±0.294c
	F2I3	12.278±0.509a	14.322±0.763a	15.056±2.195a	1.638±0.082bc	1.593±0.159bc	1.556±0.127ab	1.034±0.135de	0.959±0.089b	0.622±0.288c
	F3I1	9.322±1.02c	12.767±0.776c	13.233±1.489c	1.752±0.121a	1.716±0.141a	1.677±0.116a	1.262±0.053ab	1.141±0.113a	0.903±0.05a
	F3I2	10.589±1.061bc	13.278±0.814bc	14.044±1.09ab	1.717±0.153ab	1.672±0.114ab	1.638±0.131a	1.135±0.061bcd	1.032±0.172ab	0.774±0.048abcc
	F3I3	10.478±1.148bc	13.256±0.922bc	14.122±1.041ab	1.653±0.073abc	1.611±0.145abc	1.573±0.066ab	1.146±0.089bc	1.006±0.142b	0.714±0.101bc
Autumn	F1I1	7.5±0.829bc	10.378±1.332	11.6±1.436c	1.641±0.099ab	1.583±0.09ab	1.523±0.091bcd	1.296±0.094ab	1.26±0.101ab	0.857±0.091bc
	F1I2	8.022±0.712abc	12.244±2.044abc	12.922±1.935abc	1.612±0.072ab	1.544±0.115b	1.5±0.125cd	1.202±0.12bc	1.236±0.144abc	0.807±0.099bcd
	F1I3	7.967±0.911abc	12.267±2.303abc	13±1.909abc	1.576±0.104b	1.521±0.108b	1.449±0.089d	1.177±0.136bc	1.133±0.068cd	0.771±0.059cde
	F2I1	8.033±0.872abc	11.156±1.899bcd	12.789±1.3abc	1.694±0.115ab	1.646±0.143ab	1.593±0.102abc	1.283±0.122abc	1.253±0.07ab	0.81±0.082bcd
	F2I2	8.822±1.899a	13.411±1.554a	14.544±1.448a	1.648±0.183ab	1.596±0.121ab	1.568±0.13abc	1.169±0.206bc	1.129±0.194cd	0.728±0.107de
	F2I3	8.456±0.602ab	12.8±1.658ab	13.967±2.144ab	1.613±0.145ab	1.567±0.122b	1.494±0.111cd	1.15±0.141c	1.09±0.103d	0.698±0.109e
	F3I1	6.989±0.715c	9.5±1.256d	11.111±2.345c	1.718±0.085a	1.683±0.126a	1.64±0.105a	1.362±0.109a	1.318±0.071a	0.955±0.093a
	F3I2	7.744±1.153bc	11.344±2.194bcd	12.378±2.149bc	1.688±0.103ab	1.644±0.151ab	1.619±0.077ab	1.262±0.081abc	1.229±0.091abc	0.885±0.083ab
	F3I3	7.667±0.731bc	11.3±1.648bcd	12.2±0.927bc	1.649±0.101ab	1.587±0.098ab	1.568±0.123abc	1.216±0.09bc	1.162±0.05bcd	0.81±0.087bcd

Note: F: irrigation frequency; I: irrigation amount; TOC: total organic carbon; TN: total nitrogen; TP: total phosphorus. the data are shown as the mean and standard deviation in the table, different lowercase letters meant significant difference at 0.05 level. * : P≤0.05, **: P≤0.01, ns: P＞0.05, the same below

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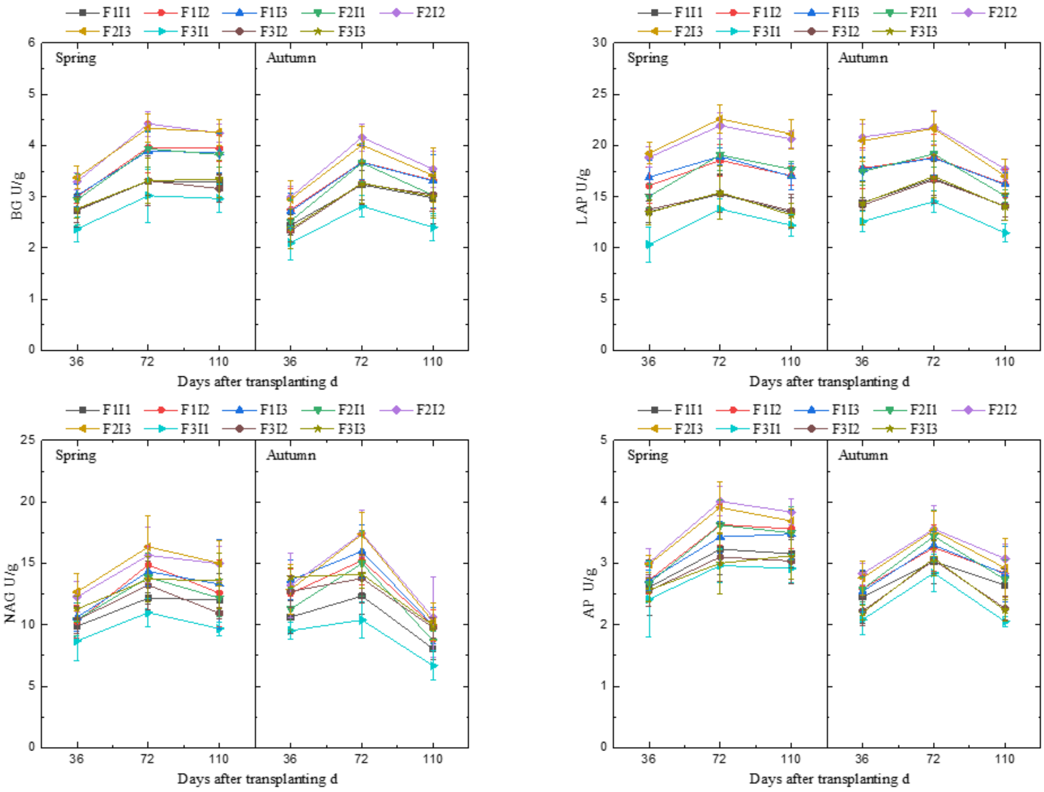

Figure 4. *Effects of different treatments on soil enzyme activities of greenhouse tomato. BG : β-Glucosidase active enzyme; LAP : Leucine aminopeptidase activity; NAG : N-acetyl-d-glucosaminidasealk; AP : aline phosphatase activity*

At the same planting days, the soil enzyme activity of spring tomato in greenhouse was higher than that of autumn tomato. F and I had significant effects on soil BG, LAP, NAG and AP activities of soil with spring tomato and autumn tomato.

With the decrease of F, the soil BG activity of spring tomato and autumn tomato increased first and then decreased. The soil BG activity of F2 in the growth period of tomato was higher than that of F1, F3 about 11.56% and 10.61% (Average of spring tomato and autumn tomato, the same as below), 27.93% and 23.10%. With the decrease of F, the soil LAP activity of spring tomato and autumn tomato increased first and then decreased. The soil LAP activity of F2 in the growth period of tomato was higher than that of F1 and F3 by about 12.34% and 7.20%, 20.16% and 15.16%, respectively. With the decrease of F, the soil NAG activity of spring tomato and autumn tomato increased first and then decreased. The soil NAG activity of F2 in the growth period of tomato was higher than that of F1 and F3 by about 19.99% and 13.36%, 45.55% and 32.85%, respectively. With the decrease of F, the soil AP activity of spring tomato and autumn tomato increased first and then decreased. The soil AP activity of F2 in the growth period of tomato was higher than that of F1 and F3 by 9.30% and 7.67%, 21.22% and 22.46%, respectively.

With the increase of I, the soil BG activity of tomato and autumn tomato increased first and then decreased. The soil BG activity of I2 in the growth period of tomato was higher than that of I1 and I3 about 14.02% and 14.46%, 0.35% and 1.81%. With the increase of I, the LAP activity of spring tomato and autumn tomato soil increased first

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and then decreased. During the growth period of tomato, the LAP activity of I2 soil was higher than that of I1 and I3 by 14.05% and 22.50%, -2.14% and 1.35%, respectively. With the increase of I, the soil NAG activity of spring tomato and autumn tomato increased first and then decreased. The soil NAG activity of I2 in the growth period of tomato was higher than that of I1 and I3, respectively. With the increase of I, the AP activity of spring tomato and autumn tomato soil increased first and then decreased. Among them, the AP activity of I2 soil in the growth period of tomato was higher than that of I1 and I3 by about 10.44% and 7.67%, 2.63% and 2.49%, respectively.

Characteristics of carbon, nitrogen and phosphorus stoichiometry and enzyme stoichiometry in greenhouse tomato soil under different treatments

Soil carbon, nitrogen and phosphorus stoichiometry

It can be seen from *Table 3* that with the advancement of tomato growth period, the soil C/N, C/P and N/P of spring tomato and autumn tomato in greenhouse showed an increasing trend. F and I had significant effects on C/N, C/P and N/P. With the decrease of F, the soil C/N, C/P and N/P of spring tomato and autumn tomato under micro-sprinkling irrigation increased first and then decreased. Among them, the soil C/N of F2 of spring tomato and autumn tomato was about 0.77% and 5.28% higher than that of F1, and about 13.13% and 18.57% higher than that of F3. The soil C/P of F2 of spring tomato and autumn tomato was about 21.30% and 14.55% higher than that of F1, and about 36.27% and 27.85% higher than that of F3. The soil N/P of F2 of spring tomato and autumn tomato was about 21.21% and 9.28% higher than that of F1, and about 21.22% and 8.49% higher than that of F3. With the increase of I, the soil C/N of spring tomato and autumn tomato under MSPF showed an increasing trend. The soil C/N of spring tomato and autumn tomato I2 treatment was higher than I1 by about 10.14% and 16.11%, lower than I3 by about 2.62% and 0.70%. With the increase of I, soil C/P and N/P increased first and then decreased. The soil C/P of spring tomato and autumn tomato I2 treatment was about 30.65% and 23.61% higher than that of I1, and about 2.94% and-1.32% higher than that of I3. The soil N/P of spring tomato and autumn tomato I2 was higher than I1 and I3.

Soil ecoenzymatic stoichiometry

Table 4 shows that with the advance of tomato growth period, the soil BG/(LAP+NAG), BG/AP, (LAP + NAG)/AP of spring tomato and autumn tomato in greenhouse showed an increasing trend. With the decrease of F, the soil BG/(LAP+NAG) of spring tomato and autumn tomato decreased first and then increased. The soil BG/(LAP+NAG) of spring tomato and autumn tomato in F2 treatment was lower than that of F1 by about 4.26% and 2.85%, and also lower than that of F3 by about 13.13% and 18.57%. With the decrease of F, the soil BG/AP and (LAP+NAG)/AP of spring tomato and autumn tomato increased first and then decreased. The soil BG / AP of spring tomato and autumn tomato in F2 treatment was 1.97% and 0.33% higher than that in F1, and 5.04% and 1.19% higher than that in F3. The soil (LAP + NAG)/AP of spring tomato and autumn tomato in F2 treatment was about 3.35% and 2.94% higher than that in F1, and about 9.82% and 0.36% higher than that in F3.

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Table 3. *Effects of different treatments on soil carbon, nitrogen and phosphorus stoichiometric ratios of greenhouse tomato*

	Treatment	C/N			C/P			N/P		
		36d	**72d**	**110d**	**36d**	**72d**	**110d**	**36d**	**72d**	**110d**
Spring	F1I1	6.411±0.624b	7.864±0.873bc	8.927±1.096abc	8.786±1.281cd	11.823±1.1de	17.104±2.353c	1.372±0.174c	1.512±0.131b	1.938±0.309c
	F1I2	7.079±0.426ab	9.04±0.846ab	9.503±1.119ab	9.986±0.833c	14.013±0.977bc	22.398±2.915bc	1.412±0.111ab	1.56±0.148ab	2.361±0.22bc
	F1I3	7.29±0.586ab	9.277±0.81a	9.773±1.069a	10.618±1.406bc	14.549±1.287abc	21.872±3.327bc	1.458±0.172ab	1.572±0.113ba	2.234±0.215bc
	F2I1	6.687±2.182ab	7.97±0.852c	8.818±1.036abc	9.163±2.758cd	13.019±1.727cd	21.59±8.798bc	1.39±0.157ab	1.64±0.196ab	2.469±0.959abc
	F2I2	7.304±0.802ab	8.897±0.8ab	9.54±1.009ab	13.634±3.282a	15.816±2.986a	31.887±17.834a	1.867±0.414a	1.776±0.303a	3.39±1.851a
	F2I3	7.522±0.624a	9.129±1.092ab	9.702±1.401ab	12.062±1.542ab	15.047±1.123ab	30.377±18.325ab	1.614±0.257b	1.667±0.199ab	3.23±1.889ab
	F3I1	5.341±0.714c	7.481±0.695c	7.922±1.02c	7.393±0.765d	11.254±0.95e	14.666±1.826c	1.391±0.118ab	1.519±0.209b	1.858±0.131c
	F3I2	6.256±1.152b	7.969±0.675c	8.601±0.683bc	9.347±1.113c	13.156±2.265cd	18.244±2.023c	1.514±0.15ab	1.651±0.236ab	2.129±0.269c
	F3I3	6.343±0.692bc	8.3±1.02bc	8.984±0.683abc	9.162±1.03cd	13.389±2.22bcd	20.119±2.756c	1.452±0.149ab	1.624±0.259ab	2.244±0.291bc
Autumn	F1I1	4.592±0.64ab	6.587±0.998cd	7.606±0.724cd	5.813±0.723bc	8.274±1.147cd	13.597±1.612cd	1.273±0.123ab	1.267±0.135	1.792±0.182bc
	F1I2	4.993±0.586a	7.986±1.547abc	8.616±1.154abc	6.75±1.063ab	9.994±1.874bc	16.177±2.702bc	1.352±0.138a	1.267±0.196b	1.878±0.195bc
	F1I3	5.099±0.811a	8.162±1.944ab	8.974±1.229ab	6.81±0.834ab	10.873±2.193ab	16.962±3.048b	1.357±0.189a	1.347±0.126aab	1.888±0.168bc
	F2I1	4.779±0.764ab	6.829±1.342bcd	8.081±1.192bc	6.292±0.731b	8.874±1.302cd	15.958±2.607bc	1.329±0.121ab	1.317±0.17ab	1.986±0.257ab
	F2I2	5.482±1.599a	8.424±0.964a	9.302±0.948a	7.622±1.64a	12.094±1.916a	20.266±2.829a	1.45±0.305a	1.446±0.273a	2.191±0.331a
	F2I3	5.288±0.699a	8.34±1.405a	9.369±1.398a	7.432±0.81a	11.83±1.682a	20.29±3.445a	1.424±0.213a	1.428±0.159a	2.176±0.261a
	F3I1	4.07±0.411b	5.668±0.859c	6.752±1.203d	5.166±0.671c	7.254±1.216d	11.726±2.479d	1.268±0.104b	1.281±0.111ab	1.733±0.161c
	F3I2	4.622±0.859ab	6.998±1.665abcd	7.657±1.318cd	6.161±1.007b	9.268±1.883bc	14.051±2.607cd	1.344±0.123a	1.341±0.12ab	1.842±0.18bc
	F3I3	4.666±0.525ab	7.149±1.159abc	7.84±1.01bcd	6.347±0.83b	9.736±1.392bc	15.217±1.82bc	1.361±0.103a	1.371±0.119a	1.96±0.254abc

Note: C: total organic carbon; N: total nitrogen; P: total phosphorus. The data are shown as the mean and standard deviation in the table, different lowercase letters meant significant difference at 0.05 level. * : P≤0.05; ** : P≤0.01; ns: P＞0.05, the same below

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***Table 4.** Effects of different treatments on soil enzyme stoichiometric ratio of greenhouse tomato*

	Treatment	BG/(LAP+NAG)			BG /AP			(LAP+NAG)/AP		
		36	72	110	36	72	110	36	72	110
Spring	F1I1	0.117±0.012ab	0.121±0.01a	0.13±0.015ab	1.065±0.168b	1.035±0.132b	1.043±0.066bc	9.171±1.359bc	8.581±0.898b	8.091±1cd
	F1I2	0.115±0.012ab	0.119±0.012ab	0.134±0.016a	1.109±0.124ab	1.093±0.1ab	1.111±0.051abc	9.789±1.978ab	9.267±0.95ab	8.428±1.339bcd
	F1I3	0.11±0.007b	0.117±0.009ab	0.128±0.013ab	1.115±0.109ab	1.142±0.134ab	1.117±0.128ab	10.136±1.211ab	9.755±1.002a	8.795±1.073bc
	F2I1	0.116±0.018ab	0.12±0.01a	0.128±0.007ab	1.098±0.128ab	1.094±0.108ab	1.106±0.132abc	9.615±1.333ab	9.144±0.674ab	8.647±1.086bc
	F2I2	0.106±0.006b	0.118±0.008ab	0.12±0.008b	1.1±0.1ab	1.107±0.082ab	1.108±0.062abc	10.387±1.119ab	9.419±0.939ab	9.308±0.839ab
	F2I3	0.106±0.008b	0.112±0.011b	0.119±0.012b	1.133±0.091a	1.122±0.13a	1.156±0.063a	10.703±0.813a	10.094±1.55a	9.827±0.956a
	F3I1	0.126±0.019a	0.122±0.018a	0.136±0.011a	1.023±0.218b	1.016±0.126b	1.017±0.075c	8.193±1.756c	8.403±0.733b	7.536±0.713d
	F3I2	0.114±0.012ab	0.116±0.013ab	0.129±0.007ab	1.085±0.147ab	1.069±0.102ab	1.044±0.063bc	9.544±1.332abc	9.265±0.852ab	8.149±0.653cd
	F3I3	0.112±0.009b	0.114±0.013b	0.126±0.018ab	1.084±0.116ab	1.127±0.242a	1.077±0.106abc	9.695±1.063ab	9.875±1.533a	8.692±1.336bc
Autumn	F1I1	0.098±0.01a	0.111±0.01a	0.136±0.03a	1.034±0.243a	1.079±0.149ab	1.13±0.183b	10.506±1.864c	9.708±1.15bc	8.452±1.128c
	F1I2	0.091±0.009ab	0.109±0.008ab	0.127±0.022ab	1.064±0.171a	1.134±0.104a	1.179±0.159ab	11.749±1.275abc	10.48±0.816ab	9.447±1.553abc
	F1I3	0.087±0.013ab	0.106±0.008b	0.127±0.021ab	1.078±0.15a	1.114±0.081ab	1.179±0.159ab	12.456±1.367ab	10.569±0.942ab	9.464±1.479abc
	F2I1	0.089±0.016ab	0.108±0.014ab	0.127±0.015b	0.981±0.157a	1.068±0.085ab	1.113±0.144b	11.17±0.927ab	9.997±1.169ab	8.779±0.987c
	F2I2	0.089±0.01ab	0.106±0.009b	0.127±0.016ab	1.059±0.095a	1.184±0.181a	1.16±0.167ab	12.039±1.125ab	11.134±1.456a	9.279±1.638abc
	F2I3	0.089±0.013ab	0.103±0.007b	0.125±0.017b	1.068±0.103a	1.139±0.103a	1.188±0.224ab	12.105±1.09ab	11.104±1.078a	9.564±1.735abc
	F3I1	0.095±0.016ab	0.113±0.011a	0.133±0.016a	1.013±0.155a	0.994±0.072b	1.171±0.115ab	10.728±1.279c	8.862±1.108c	8.83±0.752c
	F3I2	0.087±0.009ab	0.107±0.011ab	0.128±0.013ab	1.061±0.16a	1.067±0.106ab	1.348±0.18a	12.222±1.426ab	10.003±1.124ab	10.625±1.376ab
	F3I3	0.084±0.011b	0.105±0.008b	0.126±0.015ab	1.079±0.151a	1.066±0.154ab	1.351±0.215a	12.873±0.902a	10.151±0.969ab	10.76±1.056a

Note: BG: β-Glucosidase active enzyme; LAP: Leucine aminopeptidase activity; NAG: N-acetyl-d-glucosaminidasealk; AP: aline phosphatase activity. the data are shown as the mean and standard deviation in the table, different lowercase letters meant significant difference at 0.05 level. *: P≤0.05; **: P≤0.01; ns: P＞0.05, the same below

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The soil BG/(LAP+ NAG) of spring tomato and autumn tomato decreased with the increase of I. The BG/(LAP + NAG) of spring tomato and autumn tomato soil treated with F2 was about 2.71% and 3.15% lower than that of F1, and about 2.79% and 1.71% higher than that of F3. With the increase of I, the soil BG/AP of spring tomato and autumn tomato increased. The BG/AP of spring tomato and autumn tomato soil in F2 treatment was about 2.89% and 5.87% higher than that in F1, and about 2.30% and -0.22% lower than that in F3. With the increase of I, the soil (LAP + NAG) / AP of spring tomato and autumn tomato increased. The soil (LAP+NAG)/AP of spring tomato and autumn tomato in F2 treatment was about 6.29% and 9.41% higher than that in F1, and about 4.79% and 1.77% lower than that in F3.

Effects of different treatments on yield of greenhouse tomato

It can be seen from *Figure 5* that the yield of F2I2 spring tomato and autumn tomato was significantly higher than that of F1I1, F2I1, F3I1, F3I2 and F3I3 by about 33.44% and 31.00%, 31.88% and 28.03%, 44.08% and 43.38%, 27.49% and 16.73%, 21.04% and 32.03%. The WUE of F2I2 spring tomato and autumn tomato was significantly higher than that of F1I3, F2I3, F3I2 and F3I3 by about 26.44% and 25.97%, 23.36% and 12.27%, 23.05% and 12.33%, 37.89% and 42.53%.

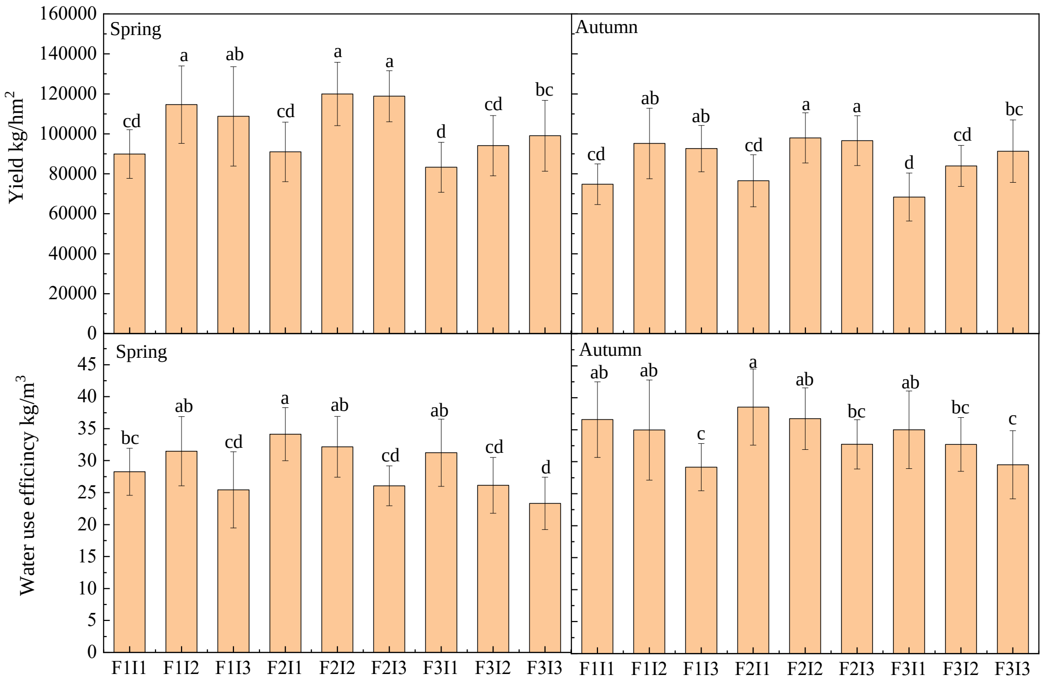

Figure 5. *Effects of different treatments on yield and water use efficiency of tomato in greenhouse. F: irrigation frequency; I: irrigation amount; The data in the figure are displayed as the mean and standard deviation. If different letters are present in the same color column, it indicates a significant difference at the 0.05 level; the same below*

With the decrease of F, the yield and WUE of spring tomato and autumn tomato increased first and then decreased. The yield of spring tomato and autumn tomato in F2 was higher than that in F1 and F3 by 5.27% and 3.24%, 19.31% and 11.30%, respectively. The WUE of F2 spring tomato and autumn tomato was about 8.44% and 7.24% higher

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than that of F1, and about 11.46% and 11.06% higher than that of F3. With the increase of I, the yield and WUE of spring tomato and autumn tomato increased first and then decreased. The yield of spring tomato and autumn tomato of I2 was 24.44% and 26.15% higher than that of I1, and 1.64% and 3.06% higher than that of I3. The WUE of spring tomato and autumn tomato in I2 was about 8.44% and-5.21% higher than that in I1, and about 14.46% and 19.10% higher than that in I3.

Correlation analysis of greenhouse tomato yield with soil enzyme activity, soil carbon, nitrogen and phosphorus

Through the Pearson two-tailed test of the correlation between soil carbon nitrogen phosphorus stoichiometry, soil enzyme stoichiometry and yield in different tomato planting periods, it was found that the correlation between soil carbon nitrogen phosphorus stoichiometry, soil enzyme stoichiometry and yield increased first and then decreased with the advance of tomato growth period. Among them, the soil carbon nitrogen phosphorus stoichiometric ratio and soil enzyme stoichiometric ratio at 72 days after tomato planting were most closely related to yield ($P \leq 0.05$). The correlation coefficients between soil C/N, C/P, N/P, BG/(LAP+NAG), BG/AP, (LAP+NAG)/AP and tomato yield were 0.724 and 0.748, 0.914 and 0.795, 0.683 and 0.614, -0.615 and -0.572, 0.621 and 0.674, 0.624 and 0.801, respectively. Considering the different stoichiometric ratios of soil carbon nitrogen phosphorus and soil enzyme stoichiometric ratios of spring and autumn tomatoes, this paper selected the high correlation of spring tomato and autumn tomato planting 60 d soil carbon, nitrogen and phosphorus stoichiometric ratio, soil enzyme stoichiometric ratio and yield for multiple regression analysis (*Figure 6*), in order to obtain the relationship between them qualitatively and quantitatively.

It can be seen from *Figure 5* that the stoichiometric ratio of soil carbon, nitrogen and phosphorus and the stoichiometric ratio of soil enzyme had a quadratic parabolic curve relationship with yield, and the determination coefficient $R^2 > 0.535$. The results showed that the soil carbon nitrogen phosphorus stoichiometric ratio and soil enzyme stoichiometric ratio could explain 53.50% of yield in the regression model. The soil carbon nitrogen phosphorus stoichiometric ratio and soil enzyme stoichiometric ratio could be used to estimate yield. In the regression model of soil carbon, nitrogen and phosphorus stoichiometric ratio and yield, the model of TOC/TP and yield of spring tomato and autumn tomato had better fitting degree, the determination coefficient $R^2 >$ 0.643. When the soil TOC/TP of spring tomato and autumn tomato was 24.85 and 19.02 respectively, the yield of spring tomato and autumn tomato could reach the peak value of 112637.83 and 109971.80 kg/hm^2. In the regression model of soil carbon, nitrogen and phosphorus stoichiometric ratio and yield, the model of TOC/TP and yield of spring tomato and autumn tomato had better fitting degree, the determination coefficient $R^2 >$ 0.619. When the soil BG/AP of spring tomato and autumn tomato was 1.21 and 1.31 respectively, the yield of spring and autumn tomato and autumn tomato could reach the peak of 117239.17 and 100991.83 kg/hm^2.

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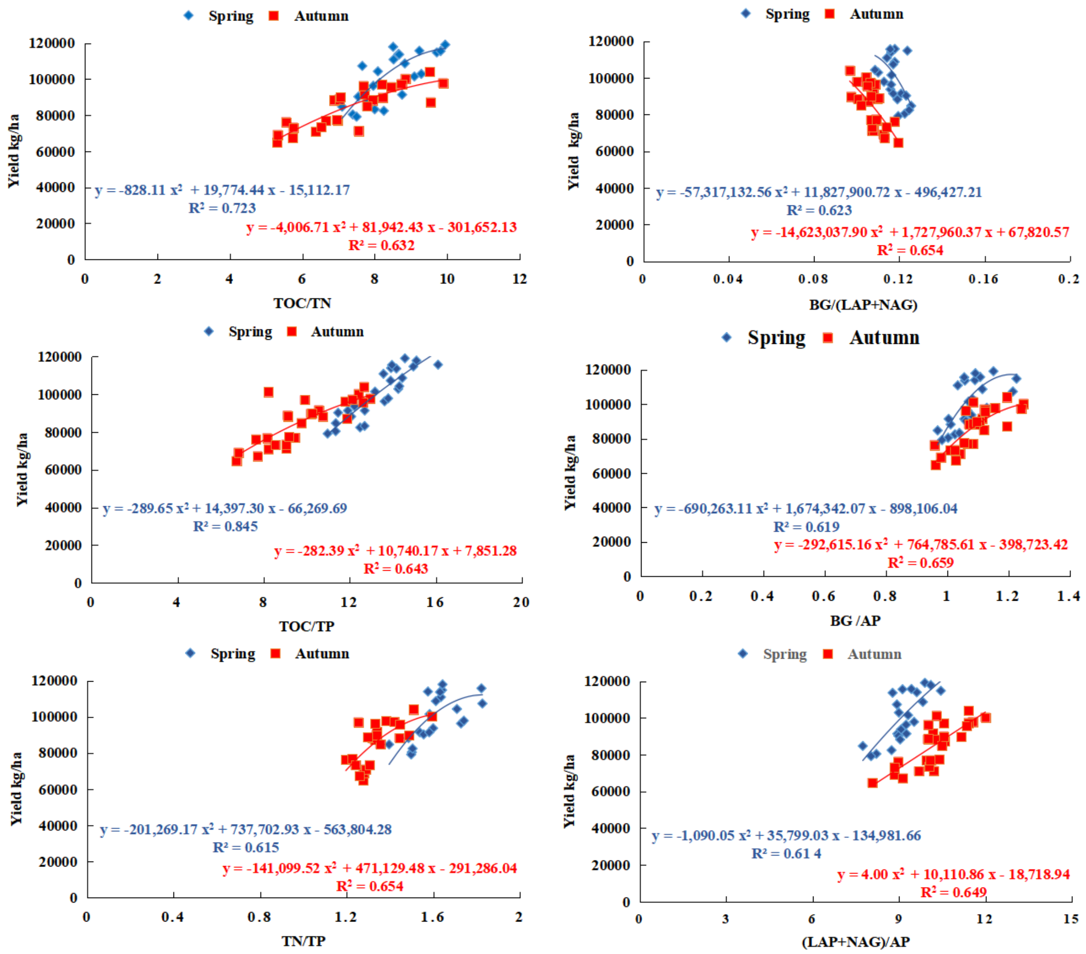

Figure 6. *Quantitative analysis of soil stoichiometry and yield of tomato in greenhouse*

Discussion

Effects of different treatments on soil carbon, nitrogen and phosphorus contents and their stoichiometric ratios of greenhouse tomato

Both F and I will change the distribution of soil moisture. Higher soil moisture can promote litter leaching, so that the clay, organic matter, carbonate and other substances in litter and humus in the surface layer enter the soil and increase the total soil organic carbon content (Henry et al., 2005; Yan et al., 2022). This study found that with the decrease of F, the soil TOC of tomato increased first and then decreased. This may be due to the long-term wetting state of shallow soil moisture under high frequency irrigation. The wetting state of soil will promote the activity of methane oxidizing bacteria, increase the decomposition of soil organic matter, increase soil CH_4 emissions, and indirectly reduce soil carbon pool (Vogeler et al., 2019; Sousa et al., 2022; Zhang et al., 2024). The low frequency irrigation soil has a large dry and wet area and a long dry and wet area. The crop roots are susceptible to drought and hypoxia stress, which reduces the root morphological development and activity, and the root metabolism is slow, which is not conducive to crop root metabolism (secretion). The accumulation of litter and microbial residues reduces the source of soil carbon pool increased by soil microorganisms and plant residues (Zhang et al., 2009; Buckeridge et al., 2020). Rebecca (Tirado-Corbalá et

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al., 2019) believed that high-frequency drip irrigation helped to reduce soil nitrogen leaching. This study found that the soil TN of tomato rhizosphere soil under high-frequency irrigation was low. We speculated that under the irrigation frequency of 3d treatment, due to the presence of gravity, the soil moisture moved downward, and the nitrogen ions moved with water, reducing the nitrogen content of the soil surface, further indicating that increasing the irrigation frequency can improve the leaching effect of irrigation on the surface soil nitrogen. Haynes and Swift (1985) found that soil after a long period of drought and wetting can increase the ion concentration in the soil solution, at the same time, the increased soil aggregate surface caused by the fragmentation of soil particles can adsorb more phosphorus energy, reduce the solubility of many compounds, resulting in the fixation of phosphorus, reducing the effectiveness of phosphorus, reducing the absorption and utilization ability of root system to soil phosphorus, which may be one of the reasons why the soil TP of 7d irrigation frequency is higher than 5d. In this study, the TP of soil with irrigation frequency of 3d was also higher than that of 5d, which may be due to the high frequency irrigation (3d). The soil moisture was concentrated in the shallow layer, and the shallow soil moisture content was higher. In addition, the crop roots were also concentrated in the shallow soil. The higher soil moisture content was conducive to the diffusion of phosphate ions from non-rhizosphere soil to rhizosphere soil (Pan et al., 2024). Phosphate ions were adsorbed on the surface of soil solid phase by ion exchange with the anions carried by soil particles, which also promoted the transformation of soil phosphorus from soluble state to insoluble state, resulting in higher total phosphorus in soil under 3d irrigation (Mbagwu and Osuigwe, 1985; Bar Yosef et al., 1989).

This study found that with the increase of I, the soil TOC of tomato increased first and then decreased. It may be due to the uniform distribution of soil moisture in I2, and there is no hypoxia stress and water stress caused by too high or too low soil volumetric water content in soil wetted body, which promotes the development of crop root morphology. The better root morphology development is beneficial to improve the abundance of root microbial population, and the residues of plants and soil microorganisms provide sufficient carbon for crop rhizosphere soil (Yao et al., 2019; Buckeridge et al., 2020). The TN of tomato soil decreased with the increase of I. It may be due to the soil under I1 treatment experienced dry-wet cycle, soil aggregates disintegrated, released more nitrogen, and increased soil nitrogen sources. Soil microbial biomass was smaller in arid environment, which reduced the amount of nitrogen fixed by microorganisms, and mineralized nutrients were more released into the soil. At the same time, lower irrigation amount can reduce the leaching of nitrogen in shallow soil (Hou et al., 2021; Lu et al., 2021). Yuan et al. (2020) found that with the increase of winter wheat I, soil TN increased first and then decreased, which was inconsistent with the conclusion that the soil TN of greenhouse tomato under MSPF decreased. It may be caused by the difference of crop planting type and the difference of water quality of crop growth source. The water demand of winter wheat not only comes from irrigation, but also is affected by rainfall. In this study, the water demand of greenhouse tomato only comes from irrigation. The source of soil phosphorus is relatively fixed, and most of the phosphorus exists in the form of stubborn organic matter, which leads to the uniform distribution of TP in the whole soil layer. The migration of phosphorus in the soil to the root surface mainly depends on diffusion. At the same time, the root morphology of the crop develops well, absorbs the nutrients of the soil with rhizosphere , and promotes the phosphorus deficiency area around the soil with rhizosphere (Song et al., 2019; Ghodszad et al., 2021; Liu et al.,

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2021).This may be one of the reasons why the TP of the soil in this study decreases first and then increases with the increase of I.

Soil stoichiometric ratio can reflect the composition of soil organic matter and the effectiveness of nutrient balance, and can also characterize the mineralization and sequestration of C, N and P (Tian et al., 2018). Soil C / N reflects a balance between soil carbon and nitrogen. It is an important index to measure the balance of soil nutrient elements, and can reflect the ability of microorganisms to meet their nutrient needs (Xia et al., 2022). The C/N (peak value was 9.702) of tomato soil in this study was lower than the average value 12.30 in China (Yao et al., 2019). Because soil C/N is inversely proportional to organic matter decomposition rate and mineralization rate (Liu, 2019), soil C is more deficient than N in this study area. The C/N of tomato soil increased first and then decreased with the decrease of F. It may be due to the fact that the high irrigation frequency (3d) will increase the water-filled porosity of the surface soil, and the soil aeration will be poor, and the shallow soil will go out of the high water period for a long time, the ground support capacity will decrease, the soil respiration and microbial activity will be inhibited, and the soil compaction will appear, the reduced litter decomposition rate and the ability to migrate to the soil will limit the source of the soil carbon pool, resulting in a decrease in the ratio of carbon to nitrogen in the soil. When the F was too low (7d), the soil was in a dry or wet state for a long time, resulting in the loss of soil macro-aggregates (Cui et al., 2024). The content of non-hydrolyzed carbon in macro-aggregates decreased by more than 50%, which increased the sensitivity of SOC to decomposition and enhanced the conversion ability of refractory carbon, resulting in the decrease of TOC in soil under low irrigation frequency (Su et al., 2020). This conclusion shows that once irrigation for 5 days under MSPF is beneficial to increase soil carbon in tomato rhizosphere. Soil C/N of tomato increased with the increase of I. It may be that the content of TOC and TN was affected by the change of I. Compared with I2, the decrease of soil TOC of spring tomato and autumn tomato under I3 treatment was lower than that of TN. The change of soil C/N with I further indicates that increasing I can reduce the degree of soil C deficiency compared with N, and the rhizosphere soil C can be increased.

Soil C/P is a measure of the ability of organic matter to be released or absorbed by phosphate mineralization (Chen et al., 2022). The C/P of tomato soil in this study area (31.887) was lower than the average level in China (52.700), which indicates that the net mineralization rate of P in greenhouse tomato soil in this area was higher and the potential of P release was greater (Xie et al., 2022). This study found that soil C/P increased first and then decreased with the decrease of F or the increase of I. It may be due to the increase of soil organic matter content (*Table 2*), the release of soil phosphorus and the increase of soil phosphorus availability under the treatment of F2 and I2. At the same time, various metabolites (such as acidic substances) released during microbial degradation can change soil pH, promote phosphorus mineralization and increase phosphorus availability, and aggravate the absorption of phosphorus in soil root zone by crops, resulting in the decrease of TP in this area, the increase of C leads to a higher level of C/P (Cui et al., 2019). This conclusion is consistent with the study of the variation of soil C/P with irrigation amount in winter wheat, indicating that the change of soil C/P with the change of I has nothing to do with crop species.

Soil N/P can be used to measure the threshold of nutrient limitation of nitrogen and phosphorus, and to determine the deficiency of nutrient supply during plant growth (Wang et al., 2022). The average value of N/P in this study area (3.369) was lower than

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that of China 's land soil (3.900) (Ågren, 2008), indicating that there is a lack of N element in this study area, and the change range of soil P element is small. The study found that soil N/P increased first and then decreased with the decrease of F. It is because that the content of TP in soil is low (0.899 and 1.034 g/mg) when the F was 5 days. The higher TN in tomato soil increased the ratio of soil N/P, so it was easy to increase the accumulation of soil N when the F was 5d. In this study, it was found that with the increase of irrigation amount, soil Nmax P increased at first and then decreased. This study found that with the increase of I, the soil N/P increased first and then decreased. It may be due to the fact that P element is easy to be mineralized and absorbed by plants under the I2, resulting in the phosphorus content of rhizosphere soil lower than I1 and I3, and the soil TN decreases with the increase of I, resulting in a larger ratio of N/P under I2, indicating that the irrigation amount of I2 will promote the absorption of N in soil.

Effects of different treatments on soil enzyme activity and stoichiometric ratio of greenhouse tomato

Previous studies have found that soil moisture is the most important factor affecting soil enzyme activity and stoichiometric ratio in soil physical and chemical properties (Wang et al., 2021). Soil BG, LAP, NAG and AP are four common soil extracellular hydrolases, which are involved in the decomposition of microorganisms. They are commonly used indicators of soil carbon, nitrogen and phosphorus conversion rates, and are positively correlated with the concentration of soil organic matter (Sinsabaugh et al., 2008; Liu et al., 2023; Ma et al., 2023). This study found that MSPF for 5 days could significantly increase the extracellular hydrolase activity of tomato rhizosphere soil. It may be due to the fact that too high irrigation frequency (3 d) in sandy loam will reduce soil aeration. When the irrigation frequency is too low (7 d), the soil is too dry or too wet for a long time. Soil microorganisms cannot adapt to environmental changes due to soil moisture and hypoxia stress, which reduces the diversity and population abundance of soil bacterial community structure, and indirectly or directly reduces the enzymes secreted or cracked into the environment through the environment (Sinsabaugh and Follstad Shah, 2012; Xu et al., 2020). This conclusion is inconsistent with the conclusion of Li et al. (2014) that the soil enzyme activity is higher than that of 4 days when the irrigation frequency is 8 days. It may be due to the difference of irrigation methods. The difference of irrigation methods causes the difference of soil moisture distribution, which in turn affects the distribution of soil nutrients and microbial activity. Li uses drip irrigation, and the drip flow is much smaller than the MSPF in this study. It may also be due to the difference of soil texture, the soil type of Li test site in Shandong Agricultural University is brown soil, which has high water holding capacity. This study is sandy loam with poor water holding capacity (Li et al., 2022).

Previous studies have found that irrigation increases soil moisture availability to promote plant growth and microbial-driven biological processes, thereby promoting the secretion of enzymes and the diffusion of substrates, which is beneficial to improve the activity of soil hydrolases (Vargas et al., 2012). This study found that with the increase of I, the activity of tomato soil hydrolase increased at first and then decreased. This may be due to the fact that soil moisture can directly participate in soil biochemical reactions, which directly or indirectly affect the life activities of soil microorganisms and plants. Lower soil moisture is not conducive to the diffusion of soil nutrients and the infiltration of effective elements into microorganisms. At the same time, the decrease of soil moisture can limit the leaching of litter and inhibit the increase of soil hydrolase activity (Baldrian

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et al., 2010). When the I is too high (I3), the soil aeration is poor, and the low oxygen soil micro-environment will inhibit the increase of aerobic microorganisms (Bacillus, Lactobacillus, etc.), resulting in the decrease of soil microbial community structure diversity and population abundance, the decrease of root absorption and utilization of soil nutrients, and the restriction of crop root metabolic cycle. The lower root cycle metabolites, root exudates and soil microbial biomass directly limit the increase of soil hydrolase activity (Wang, 2017). This conclusion is consistent with the variation of soil BG activity by Ye et al. (2016) and soil AP activity by Zhou et al. (2020) with the change of I.

On the global scale,the enzyme activity stoichiometric ratio of BG/LAP+NAG/AP was 1.000:1.000:1.000, reflecting a coupling relationship between carbon, nitrogen and phosphorus cycles. However, this study found that the enzyme activity stoichiometric ratio of BG/LAP+NAG/AP was 1.000:11.901:1.133 in tomato rhizosphere soil under different treatments of MSPF in this area, it is deviated greatly from 1.000:1.000:1.000. The results showed that C-degrading enzyme activity was less than N-degrading or P-degrading enzyme activity and N-degrading enzyme activity was the largest among the three. This indicated that the input of microorganisms to the enzymes related to soil C, N and P cycle was significantly different under different F and I. It also shows the regionality of the test area (Yang et al., 2020). The stoichiometric ratio of soil ecological enzymes can also be used to evaluate the nutrient demand of microbial carbon, nitrogen and phosphorus (Sinsabaugh et al., 2009). Previous studies have found that the enzyme activity stoichiometric ratio of BG/AP and (LAP+NAG)/AP are higher than the global scale soil enzyme activity stoichiometric ratio of BG/AP (0.62) and (LAP+NAG)/AP (0.44), indicating that soil microorganisms in this area were limited by carbon and nitrogen (Bell et al., 2014). In this study, it was found that the BG/AP and (LAP+NAG)/AP of tomato soil in greenhouse were higher than those in the global scale, which further indicated that the rhizosphere soil microorganisms in this area were limited by carbon and nitrogen. It was also found that tomato yield was negatively correlated with soil BG/(LAP+NAG), while tomato yield was positively correlated with (LAP+NAG)/AP. It may be that there is a positive correlation between tomato yield and soil moisture in a certain range. The increase of soil moisture will aggravate the N limitation of soil microorganisms, which will lead to the production of more NAG and LAP enzymes that decompose N by soil microorganisms, and ultimately increase the activity of soil hydrolyzable nitrogen enzymes. The higher enzyme activity was beneficial to the absorption of soil nutrients by crop roots and promote the increase of tomato yield (Feng et al., 2018).

With the decrease of F, the BG/AP and (LAP+NAG)/AP of tomato soil increased first and then decreased. The reason may be that the ratio of soil extracellular enzyme activity is closely related to nutrient concentration or soil C/N/P value, the soil moisture distribution is relatively uniform under the treatment of F2, which promotes the tomato rhizosphere soil without drought and hypoxia stress. The suitable environment promotes root morphological development, promotes tomato root metabolism, increases the concentration of organic matter in rhizosphere soil, and indirectly improves soil enzyme activity. Compared with F1, the increase of BG and LAP + NAG enzyme activities (11.56% and 10.61%, 16.17% and 10.28%) was higher than that of AP activity (9.30% and 7.69%) under F2. Compared with the F3, the increase of soil BG and LAP + NAG enzyme activity (27.93% and 23.10%, 32.86% and 24.01%) was higher than that of AP activity (21.22% and 22.46%) under F2. The above conclusions further indicate that the

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F2 can reduce the carbon and nitrogen limitation of tomato rhizosphere soil microorganisms. With the increase of I, the BG/AP and (LAP+NAG)/AP of tomato soil increased. The reason may be that the decrease of AP activity in tomato rhizosphere soil (2.63% and 2.49%, compared with 1.00 Epan) was higher than that the decrease of BG (0.35% and 1.81%) and LAP + NAG (-2.24% and 0.09%) under I3. It was further indicated that increasing I could increase the content of carbon and nitrogen in rhizosphere soil, which was beneficial to the growth of rhizosphere soil microorganisms.

Conclusion

The results showed that with the decrease of F, the C/P, N/P, BG/AP, (LAP+NAG)/AP of tomato soil increased first and then decreased. With the increase of I, the C/N, BG / AP, (LAP+NAG)/AP of tomato soil increased. With the increase of I, the C/P and N/P of tomato soil increased first and then decreased. With the increase of I, the BG/(LAP NAG) of tomato soil decreased. The yield and WUE of spring tomato and autumn tomato with F2 were higher than those of F1about 5.27% and 3.24%, 8.44% and 7.24%, respectively, and higher than those of F3 about 19.31% and 11.30%, 11.46% and 11.06%, respectively. The yield of spring tomato and autumn tomato under I2 was higher than that of I1 and I3 by about 24.44% and 26.15%, 1.64% and 3.06%, respectively. The WUE of spring tomato and autumn tomato under I2 was also higher than I1 and I3 about 8.44% and -5.21%, 14.46% and 19.10%, respectively. The relationship between soil carbon, nitrogen and phosphorus stoichiometric ratio, soil enzyme stoichiometric ratio and yield was quadratic curve at 72 days after tomato planting. Among them, TOC/TP and BG/AP had better correlation with yield , which could realize the prediction of tomato yield and could be used as an important index to measure soil nutrient cycling in greenhouse agriculture in this area. From the point of view of ecological stoichiometry, yield and WUE, the F2I2 is recommended for irrigation parameters of greenhouse tomato under MSPF in northwest China.

Declarations. Availability of data and materials: The data and materials in the study are available from the corresponding author on reasonable request.

Competing interests. The authors declare that they have no competing interests.

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