Effects of Magnetic-Nitrogen Coupling on Yield and Water-Fertilizer Use Efficiency of Processing Tomatoes under Mulched Drip Irrigation (Postprint)

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Abstract

To investigate a suitable magnetized water fertilization regime for processing tomatoes under mulched drip irrigation, this study targeted yield and water-fertilizer use efficiency, establishing four magnetized water intensities (0 Gs (M0), 2000 Gs (M1), 3000 Gs (M2), and 4000 Gs (M3)) and three nitrogen application rates (200 kg $N \cdot hm^{-2}$ (N1), 250 kg $N \cdot hm^{-2}$ (N2), and 300 kg $N \cdot hm^{-2}$ (N3)) in a split-plot experimental design for field trials. By monitoring soil water content, plant height, stem diameter, and aboveground biomass throughout the growth period of processing tomatoes, combined with final yield metrics, the effects of various magnetized water-nitrogen combinations on water-fertilizer use efficiency were examined. The results demonstrated that magnetized water drip irrigation significantly increased soil water content and soil water storage for processing tomatoes, with magnetized water-nitrogen coupling significantly enhancing soil water content in the 20–40 cm soil layer. Magnetized water intensities ranging from 2270–3678 Gs and nitrogen application rates of 220–230 kg $N \cdot hm^{-2}$ promoted processing tomato growth, whereas magnetization intensities exceeding 4000 Gs combined with nitrogen application rates surpassing 250 kg $N \cdot hm^{-2}$ failed to further improve growth. With increasing magnetization intensity, processing tomato yield and water-fertilizer use efficiency exhibited a trend of initial increase followed by decrease; increasing nitrogen application rates enhanced yield and water use efficiency but reduced nitrogen partial factor productivity. Specifically, the M2N3 treatment achieved maximum yield and water use efficiency at 169.67 $t \cdot hm^{-2}$ and 35.61 $kg \cdot m^{-3}$, respectively, while the M2N1 treatment attained maximum nitrogen partial factor productivity at 822.54 $kg \cdot kg^{-1}$. Through regression analysis integrated with spatial analysis methods, the optimal magnetized water-nitrogen intervals for simultaneously achieving relatively high values of yield, water use efficiency, and nitrogen partial factor productivity were determined to be 2270–3678 Gs and 220–230 kg $N \cdot hm^{-2}$. This study provides theoretical support for the scientific application of magnetized water and nitrogen fertilizer in processing tomato cultivation in Xinjiang, and offers scientific guidance for optimizing magnetized water-nitrogen combinations to enhance processing tomato yield.

Full Text

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Abstract

To explore an optimal magnetized water fertilization regime for processing tomatoes under mulched drip irrigation, this study targeted yield and water-fertilizer use efficiency as primary objectives. Four magnetized water intensities (0 Gs, 2000 Gs, 3000 Gs, and 4000 Gs) and three nitrogen application rates (200 kg $N \cdot hm^{-2}$, 250 kg $N \cdot hm^{-2}$, and 300 kg $N \cdot hm^{-2}$) were established using a split-plot experimental design for field trials. By monitoring soil moisture content, plant height, stem diameter, and aboveground biomass throughout the tomato growth period, combined with final yield measurements, the effects of various magnetic-nitrogen combinations on water-fertilizer use efficiency were investigated. Results demonstrated that magnetized water drip irrigation significantly increased soil moisture content and soil water storage, with magnetic-nitrogen coupling particularly enhancing moisture levels in the 20–40 cm soil layer. When magnetized water intensity ranged from 2270–3678 Gs and nitrogen application rate was 220–230 $kg \cdot hm^{-2}$, tomato growth was promoted. However, when magnetization intensity exceeded 4000 Gs and nitrogen rate surpassed 250 $kg \cdot hm^{-2}$, no further growth improvement occurred. Yield and water-fertilizer use efficiency exhibited an initial increase followed by a decrease with increasing magnetization intensity. While higher nitrogen rates increased yield and water use efficiency, they reduced nitrogen partial factor productivity. The M2N3 treatment (3000 Gs, 300 kg $N \cdot hm^{-2}$) achieved maximum yield and water use efficiency at 169.67 $t \cdot hm^{-2}$ and 35.61 $kg \cdot m^{-3}$, respectively, whereas M2N1 (3000

Gs, 200 kg N • hm^{-2}) showed the highest nitrogen partial factor productivity at 822.54 kg • kg^{-1}. Regression analysis combined with spatial analysis identified the optimal magnetic-nitrogen range for simultaneously achieving high values of yield, water use efficiency, and nitrogen partial factor productivity as 2270-3678 Gs and 220-230 kg N • hm^{-2}. This study provides theoretical support for the scientific application of magnetized water and nitrogen fertilizer in tomato production in Xinjiang and offers scientific guidance for optimizing magnetic-nitrogen combinations to enhance processing tomato yield.

Keywords: mulched drip irrigation; magnetic-nitrogen coupling; yield; water-fertilizer utilization efficiency; spatial analysis; processing tomatoes

Introduction

Xinjiang, as China' s largest production base for processing tomatoes, maintains an average planting area of 46,667 × 10^3 hm^2 with annual exports exceeding 1$×10^{6}$ t [1]. However, tomato cultivation in Xinjiang faces challenges of water resource scarcity and irrational fertilizer use, leading to yield reduction and quality decline [2,3]. To ensure sustainable development of the tomato industry, extensive research has been conducted focusing on two main aspects: first, optimizing irrigation quotas, frequency, and fertilization rates to develop rational irrigation-fertilization strategies that enhance yield, quality, and water-fertilizer use efficiency [4,5]; and second, treating irrigation water itself through methods such as aeration, electron removal, and magnetization to improve crop performance [6,7]. For instance, Zhang et al. [8] investigated the interactive effects of different irrigation quotas and aeration methods on water consumption and growth characteristics of drip-irrigated processing tomatoes, proposing an optimal water-aeration combination for northern Xinjiang. Wang et al. [9] used principal component analysis to evaluate different water-fertilizer-gas combinations, finding that an irrigation quota of 4050 m^3 • hm^{-2} and nitrogen rate of 250 kg • hm^{-2} improved water-fertilizer use efficiency. Xing et al. [10] determined through water-fertilizer coupling experiments that tomato yield and water-fertilizer use efficiency peaked at irrigation amounts of 198-208 mm and nitrogen rates of 442-480 kg • hm^{-2}.

Magnetized water irrigation technology, as an advanced agricultural technique, has attracted considerable attention due to its sustainability and environmental compatibility [11]. Current research primarily focuses on soil water-salt transport, nutrient absorption, seed germination, and crop physiological growth. Studies by Wang and colleagues [12,13] revealed that magnetized water irrigation enhances soil water retention, reduces soil salinity, and improves nutrient ion solubility, though it may cause nitrogen loss and reduce fertilizer use efficiency. Zhang et al. [14] found that magnetized water intensities of 1600-2400 Gs advanced wheat seed germination and improved quality, but this effect diminished at intensities above 3600 Gs. Zhou et al. [15] demonstrated that magnetized water intensities exceeding 3000 Gs reduced sugar-acid ratio and vitamin C content in processing tomatoes. However, research on magnetized water irrigation effects on crop water-fertilizer use efficiency remains limited.

Scientific nitrogen application is crucial for ensuring yield and quality improvement in processing tomatoes. Numerous studies indicate that rational nitrogen fertilization promotes stem diameter and plant height growth, but excessive rates inhibit root development, induce stress responses, cause yield reduction, intensify nitrogen loss, and waste fertilizer resources [3,18,19]. Therefore, controlled nitrogen release benefits tomato yield and quality enhancement.

In summary, research on the combined effects of magnetized water irrigation and nitrogen application on tomato growth is scarce [20], and further investigation into magnetic-nitrogen coupling effects on water-fertilizer use efficiency is essential for promoting magnetized water irrigation technology and ensuring sustainable tomato industry development. This study examined different magnetized water intensities and nitrogen rates to investigate their effects on tomato growth, yield, and water-fertilizer use efficiency, aiming to provide theoretical basis and technical reference for magnetized water drip irrigation of processing tomatoes in Xinjiang.

1. Materials and Methods

1.1 Experimental Site Overview

Field experiments were conducted from April to August 2022 at the Water-Saving Irrigation Experimental Station of Shihezi University (44°18 28 N, 86°01 47 E), located in the mid-section of the northern Tianshan foothills. The region features a temperate continental climate with average annual precipitation of 203 mm, annual evaporation of approximately 1689 mm, sunshine duration of about 2846 h, and a frost-free period of approximately 173 d. Soil properties are classified as sandy loam, with a bulk density of 1.52 $g \cdot cm^{-3}$ in the 0–60 cm layer. Daily temperature and rainfall during the 2022 tomato growth period are shown in [Figure 1: see original paper]. The tomato variety was "Jinfan 3165," planted in a "one film, two drip tapes, four rows" pattern (film width 1.45 m). Seedlings were transplanted in early May and harvested in late August. The magnetizer, produced by Baotou Xinda Magnetic Materials Factory with sintered neodymium-iron-boron permanent magnets, was vertically installed at the main-sub pipe interface, with magnetic intensity calibrated using a CT3-type digital tesla meter.

1.2 Experimental Design

The experiment employed a split-plot design with four magnetized water intensities (0 Gs [M0], 2000 Gs [M1], 3000 Gs [M2], and 4000 Gs [M3]) as main plots and three nitrogen rates (200 $kg\ N \cdot hm^{-2}$ [N1], 250 $kg\ N \cdot hm^{-2}$ [N2], and 300 $kg\ N \cdot hm^{-2}$ [N3]) as subplots, totaling 12 treatments with three replications. Based on previous research [9] and local practices, the irrigation quota was set at 360 $kg \cdot hm^{-2}$ per application, with nitrogen applied as urea and phosphorus-potassium as monopotassium phosphate. Fertilizer was applied with water in

11 split applications throughout the growth period. Field management followed local production practices. The irrigation schedule is detailed in .

1.3 Measurement Indicators and Methods

1.3.1 Soil Moisture Content During the tomato fruit expansion period, soil samples were collected with an auger at 10 cm intervals to 60 cm depth beneath drip lines. Gravimetric soil moisture content was determined using the oven-drying method (105°C for 24 h). Soil water storage (W) in the 0–60 cm root zone was calculated as:

$$W = \sum_{i=1}^{6} \gamma_i \times \theta_i \times H_i \times 10$$

where W is soil water storage (mm), γi is soil bulk density ($\mathrm{g \cdot cm^{-3}}$) of layer i, Hi is layer thickness (cm, Hi = 10 cm), and i is soil moisture content (%) of layer i.

1.3.2 Plant Height, Stem Diameter, and Aboveground Biomass During fruit expansion, five representative plants per treatment were randomly selected. Plant height and stem diameter at 5 cm above ground were measured using a tape measure and vernier caliper. Aboveground biomass was determined by harvesting three representative plants per plot, separating them into stems, leaves, and fruits, oven-drying at 105°C for 30 minutes, then at 75°C to constant weight.

1.3.3 Yield, Water Use Efficiency, and Nitrogen Partial Factor Productivity Yield (Y) was measured by harvesting all tomatoes in each plot at maturity, recording total mass, single fruit mass, and fruit number per plant. Seasonal evapotranspiration (ET) was calculated using the water balance method:

$$ET = Ir + Pr + U - D - \Delta W$$

where Ir is total irrigation (mm), Pr is total rainfall (mm), U is groundwater contribution (mm), D is deep percolation (mm), and ΔW is the difference in soil water storage (mm) between transplanting and harvest. With groundwater depth > 10 m, U was considered negligible. Due to mulched drip irrigation with small quotas, D was also considered negligible.

Water use efficiency (WUE) was calculated as:

$$WUE = \frac{Y}{ET}$$

where WUE is water use efficiency ($kg \cdot m^{-3}$) and Y is yield ($kg \cdot hm^{-2}$).

Nitrogen partial factor productivity (NPFP) was calculated as:

$$NPFP = \frac{Y}{N}$$

where NPFP is nitrogen partial factor productivity ($kg \cdot kg^{-1}$) and N is total nitrogen applied ($kg \cdot hm^{-2}$).

1.4 Analysis Methods

1.4.1 Spatial Analysis Spatial analysis is a multi-objective optimization method that projects multivariate regression surfaces to identify overlapping acceptable regions for multiple indicators. Due to different dimensions among indices, data were normalized after regression analysis to determine the optimal magnetic-nitrogen combination range satisfying all targets.

1.4.2 Statistical Analysis Data were processed using Excel 2020. ANOVA and significance tests were performed with SPSS 26.0, while multivariate regression and spatial analysis were conducted using Origin 2022.

2. Results

2.1 Effects of Different Magnetic-Nitrogen Combinations on Soil Moisture Content

Average soil moisture content under different treatments is shown in [Figure 2: see original paper]. Magnetized water intensity effects followed the pattern M2 > M1 > M3 > M0. Soil moisture decreased with increasing nitrogen rate, peaking under M2N1 treatment. In all soil layers, moisture content initially increased then decreased with magnetization intensity at the same nitrogen rate. Moisture increased from 12.97-14.58% in the 0-20 cm layer to 14.22-15.85% in the 20-30 cm layer (increase rate: 0.06-0.13% per cm), then to 14.55-15.87% in the 30-40 cm layer (increase rate: 0.03-0.04% per cm), before decreasing to 12.77-14.21% in the 40-50 cm layer and 13.15-14.48% in the 50-60 cm layer. Increased nitrogen application generally reduced soil moisture content.

Two-way ANOVA revealed that both magnetized water intensity and nitrogen rate significantly affected soil moisture and water storage ($P < 0.05$), though their interaction significance varied. The interaction significantly affected 20-40 cm soil moisture ($P < 0.05$) but not other layers or total soil water storage ($P > 0.05$). Magnetized water drip irrigation improved soil moisture across all layers, with magnetic-nitrogen coupling primarily enhancing moisture in the 20-40 cm layer and increasing root zone water storage.

2.2 Effects of Different Magnetic-Nitrogen Combinations on Tomato Growth

Plant height, stem diameter, and aboveground biomass under different treatments are presented in . Both magnetized water intensity and nitrogen rate significantly affected tomato growth ($P < 0.01$), with significant coupling effects on plant height and leaf dry matter. Increased nitrogen promoted plant height, stem diameter, and biomass accumulation at all magnetization intensities.

Plant height increased from 52.71-64.77 cm at 0-2000 Gs to 56.43-71.03 cm at 2000-3000 Gs (increase rate: 6.54-9.74%), then decreased to 61.34-75.05 cm at 3000-4000 Gs (increase rate: 4.83-8.67%). Stem diameter increased from 15.43-16.81 cm at 0-2000 Gs to 15.86-17.57 cm at 2000-3000 Gs (increase rate: 3.74-5.77%), then decreased to 16.44-18.18 cm at 3000-4000 Gs (increase rate: 1.88-3.46%). Aboveground biomass increased from 256.22-270.03 $\mathrm{g \cdot plant^{-1}}$ at 0-2000 Gs to 258.87-277.50 $\mathrm{g \cdot plant^{-1}}$ at 2000-3000 Gs (increase rate: 6.01-7.18%), then decreased to 274.43-294.83 $\mathrm{g \cdot plant^{-1}}$ at 3000-4000 Gs (increase rate: 1.66-3.27%).

At N1 level, magnetized treatments significantly increased plant height by 7.05-22.36% and stem diameter by 1.90-9.68% compared to M0. At N2 and N3 levels, similar significant improvements were observed. Magnetized water intensity effects on growth followed M2 > M1 > M3 > M0, though the enhancement diminished with increasing nitrogen rate.

2.3 Effects of Different Magnetic-Nitrogen Combinations on Yield and Water-Fertilizer Use Efficiency

Yield components and water-fertilizer use efficiency are shown in . Magnetization intensity effects on yield and WUE followed M2 > M1 > M3 > M0. While increased nitrogen improved yield and WUE, it reduced NPFP. Single fruit mass increased with magnetization up to M2 then decreased, with M2 significantly increasing fruit mass by 1.75-11.43% compared to M0. No significant differences were found in fruit number per plant among treatments.

Yield increased by 1.57-1.76% at M1, 2.31-3.54% at M2, and 1.45-2.83% at M3 compared to M0. WUE increased by 0.65-2.50% at M1, 3.30-4.84% at M2, and 1.79-3.41% at M3. NPFP decreased by 0.93-9.19% with increasing nitrogen but increased with magnetization up to M2.

The M2N3 treatment achieved maximum yield (169.67 $\mathrm{t \cdot hm^{-2}}$) and WUE (35.61 $\mathrm{kg \cdot m^{-3}}$), while M2N1 achieved maximum NPFP (822.54 $\mathrm{kg \cdot kg^{-1}}$). Regression analysis ([Figure 3: see original paper]a-c) showed that yield, WUE, and NPFP all initially increased then decreased with magnetization intensity, with determination coefficients above 0.85. Spatial analysis ([Figure 3: see original paper]d) identified the optimal range as 2270-3678 Gs for magnetization and 220-230 $\mathrm{kg \cdot hm^{-2}}$ for nitrogen application, where all three indices achieved 60-70% of their maximum values simultaneously.

3. Discussion

This study demonstrated that magnetized water irrigation increased soil moisture content while nitrogen application decreased it, with magnetic-nitrogen coupling significantly affecting the 10–30 cm soil layer, consistent with previous findings [11,25]. Research indicates that magnetization reduces intermolecular water forces and viscosity, decreasing water flow velocity in soil and thereby enhancing water retention [12,13]. Increased nitrogen supply enhances root water uptake and nutrient absorption, promoting growth and increasing water consumption, which reduces soil moisture [3,18]. Li et al. [26] found that both magnetized water and nitrogen solution significantly improved soil infiltration, increasing moisture content with significant coupling effects. However, this study found coupling effects were not significant in surface (0–10 cm) and deep (30–60 cm) layers, possibly due to field soil property variations.

Both magnetized water intensity and nitrogen rate significantly affected tomato growth ($P < 0.05$), with growth initially increasing then decreasing with magnetization and increasing with nitrogen rate. Magnetic-nitrogen coupling significantly affected plant height ($P < 0.05$). Previous research [27] showed magnetized irrigation enhances soil nitrogen supply and mineralization, promoting nitrogen absorption and increasing nitrogen content in crop organs. Different magnetization intensities alter water’ s magnetic and chemical properties differently, affecting soil environments variably [28]. Wei et al. [29] found magnetized water-nitrogen combinations improved photosynthetic capacity and optimized biomass allocation in grapes, similar to this study’ s results. Since plant height is more sensitive to soil environmental changes, magnetic-nitrogen coupling showed significant effects on this parameter.

This study found that yield increased then decreased with magnetization intensity at the same nitrogen level, while WUE significantly improved with magnetized water treatment. Zhou et al. [15] used principal component analysis to demonstrate that magnetized drip irrigation significantly improved tomato quality and increased yield, consistent with these results. Magnetized water maintained higher soil moisture levels for extended periods, satisfying root water uptake, reducing water loss, decreasing crop water consumption, and thereby improving WUE. Xing et al. [10] showed that optimal water-fertilizer combinations improved tomato WUE, while excessive or deficient fertilization reduced it, aligning with our findings. The observed NPFP decline may result from enhanced water retention causing nitrogen leaching [12]. This study used one-year data to determine optimal magnetic-nitrogen ranges, requiring further validation through multi-year trials.

4. Conclusion

Rational nitrogen application under magnetized drip irrigation can alter water physicochemical properties and improve the soil environment in crop root zones, thereby promoting growth and enhancing water-fertilizer use efficiency. Based on experiments with different magnetic-nitrogen combinations, the following conclusions were drawn:

1) Magnetic-nitrogen coupling increased soil moisture content, creating better water conditions for tomato growth. Soil moisture in all layers was significantly affected by individual factors (magnetization intensity and nitrogen rate), with their interaction significantly influencing 20–40 cm layer moisture ($P < 0.05$). Increased soil moisture enhanced water storage, laying the foundation for improved growth and water-fertilizer use efficiency.

2) All magnetic-nitrogen combinations promoted tomato growth. Compared to non-magnetized treatment, magnetized drip irrigation increased plant height, stem diameter, and aboveground biomass by 1.90–22.36%, 4.92–16.37%, and 0.93–9.19%, respectively. Rational nitrogen application enhanced the growth-promoting effects of magnetized water. Magnetic-nitrogen coupling significantly improved yield, WUE, and NPFP. The M2N3 treatment achieved maximum yield (169.67 $\mathrm{t \cdot hm^{-2}}$), M2N2 achieved maximum WUE (35.61 $\mathrm{kg \cdot m^{-3}}$), and M2N1 achieved maximum NPFP (822.54 $\mathrm{kg \cdot kg^{-1}}$).

3) Regression and spatial analyses of yield, WUE, and NPFP revealed that magnetization intensity of 2270–3678 Gs combined with nitrogen application of 220–230 $\mathrm{kg \cdot hm^{-2}}$ enabled these three indices to simultaneously reach 60–70% of their maximum values. Using this magnetic-nitrogen combination range can improve tomato yield and water-fertilizer use efficiency.

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