Effects of Plastic Film Mulching and Conventional Irrigation on Water Consumption Characteristics and Yield of Winter Wheat: Postprint

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Abstract

To further elucidate the agricultural production potential of plastic film mulching, this study designed four experimental treatments at the National Precision Agriculture Demonstration Base (40°10 33.26 N, 116°23 37.07 E) in Xiaotangshan Town, Changping District, Beijing [T1: plastic film mulching (covering the film with a 1 cm soil layer on top of conventional plastic film mulching) + no irrigation; T2: no plastic film + winter irrigation; T3: no plastic film + winter irrigation + jointing stage irrigation; T4: no plastic film + winter irrigation + jointing stage irrigation + flowering stage irrigation], and employed weighing lysimeters to investigate water consumption characteristics and yield formation mechanisms of winter wheat under this mulching practice. The results demonstrated that cumulative evapotranspiration for all four treatments followed a cubic polynomial dynamic equation with days after sowing, with absolute coefficients $R^2 > 0.99$, indicating high goodness of fit. The maximum theoretical and actual values of the soil-crop coefficient (Kc) for T1 and T4 occurred at the heading stage, whereas those for T2 and T3 occurred at the jointing stage; Kc for all four treatments followed a quadratic equation with days after sowing, with absolute coefficients $R^2 > 0.70$ ($R^2 = 0.69$ for T2). Regarding stage-specific water consumption, during the sowing-jointing period, T1 was significantly lower than T2 (as well as T3/T4); during the jointing-maturity period, no significant difference existed between T1 and T2, but both were significantly lower than T3 and T4 ($P < 0.05$). During the booting-flowering and flowering-maturity periods, T1 increased water consumption by 3.10 mm and 21.43 mm compared with T2, respectively ($P > 0.05$). In the late growth stage, water consumption from the 50-100 cm soil layer increased. In terms of evapotranspiration rate and Kc, the peak evapotranspiration of T1 was higher than that of T2 but lower than that of T3 and T4; the timing of the maximum post-winter evapotranspiration peak for T1 (215 days after sowing) was later than that for T2, T3, and T4 (194 days after sowing). The timing of the maximum Kc value for T1 was identical to that for T4 (214 days after sowing) but later than for T2 and T3 (200 and 199 days after sowing, respectively). Compared with T2 and T3, T1 increased flag leaf water potential, delayed leaf senescence, and raised surface soil layer (0–5 cm) temperature by 0.5 °C, although the increase was not significant, which was beneficial for reducing inter-plant soil evaporation. Regarding yield components and water use efficiency, grains per spike and thousand-grain weight of T1 were higher than those of T2 and T3 but lower than those of T4, with no significant differences. The yield of T1 showed no significant difference from T2 and T3 but was significantly lower than that of T4, while water use efficiency was significantly increased by 22.6% ($P < 0.05$). These results indicate that under conditions of sufficient pre-sowing soil moisture, plastic film mulching can substitute for winter and jointing stage irrigations. By reducing soil evaporation during the early stage, substantial water can be conserved for the late growth stage of winter wheat, thereby reducing total water consumption throughout the entire growth period while maintaining yield and improving crop water use efficiency.

Full Text

Preamble

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Effects of Plastic Film Mulching and Conventional Irrigation on Water Consumption Characteristics and Yield of Winter Wheat*

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Abstract

To further clarify the agricultural production potential of plastic film mulching, this study designed four experimental treatments at the National Precision Agriculture Demonstration Base in Xiaotangshan Town, Changping District, Beijing (40°10 33.26 N, 116°23 37.07 E): T1: plastic film mulching (with a 1 cm soil layer covering the conventional plastic film) + no irrigation; T2: no film mulching + winter irrigation; T3: no film mulching + winter irrigation + jointing stage irrigation; T4: no film mulching + winter irrigation + jointing stage irrigation + flowering stage irrigation. Weighing lysimeters were used to investigate water consumption characteristics and yield formation mechanisms of winter wheat under this mulching practice. The results showed that cumulative evapotranspiration for all four treatments followed a cubic polynomial dynamic equation with days after sowing, with determination coefficients $R^2 > 0.99$, indicating high goodness of fit. Both the theoretical and actual maximum values of the soil-crop coefficient (Kc) for T1 and T4 occurred at the heading stage, while those for T2 and T3 occurred at the jointing stage. The Kc values for all four treatments showed a quadratic relationship with days after sowing, with determination coefficients $R^2 > 0.70$ ($R^2 = 0.69$ for T2). In terms of stage-specific water consumption, T1 was significantly lower than T2 (and T3/T4) during the sowing-jointing period. During the jointing-maturity period, T1 and T2 showed no significant difference but were both significantly lower than T3 and T4 ($P < 0.05$). During the booting-flowering and flowering-maturity periods, T1 increased water consumption by 3.10 mm and 21.43 mm compared to T2, respectively ($P > 0.05$). In the late growth stage, water consumption from the 50-100 cm soil layer increased. Regarding evapotranspiration rate and Kc, the peak evapotranspiration rate of T1 was higher than T2 but lower than T3 and T4. The maximum post-winter evapotranspiration peak for T1 occurred later (215 days after sowing) than for T2, T3, and T4 (194 days after sowing). The timing of maximum Kc for T1 coincided with T4 (214 days after sowing) but was later than T2 (200 days after sowing) and T3 (199 days after sowing). Compared with T2 and T3, T1 increased flag leaf water potential and delayed leaf senescence, while soil surface temperature (0–5 cm) increased by 0.5 °C, though not significantly, which helped reduce soil evaporation between plants. In terms of yield components and water use efficiency, T1 showed higher grain number per spike and 1000-grain weight than T2 and T3, but lower than T4, with no significant differences. T1 yield showed no significant difference from T2 and T3 but was significantly lower than T4, while water use efficiency increased significantly by 22.6% ($P < 0.05$). These results indicate that under conditions of sufficient pre-sowing soil moisture, plastic film mulching can replace the functions of winter and jointing stage irrigations by reducing early-stage soil evaporation, thereby conserving substantial water for the late growth stage of winter wheat, reducing total water consumption while maintaining yield and improving crop water use efficiency.

Keywords: plastic film mulching; irrigation; wheat; water consumption characteristics; soil-crop coefficient; yield

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Plastic film mulching technology is widely used in agricultural production to limit crop evapotranspiration. In order to clarify the potential of plastic mulching on agricultural productivity and to explore the effect of maximum water-saving on the growth and yield of winter wheat in arid/semi-arid regions, a field experiment was conducted at the National Experiment Station of Precision Agriculture in Changping, Beijing (N40°10 33.26 , E116°23 37.07). The experiment consisted of four treatments –T1 (plastic film mulching with no irrigation), T2 (wintering watering with no film mulching), T3 (wintering and jointing watering with no film mulching), and T4 (wintering, jointing and flowering watering with no film mulching).

Compared with conventional film mulching, the T1 treatment was covered with a 1 cm soil layer over the plastic film surface. Water consumption characteristics and yield were determined using weighing lysimeters throughout the whole growth stage and sampling methods. Concurrently, soil moisture content at 200 cm depth was measured daily from April to May using a Diviner 2000. The results showed that T1 efficiently utilized soil moisture. There was a cubic function between cumulative evapotranspiration and the number of days after sowing for the four treatments, with determination coefficient $R^2 > 0.99$. The heading stage had the maximum theoretical and actual values of soil-crop coefficient (Kc) under T1 and T4. For T2 and T3, Kc had a quadratic function with the number of days after sowing during jointing stage, with determination coefficient $R^2 > 0.70$ (that for T2 was 0.69). Water consumption was significantly lower under T1 than under other treatments during the sowing–jointing period. However, during the jointing–maturity period, T1 and T2 were not statistically different in terms of water consumption, but had lower values than T3 and T4 ($P < 0.05$). During booting–flowering period and flowering–maturity period, water consumption under T1 was higher, respectively, by 3.1 mm and 21.43 mm than that of T2, but not statistically different ($P > 0.05$). However, this increased water consumption at the 50–100 cm soil depth at late growth stage. The peak evapotranspiration under T1 was higher than that of T2, but both lower than those of T3 and T4. The time of peak evapotranspiration under T1 (215 d after sowing) came later than those of T2, T3 and T4 (194 d after sowing). The time of Kc-max of T1 was consistent with that of T4 (214 d after sowing), but occurred later than that of T2 (200 d after sowing) and T3 (199 d after sowing). Compared with T2 and T3, T1 enhanced flag leaf water potential and delayed leaf senescence, with soil surface (0–5 cm layer) temperature improving by 0.5 °C. This temperature increase was not statistically significant ($P > 0.05$) and contributed minimally to soil evaporation. In terms of yield, yield components and water use efficiency, grain number per spike and the 1000-grain weight of T1 were higher than those of T2 and T3, which were in turn lower than those of T4; but were not statistically different ($P > 0.05$). The yield of T1 was not statistically different from that of T2 and T3, but significantly lower than that of T4 ($P < 0.05$) and with 22.6% increase in water use efficiency ($P < 0.05$). It suggested that plastic film mulching could widely replace wintering and jointing water application by limiting soil evaporation at the early growth stage in semi-humid regions with sufficient soil water content before sowing. The water saved was used for the late growth stage, which thereby reduced the amount of water consumption and increased water use efficiency of winter wheat. Irrespectively, this form of water-saving was not at the expense of crop yield.

Keywords: Plastic film mulching; Conventional irrigation; Wheat; Water consumption characteristics; Soil-crop coefficient; Yield

Introduction

Plastic film mulching technology is widely used in agricultural production to limit crop evapotranspiration. In order to clarify the potential of plastic mulching on agricultural productivity and to explore the effect of maximum water-saving on the growth and yield of winter wheat in arid/semi-arid regions, a field experiment was conducted at the National Experiment Station of Precision Agriculture in Changping, Beijing (N40°10 33.26 , E116°23 37.07). The experiment consisted of four treatments –T1 (plastic film mulching with no irrigation), T2 (wintering watering with no film mulching), T3 (wintering and jointing watering with no film mulching), and T4 (wintering, jointing and flowering watering with no film mulching).

Compared with conventional film mulching, the T1 treatment was covered with a 1 cm soil layer over the plastic film surface. Water consumption characteristics and yield were determined using weighing lysimeters throughout the whole growth stage and sampling methods. Concurrently, soil moisture content at 200 cm depth was measured daily from April to May using a Diviner 2000. The results showed that T1 efficiently utilized soil moisture. There was a cubic function between cumulative evapotranspiration and the number of days after sowing for the four treatments, with determination coefficient $R^2 > 0.99$. The heading stage had the maximum theoretical and actual values of soil-crop coefficient (Kc) under T1 and T4. For T2 and T3, Kc had a quadratic function with the number of days after sowing during jointing stage, with determination coefficient $R^2 > 0.70$ (that for T2 was 0.69). Water consumption was significantly lower under T1 than under other treatments during the sowing-jointing period. However, during the jointing-maturity period, T1 and T2 were not statistically different in terms of water consumption, but had lower values than T3 and T4 ($P < 0.05$). During booting-flowering period and flowering-maturity period, water consumption under T1 was higher, respectively, by 3.1 mm and 21.43 mm than that of T2, but not statistically different ($P > 0.05$). However, this increased water consumption at the 50-100 cm soil depth at late growth stage. The peak evapotranspiration under T1 was higher than that of T2, but both lower than those of T3 and T4. The time of peak evapotranspiration under T1 (215 d after sowing) came later than those of T2, T3 and T4 (194 d after sowing). The time of Kc-max of T1 was consistent with that of T4 (214 d after sowing), but occurred later than that of T2 (200 d after sowing) and T3 (199 d after sowing). Compared with T2 and T3, T1 enhanced flag leaf water potential and delayed leaf senescence, with soil surface (0–5 cm layer) temperature improving by 0.5 °C. This temperature increase was not statistically significant ($P > 0.05$) and contributed minimally to soil evaporation. In terms of yield, yield components and water use efficiency, grain number per spike and the 1000-grain weight of T1 were higher than those of T2 and T3, which were in turn lower than those of T4; but were not statistically different ($P > 0.05$). The yield of T1 was not statistically different from that of T2 and T3, but significantly lower than that of T4 ($P < 0.05$) and with 22.6% increase in water use efficiency ($P < 0.05$). It

suggested that plastic film mulching could widely replace wintering and jointing water application by limiting soil evaporation at the early growth stage in semi-humid regions with sufficient soil water content before sowing. The water saved was used for the late growth stage, which thereby reduced the amount of water consumption and increased water use efficiency of winter wheat. Irrespectively, this form of water-saving was not at the expense of crop yield.

Keywords: Plastic film mulching; Conventional irrigation; Wheat; Water consumption characteristics; Soil-crop coefficient; Yield

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1.1 Experimental Design

The experiment was conducted at the National Precision Agriculture Demonstration and Research Base in Xiaotangshan Town, Changping District, Beijing. Winter wheat was sown on September 29, 2014, and harvested on June 1, 2015. The experimental site was equipped with weighing lysimeters (designed by Steve Evett of CPRL, USDA in Bushland, Texas), each with an effective planting area of 0.75 m^2 (1 m × 0.75 m) and a depth of 2 m, filled with undisturbed field soil. The lysimeters were equipped with a data acquisition system (provided by Beijing Research Center of Agricultural Intelligent Equipment Technology) that converted pressure signals into electrical signals, recording soil weight changes every 5 minutes with a sensitivity of 0.05 mm for water content changes, automatically controlled and recorded by computer. The experimental site was also equipped with an automatic weather station that continuously recorded air temperature, humidity, solar radiation intensity, wind speed, wind direction, and precipitation at hourly intervals.

The soil bulk density in the 0–40 cm tillage layer within the lysimeters was 1.43 g · cm ^{3}. The winter wheat cultivar was 'Nongda 212' . Organic fertilizer was applied as basal dressing before sowing, and sufficient pre-sowing irrigation was applied. Chemical fertilizer application rates per plot were: urea 45 g · m ^{2}, diammonium phosphate 45 g · m ^{2}, potassium sulfate 30 g · m ^{2}, and zinc sulfate 1.5 g · m ^{2}, equivalent to N 30.54 g · m ^{2}, P O 20.79 g · m ^{2}, and K O 16.21 g · m ^{2}.

Four treatments were established: T1: plastic film mulching (with a 1 cm soil layer covering the conventional plastic film) + no irrigation; T2: no film mulching + winter irrigation + no spring irrigation; T3: no film mulching + winter irrigation + jointing stage irrigation; T4: no film mulching + winter irrigation + jointing stage irrigation + flowering stage irrigation. Each treatment had three replicates arranged randomly. Irrigation amounts and timing for each treatment followed field standards and are shown in Table 1 . To prevent accelerated winter wheat growth due to plastic mulching before winter, the non-mulched treatments (T2, T3, T4) were sown on September 29, 2014, with five rows per lysimeter plot at 15 cm row spacing and 1 cm plant spacing. The T1 treatment was sown on October 9, 2014 (10 days later than the non-mulched treatments). Immediately after sowing, each experimental plot was covered with whole plastic film, and a uniform 1 cm soil layer was spread over the film surface, except for the area where wheat seeds were located (plot area 0.75 m^{2}). Five to seven days after sowing, when wheat seedlings emerged, the film was carefully cut along the seedling rows with a blade. To ensure safe winter survival, all non-mulched plots received uniform winter irrigation of 75 mm. No rain shelter was used during the sowing-regreening period, during which cumulative rainfall was 26.1 mm. After regreening, rain shelters were used to block precipitation. No topdressing was applied in spring, and conventional cultivation management was practiced.

1.2.1 Evapotranspiration and Soil-Crop Coefficient (Kc)

1) Reference evapotranspiration (ETp)
The Penman-Monteith equation was used to calculate reference evapotranspiration ETp [21]:

$$ET_p = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}u_2(e_s - e_d)}{\Delta + \gamma(1 + 0.34u_2)}$$

Where: ETp is reference evapotranspiration (mm · d ^{1}); Rn is net radiation (MJ · m ^{2} · d ^{1}); G is soil heat flux density (MJ · m ^{2} · d ^{1}), G = 4.2(T_{i+1} - T_{i-1})/T_i (T is the average temperature between day i-1 and i+1 at the same time, °C); = 2.501 - 0.002361T, where is latent heat flux for evaporation at average temperature (MJ · kg ^{1}); Δ = 0.200[0.00738T + 0.8072] - 0.000116, where Δ is the slope of the saturation vapor pressure-temperature curve (kPa · °C ^{1}); = 0.00163P/ , where is the psychrometric constant, P = 101.3 - 0.01055H, with P in kPa and H being altitude in m; u is wind speed at 2 m height (m · s ^{1}); e_s is saturation vapor pressure at temperature T (kPa), e_s = exp[(16.78T - 116.9)/(T + 273.3)]; e_d = RH × e_s, where e_d is actual vapor pressure (kPa) and RH is relative humidity.

2) Actual evapotranspiration (ETa)
The weighing lysimeters automatically and continuously recorded weight changes of each plot. During the experiment, a standard curve for weight-voltage (kg-mV) was established by adding or removing lead blocks on each lysimeter, allowing calculation of actual water consumption:

$$ET_a = \frac{A \times \Delta V}{B \times S}$$

Where: ETa is actual evapotranspiration of wheat (mm · d ^{1}), A and B are constants, ΔV is the daily voltage change value (mV), and S is the area of each lysimeter plot (m^{2}).

3) Soil-crop coefficient (Kc)
Kc was calculated as the ratio of actual to reference evapotranspiration: Kc = ETa/ETp.

1.2.2 Flag Leaf Water Potential Measurement Method

Measurements were taken during the flowering stage at 10-day intervals, always after 13:00 each day, with three replicates per treatment. Three flag leaves of similar growth status were selected from each plot, cut into pieces, and placed in a dew point water potential meter (WP4, Decagon, USA). Data were recorded after measurement equilibrium was reached.

1.2.3 Determination of Leaf Area Index for Upper Four Leaves

The total area of the upper four leaves was measured at late jointing (April 21), heading (April 29), flowering (May 7), and early grain filling (May 12) stages. Specifically, three plants were selected from each plot (as replicates), and the length and width of each plant' s upper four leaves were measured. The total area of the upper four leaves was calculated using the wheat leaf area formula [22] (wheat leaf area = length × width × 0.7). The average value was multiplied by the total number of plants in the plot to obtain the total area of the upper four leaves for that plot. The leaf area index for the upper four leaves was obtained by dividing this total area by the plot area.

1.2.4 Measurement of Soil Temperature and Moisture Content

Soil temperature was measured using a handheld digital thermometer (DT-130, Huashengchang Industrial Co., Ltd.) at late jointing (April 21), heading (April 29), flowering (May 7), and early grain filling (May 12) stages. Measurements were taken between 13:00 and 15:00, with three replicates per plot at the same position (between rows 1 and 2) and as far from lysimeter boundary effects as possible. A 10 cm probe was inserted vertically 5 cm into the ground surface, and readings were taken after stabilization. Soil moisture content at 160 cm depth was measured using a Diviner 2000 (Sentek, Australia) every day between 16:00 and 17:00 at 10 cm intervals ($cm^3 \cdot cm^{3}$), with three replicates per plot averaged. Prior to this, soil samples were taken every 10 cm using an auger, and oven-drying methods were used to calibrate Diviner 2000 measurements.

1.2.5 Biomass, Yield, and Water Use Efficiency

Mature biomass: Ten representative plants were sampled from each plot, killed at 105 °C for 0.5 h, then oven-dried and weighed. **Yield and yield components:** At maturity, each treatment plot was harvested to determine grain dry weight and 1000-grain weight. Water use efficiency was calculated as:

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

Where: WUE is water use efficiency (kg · m ^{3}), Y is grain yield (kg · m ^{2}), and ET is actual water consumption (mm).

1.3 Data Analysis and Processing

Microsoft Office 2010 was used for data processing and graphing, and IBM SPSS 20.0 was used for significance testing.

2.1 Effects of Plastic Film Mulching and Different Irrigation Treatments on Water Consumption Characteristics of Winter Wheat

Figure 1 [Figure 1: see original paper] shows water consumption characteristics of winter wheat throughout the growth period under different irrigation treatments. The evapotranspiration curve exhibited a bimodal pattern, with peaks occurring during sowing-pre-winter (October 1-November 30, i.e., 1-61 days after sowing) and regreening-maturity (March 11-May 31, i.e., 163-244 days after sowing) periods. Peak evapotranspiration rates differed among treatments. During sowing-pre-winter (October 1-November 20, i.e., 1-51 days after sowing), the peak evapotranspiration rate was 1.79 mm · d ^{1} for T1 and averaged 2.45 mm · d ^{1} for T2, T3, and T4. During winter dormancy (November 21-March 2, i.e., 52-152 days after sowing), daily water consumption decreased for all treatments, averaging 0.5 mm · d ^{1}. From regreening (March 3, i.e., 153 days after sowing) onward, daily water consumption gradually increased, reaching maximum values at the jointing stage: 8.34 mm · d ^{1} (May 3, i.e., 216 days after sowing) for T1, 8.05 mm · d ^{1} (April 16, i.e., 199 days after sowing) for T2, 11.27 mm · d ^{1} (April 16, i.e., 199 days after sowing) for T3, and 11.26 mm · d ^{1} (April 16, i.e., 199 days after sowing) for T4. The T1 treatment delayed the timing of the peak evapotranspiration rate.

Based on evapotranspiration curve characteristics, the winter wheat growth period was divided into three stages: sowing-pre-winter (October 1-November 30, i.e., 1-61 days after sowing), winter-regreening (December 1-March 10, i.e., 62-162 days after sowing), and regreening-maturity (March 11-May 31, i.e., 163-244 days after sowing). During sowing-pre-winter, evapotranspiration increased as wheat leaf area expanded. From November 1-30 (i.e., 1-61 days after sowing), decreasing temperatures led to reduced water consumption. After December 1 (i.e., 62 days after sowing), further temperature drops caused wheat to enter winter dormancy, minimizing evapotranspiration. After March, rising temperatures promoted wheat regreening, leaf area expansion, and advancing growth stages, causing evapotranspiration rates to peak at the jointing stage.

The relationship between evapotranspiration rate (y) and time (x) for each stage followed a quadratic equation. From the first-stage quadratic equation, the theoretical timing of pre-winter evapotranspiration peaks for T1 and T2 (T3/T4) were 41 and 28 days after sowing, respectively. The calculation process was as follows:

T1:
$y = -0.0006x^2 + 0.0491x - 0.163$ ($R^2 = 0.3741$)
Theoretical peak timing = 0.0491/[-2 × (-0.0006)] = 41 days, with a theoretical peak value of 0.85 mm · d ^{1}. The theoretical bare soil evapotranspiration value was negative (i.e., at $x = 0$, T1 maximally suppressed surface evaporation). The actual evapotranspiration peak occurred 33 days after sowing at 1.79 mm · d ^{1}.

T2 (T3/T4):
$y = -0.0005x^2 + 0.029x + 1.0822$ ($R^2 = 0.0888$)
Peak timing = 0.029/[-2 × (-0.0005)] = 29 days, with a theoretical peak value of 1.49 mm · d ^{1}. The theoretical bare soil evapotranspiration value reached 1.02 mm · d ^{1} (i.e., at $x = 0$). The actual evapotranspiration peak occurred 36 days after sowing at 2.45 mm · d ^{1}.

Since T1 was sown 10 days later than T2 (T3/T4), the theoretical pre-winter evapotranspiration peak timing for both T1 and T2 (T3/T4) was approximately one month after sowing, which was generally consistent with actual peak timing.

During the second stage [winter–regreening (December 1–March 10, i.e., 62–162 days after sowing)], the theoretical minimum values for T1 and T2 (T3/T4) both occurred in mid-to-late January. During the third stage [regreening–maturity (March 11–May 31, i.e., 163–244 days after sowing)], evapotranspiration peaks occurred at 215, 194, 194, and 194 days after sowing, respectively, corresponding to mid-to-late April to early May (the jointing–heading stage), a period of high daily water consumption.

2.2 Water Consumption at Different Growth Stages Under Plastic Film Mulching and Different Irrigation Treatments

Table 2 shows that T1 had significantly lower water consumption than T2 (and T3/T4) during sowing–pre-winter, winter–regreening, and regreening–jointing stages. During jointing–booting, T2 water consumption was significantly lower than T3/T4 but not significantly different from T1. During booting–flowering and flowering–maturity, T1 water consumption was higher than T2 and lower than T3, but differences were not significant. Compared with T2, T1 had lower water consumption during sowing–booting but higher during booting–maturity. Compared with T3, flowering water supplementation increased stage water consumption in T4, but the difference was not significant ($P > 0.05$).

2.3 Cumulative Water Consumption Under Plastic Film Mulching and Different Irrigation Treatments

Overall, cumulative water consumption trends were consistent across treatments, with total evapotranspiration at harvest following the order T4 > T3 > T2 > T1. The cumulative water consumption curve showed a bimodal pattern throughout the growth period. The relationship between cumulative stage water consumption and time followed a cubic equation (Figure 2 [Figure 2: see original paper]), with $R^2 > 0.99$ for all treatment-stage combinations. Due to the absence of plastic film cover in T2, T3, and T4, surface evaporation was greater in early stages, resulting in lower cumulative water consumption for T1. After April, when winter wheat entered the jointing stage (195 days after sowing) with maximum water demand, differences in cumulative water consumption emerged: T3/T4 increased most rapidly, followed by T1, then T2. After May, during flowering-grain filling (217-236 days after sowing), winter wheat water demand remained high. Except for T4, stage cumulative water consumption decreased for T1, T2, and T3, though T1 maintained higher cumulative consumption than T2 and T3. This indicates that plastic film mulching reduced early-stage soil evaporation, conserving soil water for the jointing-grain filling period and alleviating water stress during this critical growth stage.

2.4 Dynamics of Soil-Crop Coefficient (Kc) Under Plastic Film Mulching and Different Irrigation Treatments

The Kc values for all four treatments showed consistent trends with days after sowing, gradually increasing from early March, peaking in mid-to-late April (after jointing water on April 11), with maximum Kc values of 1.55 (May 2, 215 days after sowing), 1.61 (April 18, 201 days after sowing), and 1.96 (May 2, 215 days after sowing) for T1, T2, and T3, respectively. After April 25 (208 days after sowing), winter wheat entered the booting-heading stage, and Kc gradually decreased for the first three treatments. However, flowering water in T4 (May 4, 217 days after sowing) caused Kc to rise again to 1.55 before gradually decreasing.

Figure 3 [Figure 3: see original paper] shows that before jointing (194 days after sowing), T1 had the lowest Kc. After jointing (195 days after sowing), T2 had the lowest Kc. During booting-flowering (208-216 days after sowing), Kc differences between T1 and T3 were not significant. Based on Kc variation characteristics, the growth period was divided into three quantified stages: sowing-pre-winter (October 1-November 30, i.e., 1-61 days after sowing), when high bare soil evaporation resulted in high initial Kc that decreased as surface soil moisture was lost; after seedling emergence, increasing tillering raised transpiration and Kc, which then decreased with falling temperatures and reduced water consumption; winter-regreening (December 1-March 10, i.e., 62-162 days after sowing), when Kc was lowest during winter dormancy; and regreening-maturity (March 11-May 31, i.e., 163-244 days after sowing), when rising temperatures and advancing growth stages increased water consumption and Kc, peaking at jointing-booting (195-204 days after sowing). The quantitative equations revealed that Kc variation during sowing-pre-winter followed a cubic function, while during winter-regreening and regreening-maturity, Kc followed quadratic functions. From these equations, the theoretical maximum Kc values were 1.98 for T1 at 210 days after sowing (April 28), 1.23 for T2 at 202 days after sowing (April 20), 0.45 for T3 at 194 days after sowing (April 12), and 2.71 for T4 at 214 days after sowing (May 2). The actual maximum Kc values were 1.55 for T1 at 204 days after sowing (May 2), 1.61 for T2 at 200 days after sowing (April 18), 1.67 for T3 at 199 days after sowing (April 17), and 1.96 for T4 at 214 days after sowing (May 2).

2.5 Effects of Plastic Film Mulching and Different Irrigation Treatments on Flag Leaf Water Potential

Figure 4 [Figure 4: see original paper] shows that flowering water (T4) effectively alleviated the rate of flag leaf water potential decline. On May 2, flag leaf water potentials were -2.79 MPa, -3.78 MPa, -3.57 MPa, and -2.30 MPa for T1, T2, T3, and T4, respectively, with T1 significantly higher than T2 and T3 but lower than T4 (not significantly). Flag leaf water potential determines the smooth progress of photosynthesis ($P < 0.05$). One week after flowering water irrigation (May 12), leaf water potentials were -1.66 MPa, -1.95 MPa, -1.79 MPa, and -1.47 MPa for T1, T2, T3, and T4, respectively. At late grain filling (May 22), leaf water potentials were -2.79 MPa, -3.78 MPa, -3.57 MPa, and -2.30 MPa for T1, T2, T3, and T4, respectively, with T1 significantly higher than T2 and T3 but lower than T4 (not significantly).

2.6 Variation of Soil Temperature at 5 cm Depth Under Plastic Film Mulching and Different Irrigation Treatments

From jointing-booting (April 12-24), booting-flowering (April 25-May 3), and flowering-grain filling (May 4-28), the average soil temperature at 5 cm depth under T1 was 0.5 °C higher than T2, though not significantly different. On April 21, soil temperatures for the four treatments were 15.7 °C, 15.2 °C, and 13.5 °C (T1, T2, T3/T4). Compared with T2, jointing water irrigation (April 14) reduced soil temperature at 5 cm depth in T3, but not significantly. Flowering water (May 4) reduced soil temperature in T4. On May 12, soil temperatures were 15.8 °C, 15.6 °C, 15.7 °C, and 14.7 °C for the four treatments, with no significant differences among treatments ($P > 0.05$) (Figure 5 [Figure 5: see original paper]).

2.7 Changes in Leaf Area Index of Upper Four Leaves Under Plastic Film Mulching and Different Irrigation Treatments

Figure 6 [Figure 6: see original paper] shows that plastic film mulching increased the total area of the upper four leaves and slowed the decline in leaf area index. T2 significantly reduced the leaf area index of the upper four leaves. T3 maintained a relatively high leaf area index during jointing-flowering, but it declined significantly after flowering. Flowering water (T4) increased the leaf area index of the upper four leaves, though not significantly different from T3. Overall, all treatments showed consistent trends in leaf area index changes, with plastic film mulching, jointing water, and flowering water delaying leaf senescence, but plastic film mulching showed the best effect ($P < 0.05$).

2.8 Effects of Plastic Film Mulching on Soil Moisture Content at 100 cm Depth

After winter wheat entered the jointing stage, T2 treatment showed rapid water consumption in the 80–100 cm soil layer, while the 20–40 cm soil water content remained almost unchanged (Figure 7a [Figure 7: see original paper]). In contrast, the plastic film mulching treatment (T1) showed rapid water consumption in the 50–100 cm soil layer (Figure 7b [Figure 7: see original paper]). This occurred because plastic film mulching (T1) relatively increased soil water content in the 60–90 cm layer while decreasing it in the 40–50 cm layer compared to the spring non-irrigated treatment (T2). The plastic film treatment increased water consumption from the 0–10 cm soil layer and improved water use efficiency.

2.9 Effects of Plastic Film Mulching and Different Irrigation Treatments on Wheat Yield and Water Use Efficiency (WUE)

Table 3 shows that T4 produced the highest mature biomass at 2.35 kg · m ^{2}. Compared with T2 and T3, T1 reduced biomass, but not significantly; T2 and T3 biomass did not differ significantly. From yield and yield component perspectives, compared with T2 and T3, T1 increased grain number per spike and 1000-grain weight but reduced spike number, though not significantly. Compared with T2, T1 increased yield. Regarding water use, T1 reduced water consumption by 56.8 mm compared with T2 and by 115.5 mm compared with T3. T1 achieved the highest water use efficiency at 2.01 kg · m ^{3} compared with T2, T3, and T4. The yield reduction in T1 compared with T3 was not significant, likely because T1 effectively reduced soil evaporation during early growth. Overall, T1 could replace the function of jointing water in T3.

3 Discussion and Conclusion

Based on evapotranspiration rate variation characteristics during winter wheat growth, the temporal variation of evapotranspiration rate was divided into three stages: sowing-pre-winter (October 1-November 30), winter-regreening (December 1-March 10), and regreening-maturity (March 11-May 31). Quantitative analysis revealed that theoretical and actual evapotranspiration peak times were essentially consistent. The quantified relationship between cumulative stage evapotranspiration and time was a cubic equation with $R^2 > 0.99$, showing high goodness of fit. The relationship between stage crop coefficient and time was quadratic, differing from the cubic relationship reported by Liang Wenqing [23] and the sixth-order relationship reported by Sun Jingsheng et al. [24], possibly due to differences in selected time points and crop varieties. This study divided the quantified equations into three stages based on winter wheat evapotranspiration variation characteristics, and the theoretical maxima derived from the equations were consistent with actual maxima ($R^2 > 0.8$), showing good fit.

Plastic film mulching reduced winter wheat evapotranspiration rates. During sowing-pre-winter (September 30–November 20), T1 peak evapotranspiration was lower than T2 (T3/T4) because T2 had bare soil with greater soil evaporation [25-30], while T1 converted ineffective evaporation into effective transpiration [31]. Due to the warming and moisture-conserving effects of plastic film [19], early-stage soil evaporation was suppressed, delaying the evapotranspiration peak and conserving more water for later growth stages while increasing water use from the 50–100 cm soil layer. Compared with T2, T3, and T4, the delayed evapotranspiration peak in T1 may have been due to increased surface soil moisture under film, which was less favorable for wheat growth and delayed growth stages. After winter wheat entered the booting-heading stage, Kc values for T1, T2, and T3 gradually decreased. The timing of maximum Kc generally coincided with evapotranspiration peaks, consistent with previous research [32].

Compared with T3, T1 reduced spike number and grain number per spike but increased 1000-grain weight. This occurred because high surface soil moisture under plastic film was unfavorable for spikelet formation [14], reducing post-anthesis biomass accumulation while allocating more water to grain filling. Compared with T2, T1 increased average soil temperature by 0.5 °C, lower than conventional plastic film warming [33]. The whole-film soil-covering approach reduced solar radiation warming of surface soil, which was more effective for reducing inter-plant evaporation. Compared with T2, T1 yield increase was not significant, but total water consumption was reduced by 56.79 mm, while water consumption during booting-flowering and flowering-maturity increased due to greater water use from the 50–100 cm soil layer in late growth stages. After late April, T1 significantly increased the leaf area index of the upper four leaves compared with T2, possibly due to increased root absorption area and root activity [34]. Leaf water potential reflects plant water demand, and T1 significantly increased leaf water potential compared with T3 by utilizing deep soil water. Increased leaf water potential facilitates photosynthesis [35] and grain filling, which may be one reason for increased 1000-grain weight. The biomass reduction in T1 compared with T2/T3 may have been due to experimental error (rain shelter malfunction).

Overall, under conditions of sufficient pre-sowing soil moisture, T1 could not only replace winter irrigation but also jointing irrigation, increasing water consumption from the 50-100 cm soil layer during late growth stages and improving water use efficiency.

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Note: Figure translations are in progress. See original paper for figures.