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Effects of Micro-wetting Irrigation on Crop Yield and Water Use Efficiency (Postprint)

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Date: 2017-11-08T00:00:00+00:00

Abstract

To investigate the effects of micro-irrigation on crop growth and yield, summer maize and winter wheat were selected as test crops in a completely randomized experimental design to compare the impacts of different micro-irrigation lateral spacing arrangements (20 cm, 40 cm, and 60 cm), subsurface drip irrigation, and no irrigation on field crop yield, water use efficiency, and soil electrical conductivity. The results indicated that, compared with subsurface drip irrigation, the irrigation amount of micro-irrigation was approximately 1/4 to 4/5 of that of subsurface drip irrigation; due to the substantial difference in irrigation, crop yield decreased, with summer maize yield decreasing significantly ($P<0.05$), while winter wheat yield decreased but was not significant ($P>0.05$); the water use efficiency of both crops improved, but the difference was not significant ($P>0.05$); irrigation water use efficiency increased significantly ($P<0.05$). With decreasing micro-irrigation tube spacing, crop yield exhibited an increasing trend, while both crop water use efficiency and irrigation water use efficiency exhibited decreasing trends. Based on comprehensive analysis, in relatively water-deficient Lou soil areas, the optimal micro-irrigation tube spacing is 60 cm, which can improve water use efficiency without significantly reducing yield. Furthermore, micro-irrigation tube spacing had a minor effect on soil electrical conductivity. When applying micro-irrigation and subsurface drip irrigation treatments, soil electrical conductivity at various crop growth stages showed no significant differences ($P>0.05$) with increasing soil depth, and the changing trends were basically consistent, indicating that the effects of micro-irrigation and subsurface drip irrigation on soil were consistent. Under micro-irrigation, crop yield was significantly correlated with soil electrical conductivity in the 10-20 cm soil layer and the average electrical conductivity in the 10-80 cm soil layer during the grain filling and maturity stage. Therefore, using soil electrical conductivity in the 10-20 cm soil layer or the average electrical conductivity in the 10-80 cm soil layer during the grain filling and maturity stage to estimate crop yield under micro-irrigation is feasible. The above research can provide a basis for the promotion and application of micro-irrigation technology.

Full Text

Effect of Moistube-Irrigation on Crop Yield and Water Use Efficiency

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Supported by the Henan Province Basic Research Business Expenses, Henan Province Water Science and Technology Breakthrough Project (GG201602), the National Key Research Project of China (2016YFC0400202) and the Natural Science Foundation of China (51679205)

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Abstract

This study investigated the effects of moistube-irrigation on crop growth and yield using summer maize and winter wheat as test crops. A completely randomized field experiment was conducted to compare crop yield, water use efficiency, and soil electrical conductivity under different moistube spacing configurations (20 cm, 40 cm, and 60 cm), subsurface drip irrigation, and no irrigation. Results showed that moistube-irrigation applied approximately 1/4 to 4/5 of the water volume used in subsurface drip irrigation. Due to these substantial differences in irrigation amount, crop yields decreased under moistube-irrigation, with summer maize showing significant reductions ($P < 0.05$) while winter wheat yields declined but not significantly ($P > 0.05$). Water use efficiency improved for both crops, though not significantly ($P > 0.05$), whereas irrigation water use efficiency increased significantly ($P < 0.05$) under all moistube treatments. As moistube spacing decreased, crop yield increased while both crop water use efficiency and irrigation water use efficiency decreased. Comprehensive analysis indicated that in water-scarce Lou soil regions, the optimal moistube spacing was 60 cm, which improved water use efficiency without significantly reducing yield. Additionally, moistube spacing had minimal impact on soil electrical conductivity. Both moistube-irrigation and subsurface drip irrigation showed consistent effects on soil electrical conductivity, with no significant differences ($P > 0.05$) observed across growth stages as soil depth increased, and similar changing trends were observed. Under moistube-irrigation, crop yield correlated significantly with soil electrical conductivity in the 10–20 cm layer and the average electrical conductivity across the 10–80 cm profile during the grain-filling stage. Therefore, using soil electrical conductivity from the 10–20 cm layer or the 10–80 cm average during the grain-filling stage to predict crop yield under moistube-irrigation is feasible. These findings provide a basis for the promotion and application of moistube-irrigation technology.

Keywords: Moistube-irrigation; Subsurface drip irrigation; Yield; Water use efficiency; Soil electrical conductivity; Summer maize; Winter wheat

Introduction

Moistube-irrigation is a novel micro-irrigation technology characterized by simple product structure, low operating costs, improved soil water-air environment, reduced surface evaporation, strong anti-clogging capability, and significant water-saving benefits. Similar to subsurface irrigation, moistube-irrigation provides continuous water supply throughout the crop growth period with uniformly distributed low flow rates along the entire tube length. The flow rate increases linearly with working pressure within a certain range, and field application rates can be adjusted by altering moistube spacing, thereby affecting crop growth. Previous research has demonstrated that moistube-irrigation achieves higher net benefit ratios than drip or sprinkler irrigation, with better soil water distribution uniformity under continuous irrigation compared to intermittent drip irrigation. In slightly saline soils, potted maize (*Zea mays* L.) exhibited higher photosynthetic rates under moistube-irrigation than under drip or surface irrigation. In greenhouse cucumber (*Cucumis sativus* L.) cultivation, moistube-irrigation significantly improved yield and water use efficiency compared to furrow irrigation. Tomato (*Lycopersicon esculentum* Miller) yields and water use efficiency were lower under drip irrigation than moistube-irrigation, and moistube-irrigation effectively reduced evaporation while significantly improving water and fertilizer use efficiency for fruit trees. However, as a low-flow continuous irrigation system, moistube-irrigation currently lacks technical standards and specifications, and large-scale field 实践经验 remains limited. Key questions remain unanswered: How does the low discharge rate affect yield and water use efficiency for field crops like summer maize and winter wheat? Does moistube-irrigation demonstrate similar applicability to drip irrigation for field crops? Can it meet the water demands of field crops during critical growth stages?

Different irrigation technologies create distinct soil water distribution patterns, which in turn affect soil nutrient and salt distribution. Soil electrical conductivity reflects multiple soil properties including moisture content, salinity, organic matter, soil enzymes, bulk density, and porosity, making it an important indicator for assessing soil salinization, fertility quality, and pollution levels. It holds significant value for determining spatial soil distribution differences and evaluating crop growing environments. Research indicates that soil electrical conductivity peaks during main crop growth stages, following a trend of initial increase then decrease throughout the growth period. Within certain ranges, yields of cotton (*Gossypium hirsutum* L.), maize, and wheat increase with soil electrical conductivity, showing varying degrees of correlation that enable its use as an indicator of soil production potential. However, under continuous low-flow moistube-irrigation conditions, how does soil electrical conductivity change? Does it affect soil electrical conductivity similarly to drip irrigation? What correlation exists between soil electrical conductivity and crop yield under moistube-irrigation?

To address these questions and support field application of moistube-irrigation technology, this study established three moistube spacing treatments and compared them with subsurface drip irrigation and no irrigation to analyze changes in root zone soil electrical conductivity and their impacts on yield and water use efficiency for winter wheat and summer maize. The research provides theoretical reference for the promotion and application of moistube-irrigation technology.

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1. Materials and Methods

1.1 Experimental Site

The experiment was conducted from July 2014 to June 2015 at the Irrigation Experiment Station of the Key Laboratory of Agricultural Soil and Water Engineering in Arid Areas, Ministry of Education, Northwest A&F University, Yangling, Shaanxi Province (108°24 E, 34°20 N). The station is located at 521 m altitude in a warm temperate semi-humid climate zone with a frost-free period of 221 days and annual sunshine duration of 2,163.8 hours. Annual precipitation ranges from 550–650 mm, concentrated primarily in July–September. Precipitation and temperature during the crop growth periods for the 2014–2015 summer maize and winter wheat rotation are shown in [Figure 1: see original paper]. The test soil was Lou soil from Yangling with basic nutrient status as follows: organic matter 16.88 $\text{g} \cdot \text{kg}^{-1}$, total nitrogen 0.94 $\text{g} \cdot \text{kg}^{-1}$, total phosphorus 0.32 $\text{g} \cdot \text{kg}^{-1}$, and total potassium 11.2 $\text{g} \cdot \text{kg}^{-1}$. Pre-planting soil electrical conductivity in the 10–20 cm, 20–30 cm, 30–40 cm, 50–60 cm, and 70–80 cm layers was 4.27, 4.34, 4.39, 4.19, and 3.79 $\text{mS} \cdot \text{cm}^{-1}$ for summer maize, and 2.68, 3.71, 4.07, 3.94, and 3.74 $\text{mS} \cdot \text{cm}^{-1}$ for winter wheat, respectively. Soil pH was 8.05. The average field capacity within the 80 cm profile was 31.68% (volumetric water content), saturated water content was 60.1%, wilting point was 8.5%, and bulk density was 1.32 $\text{g} \cdot \text{cm}^{-3}$. Groundwater depth exceeded 5 m, so groundwater contribution was considered negligible.

1.2 Experimental Design

Summer maize variety ‘Zhengdan 958’ was planted at a density of 50,000 plants $\cdot$ hm^{-2} with 30 cm plant spacing and 60 cm row spacing. Sowing occurred on July 1, 2014, and harvest on October 12, 2014. Effective precipitation during the summer maize growth period was calculated as 325.6 mm using empirical formulas. Basal fertilizer application before sowing included 600 kg $\cdot$ hm^{-2} organic fertilizer (N, P, K $\geq$ 5%, organic matter $\geq$ 45%) and 750 kg $\cdot$ hm^{-2} compound fertilizer (N, P, K $\geq$ 15%). Urea was top-dressed at 600 kg $\cdot$ hm^{-2} during the jointing stage (August 6). Winter wheat variety ‘Xiaoyan 22’ was sown on October 25, 2014, at a density of 224.88 kg $\cdot$ hm^{-2} with 20 cm row spacing, broadcast in furrows at 5 cm depth, and harvested on June 7, 2015. The total growth period averaged 230 days. To prevent moistube freezing, irrigation was suspended during the 84-day overwintering period. Effective precipitation was 232.7 mm. Basal fertilizer included 600 kg $\cdot$ hm^{-2} organic fertilizer and 750 kg $\cdot$ hm^{-2} compound fertilizer, both broadcast applied.

Three irrigation methods were established: moistube-irrigation, subsurface drip irrigation (CK1), and no irrigation (CK2). Since moistube flow rate can be controlled through spacing, three spacing treatments were implemented: 60 cm (I1), 40 cm (I2), and 20 cm (I3). Moistubes (Shenzhen Moistube Irrigation Co., Ltd.) had 16 mm diameter, with flow rates of approximately 4 L $\cdot$ (m $\cdot$ d)$^{-1}$ at 200 kPa working pressure. The actual operating pressure was 40 kPa, and tubes were buried at 20 cm depth. Subsurface drip tape (Gansu Dayu, inlaid patch type) had 16 mm diameter, 60 cm lateral spacing, 40 cm emitter spacing, 20 cm burial depth, 100 kPa operating pressure, and 2.2 L $\cdot$ h^{-1} emitter flow rate. The experiment followed a completely randomized design with five treatments and three replications, totaling 15 plots arranged randomly. Each plot measured 2.8 m × 4 m with 1 m spacing between plots. A 1 m deep waterproof membrane (styrene-butadiene-styrene block copolymer, SBS) was installed in the center of each plot to prevent lateral water movement. Irrigation amounts for each treatment are shown in .

Irrigation amount calculation and control for subsurface drip irrigation was based on upper and lower soil moisture limits. Irrigation commenced when soil moisture in the planned wetting layer fell below 65% of field capacity, and was withheld when moisture exceeded 90% of field capacity (F). Irrigation amount (M) was calculated using the formula:

$$M = 10 \times H \times p \times (\theta_F - \theta_i) \times \gamma \tag{1}$$

where M is irrigation amount (m^3 $\cdot$ hm^{-2}), H is planned wetting layer depth (m), p is soil wetting ratio (0.9 for drip irrigation), F is field capacity, i is average soil moisture content (weight basis) in the H layer, and γ is soil bulk density (g $\cdot$ cm^{-3}). Planned wetting depths were 40 cm during seedling stage and 60 cm during jointing, tasseling, and grain-filling stages. Irrigation duration was calculated based on the target irrigation amount and emitter flow rate.

For moistube-irrigation, irrigation was suspended during rainfall or when soil moisture reached 90% of field capacity. After rainfall, soil moisture was monitored dynamically, and irrigation resumed when soil moisture reached 65%, 71%, and 77% of field capacity for the 60 cm, 40 cm, and 20 cm spacing treatments, respectively. These thresholds were determined through preliminary tests showing that after 60 hours of continuous irrigation, soil moisture in the 0–80 cm layer stabilized at 65%, 71%, and 77% of field capacity for the respective spacing treatments. Irrigation amounts were calculated based on the number and length of moistubes and actual irrigation duration.

Precipitation data were obtained from a national meteorological station located approximately 300 m from the experimental site, assuming uniform precipitation across all plots. Before sowing, both summer maize and winter wheat seeds were irrigated to 80% of field capacity to ensure uniform germination.

1.3 Measurement Indicators and Methods

1.3.1 Yield and Water Use Efficiency At harvest, all grain from each plot was threshed and air-dried to determine yield, expressed in $\mathrm{kg} \cdot \mathrm{hm}^{-2}$. Soil volumetric water content was measured throughout the growth period using TRIME-PICO (Germany) at 3-day intervals, with additional measurements 24 hours after rainfall or irrigation. Two monitoring points were established per plot: for drip irrigation (CK1), one TRIME tube was installed 30 cm from the drip tape (midpoint between two laterals) and midway between two emitters, while another was placed 20 cm along the drip tape direction from an emitter [Figure 2a: see original paper]. For moistube treatments I1, I2, and I3, one TRIME tube was installed between two moistubes at distances of 30 cm, 20 cm, and 10 cm, respectively, and another was placed 20 cm along the moistube direction from a random point [Figure 2b: see original paper]. For the no-irrigation treatment (CK2), two TRIME tubes were installed diagonally in a randomly selected 30 cm × 20 cm rectangle. Soil moisture was measured at depths of 0–10 cm, 10–20 cm, 20–30 cm, 30–40 cm, 50–60 cm, and 70–80 cm.

Crop water consumption (ETa) was calculated using the field water balance equation:

$$ETa = P + I - \Delta W \tag{2}$$

where ETa is crop water consumption during the growth period (mm), P is precipitation (mm), I is irrigation amount (mm), and ΔW is the change in soil water storage between sowing and harvest (mm).

Crop water use efficiency (WUE) was calculated as:

$$WUE = \frac{Y}{ETa} \tag{3}$$

where WUE is crop water use efficiency ($\text{kg} \cdot \text{hm}^{-2} \cdot \text{mm}^{-1}$) and Y is grain yield ($\text{kg} \cdot \text{hm}^{-2}$).

Irrigation water use efficiency (iWUE) was calculated as:

$$iWUE = \frac{Y}{I} \tag{4}$$

where iWUE is irrigation water use efficiency ($\text{kg} \cdot \text{hm}^{-2} \cdot \text{mm}^{-1}$), Y is grain yield ($\text{kg} \cdot \text{hm}^{-2}$), and I is irrigation amount during the growth period (mm).

1.3.2 Soil Electrical Conductivity Soil electrical conductivity (ECi) was monitored using TRIME-PICO (Germany) at the same positions as soil moisture measurements [Figure 2: see original paper]. Measurements were taken at 18, 44, 66, and 92 days after sowing for summer maize, and at 29, 72, 131, 165, 186, and 224 days for winter wheat. Measurements were conducted at depths of 10-20 cm, 20-30 cm, 30-40 cm, 50-60 cm, and 70-80 cm. The average electrical conductivity across the 10-80 cm profile (EC) was calculated as:

$$\overline{EC} = \frac{\sum_{i=1}^{n} EC_i}{n} \tag{5}$$

where $\overline{EC}$ is average soil electrical conductivity ($\text{mS} \cdot \text{cm}^{-1}$), ECi is soil electrical conductivity at different depths ($\text{mS} \cdot \text{cm}^{-1}$), and i is the soil layer number. The instrument could not measure the 0-10 cm layer, so this layer was excluded from analysis.

1.3.3 Data Processing Data were analyzed using SPSS 22.0 for mean error analysis and Origin Pro 9.0 for graphing. Significance testing was performed using F-tests at $P < 0.05$. Unless otherwise specified, all data represent means of three replicates.

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2. Results

2.1 Effects of Moistube-Irrigation on Crop Yield, Water Use Efficiency, and Irrigation Water Use Efficiency

As shown in [Figure 3: see original paper], compared with subsurface drip irrigation (CK1), summer maize yields under moistube-irrigation treatments I1, I2, and I3 decreased significantly by 19.52%, 16.61%, and 10.73%, respectively. Winter wheat yields under I1 and I2 were lower than CK1 but not significantly different, while I3 yield was slightly higher than CK1 with minimal difference. Compared with no irrigation (CK2), summer maize yields under I1, I2, and I3 increased significantly by 9.81%, 13.78%, and 21.79%, respectively, while winter wheat yields increased by 7.01%, 8.19%, and 9.42%, respectively, though not significantly ($P > 0.05$). As moistube spacing decreased, yields of both crops increased. Summer maize and winter wheat yields under I3 were 10.91% and 7.04% higher than I1, and 7.04% and 1.13% higher than I2, respectively, with significant differences among summer maize treatments but not among winter wheat treatments.

Crop water use efficiency under I1, I2, and I3 was higher than CK1 for both crops, though not significantly different. Irrigation water use efficiency for summer maize under I1, I2, and I3 was significantly higher than CK1 by 211.52%, 115.18%, and 72.74%, respectively. For winter wheat, the increases were 133.51%, 57.39%, and 19.41%, respectively, all significant ($P < 0.05$). As moistube spacing decreased, both crop water use efficiency and irrigation water use efficiency decreased. For summer maize, I1 irrigation water use efficiency was significantly higher than I2 and I3 by 43.47% and 84.03%, respectively. For winter wheat, the differences were 48.36% and 95.62%, respectively.

2.2.1 Changes in Average Soil Electrical Conductivity (10-80 cm) During Growth Periods

[Figure 4: see original paper] illustrates the temporal variation of average soil electrical conductivity under different treatments. No significant differences in average soil electrical conductivity were observed among moistube-irrigation, subsurface drip irrigation (CK1), and no irrigation (CK2) treatments at the same growth stage. Different crops exhibited distinct trends throughout the growth period. For summer maize, average soil electrical conductivity increased initially then decreased from seedling to grain-filling stage, peaking at the jointing stage. For winter wheat, it decreased initially, then increased, then decreased again, peaking at the seedling stage. Average soil electrical conductivity differed substantially between crops, ranging from 3.90-4.90 $mS \cdot cm^{-1}$ for summer maize and 3.20-3.80 $mS \cdot cm^{-1}$ for winter wheat.

2.2.2 Variation of Soil Electrical Conductivity at Different Depths

2.2.2.1 Trends of Average Soil Electrical Conductivity with Soil Depth Single-factor ANOVA revealed no significant differences ($P > 0.5$) in soil electrical conductivity among treatments at the same growth stage as soil depth increased, with all treatments showing similar trends. This indicates that moistube-irrigation, subsurface drip irrigation, and no irrigation had comparable effects on soil electrical conductivity. [Figure 5: see original paper] shows the variation of average soil electrical conductivity with depth during the entire growth period for both crops, with values at 15 cm, 25 cm, 35 cm, 55 cm, and 75 cm representing the 10-20 cm, 20-30 cm, 30-40 cm, 50-60 cm, and 70-80 cm layers, respectively.

For summer maize, average soil electrical conductivity increased initially then decreased with depth, peaking in the 50-60 cm layer, with subsurface drip irrigation showing higher values. For winter wheat, average soil electrical conductivity increased consistently with depth.

2.2.2.2 Trends of Soil Electrical Conductivity at Different Growth Stages [Figure 6: see original paper] shows soil electrical conductivity variation with depth at different summer maize growth stages. During the seedling stage, soil electrical conductivity generally decreased with depth. At the jointing stage, it showed an "S-shaped" pattern with minimal variation across depths (4.5-5.0 $\mathrm{mS \cdot cm^{-1}}$). During tasseling and grain-filling stages, it increased with depth, with the increasing trend accelerating toward the end of the growth period. In early growth stages, shallow layers had significantly higher electrical conductivity than deep layers. As summer maize developed, shallow layer conductivity gradually decreased while deep layer conductivity increased. By the end of the growth period, deep layer conductivity was significantly higher than shallow layer conductivity, with the jointing stage serving as the turning point when average conductivity peaked.

Different irrigation treatments resulted in varying soil electrical conductivity values. CK1 (subsurface drip irrigation) consistently showed the highest values throughout the growth period. During seedling and grain-filling stages, I3 had the lowest values, while CK2 (no irrigation) had the lowest values during tasseling and grain-filling stages. The greatest difference among treatments occurred in the 50-60 cm layer during the seedling stage, where CK1 reached 4.48 $\mathrm{mS \cdot cm^{-1}}$ and I3 reached 3.94 $\mathrm{mS \cdot cm^{-1}}$, representing a 13.71% difference.

Single-factor ANOVA revealed different significant differences among soil layers under different treatments. During the summer maize seedling stage with minimal rainfall, soil moisture increase depended on irrigation. For I2, soil electrical conductivity showed minimal variation across depths, with no significant differences in the 10-60 cm layer, only between 70-80 cm and 10-60 cm layers. I1 and I3 showed similar patterns, with no significant differences in the 10-40 cm layer but significant differences between 50-60 cm and 70-80 cm layers and the 10-40 cm layer. Compared with subsurface drip irrigation (CK1), larger irrigation amounts under moistube-irrigation created greater differences in soil electrical conductivity among depths. Compared with no irrigation (CK2), larger moistube spacing (smaller irrigation amount) resulted in smaller differences among depths. During jointing and tasseling stages with abundant rainfall, no significant differences were observed among soil depths for any treatment. During grain-filling stage, I2 showed minimal variation, while I1, I3, subsurface drip irrigation, and no irrigation treatments showed significant differences following the pattern: 70-80 cm > 50-60 cm > 30-40 cm > 20-30 cm > 10-20 cm.

[Figure 7: see original paper] shows soil electrical conductivity variation with depth at different winter wheat growth stages. For all growth stages, soil electrical conductivity increased consistently with depth, following the pattern: 70-80 cm > 50-60 cm > 30-40 cm > 20-30 cm > 10-20 cm. As winter wheat developed, shallow layer conductivity generally decreased while deep layer conductivity remained relatively stable. All soil layers showed higher conductivity during the seedling stage than at other stages. The 40–80 cm layers had significantly higher conductivity than the 10–40 cm layers throughout the growth period, with the maximum value occurring in the 80 cm layer during the seedling stage. Minimal differences were observed among treatments, with no significant differences.

Single-factor ANOVA revealed significant differences among soil layers under different treatments at all winter wheat growth stages. The 50–60 cm and 70–80 cm layers consistently showed significantly higher conductivity, while the 10–20 cm layer showed the lowest values. I2 treatment showed minimal variation, while the control group and I3 showed similar patterns.

2.3 Correlation Between Soil Electrical Conductivity and Yield Under Moistube-Irrigation

Pearson correlation coefficients were used for two-tailed significance testing between soil electrical conductivity at different depths and growth stages and crop yields, with results shown in . Based on correlation analysis, summer maize and winter wheat yields showed significant positive correlations ($P < 0.05$) with soil electrical conductivity in the 10–20 cm layer and average conductivity across the 10–80 cm profile during the grain-filling stage. Linear regression models were therefore established between yield and 10–80 cm average soil electrical conductivity during grain-filling stage [Figure 8: see original paper].

As shown in , crop yields correlated positively with soil electrical conductivity, with significant correlations during the grain-filling stage for both the 10–20 cm layer and the 10–80 cm average. The regression models [Figure 8: see original paper] indicate that summer maize and winter wheat yields increased linearly with 10-80 cm average soil electrical conductivity within the ranges of 3.86–4.44 $\mathrm{mS \cdot cm^{-1}}$ and 2.96–3.48 $\mathrm{mS \cdot cm^{-1}}$, respectively. Both models showed high coefficients of determination (R^2) and Pearson correlation coefficients, confirming the feasibility of using soil electrical conductivity from the grain-filling stage to predict crop yields under moistube-irrigation.

3. Discussion

3.1 Effects of Moistube-Irrigation on Yield, Crop Water Use Efficiency, and Irrigation Water Use Efficiency

Moistube-irrigation provides low discharge rates over long durations, functioning as line-source irrigation, whereas drip irrigation provides high discharge rates over short durations as point-source irrigation. These different soil water spatiotemporal distribution patterns affect root water uptake, thereby influencing crop yield and water use efficiency. Previous studies reported that moistube-irrigation achieved higher water use efficiency than drip irrigation for greenhouse cucumbers, while mulched drip irrigation produced higher maize yields but significantly lower water use efficiency than moistube-irrigation, with 60 cm moistube spacing showing high soil water use efficiency. In this study, summer maize yield was significantly lower under moistube-irrigation than subsurface drip irrigation, likely because summer maize experiences high temperatures and evaporation rates throughout its growth period, making it sensitive to irrigation amount. Moistube-irrigation supplied approximately half the water volume of subsurface drip irrigation. Although moistube-irrigation provided continuous and stable water supply, the water demand during critical growth stages far exceeded the moistube supply rate, limiting growth and yield increase. In this field rotation experiment, moistube-irrigation (20 cm spacing) applied half the water volume of subsurface drip irrigation for summer maize and four-fifths for winter wheat. As moistube irrigation amount increased, the yield gap with subsurface drip irrigation gradually narrowed, and when irrigation reached four-fifths of the drip amount, yields began to exceed those of subsurface drip irrigation. To improve crop water use efficiency and enhance field applicability, we recommend increasing moistube operating pressure and irrigation amount during critical water demand periods (tasseling and grain-filling for summer maize; heading and grain-filling for winter wheat) to reduce yield differences with subsurface drip irrigation. This study also found that as moistube spacing decreased, crop yield increased while irrigation water use efficiency decreased significantly ($P < 0.05$). Reduced spacing increased plot irrigation amount, and analysis of average soil volumetric water content in the 10–80 cm layer showed values of 25.58%, 26.19%, and 27.93% for the three spacing treatments, respectively. The positive correlation between soil water content and yield (with irrigation thresholds of 40–75% field capacity) explained the yield increase. Although no significant yield differences were observed among the 60 cm, 40 cm, and 20 cm spacing treatments for either crop, significant differences existed in irrigation amounts, resulting in significantly decreased irrigation water use efficiency with reduced spacing. Comprehensive analysis indicates that 60 cm spacing is optimal for water-scarce Lou soil regions, as it improves water use efficiency without significantly reducing yield.

3.2 Effects of Moistube-Irrigation on Soil Electrical Conductivity

Soil electrical conductivity is influenced by total nitrogen content, K^+, ${NO_3}^-$, pH, volumetric water content, dry weight, and organic matter. Increased soil nutrient ions and organic matter content raise soil cation concentrations, which increases adsorbed anions on soil colloids and consequently increases soil electrical conductivity. Within certain ranges, crop yield increases with soil electrical conductivity, but excessive Na^+, Mg^{2+}, and other salinization ions can cause soil salinization that negatively affects crop growth and yield. This experiment used non-saline soil and tap water with low Na^+ and Mg^{2+} content, so soil electrical conductivity changes primarily reflected variations in soil nutrient ion content. Single-factor ANOVA revealed no significant differences ($P > 0.05$) in soil electrical conductivity among treatments at different depths, indicating that moistube-irrigation, subsurface drip irrigation, and no irrigation had similar effects on soil electrical conductivity (nutrient ion content). This confirms the suitability of this novel irrigation technology for field summer maize and winter wheat production. As a low-flow continuous irrigation system, moistube discharge remains in dynamic equilibrium with crop water demand, resulting in slow nutrient leaching and stable nutrient supply within the root zone, further enhancing field applicability.

Soil soluble ion composition, content, and proportions are important factors affecting soil electrical conductivity. Research suggests that soil water content is the primary factor affecting electrical conductivity at 15-30% volumetric water content, while nutrient ions become dominant above 30%. This study found significantly higher soil electrical conductivity for summer maize than winter wheat. Analysis of 10-80 cm soil water content revealed that summer maize had approximately 4% higher average volumetric water content than winter wheat. Additionally, urea top-dressing during summer maize jointing stage (August 6) significantly increased NH_4^+, which enhanced exchange of adsorbed base cations and increased water-soluble K^+, Na^+, Ca^{2+}, and Mg^{2+} concentrations, resulting in higher soil water content and ion concentrations for summer maize. The study also found different depth trends: summer maize showed an initial increase then decrease with depth, while winter wheat showed a consistent increase. For summer maize, high temperatures caused substantial evaporation from shallow layers (10-20 cm water content was about 6% lower than 50-60 cm), and main root systems concentrated in the 10-20 cm layer, absorbing nutrients and reducing ion content with depth (since electrical conductivity correlates positively with ion content). The combined effects of water content and root ion absorption resulted in lower conductivity in the 10-20 cm layer than 50-60 cm, while the 70-80 cm layer showed lower conductivity than 50-60 cm, likely due to water content differences. Moistube low flow rates, after crop uptake, maintained residual water near the tubes with difficulty replenishing deep layers, resulting in about 2% lower water content in the 70-80 cm layer than the 50-60 cm layer. For winter wheat, low temperatures minimized upward water and ion movement, high planting density concentrated roots in surface layers, and decreasing root volume with depth reduced ion absorption. Combined with increasing water content with depth, these factors caused electrical conductivity to increase consistently with depth.

3.3 Correlation Between Soil Electrical Conductivity and Crop Yield Under Moistube-Irrigation

Soil electrical conductivity may correlate differently with yields of different crops. Studies have reported significant correlations and high grey relational degrees between soil electrical conductivity and maize yield, enabling yield assessment. Different soil depths show varying correlations with yield, and different crop varieties exhibit different correlation degrees. For example, tomato yield shows an inverse relationship with soil electrical conductivity, while cotton and maize yields increase with conductivity within certain ranges. Some researchers have found no consistent relationship between yield and soil electrical conductivity. This study found significant positive correlations between summer maize and winter wheat yields and soil electrical conductivity in the 10–20 cm layer and 10–80 cm average during the grain-filling stage. The grain-filling stage is critical for dry matter accumulation and translocation, where root growth environment directly determines yield. With small but continuous moistube discharge and consistent management practices, the soil water-fertilizer environment in the root zone remained relatively stable. Since moistubes were buried at 20 cm depth—the root concentration zone for summer maize—and significant relationships exist between root growth and yield, using grain-filling stage soil electrical conductivity to predict yield is feasible. However, this finding contrasts with Zhao et al., who reported negative correlations between grain-filling stage soil electrical conductivity and winter wheat yield. This discrepancy may result from differences in irrigation methods, measurement techniques, and instruments. Zhao et al. used a DDB-307 conductivity meter with a 5:1 water:soil ratio on disturbed samples, primarily measuring ion content without reflecting intact soil conditions. This study used TDR on undisturbed soil, capturing comprehensive soil factors including salts, water, organic matter, inorganic matter, and soil structure.

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4. Conclusions

1. Compared with subsurface drip irrigation, moistube-irrigation demonstrated significant water-saving effects, with crop yields decreasing to varying degrees depending on crop type. Irrigation water use efficiency increased significantly by 211.52–72.74% for summer maize and 133.51–19.41% for winter maize ($P < 0.05$). As moistube irrigation amount increased, the yield difference with subsurface drip irrigation gradually decreased, and yields exceeded subsurface drip irrigation at certain irrigation levels. To improve field applicability, we recommend increasing moistube operating pressure and irrigation amount during critical water demand periods (tasseling and grain-filling for summer maize; heading and grain-filling for winter wheat) to ensure high yields.

2. As moistube spacing decreased, yields of both summer maize and winter wheat increased while water use efficiency and irrigation water use efficiency decreased. Comprehensive analysis indicates that 60 cm spacing is optimal for water-scarce Lou soil regions, as it improves water use efficiency without significantly reducing yield.

3. Moistube spacing had minimal impact on soil electrical conductivity. Moistube-irrigation, subsurface drip irrigation, and no irrigation showed

similar trends in soil electrical conductivity across growth stages and soil depths, with no significant differences among treatments ($P > 0.05$), confirming that moistube-irrigation is equally suitable for field summer maize and winter wheat production.

4. Under moistube-irrigation, summer maize and winter wheat yields showed significant positive correlations with soil electrical conductivity in the 10-20 cm layer and the average across the 10-80 cm profile during the grain-filling stage. Therefore, using soil electrical conductivity from the grain-filling stage can reliably predict crop yields under moistube-irrigation.

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