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Straw Strip Mulching Increases Winter Wheat Yield by Optimizing Water Consumption Characteristics in a Semi-Arid Environment

Caixia Huang [1], Yanlin Wu [1], Yuansheng Ye [1], Yazhen Li [1], Juhua Ma [1], Jiantao Ma [2], Jixuan Yan [1], Lei Chang [2], Zeyi Wang [1], Yucai Wang [1] and Hengjia Zhang [1,*]

[1] College of Water Resources and Hydropower Engineering, Gansu Agricultural University, Lanzhou 730070, China; xlish2008@163.com (C.H.); wjlz03256@sina.com (Y.W.); ymail10@126.com (Y.Y.); zhen_04@126.com (Y.L.); ftmeiz@126.com (J.M.); yanjx@gsau.edu.cn (J.Y.); peterwangzy@126.com (Z.W.); wangyucai@gsau.edu.cn (Y.W.)

[2] College of Agronomy, Gansu Agricultural University, Lanzhou 730070, China; mjt0323@163.com (J.M.); chang3258@126.com (L.C.)

* Correspondence: zhanghj@gsau.edu.cn; Tel.: +86-13619365883

Abstract: To investigate the feasibility of replacing plastic film with straw in semi-arid areas and establishing coordinated cultivation technology for high winter wheat yield and efficient resource utilization, a two-year field experiment was conducted under six treatments, specifically CK (no-mulching), S1 (59% of the field area straw mulched), S2 (50% of the field area straw mulched), S3 (42% of the field area straw mulched), BM (full-cover transparent plastic mulch), and HM (full-cover black plastic mulch). The effects of mulching measures on soil moisture, water consumption characteristics, yield and water use efficiency (WUE) of winter wheat farmland in rain-fed semiarid regions were studied. The results showed that, compared with CK, straw strip mulching reduced total water consumption by 15.39 mm on average, the soil organic carbon content at the 0–40 cm soil layer increased by 4.68%, yield by 6.90%, WUE_r by 11.27%, and WUE_b by 16.51%. Compared with CK, the total water consumption and soil organic carbon content in each growth period of plastic film mulching were not significantly different, but the yield, WUE_r, and WUE_b increased by 16.28%, 15.29%, and 25.50%, respectively. Among the three straw strip mulching treatments, treatment S3 had the highest yield, which was equivalent to that of plastic film mulching. The S3 treatment with 42% of the field area straw mulched is recommended in this stusy as the optimal replacement of plastic film mulching in semi-arid environments.

Keywords: straw strip mulching; grain yield; water use efficiency; soil moisture; winter wheat; semi-arid areas

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1. Introduction

The Loess Plateau of northern China covers an area of about 640 × 10^3 km^2, with a population of about 8.5% the total population of China, and an area of 13.3 million ha of arable land [1]. Wheat is one of the main grain crops in this region, with an annual planting area of 4.3–4.7 million ha [2]. As a typical rain-fed agricultural area, this region has good light and heat conditions and diverse and complex land types, but a serious shortage of water resources, low vegetation coverage, serious soil erosion, misalignment of rainfall and wheat water demand, and frequent drought and frost damage [3,4], which affect the large-scale cultivation of winter wheat and cause great challenges to the sustainable development of agriculture in this area.

To make full use of limited rainfall resources, surface mulching has become an effective measure to increase yield in dry farming agroecosystems. Among the mulching methods, plastic film mulching has been widely used in the agricultural production of arid and semi-arid regions and has demonstrated yield-increasing effects [4–8]. Especially after whole plastic film mulching is adopted, a closed physical barrier is formed on the surface that effectively reduces soil evaporation and noticeably enhances crop yield and water-use efficiency (WUE) [8–10]. However, studies [11–14] have shown that residues from long-term plastic film mulching can have a significant negative impact on agricultural soils and may cause serious environmental pollution problems, which can affect the healthy and sustainable development of dryland farming. For the above reasons, conservation tillage techniques such as cover and straw return, which are more environmentally friendly, have been highly valued and developed [2,15]. Studies have shown [15–20] that straw mulching could change the soil water ecological environment by decreasing soil water evaporation and increasing soil water storage, as well as improve soil fertility by modifying the soil structure, promoting the accumulation of soil organic matter, and affecting the coordinated development of ecological, economic and social benefits. However, the disadvantages of straw mulching including yield reduction and pest and weed infestation have attracted widespread attention [21,22], and continuous inquiry and improvement have been made given the disadvantages of straw mulching [23,24].

Straw strip mulching has been proposed as a new dry farming technology that partially covers the ground with whole corn stalks (*Zea mays* L.). This method uses strips of straw mulch, with strips planted between them that have no mulch cover [25]. In recent years, straw strip mulching has been reported to improve soil water and heat conditions, which is beneficial to crop growth and high yield formation in the Loess Plateau of Northwest China [7,24,26]. At present, this technology mainly focuses on the effects of straw strip mulching on soil water, soil temperature, and other ecological factors, but the coordination mechanisms in improving high yield and efficient use of resources remains unclear. In particular, few studies have covered winter wheat in this way. Furthermore, the complexity of farmland ecosystems and differences in experimental areas may lead to different results. Therefore, the objectives of present study were to determine the following: (1) the effects of full-cover plastic mulch and straw mulch on winter wheat grain yield and WUE; (2) the effects of straw strip mulching on soil water and soil organic carbon within the soil profile; and (3) the characteristics of water consumption and a relatively appropriate mulching cultivation pattern for winter wheat. In this study, we tested the hypothesis that there is a great advantage to increasing crop yield and WUE when straw strip mulching technology is applied to a winter wheat cropping system in the semi-arid region of northwest China.

2. Materials and Methods

2.1. Site Description

Field experiments were conducted at Tongwei Modern Dryland Circular Farming Experiment Station (35°11′ N, 105°19′ E; asl. 1750 m) of Dingxi City, Gansu Province of China in two winter wheat growing seasons of 2019 to 2020 and 2020 to 2021. The average annual evaporation is 1500 mm, the average annual temperature is 7.2 °C, and the annual sunshine hours are 2100 h. The average annual rainfall is 390.7 mm with 70–80% of rainfall is concentrated in July, August, and September and relatively less rainfall in the main wheat water-demanding period. The precipitation throughout the growth period of winter wheat in 2019–2020 was 243.40 mm and in 2020–2021 it was 176.60 mm.

The soil is Loess soil, with an average soil bulk density of 1.25 g·cm^{-3} in the top 0–200 cm layer. In the 0–200 cm layer, the field capacity and wilting point are 25.3% and 6.8%, respectively. The fundamental soil characteristics within 0–20 cm increments are as follows: 8.81–9.12 g·kg^{-1} of soil organic carbon, 0.69–0.72 g·kg^{-1} of total nitrogen, 6.95–7.66 mg·kg^{-1} of available phosphorus, 115.51–133.80 mg·kg^{-1} of available potassium, and 8.1–8.5 of pH.

2.2. Experimental Design and Field Management

This experiment was organized in a randomized block design with five treatments including three straw strip mulching (S1, S2, S3), two plastic film mulching (BM, HM), and one control (CK) with no mulching (open field) planting. Each treatment and the control were replicated three times.

(1) Straw strip mulching (the high coverage rate, S1): using alternating straw strip (0.5 m) and plant strip (0.35 m), with the coverage rate maintained at 59%.
(2) Straw strips mulching (the moderate coverage rate, S2): using alternating straw strip (0.5 m) and plant strip (0.5 m), with the coverage rate maintained at 50%.
(3) Straw strips mulching (the low coverage rate, S3): using alternating straw strip (0.5 m) and plant strip (0.7 m), with the coverage rate maintained at 42%.
(4) Full-cover transparent plastic film mulching (BM): coverage rate approximately maintained at 100%.
(5) Full-cover black plastic film mulching (HM): coverage rate approximately maintained at 100%.
(6) No coverage (CK): using conventional flat planting without mulching.

The area of each plot was verified to be more than 50 m^2 and had the same sowing density of 375×10^4 plant·ha^{-1}. The sowing density per unit area with straw strip mulching was calculated according to the total area of the straw strip zones and the plant strip zones. Row drill seeding with local density was evenly carried out in the plant strip. The row spacing was 15 cm, and a spacing of 2.5 cm between the edge of the straw strip zone and the rows on both sides of the plant strip zone were left to prevent the straw from pressing the seedlings. The air-dried maize straw collected from locally harvested maize fields were mulched on the pre-reserved straw strips at wheat three-leaf stage by hand with the mulching amount of 9000 kg·ha^{-1}. The soil tillage, sowing time, fertilizer amount, and other field management strategies were the same in each treatment and CK.

The experimental variety of winter wheat was "Longzhong 2". According to the irrigation test specification and the actual growth process for local winter wheat, the growth period can be divided into 6 stages: overwintering (OS), regreening (RS), jointing (JS), flowering (BS), filling (GS), and maturity stages (MS). The sowing density of winter wheat per unit area was 225 kg·ha^{-1} for all treatments. The amount of fertilizer in the two growing seasons was the same. Net nitrogen of 120 kg·ha^{-1} and P_2O_5 of 90 kg·ha^{-1} were added as the base fertilizer, evenly broadcasted on the soil surface and plowed into the soil prior to sowing, and no topdressing was applied during the growth period.

2.3. Sampling and Measurements

2.3.1. Soil Water Content

Soil gravimetric water contents within 0–20, 20–40, 40–60, 60–90, 90–120, 120–150, 150–180, and 180–200 cm soil layers were measured at OS, RS, JS, BS, GS, and MS of winter wheat from 2019 to 2021. The soil samples for each plot were taken using a steel-core auger of 5 cm diameter and determined by the oven-drying method at 105 °C for 48 h until a constant weight. Each index was calculated as follows:

(1) Soil water storage (mm) = soil depth (cm) × soil bulk density (g·cm^{-3}) × soil gravimetric water content (%) × 10.
(2) Stage water consumption (mm) = soil water storage (mm) at the beginning of a growth period − soil water storage (mm) at the end of the growth period + effective precipitation (mm) more than 5 mm at the corresponding stage.
(3) Water use efficiency (kg·ha^{-1}·mm^{-1}) for grain yield (WUE_r) = grain yield (kg·ha^{-1})/soil water total consumption (mm) throughout the growth stage.
(4) Water use efficiency (kg·ha^{-1}·mm^{-1}) for aboveground biomass (WUE_b) = aboveground biomass (kg·ha^{-1})/soil water total consumption (mm) at the whole growth period.

2.3.2. Soil Organic Carbon

Soil organic carbon in the 0–10, 10–20, and 20–40 cm soil layers was measured at the JS, BS, GS, and MS of winter wheat from 2019 to 2021. The soil samples for each plot were collected using a 5 cm diameter steel-core auger and air dried. Then, the air-dried soil was sieved with 0.25 mm mesh, and a 0.25 mm terroir sample was used to measure soil organic carbon (SOC). SOC was determined using the potassium dichromate oxidation–external heating method [27].

2.3.3. Yield and Its Components

Before the harvest of winter wheat, the spike number per unit area was surveyed in the field by a sampling survey in 3 m^2 of each plot. After maturity, all plots were harvested separately, and the grain yield was recorded. Twenty similar plants were randomly selected and brought to the lab to determine dry matter, grain number per spike, and 1000-grain weight. The samples were dried in an oven to a constant weight, and the grain moisture content was adjusted to 12.5% for grain yield, aboveground biomass, and 1000-grain weight.

2.4. Data Analysis

The data and figures of soil water content, soil water storage, soil water storage consumption, soil organic carbon, grain yield, and yield components were processed using Microsoft Excel 2010 (Microsoft Crop., Raymond, WA, USA), IBM SPSS Statistical Analysis 20.0 (IBM Inc., New York, NY, USA), and Origin Pro 9 (Originlab Corp., Northampton, MA, USA). Differences in these indexes among the treatments and CK were analyzed using one-way analysis of variance (ANOVA), and the differences in mean values among the treatments and CK were compared by the least significant difference (LSD) test ($p < 0.05$). The data are presented as means ± standard error (SE).

3. Results

3.1. Differences in Soil Water Content at Different Growth Periods and Soil Layers

As shown in Figure 1, mulching had obvious effects on the soil water content of winter wheat at different growth stages. Straw strip mulching significantly improved the soil moisture conditions in the 0–200 cm soil layer compared with CK. According to the two-year average, the mean soil water contents in all the treatments within the 0–200 cm soil layer at BS, GS, and MS were 5.58%, 13.44%, 16.42%, and 13.09% higher than that of CK, respectively. The soil water content within different soil layers had the phenomenon of increasing or decreasing soil moisture at different growth periods, and the differences were inconsistent at the two growing seasons. During 2019–2020 growing season, the soil water content within 120–200 cm soil depth at JS, 60–120 cm depth at BS, and 40–90 cm depth at MS were all lower than those in CK, and those within other soil layers were higher than CK. In the 2020 to 2021 growing season, only the soil water content within the 180–200 cm soil layer at the jointing stage was lower than that of CK. Among the three straw strip mulching treatments, the average soil water content within 0–200 cm layer was generally performed with S1 > S2 > S3, but there was no significant difference between the treatments.

The water conditions of the 0–200 cm soil layer at each growth period in treatments with plastic film mulching were generally better than those of CK, and the average soil water content within the 0–200 cm soil layer was 4.46%, 11.59%, 10.37%, and 7.37% higher than that of CK at JS, BS, GS, and MS, respectively. The soil water content within different soil layers also increased or decreased at different growth periods, and the differences were inconsistent. During the 2019–2020 growing season, the soil water content decreased in the 60–180 cm soil layer at JS, BS, GS, and MS. During the 2020–2021 growing season, the soil water content decreased within both the 0–60- and 150–200 cm soil layers at JS. There was no significant difference in the water content of each soil layer between the two plastic film treatments.

Among the mulching treatments, straw strip mulching and plastic film mulching had a similar effect on the average water content of the 0–200 cm soil layer during each growth period, but there were differences across the soil layers. During the 2019–2020 and 2020–2021 growing seasons, the soil moisture conditions within the 0–40 cm soil layer in straw strip mulching treatments were significantly higher than those in plastic film mulching at JS, BS, and GS, and the soil moisture content below the 40 cm layer reduced as plant growth continued. At MS, the soil water content within the 0–90 cm soil layer was lower in the straw strip mulching treatment than that in the plastic film mulching treatment during both growing seasons, and the soil layer below 90 cm had the opposite trend.

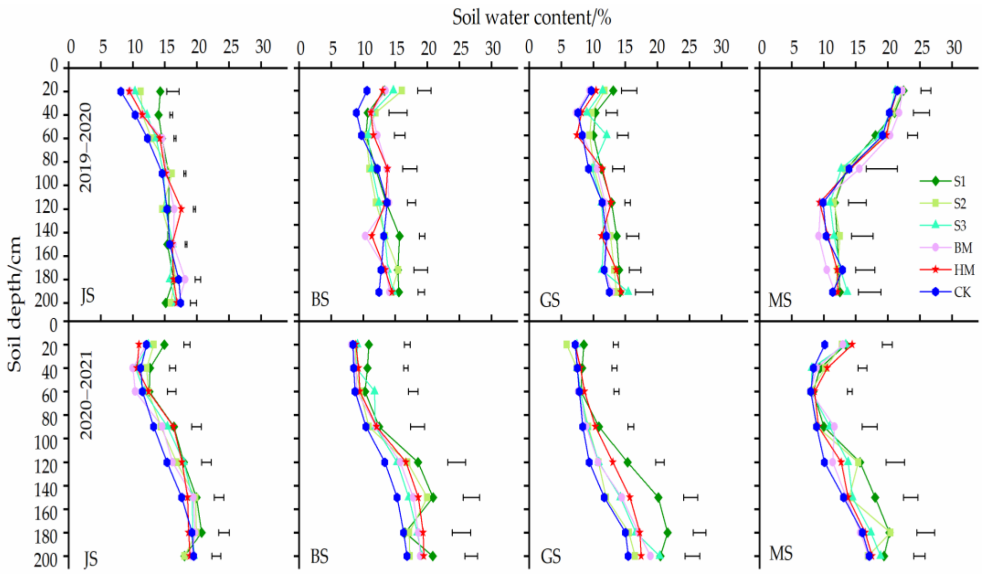

Figure 1. Soil water content in different soil layers at different growth stages.

3.2. Soil Water Storage in the 0–200 cm Soil Layer

Table 1 shows that mulching cultivation had a significant effect on soil water storage in the 0–200 cm soil layer at different growth stages of winter wheat. Compared with CK, both straw strip mulching and plastic film mulching increased soil water storage in the 0–200 cm soil layer during the 2019–2020 and 2020–2021 growing seasons by 28.02 mm within 18.61–45.49 mm and 22.95 mm within 9.84–34.25 mm, at JS by 25.77 mm within 10.32–44.05 mm and 19.23 mm within 9.13–23.72 mm, at BS by 30.52 mm within 13.55–51.41 mm and 6.73 mm within −6.93–13.14 mm, respectively. There was no significant difference ($p > 0.05$) in soil water storage within 0–200 cm soil layer between straw strip mulching and plastic film mulching at JS and BS in both the 2019–2020 and 2020–2021 growing seasons, but soil water storage in the 0–200 cm soil layer improved by 23.78 mm within 0.14–53.53 mm at MS, and the difference between S1 and BM was significant ($p < 0.05$). Among the straw strip mulching treatments, soil water storage in 0–200 cm soil layer decreased in the following order of S1 > S2 > S3 at the different growth stages of winter wheat in different years, but there was no significant difference ($p > 0.05$) that occurred among straw mulching treatments. In addition, there was also no significant difference ($p > 0.05$) between BM and HM at each stage.

Table 1. Soil water storage (0–200 cm depth) at each stage of winter wheat under different cultivation practices from 2019 to 2020 and 2020 to 2021.

Year	Treatments	Soil Water Storage before Sowing (mm)	Soil Water Storage at the JS (mm)	Soil Water Storage at the BS (mm)	Soil Water Storage after Harvest (mm)
2019–2020	S1	448.63	381.27 ± 9.52 a	337.57 ± 8.92 a	313.28 ± 13.03 a
	S2	444.18	366.95 ± 8.98 ab	326.51 ± 10.29 ab	290.15 ± 7.62 ab
	S3	434.37	364.61 ± 11.47 ab	320.50 ± 14.21 ab	285.16 ± 11.97 ab
	BM	435.97	380.25 ± 7.74 a	321.47 ± 14.99 ab	269.25 ± 14.59 b
	HM	448.51	375.14 ± 8.98 ab	321.26 ± 14.61 ab	285.02 ± 13.06 ab
	CK	445.54	346.51 ± 8.58 b	299.34 ± 9.35 b	261.87 ± 13.13 b
2020–2021	S1	490.00	427.00 ± 6.62 a	388.05 ± 16.44 a	366.60 ± 5.79 a
	S2	470.00	405.66 ± 6.18 ab	354.32 ± 9.19 ab	339.98 ± 13.88 ab
	S3	470.00	405.18 ± 22.64 ab	357.65 ± 23.97 ab	333.55 ± 3.83 ab
	BM	455.00	391.36 ± 21.44 b	353.13 ± 21.49 b	313.07 ± 22.13 b
	HM	465.00	400.09 ± 14.90 ab	367.72 ± 17.01 ab	323.35 ± 15.27 b
	CK	455.00	381.51 ± 16.09 b	344.00 ± 24.91 b	320.00 ± 12.3 ab

Note: Different lowercase letters within a column indicate significant differences between values, per one-way analysis of variance ($p < 0.05$). Values show the means ± SE ($n = 3$).

3.3. Evapotranspiration and Its Proportion at the Different Growth Stages

Table 2 shows that straw strip mulching increased the total water consumption by −15.39 mm within −36.59 to 1.45 mm during the two growing seasons of 2019–2020 and 2020–2021, and the average increase was −12.89 mm (−8.67 to −20.42 mm) from sowing to JS, but there was no difference found between JS and BS or between BS and MS. The total water consumption of wheat under plastic film mulching was basically the same as that of CK in the two growing seasons, but the water consumption increased by −13.85 mm (−8.57 to −19.55 mm) from sowing to JS. After JS, the wheat entered the vigorous growth stage, and transpiration water consumption gradually increased. The water consumption in the growth period became gradually higher than that in CK, and the water consumption from JS to BS and BS to MS increased by 3.72 mm (−5.15 to 12.12 mm) and 12.49 mm (−1.22 to 20.37 mm), respectively. Among the mulching measures, the total water consumption of straw strip mulching in the two growing seasons increased by −17.76 mm (−5.20 to −43.91 mm) compared with the plastic film mulching. The water consumption before BS was basically the same, and the difference gradually increased after BS. There was no significant difference ($p > 0.05$) in total water consumption and at different growth stages among the three straw strip mulching treatments, but S3 consumed more soil water than S1. Additionally, there was no significant difference ($p > 0.05$) in water consumption at different growth stages between BM and HM.

Table 2. Evapotranspiration (ET) at each growth stage of winter wheat under different cultivation practices during the 2019–2020 and 2020–2021 growing seasons.

Year	Treatments	ET at Each Stage									ET (mm)
		Before Sowing to JS			JS to BS			BS to MS			
		RF (mm)	CA (mm)	CP (%)	RF (mm)	WC (mm)	CP (%)	RF (mm)	WC (mm)	CP (%)	
2019–2020	S1	100.40	167.79 ± 5.78 b	44.30	66.73	110.40 ± 9.22 b	29.15	76.27	100.56 ± 4.47 b	26.55	378.75 ± 10.00 d
	S2		177.63 ± 10.28 a	44.69		107.17 ± 8.83 b	26.97		112.63 ± 9.94 ab	28.34	397.43 ± 8.64 bcd
	S3		170.15 ± 11.47 ab	43.34		110.84 ± 7.21 b	28.23		111.62 ± 3.00 ab	28.43	392.61 ± 11.96 cd
	BM		168.66 ± 3.74 b	39.90		125.51 ± 7.25 a	29.70		128.49 ± 8.09 a	30.40	422.66 ± 11.38 a
	HM		170.80 ± 6.01 ab	42.29		120.60 ± 5.95 a	29.86		112.52 ± 5.1 ab	27.86	403.92 ± 10.39 abc
	CK		188.21 ± 11.57 a	45.31		113.39 ± 10.30 a	27.30		113.74 ± 6.96 ab	27.38	415.34 ± 15.59 ab
2020–2021	S1	97.16	160.16 ± 6.62 b	53.39	21.39	60.34 ± 12.55 ab	20.11	58.05	79.51 ± 8.66 b	26.50	300.00 ± 14,22 b
	S2		161.50 ± 6.18 ab	52.67		72.72 ± 12.25 a	23.72		72.40 ± 6.45 b	23.61	306.62 ± 13.88 ab
	S3		161.98 ± 3.34 ab	51.74		68.93 ± 10.85 ab	22.02		82.14 ± 10.88 b	26.24	313.05 ± 3.23 ab
	BM		160.80 ± 5.35 b	50.48		59.62 ± 12.33 ab	18.72		98.11 ± 9.06 a	30.80	318.53 ± 7.89 a
	HM		162.07 ± 5.95 ab	50.93		53.76 ± 7.09 b	16.89		102.42 ± 3.51 a	32.18	318.25 ± 11.93 a
	CK		170.65 ± 3.30 a	54.76		58.90 ± 5.03 ab	18.90		82.05 ± 4.10 b	26.33	311.60 ± 2.35 ab

Note: RF, Rainfall ≥ 5 mm; WC, water consumption; ET, water consumption amount. CA, water consumption for period stages; CP, water consumption modulus. Different lowercase letters within a column indicate significant differences between values according to one-way analysis of variance ($p < 0.05$). Values show the means ± SE ($n = 3$).

Compared to conventional planting, the mulching measures were more conducive to adjusting the proportion of water consumption in each growth period and optimizing the water-use structure. Compared with CK, straw strip mulching decreased the water consumption ratio from sowing to JS by 2.66%, while the water consumption ratio from JS to BS and BS to MS increased by 2.98% and 1.42%, respectively. Plastic film mulching reduced the water consumption ratio from sowing to JS by 9.31% compared with CK, while the water consumption ratio from JS to BS and BS to MS was increased by 9.07% and 6.37%, respectively.

3.4. Water USE efficiency (WUE)

Figure 2 shows the effects of different mulching treatments on WUE of winter wheat in two consecutive growing seasons. In comparison to CK, straw strip mulching and plastic film mulching increased the water use efficiency of grain yield (WUE_r) and biomass yield (WUE_b). The three straw strip mulching averages increased by 11.27% (6.36–14.09%) for WUEr. The average WUE_b increased by 16.51% (3.61–29.38%) in 2019 to 2020 and 2020 to 2021, while the two plastic film mulching averages increased by 15.29% (10.67–20.60%)

for WUEr and by 25.50% (16.57–36.77%) for WUE_b. Compared with plastic film mulching, straw strip mulching caused a lower decrease in WUEr than WUE_b. Among the three straw strip mulching treatments, S3 had the highest average WUE_r and WUE_b in 2019–2020 and 2020–2021, but there was no significant difference ($p > 0.05$) between treatments. The difference in WUE_r and WUE_b between the two plastic film mulching treatments was not significant ($p > 0.05$).

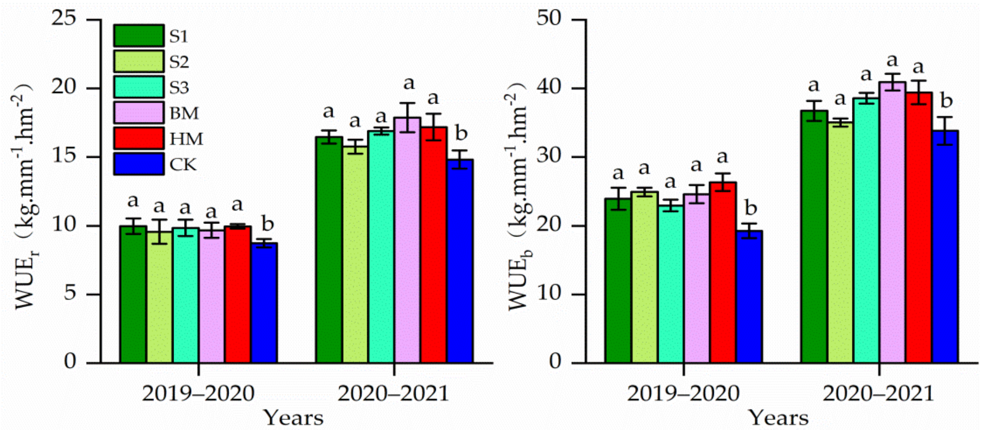

Figure 2. Water use efficiency based on the grain yield (WUE_r) and biomass yield (WUE_b) under different cultivation practices in the 2019–2020 and 2020–2021 growing seasons. Values show the means ± SE (n = 3). Different lowercase letters above the bars indicate significant differences between values, according to one-way analysis of variance ($p < 0.05$).

3.5. Soil Organic Carbon

Figure 3 shows the effects of different mulching treatments on the organic carbon content in different soil layers of wheat fields at different growth stages. The straw strip mulching treatment significantly improved the soil organic carbon content. In comparison with CK, the soil organic carbon content in the 0–40 cm soil layer increased by 5.13, 3.66, 2.48, and 7.70% at JS, BS, GS, and MS, respectively, in 2019–2020 and 2020–2021. The soil organic carbon content was gradually weakened with the deepening of the soil layer in each growth period. In the two growing seasons, the soil organic carbon content in the 0–10, 10–20, and 20–40 cm soil layers, respectively, increased by 4.61, 6.07, and 4.69% relative to CK at JS. At BS and GS soil organic carbon in the 0–10 cm soil layer was significantly higher by 5.35% and 4.03%, respectively, than that in CK, and the difference in the other soil layers was minimal. Compared to CK, the soil organic carbon content in the 0–10, 10–20, and 20–40 cm soil layers at the mature stage increased by 6.38%, 12.66% and 4.40%, respectively. Plastic film mulching had little effect on the organic carbon content in the 0–40 cm soil layer in each growth period. Compared to CK, the soil organic carbon content in the different soil layers in each growth period of the two growing seasons was similar. The effect of straw strip mulching on soil organic carbon content was significantly higher than that of plastic film mulching. The average organic carbon content performance of the three straw strip mulching treatments in the 0–40 cm soil layer followed the order of S1 > S2 > S3. Additionally, there was no significant difference in the organic carbon content of each soil layer between the two plastic film treatments.

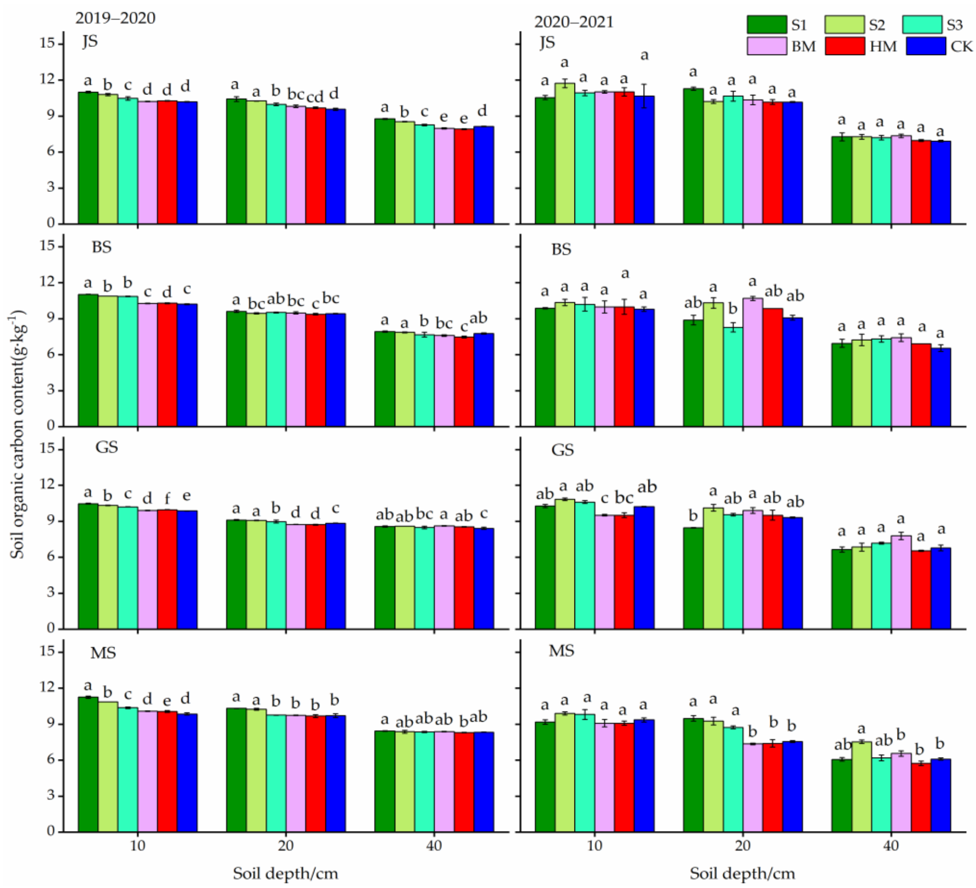

Figure 3. Organic carbon content in different soil layers of different growth stages under different cultivation practices in the 2019–2020 and 2020–2021 growing seasons. Values show the means ± SE (n = 3). Different lowercase letters above the bars indicate significant differences between values, according to one-way analysis of variance ($p < 0.05$).

3.6. Yield and Agronomic Indicators

Table 3 shows that both straw and plastic film mulching cultivation increased grain yield and WUE. Straw strip mulching was comparable to plastic film mulching in improving wheat yield. In 2019–2020 and 2020–2021, the three straw strip mulching treatments increased the average yield by 6.90% (4.01–14.62%) compared with CK, while the two plastic film mulching treatments increased the average yield by 16.28% (10.75–23.28%). Compared with plastic film mulching, the average yield of straw strip mulching decreased by −7.99% (−3.25% to −15.11%). Among the three straw strip mulching treatments, S3 maintained the highest yield and WUEr, but there was no significant difference among the treatments. Similarly, there was no significant difference in wheat yield and WUE between the two plastic film mulching treatments.

Both mulching cultivation treatments promoted the vegetative growth of winter wheat. Compared with CK, the biomass yield of straw strip mulching and plastic film mulching in the two growing seasons increased by 11.81% (1.95–14.62%) and 26.28% (19.00–33.01%), respectively, and the harvest index decreased by 6.29% (1.82–15.03%) and 10.00% (4.65–17.02%), respectively. Straw mulching and plastic film mulching promoted vegetative growth and increased the number of populations of wheat. Compared with CK, straw strip mulching and plastic film mulching increased the spike number by 29.74% (13.71–39.97%) and 40.28% (35.88–44.18%), respectively, and decreased the grain number by 14.14% (7.05–22.07%) and 17.27% (13.99–19.24%), respectively. Additionally, 1000-grain weight decreased less in the 2019–2020 crop season than in the 2020–2021 one. Among the mulching measures, straw strip mulching decreased the spike number by 7.47% compared with plastic film mulching, and the 1000-grain weight and grain number remained similar between mulching measures.

Table 3. Grain yield and agronomic indicators.

Year	Treatments	Grain Yield (kg·ha^{-1})	Thousand Grain Weight (g)	Spike Number (×10^4·ha^{-1})	Grain Number per Ear	Biomass (kg·ha^{-1})	Harvest Index (%)
2019–2020	S1	3775.78 ± 184.71 ab	42.97 ± 2.39 bc	236.90 ± 21.73 a	40.23 ± 1.91 ab	9066.27 ± 174.88 bc	41.66 ± 0.95 ab
	S2	3800.63 ± 174.31 ab	42.46 ± 3.27 c	254.64 ± 13.34 a	38.45 ± 1.70 ab	9902.47 ± 154.67 ab	38.71 ± 4.23 b
	S3	3866.57 ± 176.92 ab	43.26 ± 2.28 bc	254.50 ± 20.88 a	37.95 ± 1.56 ab	9009.86 ± 55.21 bc	42.92 ± 0.52 ab
	BM	4088.69 ± 213.49 a	47.48 ± 0.96 ab	263.15 ± 33.12 a	35.69 ± 3.97 b	10397.78 ± 579.86 ab	39.39 ± 1.93 ab
	HM	4020.74 ± 172.73 a	46.10 ± 0.87 abc	253.33 ± 12.80 a	37.23 ± 0.99 ab	10639.14 ± 239.95 a	37.80 ± 0.81 b
	CK	3630.36 ± 201.64 b	49.14 ± 1.22 a	186.45 ± 15.97 b	43.28 ± 3.83 a	7998.70 ± 631.17 c	45.56 ± 3.29 a
	mean	3863.80	45.63	241.50	38.81	9502.37	41.01
2020–2021	S1	4936.89 ± 122.08 bc	44.03 ± 1.43 a	252.33 ± bc	44.88 ± 4.39 ab	11020.56 ± 814.11 b	44.80 ± 1.82 a
	S2	4832.89 ± 147.21 bc	43.08 ± 1.57 a	276.52 ± bc	40.97 ± 2,8 b	10744.94 ± 313.23 b	44.98 ± 1.49 a
	S3	5292.65 ± 269.62 ab	43.22 ± 2.10 a	310.61 ± ab	40.40 ± 2.21 b	12073.85 ± 663.00 ab	43.62 ± 0.61 a
	BM	5692.77 ± 50.22 a	43.60 ± 1.58 a	319.95 ± a	49.24 ± 3.18 a	13032.79 ± 157.34 a	43.90 ± 0.70 a
	HM	5470.65 ± 208.84 bc	41.07 ± 2.79 a	310.47 ± bc	51.18 ± 5.67 a	12541.62 ± 532.69 ab	43.81 ± 1.85 a
	CK	4617.72 ± 78.35 c	42.41 ± 1.68 a	221.90 ± c	44.35 ± 4.29 ab	10539.33 ± 359.34 b	43.35 ± 0.78 a
	mean	5140.60	42.90	281.96	45.17	11658.85	44.08

Note: Different lowercase letters within a column indicate significant differences between values, according to one-way analysis of variance ($p < 0.05$). Values show the means ± SE ($n = 3$).

4. Discussion

4.1. Effects of Mulching on Soil Moisture Content and Water Consumption

This study showed that both straw strip mulching and plastic film mulching had a higher capability of water storage and moisture conservation during the winter wheat growth period. Compared with CK, the two mulching measures significantly improved the soil moisture conditions in the 0–200 cm soil layer. The soil water content in the 0–200 cm soil layer increased by 5.58–16.42% and 4.46–11.59%, respectively, and soil water storage increased in the 0–200 cm soil layer by 28.02–30.52 mm and 6.73–22.95 mm during the 2019–2020 and 2020–2021 growing seasons, respectively. It could be seen that straw strip mulching had a better effect on water storage and moisture conservation than plastic film mulching. Studies have shown that both plastic film and straw mulching effectively inhibit soil water evaporation and improve soil water storage [7,28]. The improvement in soil water and soil conditions due to straw mulching was multifactorial. Surface mulching prevents direct sunlight from reaching the surface, lowers ground temperature, and reduces soil water evaporation [29]. At the same time, straw mulching prolonged the time before the generation of the surface runoff and the time to soil moisture saturation, thus improving the stable infiltration rate [16]. In addition, the structure of corn straw itself is conducive to water retention [15]. Plastic film mulching reduced soil evaporation through a closed physical barrier. Meanwhile, due to the thermal insulation effect of plastic film mulching, the difference in soil temperature increased, which promoted the upward movement of soil water in the lower layer, causing it to accumulate in the surface layer and increase the soil surface water content [8]. In our study, compared with CK, straw strip mulching reduced the total water consumption during the growth period, mainly because it reduced water consumption during sowing to JS, and the difference in water consumption during JS to MS was not significant, which confirmed that straw strip mulching could regulate soil water distribution and utilization during the growth period of winter wheat, and that it was good for coordinating the relationship between crop yield and farmland. Among three straw strip mulching treatments, S1 treatment increased soil moisture the most, and S3 treatment consumed soil water the most, which showed that the moisture conservation effect of straw strip planting decreased with the decrease in the coverage rate.

The total water consumption of plastic film mulching was basically the same as that of CK, but the soil water consumption from sowing to JS was significantly reduced, and that from JS to MS was increased. Therefore, the total water consumption of straw strip mulching was lower than that of plastic film mulching. Yang et al. [7] believed that plastic film mulching reduced surface water evaporation, but the increase in soil temperature promoted plant transpiration and increased annual water consumption instead. Overall, both plastic film and straw mulching can change the water-use patterns of wheat so that crop water use and soil water storage can be coordinated [17–19]. In a mulching planting experiment of spring wheat in the Loess Plateau, Hou et al. [6] showed that mulching not only had a significant impact on the stage of water consumption, water consumption rate, and water consumption intensity of spring wheat, but that it also regulated the water consumption process. At the same time, mulching reduced water consumption in the early stages of crop growth and used more water during crop vigorous growth [7,15].

4.2. Effects of Mulching on Soil Organic Carbon

Soil organic carbon content is affected by the interaction between crop growth processes and management practices. Mao et al. [30] studied the use of mulching for spring maize in the Loess Plateau, finding that straw mulching significantly increased soil organic carbon and component content, while plastic film mulching had no obvious effect and reduced soil total organic carbon and component content in the late growth period. In our study, straw strip mulching significantly increased the soil organic carbon content in the 0–40 cm soil layer in each growth period and fluctuated as crop growth continued, which was consistent with the results of Bu et al. [31]. Straw mulching increased the input of soil organic matter [32], and the combination of exogenous straw addition and soil tillage accelerated the decomposition of the original soil organic matter [33]. In addition, straw mulching is conducive to the accumulation of soil organic carbon [31], especially when entering JS. Higher air temperature accelerated straw decomposition to supplement the soil carbon pool, and the soil organic carbon content also increased significantly. Subsequently, the vigorous growth activities of wheat stimulated soil microbial activities, and soil organic carbon gradually decreased. Until the GS, wheat growth basically stopped, and the demand for soil nutrients was reduced. In addition, the senescent plant roots, branches, and leaves supplied the organic matter for soil, increased the input of soil organic matter and led to the recovery of soil organic carbon content. In the present study, plastic film mulching had little effect on the organic carbon content in the 0–40 cm soil layer at different growth stages. Compared to CK, the organic carbon content in different soil layers at different growth stages in the two growth seasons showed a downward trend, which was consistent with the conclusion of Bu [31] but different from the results reported by Liang et al. [34]. Liang believed that plastic film mulching had little effect on the accumulation of soil organic carbon and its components, which might be related to short-term positioning. Therefore, the increase in soil temperature after plastic film mulching accelerated the mineralization of soil carbon. Achieving the sustainable management and efficient use of resources, restoring degraded lands and soils, and working towards a land degradation-neutral world are sustainable developmental goals defined by the United Nations.

4.3. Effects of Mulching on Yield and Agronomic Indexes of Winter Wheat

Improving soil moisture is the main measure used to increase wheat yield in dry-lands. The results of the study in the Loess Plateau of northwest China showed that, compared with CK, straw mulching increased dryland wheat yield by 10.9–52%, However, some research results showed that straw mulching did not increase yield or even de-creased significantly, which was thought that the decreasing spike number under straw mulching was the key reason for the reduction in grain yield of winter wheat, followed by the reduction of 1000-grain weight [21]. Plastic film mulching increased yield by −14–153%, with the WUE increasing by −15–152% for both mulching measures [7,28,35]. The reduction in yield by plastic film mulching was likely caused by insufficient soil moisture before sowing, excessive growth of crops in the early stage causing increased water con-sumption, and insufficient precipitation in the later stage causing poor ear development and shortened grain filling time [36,37]. Our study showed that straw strip mulching and plastic film mulching could improve both grain yield and WUE. In the two growing sea-sons, compared with CK, straw mulching increased grain yield by 6.90% and WUE by 11.27%. Plastic film mulching increased the grain yield by 16.28% and WUE by 15.29% compared with

CK. The main reason for increasing wheat yield under both mulching patterns was the significant increase in spike number and biological yield, and the de-crease in grain number and 1000-grain weight. This result was consistent with existing research results [7,38]. However, Li et al. [39] demonstrated that straw mulching promoted the 1000-grain weight of wheat. Our study also showed that the yield increase using plas-tic film mulching was equivalent to that of straw strip mulching, which is consistent with existing research results [2,28]. Although both straw strip and plastic film mulching could reduce the ineffective evaporation of soil moisture and increase WUE [7,28,29], the biolog-ical yield increase under plastic film mulching was higher than that of straw strip mulching, and the harvest index was significantly reduced, indicating that there was more redundant growth in wheat under plastic film mulching [10]. Since the climatic conditions in the Loess Plateau are complex, crop production is significantly affected by regional environmental conditions. Under the same total water consumption, the distri-bution proportion of water consumption in each growth stage was different, as was the yield [40]. In our experiment, mulching reduced water consumption before jointing, alle-viated the drought effect at the early stage of wheat and been conducive to the increase in spike number. At the same time, more water was reserved for middle and late production due to the water regulation effect, which has a positive effect on improving water use effi-ciency, solving the problem of water shortage, and realizing the sustainable use of fresh-water resources.

5. Conclusions

Straw strip mulching had obvious water storage and soil moisture conservation effects, reducing the total water consumption during the wheat growth period, and effectively improving the soil organic carbon content within the 0–40 cm soil layer at different growth stages. Especially, the grain yield and water use efficiency of S3 (alternating straw strip (0.5 m) and plant strip (0.7 m), and the coverage rate was 42%) treatment are similar to those of plastic film mulching, which could be used as a cultivation technology to replace plastic film mulching in reducing plastic film residue in the Loess Plateau in China.

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