

Article

Effects of Different Mulching Materials on the Grain Yield and Water Use Efficiency of Maize in the North China Plain

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Abstract: Mulches combined with drip irrigation techniques have been widely applied in China for higher yield and water use efficiency (WUE). To develop an efficient strategy that can improve maize yield and save water in the North China Plain (NCP), we conducted a two-year field experiment, using transparent plastic film mulching (T), black plastic film mulching (B), and straw mulching (S) and non-mulching (N) for spring maize in 2019 and summer maize in 2020, and high drip irrigation amount (H) and low drip irrigation amount (L) were also considered in 2019. We mainly studied the effects of mulches on soil water content, soil temperature, crop growth rate, grain yield, and water use efficiency (WUE). The results indicated that T and B treatment increased soil water content (SWC) and topsoil temperature. The T treatment promoted the growth rate significantly more than N treatment, by 27.7–43.4% at the early stage in two years. The grain yield under TH treatment was significantly ($p < 0.05$) higher than that of other treatments, by 9.8–17.4% for spring maize in 2019, and significantly ($p < 0.05$) higher under both TH and BH than under NH, by 8.9% and 4.7% for summer maize in 2020. There was a significant quadratic parabola relationship between ET and grain yield in 2019, and the correlation between SEAT of 0–10 cm soil depth with grain yield or with biomass was positive. These results indicate that the transparent plastic film with high drip irrigation amount treatment (TH) can be recommended for spring maize, and both transparent and black film mulch treatments (TH and BH) can be recommended for summer maize in the NCP.

Keywords: plastic film mulching; straw mulching; soil water content; soil temperature; spring maize; summer maize; grain yield; water-use efficiency



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1. Introduction

The North China Plain (NCP) is one of the most important agricultural regions in China. This region is of vital significance to China's food development and produced 22.7% of the nation's maize (*Zea mays* L.) in 2020 [1]. Water is a key factor in achieving higher food production and sustainable agricultural development. In the NCP, agricultural irrigation water consumption accounts for 70–80% of the total water consumption [2]. However, the shortage of water has become a limiting factor for increasing crop production, and low resource utilization efficiency, especially water use efficiency (WUE), is the main restriction of agriculture development in the NCP. Therefore, it is necessary to explore a suitable strategy that can improve maize yield and save water [3].

Different mulching types, such as transparent plastic film, black plastic film, and straw, have been widely applied to different grain or fruit crops, such as spring maize, summer maize, and sunflower [4–6]. Of these, plastic mulch is used on 20% of the cultivated land area in China [7]. Mulching is an important management practice that can play a significant

role in increasing maize grain yield and WUE [8,9]. However, different types of mulch or different colors of plastic mulch have different optical properties such as reflectivity, absorptivity, and transmittance, and their interaction with solar radiation directly affects the microclimate around the plant [10]. In the case of transparent plastic film, the light radiation can reach the soil directly, whereas black plastic film has lower light permeability and radiant heat transmittance [11], and straw mulching can protect the soil surface from the direct strike of raindrops and promote biological activity [12].

The effect of mulching varies with crop or season, resulting in different impacts on soil environment, growth, and yield. Studies showed that transparent plastic film can conserve soil moisture, improve soil temperature, accelerate crop growth, raise crop yield and water use efficiency (WUE) [13,14], and also meet the crop accumulated temperature demand with early sowing for spring maize in the NCP [15]. Soil temperatures of transparent plastic film are particularly beneficial in locations having a cool growing season [16], and changes in light availability can accelerate the photosynthetic rate and improve yields [17]. Li et al. proved that transparent plastic film combined with deficit irrigation greatly affected soil hydrothermal status and improved the spring maize growth and yield in arid areas [18]. Black plastic film mulch has a good effect on inhibiting weed growth compared to other mulches [19], but typically provides less soil warming than transparent film mulch. The effects on improving yield were not found to be significant with transparent plastic film for spring maize [20], but another study showed that yield and WUE were better than those using transparent plastic film for summer maize [21]. However, the effects of straw mulching were inconsistent. Straw mulching can increase summer maize yield by increasing photosynthetic capacity [22]. However, research has shown that, although straw mulching maintains the soil water, it decreases the soil temperature and, therefore, may decrease the grain yield [23,24].

The soil environment under mulching conditions is more complicated than that without mulching. Even the same mulch treatment may produce different results due to the diversity of climatic conditions, soil types, crop species, and management strategies [25]. In the NCP, few studies have systematically evaluated the effect of different mulches on soil water content, crop growth, yield, and water use efficiency, especially under the combination of mulches with varying irrigation amounts.

In the present study, based on the measured data of spring and summer maize in 2019 and 2020, the effects of the combination of mulching and irrigation techniques on the grain yield and water use efficiency were explored. The mulch treatments were transparent plastic film mulching (T), black plastic film mulching (B), straw mulching (S), and non-mulching (N), and the irrigation amounts were a high irrigation amount (H) and a low irrigation amount (L). In this study, we aimed to provide effective agricultural technologies for spring and summer maize planting in the North China Plain. We hypothesized that combining mulching and drip irrigation techniques would improve grain yield and WUE in maize in the NCP.

2. Materials and Methods

2.1. Experimental Site

The study area is located at the Agricultural Water Conservation Irrigation Experiment Station in the Daxing District of Beijing, China (39°39' N, 116°15' E), which experiences a temperate, continental, semi-humid, monsoon climate. The annual mean temperature of the research site is 11.6 °C, and the annual mean precipitation is 556 mm, of which 80% is distributed between July and September. The site has a loamy soil texture, and the average field capacity and the soil bulk density are 30.6% and 1.58 g cm⁻³. An automatic weather station (Monitor Sensors, Caboolture, Australia) was installed in the experimental station, providing measurements of solar radiation, air temperature, relative humidity, wind speed, and precipitation.

2.2. Experimental Design

The experiments were conducted in 2019 and 2020. The mulching treatments, namely, transparent film mulching, black film mulching, straw mulching, and non-mulching (T, B, S, and N), were applied in 2019 for spring maize and in 2020 for summer maize. For the spring maize experiments, two irrigation treatments were set up, which referred to a high irrigation amount (H) and low irrigation amount (L), i.e., TH, TL, BH, BL, SH, SL, NH, and NL. For the summer experiment, because of abundant rainfall in 2020, only supplementary irrigation was applied to ensure the treatment was consistent with the high water treatment in 2019. A completely randomized block design with three replicates was employed, with the area of each plot being 10.8 m × 4 m and a 2 m isolation zone between plots.

Spring maize (cultivar: XunTian1102) was sowed manually on 13 May and harvested on 20 September 2019. Summer maize (cultivar: JiYuan168) was sowed manually on 25 June and harvested on 17 October 2020. The maize was cultivated using conventional flat planting and wide–narrow rows. The width of the narrow rows was 40 cm and that of the wide rows was 80 cm; plant to plant spacing was set at 20 cm, which resulted in a planting density of 8.33×10^4 plants hm^{-2} . Mulching and installation of drip tape were conducted simultaneously. The plastic mulch was a transparent and black polyethylene film 60 cm wide and 0.01 mm thick. The crushed maize straw for straw mulching from the last season was mulched after sowing, at an amount of about 6 t hm^{-2} . Drip tapes were laid on the soil surface under the mulch, with one tape serving two rows of plants. The tape diameter was 16 mm, with a rated flow of 3.8 L h^{-1} , and the emitters were spaced at 0.3 m intervals on the drip tape.

Total fertilizer comprising 240 kg hm^{-2} N, 135 kg hm^{-2} P_2O_5 , and 135 kg hm^{-2} K_2O was applied during the growth period; 20% of N, 50% of P_2O_5 , and 30% of K_2O were applied as base fertilizer, and the remainder were applied as topdressing with water at the jointing stage, flare opening stage, tasseling stage, and filling stage by a venturi fertilizer applicator. Weed management in different treatments was consistent with traditional local management.

The irrigation amount (Q_i) was calculated by the upper and lower limits of soil water content in different treatments, which was determined by Equation (1):

$$Q_i = A \times H \times (\theta_{\text{up}} - \theta_{\text{low}}) \times P / \eta \quad (1)$$

where θ_{up} and θ_{low} are the upper and lower soil water content thresholds ($\text{cm}^3 \text{cm}^{-3}$), which were taken to be 95–75% and 75–50% of the field capacity for high and low irrigation amount, respectively; A is the plot area (m^2); H is the depth of the soil wetting layer (cm); P is the percentage of wetted soil; and η is the application efficiency of irrigation.

2.3. Measurements

2.3.1. Precipitation and Air Temperature

Meteorological data including air temperature and precipitation were obtained from a weather station installed at the research site. Data were collected at 30 min intervals by EM50 datalogger (Decagon Devices, Pullman, WA, USA).

2.3.2. Soil Water Content and Soil Temperature

For all treatments, soil water probes (EC-5) were installed at depths of 5, 15, 30, 50, and 70 cm, and 5TM soil temperature probes (Decagon Devices, Pullman, WA, USA) were installed at depths of 5 and 15 cm. Data of soil moisture and soil temperature were collected with a data logger once every 30 min. The soil water content was also obtained by oven drying to calibrate the EC5 sensor. The field soil samples were selected in each plot randomly at the soil depths of 0–10 cm, 10–20 cm, 20–40 cm, 40–60 cm, and 60–80 cm; soil moisture content measurement was conducted at least five times to cover different soil water content values.

Soil effective accumulated temperature (SEAT) is defined as the sum of effective mean soil temperature ≥ 10 °C at different soil depths (0–10 cm, 10–20 cm, or 0–30 cm) in a certain growth period or whole growth periods. SEAT was calculated using mean soil temperature (T_{mean}) within the 30 cm soil layer for 2019 and 2020, referring to the method of Wang et al. [26]. The basal temperature (T_{basal}) was 10 °C.

$$\text{SEAT} = \Sigma [T_{\text{mean}} - T_{\text{basal}}] \quad (2)$$

2.3.3. Biomass, Grain Yield, and Yield Composition

For the determination of biomass, three plants in each plot were sampled randomly four times in 2019 and twice in 2020 throughout the growing seasons. The four stages were the V9, VT, R3, and R5 stages, where the V9 (ninth leaf) stage means that the ninth leaf is fully expanded during vegetative stages, which occur at four weeks after the plant emerges. The VT (tasseling) stage occurs two to three days before silking. The plant has reached full height and the pollen shed begins. The R3 (milk) stage occurs is about 20 days after silking. Kernels begin to yellow on the outside but contain a milky white inner fluid. The R5 (dent) occurs stage is about 36 days after silking, when nearly all kernels are dented or denting. The above-ground samples were dried to a constant weight at 75 °C in an oven. The weight was divided by the area to extrapolate to biomass yield. At the harvest, the grain yield of maize was determined from samples of 3 m \times 1.2 m in each plot. The cob length, cob number, and 100-seed weight were also determined, which were then extrapolated to the grain yield of the plot (Y ; t hm^{-2}).

2.3.4. Evapotranspiration (ET) and Water Use Efficiency (WUE)

Evapotranspiration (ET) of maize was calculated using the water balance method, as shown in Equation (2):

$$\text{ET} = P + I - R - \Delta S - D \quad (3)$$

where ET is the evapotranspiration during the maize growth period (mm); P is the effective precipitation (mm); I is the irrigation amount (mm); R is the surface runoff (mm) (which was ignored given the flat terrain of the study area and absence of surface accumulation from the drip irrigation); ΔS is the change in mean soil water content at the 0–100 cm depth from before sowing to after harvest (mm); and D is the downward flux (mm) (deep percolation was ignored as we found negligible drainage at the site).

The water use efficiency (WUE) was calculated using Equation (3):

$$\text{WUE} = Y/\text{ET} \quad (4)$$

where Y is grain yield (t hm^{-2}), and ET is total evapotranspiration (mm).

3. Results

3.1. Meteorological Conditions and Irrigations

In 2019, precipitation during the spring maize growing season totaled 267.6 mm, and occurred 35 times, mainly during in May, July, and August, which accounted for 27.5%, 34.8%, and 34.0% of the entire growing season, respectively. Precipitation amounts above 10 mm occurred nine times, accounting for 78.9% of the total precipitation during the growing seasons. The mean daily air temperature ranged from 18.8 to 31.0 °C and averaged 25.2 °C during the maize growth period. Irrigation using the H treatment was conducted four times, and the total amount of irrigation under NH, TH, BH, and SH treatment was 155, 167, 173, and 159 mm, respectively. Irrigation under the L treatment was conducted three times, and the total amount of irrigation under NL, TL, BL, and SL treatment was 100, 80, 93, and 117 mm, respectively (Figure 1).

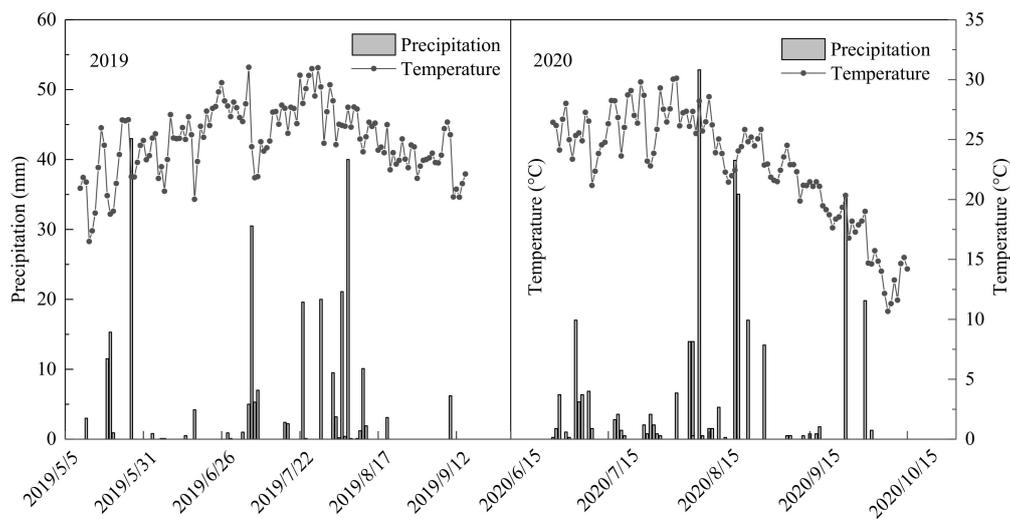


Figure 1. Precipitation and mean temperature during the 2019 and 2020 maize growing seasons.

In 2020, the precipitation during the summer maize growing season totaled 326.6 mm and occurred 43 times, mainly from June to August, which accounted for 91.1% of the total precipitation. Precipitation amounts above 10 mm occurred 10 times, accounting for 78.9% of total precipitation during the growing season. The mean daily air temperature ranged from 10.7 to 30.1 °C and averaged 22.5 °C during the maize growth period. Regarding summer maize in 2020, the irrigation was only conducted once, and the total amount of irrigation was 60 mm for the H treatment (Figure 1).

3.2. Soil Water Content (SWC)

The variations in averaged SWC at different depths (0–10 cm, 10–20 cm, 20–40 cm, 40–60 cm, 60–80 cm) under different mulches were compared 3 days before the irrigation and 3 days after the irrigation in 2019 and 2020 (Figure 2). In 2019, before the irrigation, the averaged SWC of 0–80 cm soil layer of NL, TL, BL, and SL was 0.186, 0.200, 0.182, and 0.178 cm³/cm³, respectively, and SWC of NH, TH, BH, and SH was 0.197, 0.212, 0.210, and 0.201 cm³/cm³, respectively. Among different depths, the SWC at depths of 0–10 cm or 60–80 cm was the lowest. At the depth of 10–40 cm, under the L treatment, results of the T treatment was superior: the SWC of TL was 5.7%, 16.9%, and 30.8% higher than that of NL, BL, and SL, respectively. Under H treatment, result of both T and B treatments were superior: TH and BH were 19.7% and 16.7% higher and 16.7% and 13.7% higher than NH and SH, respectively. It can be seen that, in the period of water shortage, the T treatment had better water-retention effects. After the irrigation, the SWC of 0–10 cm and 20–40 cm soil depths under the T treatment remained higher, whereas it was lower than that of B, S, and N treatments at a depth of 10–20 cm. The average SWC of NL, TL, BL, and SL was 0.250, 0.274, 0.250, and 0.240 cm³/cm³, respectively, whereas that of NH, TH, BH and SH was 0.258, 0.281, 0.280, and 0.274 cm³/cm³, respectively (Figure 2).

In 2020, before the irrigation, the SWC of the 0–10 cm soil depth was the lowest, and TH, BH, and SH were 29.5%, 19.6%, and 22.3% higher than NH, respectively. At the depth of 20–80 cm, SWC moisture content of T and B treatment was higher than that of S and N treatment. After the irrigation, the average SWC at the 0–20 cm depth of NH, TH, BH, and SH treatment was increased by 37.0%, 17.5%, 23.4%, and 22.2%, respectively, when compared with that before irrigation. The SWC at the 20–80 cm depth of T and B was higher than that of the S and N treatment. Under the condition of the H treatment, both transparent film and black film had better water retention. The averaged SWC of NH, TH, BH, and SH was 0.267, 0.284, 0.275, and 0.272 cm³/cm³ (Figure 2).

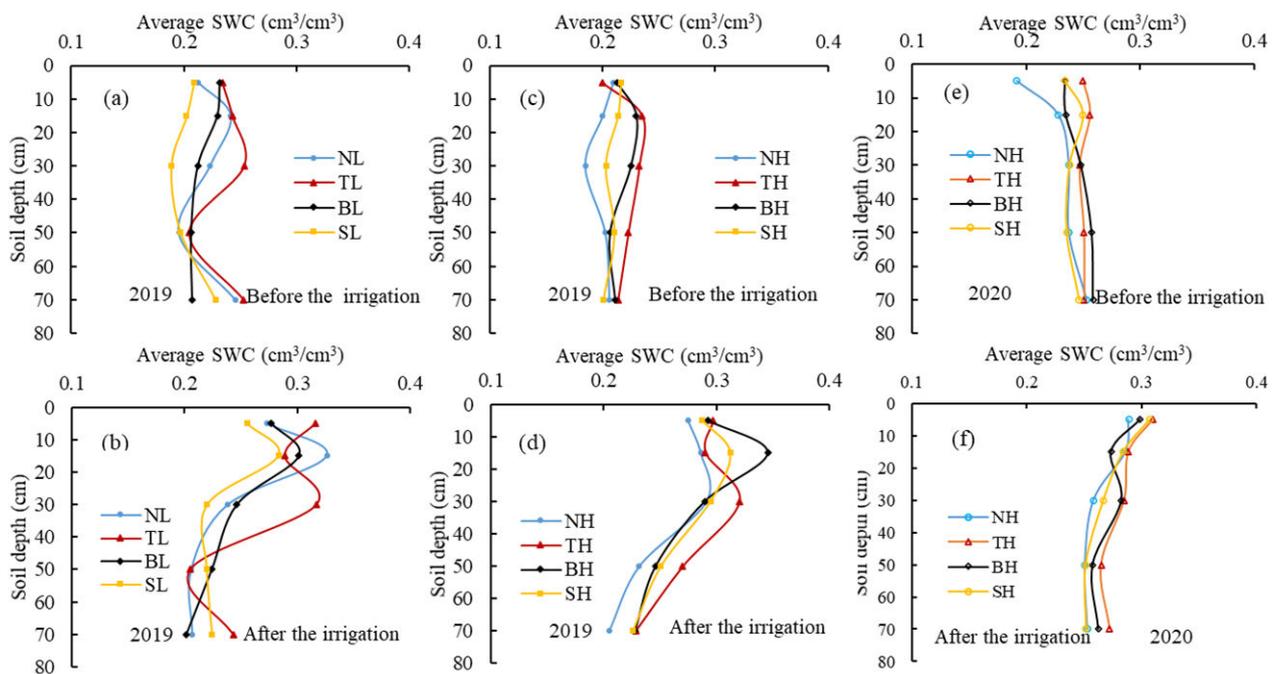


Figure 2. Average soil water content (SWC) during the 2019 and 2020 maize growing seasons. N, T, B, and S represent non-mulching, transparent plastic mulching, black plastic mulching, and straw mulching, respectively. H and L represent high irrigation and low irrigation during growing seasons. (a) SWC of NL, TL, BL, and SL treatment before the irrigation in 2019; (b) SWC of NL, TL, BL, and SL treatment after the irrigation in 2019; (c) SWC of NH, TH, BH, and SH treatment before the irrigation in 2019; (d) SWC of NH, TH, BH, and SH treatment after the irrigation in 2019; (e) SWC of NH, TH, BH, and SH treatment before the irrigation in 2020; (f) SWC of NH, TH, BH, and SH treatment after the irrigation in 2020.

3.3. Soil Temperature

In the 2019 spring maize growing season from sowing to about 60 days after sowing (DAS), compared with NL treatment, the TL and BL treatment increased temperatures by 12.0% and 7.9% at the 10 cm soil depth, and increased temperatures by 5.0% and 2.6% at the 20 cm soil depth, respectively (Figure 3). When compared with the NH treatment, the TH and BH treatments increased soil temperatures by 11.8% and 4.3% at the 10 cm depth and increased temperatures by 8.2% and 1.1% at the 20 cm depth, respectively (Figure 3). However, there was little difference between the SH treatment and NH treatment for mean soil temperatures. During the days of 60–120, the average 10 cm soil temperature of the TL, BL, and SL treatments was 3.8%, 6.3%, and 3.6% higher than that of the NL treatment, and that of the TH, BH, and SH treatments was 5.8%, 3.7%, and 3.8% higher than that of NH treatment. In 2020, compared with the mean temperature of the NH treatment at the 10 cm depth, TH and BH treatments increased the average soil temperatures by 3.4% and 2.5% during 0–60 DAS, and by 5.1% and 3.9% during 60–110 DAS, respectively. Mulching had little effect on soil temperature at a 20 cm depth. Among the mulching treatments, the soil temperatures at 10 and 20 cm depths under the T treatment were higher than those in B, S, and N treatments before 60 DAS. For the 10 cm soil depth, the greater the irrigation, the smaller the difference in soil temperature between mulched treatments. In addition, the soil temperature reached the highest level between 20 and 40 DAS of different treatments.

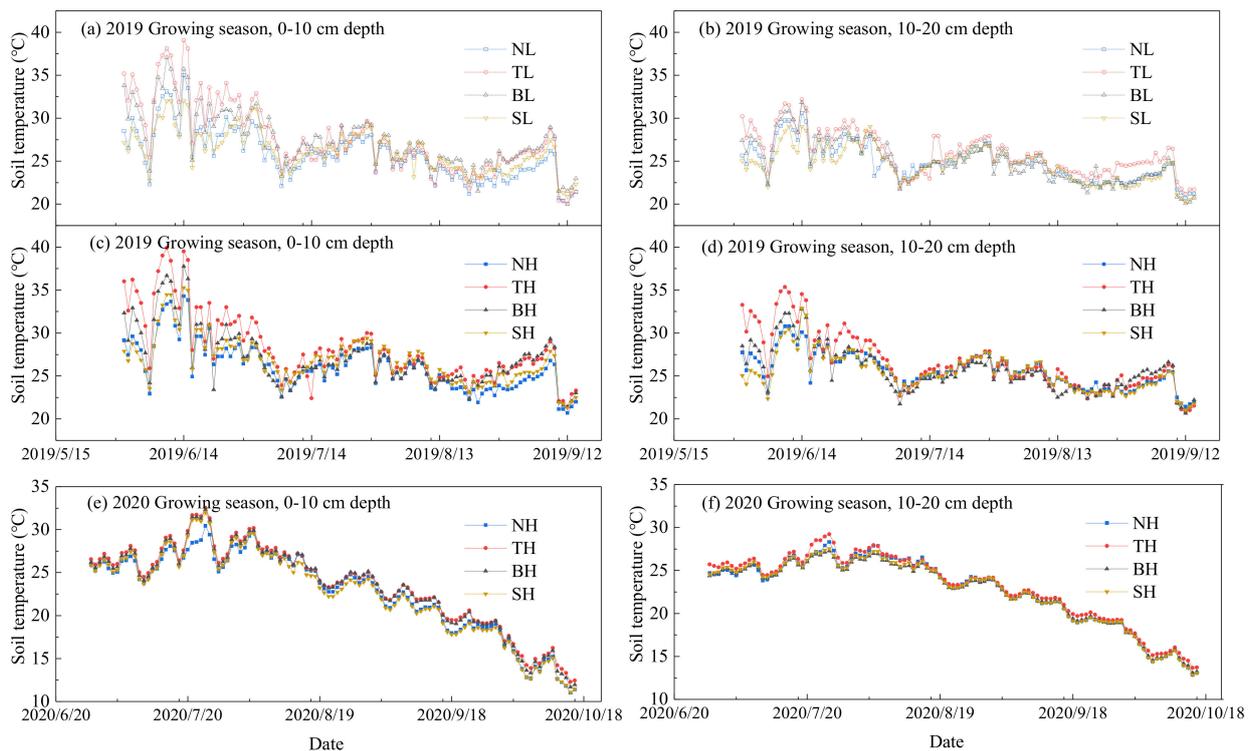


Figure 3. Dynamic change in daily soil temperatures at 10 and 20 cm depths among various treatments at the experimental site in north China. N, T, B, and S represent non-mulching, transparent plastic mulching, black plastic mulching, and straw mulching, respectively. H and L represent high irrigated and low irrigated during growing seasons, respectively. (a) Soil temperature of 0–10 cm soil depth under NL, TL, BL, and SL treatment during 2019 maize growing season; (b) soil temperature of 10–20 cm soil depth under NL, TL, BL, and SL treatment during 2019 maize growing season; (c) soil temperature of 0–10 cm soil depth under NH, TH, BH, and SH treatment during 2019 maize growing season; (d) soil temperature of 10–20 cm soil depth under NH, TH, BH, and SH treatment during 2019 maize growing season; (e) soil temperature of 0–10 cm soil depth under NH, TH, BH, and SH treatment during 2020 maize growing season; (f) soil temperature of 10–20 cm soil depth under NH, TH, BH, and SH treatment during 2020 maize growing season.

The plastic film mulching increased SEAT compared to the N treatment. In 2019, SEAT at a 10 cm soil depth under TL, BL, and SL treatments was higher than that under the NL treatment by 12.5%, 11.5%, and 2.8%, respectively; SEAT at a 0–10 cm soil depth under TH, BH, and SH treatments was higher than that under NH treatment by 13.9%, 6.5%, and 4.7%, respectively. Regarding SEAT at a 10–20 cm soil depth, that of TL was higher than that of NL by 7.4%, and that of TH was higher than that of NH by 6.3%; there was no obvious difference between BH, NH, and SH treatments or between BL, NL, and SL treatments (Table 1). The average SEAT at a 0–30 cm soil depth under the T treatment was higher than that under the N treatment by about 10%, and that under the B treatment was higher than that under the N treatment by 3.4–6.2%.

Regarding 2020, SEAT at a 10 cm soil depth under TH and BH treatments was higher than that under NH treatment by 7.2% and 5.4%, and SEAT under SH was equal to that of the NH treatment. The mean SEAT at 0–30 cm for summer maize under TH and BH treatments was higher than that under the NH treatment by 5.2% and 2.0%, but under SH it was lower than that under NH by 1.7%.

Table 1. Soil effective accumulated temperature (SEAT) of different soil depths (0–10 cm, 10–20 cm, 0–30 cm) under different irrigation and mulching patterns for the maize growing seasons in 2019 and 2020. NH represents non-mulching with high irrigation treatment; TH represents transparent plastic mulching with high irrigation treatment; BH represents black plastic mulching with high irrigation treatment; SH represents straw mulching with high irrigation treatment; NL represents non-mulching with low irrigation treatment; TL represents transparent plastic mulching with low irrigation treatment; BL represents black plastic mulching with low irrigation treatment; SL represents straw mulching with low irrigation treatment.

Year	Soil Depth (cm)	NH	TH	BH	SH	
2019	0–10	1718.7	1957.8	1829.7	1799.8	
	10–20	1666.8	1772.3	1669.5	1652.8	
	0–30	1692.7	1865.0	1749.6	1726.3	
		NL	TL	BL	SL	
	0–10	1685.7	1895.9	1878.9	1733.1	
	10–20	1588.2	1705.8	1597.6	1563.8	
	0–30	1637.0	1800.9	1738.2	1648.4	
	2020		NH	TH	BH	SH
		0–10	1407.1	1508.0	1483.0	1406.6
10–20		1404.9	1451.2	1385.0	1357.1	
0–30		1431.0	1479.6	1434.0	1381.8	

3.4. Biomass Accumulation and Growth Rate

The mulching treatments yielded higher biomass accumulation values compared with non-mulching treatments in different growth stages (Figure 4). For spring maize in 2019, during the V9 stage, average increases in biomass yield were 39.8% ($p < 0.05$), 30.8%, and 25.6% under TL, BL, and SL compared to NL treatment, respectively, and average increases were 19.0%, 5.7% and 8.2% under TH, BH, and SH compared to NH, respectively. During the VT stage, there was no significance between different treatments ($p > 0.05$). During the R3 stage, the biomass of TL, TH, BH, SH, and NH treatments was all significantly ($p < 0.05$) higher than that of the NL treatment, by 15.6%, 18.0%, 20.0%, 30.5%, and 18.6%, respectively. Regarding the dent stage (R5 stage), only the TH treatment was significantly higher than the NL treatment, by 30.9% ($p < 0.05$). For summer maize in 2020, the biomass yield of VT stage under TH, BH, and SH treatments was 18.6% ($p < 0.05$), 17.3% ($p < 0.05$), and 4.5% ($p > 0.05$) higher than that of NH treatment, respectively. There was no significance between different treatments during the dent stage in 2020.

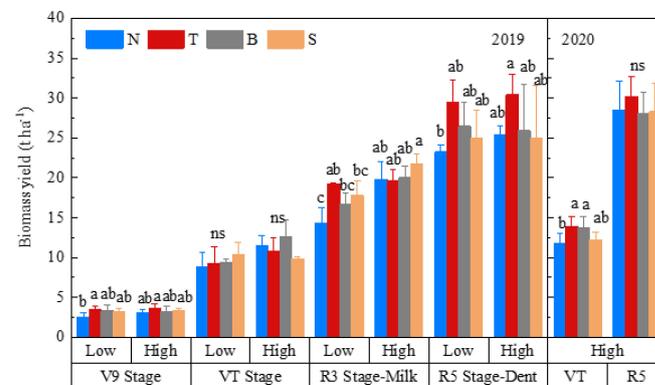


Figure 4. Biomass yield with different treatments during the maize growing season in 2019 and 2020. N, T, B, and S represent non-mulching, transparent plastic mulching, black plastic mulching, and straw mulching, respectively, H and L represent high irrigation amounts and low irrigation amounts during growing seasons, respectively. Means within the same growth stage followed by different letters are significantly different at $p < 0.05$, and ns denotes non-significance.

The growth rates were examined of different growth stages, i.e., the above-ground dry matter accumulation per unit time (Figure 5). In 2019, there was a significant difference in growth rate between the early (V9) and late (R5) stage, but no significant difference between the middle (VT and R3) stages. In the V9 stage, TL and TH treatments were significantly superior to NL treatments, by 39.8% and 43.4%, respectively. In the R5 stage, TL, BL, and TH treatment results were significantly higher than those of SH, and were 2.3, 2.7, and 2.7 times higher than those of SH respectively. In 2020, the TH results at the VT stage were significantly higher than those of NH, by 27.7%. It can be seen that white film mulch can improve crop growth rate.

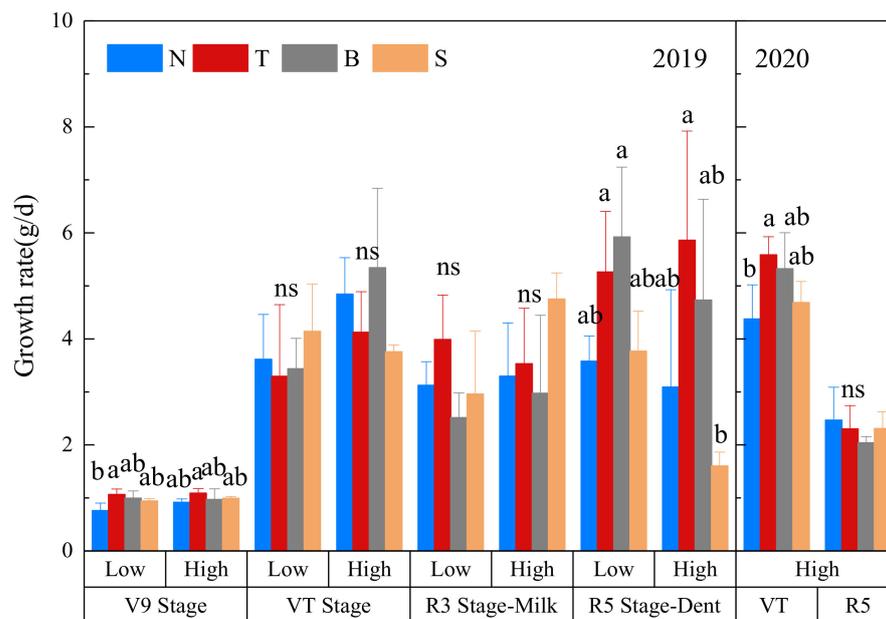


Figure 5. Growth rate with different treatments during the maize growing season in 2019 and 2020. N, T, B, and S represent non-mulching, transparent plastic mulching, black plastic mulching, and straw mulching, respectively, High and Low represent high irrigation amounts and low irrigation amounts during growing seasons, respectively. Means within the same growth stage followed by different letters are significantly different at $p < 0.05$, and ns denotes non-significance.

3.5. Grain Yield, Evapotranspiration (ET), and Water Use Efficiency (WUE)

For spring maize in 2019, Table 2 shows that cob length, cob number, and 100-kernel weight were significantly influenced by the coupling of transparent plastic mulching and a high amount of irrigation. The cob length of black plastic mulching was 4.3–6.1% lower than that of other mulching treatments, and the spike number under transparent and black plastic mulching was higher than that of non or straw mulching by 9.5–16.9%. Transparent plastic mulching and high irrigation amount increased grain yields; the yield of the TH treatment was significantly ($p < 0.05$) higher than that of BH and NH treatments, by 11.4% and 13.4%, respectively. ET was closely related to the irrigation in 2019, which ranged from 360.5 to 369.3 mm for L treatment and from 425.3 to 439.2 mm for H treatment. The average ET of the H treatment was 19.1% higher than that of the L treatment. Regarding summer maize in 2020, the 100-kernel weight under TH and BH treatments was significantly higher than that of the SH treatment, by 5.9% and 4.9%. The grain yield under TH and BH treatments was 4.9% and 4.8% significantly ($p < 0.05$) higher than that under the NH treatment. The grain yield under the SH treatment was 3.3% lower than that under the NH treatment and significantly lower than that under the TH and BH treatments. ET ranged from 373.0 to 398.3 mm. The WUE under the TH treatment was significantly higher than that under the NH and SH treatments, by 12.5% ($p < 0.05$).

Table 2. Yield compositions, ET, grain yield, and WUE during the 2019 and 2020 maize growing seasons.

Treatments	Cob Length (cm)	Cob Number (Spikes/m ²)	100 Kernel Weight (g)	ET (mm)	Grain Yield (t hm ⁻²)	WUE (kg/m ³)
2019 coupling						
NL	17.5 ab	6.3 bcd	28.8 ab	368.8	11.2 b	3.1 a
TL	16.9 bc	6.7 abc	28.0 b	359.3	11.6 b	3.2 a
BL	16.2 c	7.0 ab	28.5 b	361.0	11.1 b	3.1 a
SL	16.5 c	6.2 cd	28.4 b	360.5	10.8 b	3.0 a
NH	16.9 bc	6.4 bc	28.6 b	438.9	11.2 b	2.6 b
TH	17.7 a	7.2 a	30.5 a	425.3	12.7 a	3.0 a
BH	16.5 c	6.9 ab	27.7 b	439.2	11.4 b	2.6 b
SH	17.6 ab	5.6 d	27.8 b	434.6	11.9 ab	2.7 b
2019 mulching						
N	17.2 a	6.3 b	28.7 a	403.9	11.2 b	2.8 b
T	17.3 a	6.9 a	29.2 a	392.3	12.1 a	3.1 a
B	16.3 b	6.9 a	28.1 a	400.1	11.3 b	2.8 b
S	17.0 a	5.9 b	28.1 a	397.6	11.3 b	2.8 b
2019 Irrigation						
H	17.2 a	6.5 a	28.6 a	434.5	11.8 a	2.7 b
L	16.8 a	6.5 a	28.4 a	362.4	11.2 b	3.1 a
2020 mulching						
NH	19.4 a	5.4 a	33.5 ab	398.3	12.9 ab	3.2 b
TH	19.4 a	5.6 a	34.3 a	378.7	13.5 a	3.6 a
BH	19.4 a	5.5 a	34.0 a	373	13.5 a	3.6 a
SH	19.3 a	5.5 a	32.4 b	388.7	12.4 b	3.2 b

Notes: N, T, B, and S represent non-mulching, transparent plastic mulching, black plastic mulching, and straw mulching, respectively. H and L represent high irrigated and low irrigated during growing seasons, respectively. Different lowercase letters within a column are statistically significantly different at $p < 0.05$.

3.6. Correlations of Yield with ET and SEAT

There was a significant quadratic parabolic relationship between ET and grain yield in 2019 ($p = 0.0095$, $R^2 = 0.845$); a significant positive correlation between SEAT at 0–10 cm soil depth and grain yield in 2019 ($p = 0.061$, $R^2 = 0.465$) and 2020 ($p = 0.093$, $R^2 = 0.823$); and a significant positive correlation between SEAT at a 0–10 cm soil depth and biomass in 2019 ($p = 0.000$, $R^2 = 0.959$) and 2020 ($p = 0.000$, $R^2 = 0.992$) (Figure 6). According to the quadratic parabolic relationship, there was a critical value of ET at which the crop yield reached its highest theoretical value; when ET was less than the critical value, crop yield increased with the increase in ET, and when ET was greater than the critical value, crop yield decreased with the increase in ET.

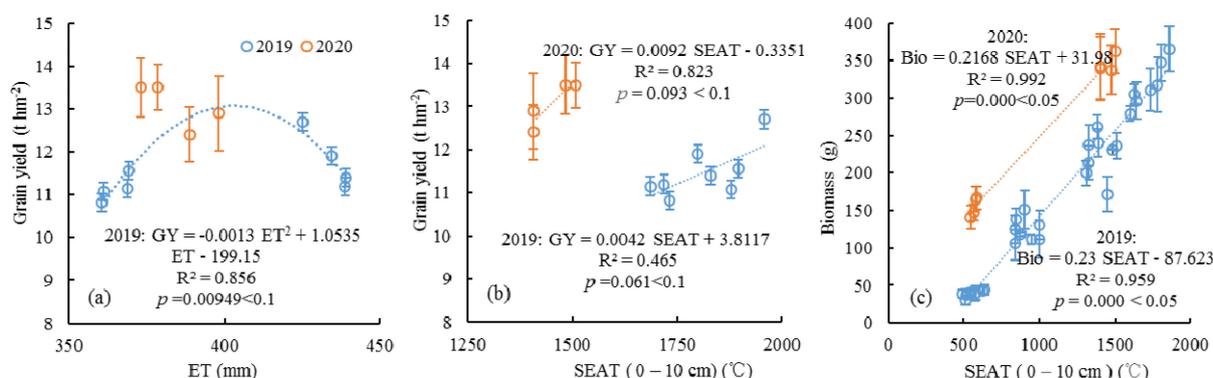


Figure 6. Relationship of ET and grain yield, SEAT of a 0–10 cm soil depth and grain yield, and SEAT of a 0–10 cm soil depth and biomass in 2019 and 2020: (a) relationship between ET and GY; (b) relationship between SEAT of 0–10 cm and GY; (c) relationship between SEAT of 0–10 cm and biomass.

4. Discussion

4.1. Soil Water Content

Mulching influences the soil water content by controlling the evaporation from the soil, which has been widely reported across the literature [20,27]. Plastic film mulch prevents the infiltration of light rain but also inhibits soil surface evaporation [28], which increases soil water content. In this study, the average SWC at a 0–80 cm soil depth under T and B treatments was higher than that under S and N treatments, whereas SWC under the S treatment had no significant effects on soil water retention (Figure 2). However, this result was different from that of Li et al., whose study showed that straw mulching could reduce runoff and increase the soil water content [29]. The soil water retained in the deeper soil layer (40–80 cm) can make a significant contribution to the crop's high water demand in late crop growth, especially when there is no incident rainfall available [30]. Thus, transparent plastic mulch can maintain higher soil moisture, and straw mulching is not appropriate for maintaining soil moisture for spring and summer maize in water-shortage areas in North China.

In addition, precipitation and irrigation also influence the soil water content [31]. The precipitation amount in the 2020 maize growth period was 60 mm more than that in 2019, and the number of precipitation events in 2020 was nine higher than in 2019; thus, supplementary irrigation was applied in 2020 to ensure adequate soil moisture. The high irrigation amount treatment particularly improved the deeper layer SWC.

4.2. Soil Temperature

Topsoil temperature in the plastic film mulched treatments was consistently higher than that in non-mulched and straw mulched treatments during the maize growth stage. Film mulching has long been recognized as an effective agricultural measure primarily to increase soil temperature, especially during early crop growth [32,33]. A similar result was shown in this study, where the soil temperature at a 10 cm depth under TH and BH treatment was 3.4–11.8% and 2.5–4.3% higher than that under the NH treatment during 0–60 DAS (Figure 3). However, the warming effect of plastic mulching gradually diminishes during the later growth stages [28]. This is most likely because the soil was able to receive more solar energy for the small plant canopy at early growth stages; when the maize leaves grew larger, more soil surface was covered and sunlight was blocked, thus reducing the soil temperature effect [34]. Straw mulching treatment decreased the soil temperature at 0–60 DAS in the current study, which was consistent with Lu et al. [35]. For this reason, straw mulching restrained the transfer of heat from solar radiation to the soil. However, this result was different from that of Akhtar et al. [36], who noted that straw mulching can increase daily mean soil temperature. The reasons for the difference may be related to the straw mulching amount, mulching rate of the soil surface, and straw thickness [37].

Soil-growing SEAT is strongly linked with crop growth. Wang et al. and Gu et al. demonstrated that SEAT was higher in plastic mulched treatment than in non-mulched treatment [34,38]. Similar results were obtained in our experiments: under the T and B treatments, the 0–30 cm SEAT was 5.2–10.0% and 2.0–6.2% higher than that of the non-mulching treatment during the two maize growing seasons (Table 1). Compared to the summer maize season, the growth period of spring maize was 10 days longer, and the difference in air temperature during the period was likely to be the reason for higher SEAT in spring maize.

4.3. Biomass, Yield, and WUE

Previous studies showed that plastic mulching treatments significantly increased biomass yield, grain yield and its components, and the WUE of maize [5,28]. Similarly, higher biomass, yield, and WUE were obtained under the TH treatment for spring maize in 2019, and under TH and BH treatments for summer maize in 2020, compared with the N treatment (Table 2). Plastic mulching also significantly improved the spike number and the 100-kernel weight, thus increasing the final grain yield. The reasons for this may be that film

mulching ensured enough soil water conservation and improved soil thermal conditions. In addition, transparent plastic can reflect more sunlight to the plant canopy to improve leaf net photosynthesis [39]. The growth rate of the T treatment in early-stage growth was higher than that under the N treatment for spring and summer maize (Figure 5). Qin et al. pointed out that black plastic film improved maize yield more than transparent plastic film in dry areas with adequate accumulated temperature [40]. In this study, the BH treatment did not improve grain yield significantly in 2019, but significantly improved grain yield in 2020 compared to that of the NH treatment. It is possible that the black plastic film may block part of the sunlight's energy, resulting in a lower topsoil SEAT at 0–10 cm compared to that under transparent plastic film.

These results may be also explained by the relationship of grain yield with ET and SEAT, or the relationship of biomass with SEAT (Figure 6). The significant positive correlation between SEAT and grain yield means that, the higher the SEAT, the higher the grain yield. The SEAT at a 10 cm soil depth under the TH treatment increased twice as much as that under the BH treatment in 2019, and the grain yield under the TH treatment was significantly higher than that under the BH treatment; however, the yield under TL and BL treatments showed no significant difference, and the main constraint may be soil moisture. By comparison, in 2020, there was no significant effect on the SEAT under TH and BH, so transparent and black film mulch both significantly improved the grain yield compared to that of the non-mulching treatment. In 2019, the relationship between ET and grain yield showed that the critical value was 403.2 mm, which means a higher grain yield of 13.1 t hm⁻² can be gained. However, there was no significant relationship between ET and grain yield in 2020, and further studies are needed to confirm our hypothesis. The significant positive correlation between SEAT and biomass of different growth periods showed that higher biomass accumulation needs higher SEAT at a 0–10 cm soil depth.

Moreover, we found that there was no significant difference in grain yield under S and N treatments, which was different from the results of previous research by Shen et al. [41]. Gao and Li indicated that straw mulching may reduce crop yield in an arid region [42]. The lower soil water content and cooling effect at the early stage caused a decrease in yield [43,44].

Furthermore, the effects of mulching on the yield and WUE differed in 2019 and 2020 for different photothermal and rainfall conditions, and irrigation amounts (Table 2). The precipitation had positive effects on the grain yield and WUE; the higher grain yield and WUE in 2020 may be attributed to the combined effects of precipitation conditions and plastic films, because the appropriate precipitation was focused primarily on the earlier and middle growth stages. For spring maize in 2019, the ET of the high irrigation treatment was 18.4–23.3% higher than that of the low irrigation treatment; this crop probably consumed more soil water via plant transpiration when the irrigation water was available, thus resulting in a higher grain yield [39]. Therefore, the combination of sufficient soil moisture with plastic mulch may act as an approach to improving maize yield and WUE in the North China Plain.

5. Conclusions

Transparent film mulching treatment resulted in a higher soil effective accumulated temperature (SEAT) than black film mulching for spring maize, thus significantly increasing the biomass and grain yield. Therefore, transparent plastic film mulch with a high drip irrigation amount (TH) proved to be an effective water-saving and yield-increasing agricultural technology for spring maize, and both transparent and black film mulches with sufficient drip irrigation amounts (TH and BH) can be recommended for summer maize in the NCP.

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