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Straw Strip Mulching Increased Soil Organic Carbon Components of a Wheat Field in Dry Farming Regions of the Loess Plateau

Caixia Huang [1], Chipi Cheng [2], Zeyi Wang [1], Xia Zhao [1], Yong Yang [1], Liangliang Hu [1], Yazhen Li [1], Juhua Ma [1], Longlong Wang [1], Lei Chang [3], Yuansheng Ye [1] and Hengjia Zhang [1,*]

[1] College of Water Resources and Hydropower Engineering, Gansu Agricultural University, Lanzhou 730070, China
[2] Dingxi Institute of Water Resources Science, Dingxi 730070, China
[3] College of Agronomy, Gansu Agricultural University, Lanzhou 730070, China
* Correspondence: zhanghj@gsau.edu.cn; Tel.: +86-13619365883

Abstract: To explore the response of soil organic carbon (SOC) and carbon components to surface coverage in wheat fields in semi-arid rainfed regions, a two-year field experiment was conducted under three treatments: straw strip mulching (SM), transparent plastic film mulching (PM) and no mulching (CK). We researched the dynamic feature of soil organic carbon (SOC) and its components at different growth stages of winter wheat under different mulching methods, including microbial biomass carbon (MBC), dissolved organic carbon (DOC), mineralizable carbon (PCM) and easily oxidized carbon (EOC). The results showed that SOC and its components in different soil layers decreased with an increase of soil layer depth. Compared with CK, the SM treatment increased SOC in the 0–40 cm soil layer by 2.83–8.92%, MBC by 12.09–18.40%, DOC by 3.73–9.79%, PCM by 4.82–12.48% and EOC by 6.01–11.68% during the different periods, and an overall increase was greater in the 0–20 cm soil layer than in the 20–40 cm soil layer. The impact of PM on SOC was less significant compared with CK; MBC and PCM had an overall positive effect, and DOC and EOC behaved differently from year to year. In conclusion, SM can improve SOC and its components content in dryland of northwest China, which is conducive to the sustainable management and efficient utilization of maize straw resources and has significant ecological benefits.

Keywords: straw strip mulching; soil organic carbon; carbon components; winter wheat

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1. Introduction

Soil organic carbon (SOC), which offers carbon nutrients to plant and soil biological life, is the collective term for the carbon formed by the action of humus, plant and animal residues and microorganisms in the soil. SOC could adjust the physical and biological properties of soils and improve soil steadiness, and the ecological conditions of soil water, fertilizer, gas and heat could be influenced by the accumulation and mineralization of SOC. Moreover, the absorption and release of related substances in the soil were also affected [1]. At the same time, SOC's potential carbon sequestration plays a key role in the global carbon cycle and climate change. In addition, the SOC content is closely related to soil quality and agricultural productivity [2]. Therefore, the study of cycling changes in SOC pools is of great importance for improving soil management and maintaining the sustainability of agro-ecosystems. Relative reports stated that soil management practices have a significant effect on the SOC content and organic matter accumulation [3–5], but they cannot quickly and accurately reflect the characteristics of changes under the influence of cultivation practices because of the large soil carbon stock, the complex composition and the coexistence of active, slow-acting and inert materials [6–8], whereas the active organic carbon fraction has a short transformation cycle, is sensitive to soil management practices, is highly correlated with intrinsic soil productivity, has an important influence on regulating soil nutrient flow and is often employed as a sensitive index of the soil carbon cycle and the turnover of effective nutrient changes [9,10].

The Loess Plateau region in northwestern China is an important grain producing area which has good light and heat conditions and diverse and complex land types, but there is a serious lack of water resources and low vegetation coverage and severe soil erosion, and the long-term rough agricultural development method has caused soil erosion to varying degrees across approximately 80% of the farmland, with declining SOC content and land productivity [11], posing a huge challenge to the sustainable development of agriculture in the region. Over the years, surface coverage has been developed as an effective measure to increase yields in dry agro-ecosystems. Some studies have believed that straw mulching can effectively contribute to an increase in the content of SOC and its components but is closely related to the amount of mulch, mulching time and mulching method [4]. By contrast, research on the influence of plastic film mulching (PM) on SOC are inconsistent, with some studies showing no significant changes in SOC and its components compared to uncovered soils [12–14]. Zhou et al. [15] suggested that mulching contributed to the growth of soil microbial carbon, while Li et al. [16] showed that mulching had a negative effect on soil microbial carbon. Straw strip mulching (SM) with maize is a new cultivation technique to conserve moisture and increase yield in drylands, which has been well proven and promoted in the dry farming areas of China. Now, this technique mainly focuses on the study of soil water temperature effect and yield [17,18], with less attention paid to the effect of SOC and its components, especially the dynamic process of winter wheat under mulching conditions, which has rarely been reported. Moreover, white pollution caused by PM has attracted widespread attention as a major cultivation practice in the western region of China. In our work, the dynamic feature of soil carbon component in each growing period of the winter wheat under SM and PM conditions were studied in the Loess Plateau region of Northwest China, which is based on the hypothesis that straw mulching can promote the content of SOC and its components. The objectives were to: (1) analyze the dynamic impacts of mulching practices on SOC and its components and (2) to investigate whether SM can be an alternative to surface coverage in improving soil quality.

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; altitude 1750 m) in Dingxi city, China, in two winter wheat growing seasons of 2019–2020 and 2020–2021. The test site is marked by a representative semiarid, rainfed agricultural areas of the Loess Plateau. Based on the relative meteorological data, the annual mean evaporation, temperature, sunshine duration and rainfall are 1500 mm, 7.2 °C, 2100 h and 390.7 mm, respectively, and 70–80% of rainfall is concentrated in late summer and early fall, which happens to be the fallow period in the local area. The precipitation for the whole growing season of winter wheat in 2019–2020 was 243.40 mm and that in 2020–2021 was 176.60 mm.

In accordance with the United States Department of Agriculture (USDA) texture classification system, the soil type of this experimental site is sorted into loess soil [19]. The average soil bulk density, field capacity (FC) and wilting coefficient in 0–20 cm soil layer is 1.25 g·cm^{-3}, 25.3% and 6.8%, respectively. The fundamental soil characteristics within 0–20 cm soil layer are as follows: 8.81–9.12 g·kg^{-1} of SOC, 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 a pH value of 8.1–8.5.

2.2. Experimental Design and Field Management

Field experiment was organized in a completely randomized block design (CRB) with three patterns: straw strip mulching (SM), plastic film mulching (PM) and one control (CK) with no mulching (open field) planting. Each treatment and the control were replicated three times. Straw strip mulching used alternating straw (0.5 m) and plant (0.5 m) strips. Full-cover transparent PM was maintained at an approximate 100% coverage rate.

The plot area of each experimental treatment was 50 m^2, which had the consistent sowing density of 3,750,000 plants·ha^{-1}. Five rows of winter wheat were planted in plant strip with 15 cm spacing between rows. Air-dried maize straw was mulched at the wheat three-leaf stage by hand with an amount of 9000 kg·ha^{-1}. Other management measures were consistent in all treatments.

The winter wheat variety tested was Longzhong No. 2. According to the irrigation test specifications and the actual growth process for local winter wheat, the growth period can be divided into six stages: overwintering (OS), regreening (RS), jointing (JS), flowering (BS), filling (GS) and maturity (MS) stages. The sowing density of winter wheat 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 basal fertilizer, which were plowed into the soil before sowing, and no topdressing was applied.

2.3. Sampling and Measurements

Before sowing and each growth stage of winter wheat, soil was collected in layers of 0–10, 10–20 and 20–40 cm, and the fresh soil sample removed from experimental plot was classified into two parts. Part of it was sieved with 2 mm sieve and put into sealed bags, then was kept in a 4 °C refrigerator, which was used to determine soil microbial carbon and soluble organic carbon. The rest part was natural air drying and sieved with 2 mm and 0.25 mm sieves; the 2 mm air-dried soil sample was used to measure the soil mineralized organic carbon content, and the 0.25 mm air-dried soil sample was adopted to measure SOC and carbon dioxide easily. The SM treatments were sampled in the planting strip and mulch strip, and the results were weighted by average, while the other treatments were sampled between the wheat planting rows. The measurement method is as follows:

(1) Soil organic carbon (SOC): weigh 0.1 g soil sample passed with 0.25 mm sieve, treat it and then analyze it using an organic carbon analyzer (TOC-2000, Shanghai Metash Instruments Co., Ltd. Shanghai, China).

(2) Soil microbial biomass carbon (MBC): according to the reference [20], the chloroform fumigation method was used. Weigh 25 g fresh soil passed through a 2 mm sieve in a beaker, carry out chloroform fumigation in a desiccator and set up a control treatment without fumigation. After one day, add 0.5 mol·L^{-1} K_2SO_4 solution to extract and compute the MBC content by shaking, filtration and titration with $FeSO_4$ solution (0.5 mL·L^{-1}) after heating.

(3) Soil dissolved organic carbon content (DOC): according to the reference [21], DOC was measured through the cold-water leaching method. Weigh 10 g fresh soil passed through a 2 mm sieve into a centrifuge tube and add 50 mL of deionized water at room temperature. Shake and centrifuge the tube, pass the supernatant with a 0.45-µm filter membrane, and place the filtrate in a total organic carbon (TOC) analyzer for determination.

(4) Soil easily oxidized carbon content (EOC): the $KMnO_4$ oxidation method was used [22]. Weigh 1.5 g soil sample passed through a 0.25 mm sieve in a centrifuge tube, add 25 mL of potassium permanganate solution (the concentration was 333 mmol·L^{-1}), shake and centrifuge the tube at room temperature, separate out the supernatant and add deionized water at a ratio of 1:250, colorimetrically analyze the diluted solution using a Visible Spectrophotometer (V1800, Unico (Shanghai) Instruments Co., Ltd. Shanghai, China) at a wavelength of 565 nm; repeat three times and calculate oxidized carbon content of the sample according to the change in the $KMnO_4$ concentration.

(5) Soil mineralizable carbon content (PCM): the incubation method was used [23]. Weigh 10 g soil sample passed through a 2 mm sieve in a beaker, fill it to 60% of the field capacity, place the sample in a culture flask, add 4 mL of 0.5 mol·L^{-1} NaOH solution to the flask and incubate this under airtight conditions for 10 days. After 10 days, titrate the mixture with $BaCl_2$ solution at a concentration of 1.5 mol·L^{-1} and 0.1 mol·L^{-1}

HCl, calculate the amount of CO_2 absorbed by the NaOH solution and calculate the mineralized organic carbon content.

2.4. Data Analysis

The data and figures of SOC and its 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). One-way ANOVA was adopted to analyze the differences in these indexes among mulching treatments and CK, and the least significant difference (LSD) was used for post hoc multiple comparisons.

3. Results

3.1. Differences in SOC Contents under Different Mulching Treatments

As shown in Figure 1, the SOC content of different soil layers in each treatment decreased with increasing soil depth. Compared with CK, the SOC content in the 0–40 cm layer in the SM treatment increased by 2.83–8.92% in the two growing seasons, with a 5.55–9.81% increase in the 0–10 cm layer and a 0.73–14.71% increase in the 10–20 cm layer, both with the greatest increase and significant difference at MS but with no significant difference in the 20–40 cm layer. There was no significant difference in SOC between SM and CK in the 20–40 cm soil layer. The effect of the PM treatment on SOC was small, and the SOC content of different soil layers showed a dual effect of increasing or decreasing across all growth stages but no significant difference compared to CK. The SOC content of the PM treatment was lower than that of the SM treatment in different soil layers at all growth stages and was significantly reduced by 9.99–21.36% in the 10–20 cm soil layer at MS.

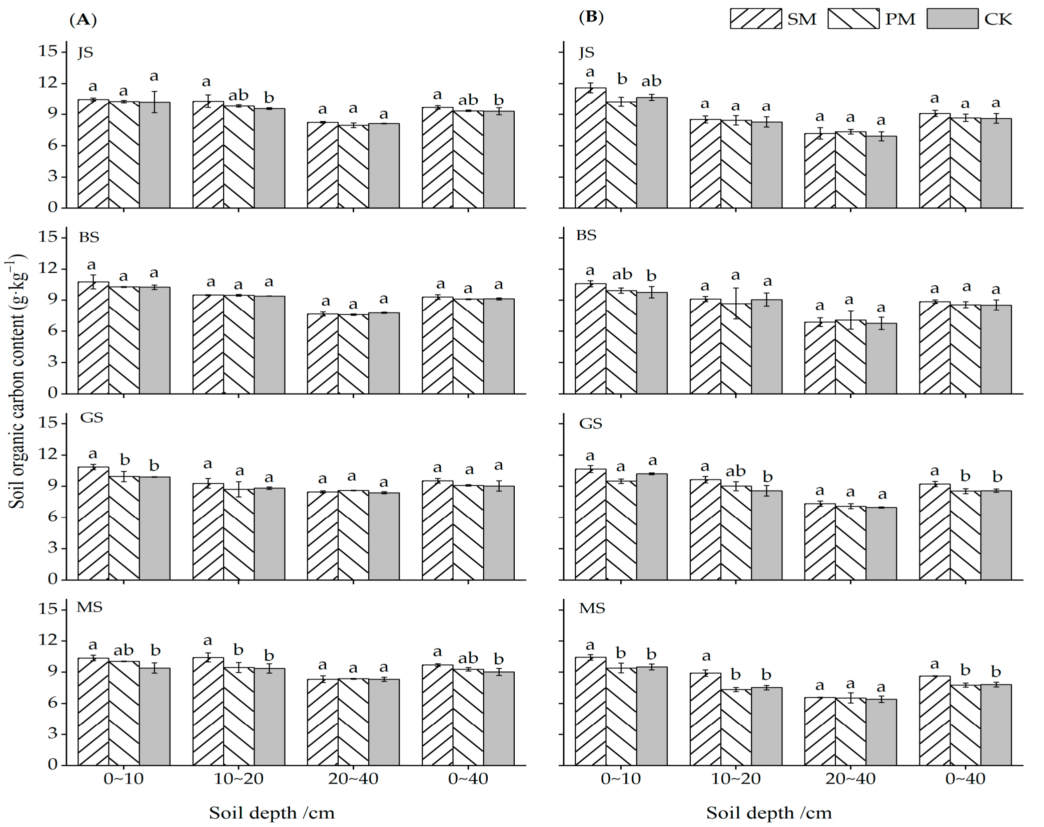

Figure 1. Soil organic carbon (SOC) contents in different growing periods of winter wheat. (**A**) 2019–2020; (**B**) 2020–2021. Lowercase letters denote significance at 5% significance level among treatments. SM: corn straw strip mulching; PM: plastic film mulching; CK: no mulching; JS: jointing stage; BS: blooming stage; GS: filling stage; MS: maturity stage.

3.2. Differences in MBC Contents under Different Mulching Treatments

Figure 2 shows that the MBC content in different soil layers of each treatment decreased with an increasing soil layer depth in all growth periods, except for that in the 10–20 cm layer, which was higher than that in the 0–10 cm layer during the GS from 2020 to 2021. Compared with CK, the SM treatment significantly increased the MBC content in the 0–40 cm layer by 12.09–18.40% in both growing seasons; the increase was 12.87–22.23% in the 0–10 cm layer, with the highest increase at GS and significant differences in whole growth stages. The increase in the 10–20 cm layer was 11.54–23.90%, with significant differences at JS and BS. The increase in the 20–40 cm layer ranged from 10.08% to 15.75%, with significant differences in all growth stages from 2019 to 2020 and insignificant differences from 2020 to 2021. Compared with CK, the overall impact of the PM treatment on MBC was positive, and the MBC content in the 0–40 cm layer increased by 3.77–7.98% at whole growth stages in both growing seasons and that in the 0–10 cm layer increased by 4.40–10.45%, and the differences were significant at JS and GS. The MBC content in the 10–20 cm and 20–40 cm layers increased by 3.09–12.29% and −1.97–6.12%, respectively, with significant differences in each growth period from 2019 to 2020 and insignificant differences from 2020 to 2021. The MBC content of the PM treatment was lower than that of the SM treatment in different soil layers at all growth stages, and significant differences in different soil layers existed in different growing seasons.

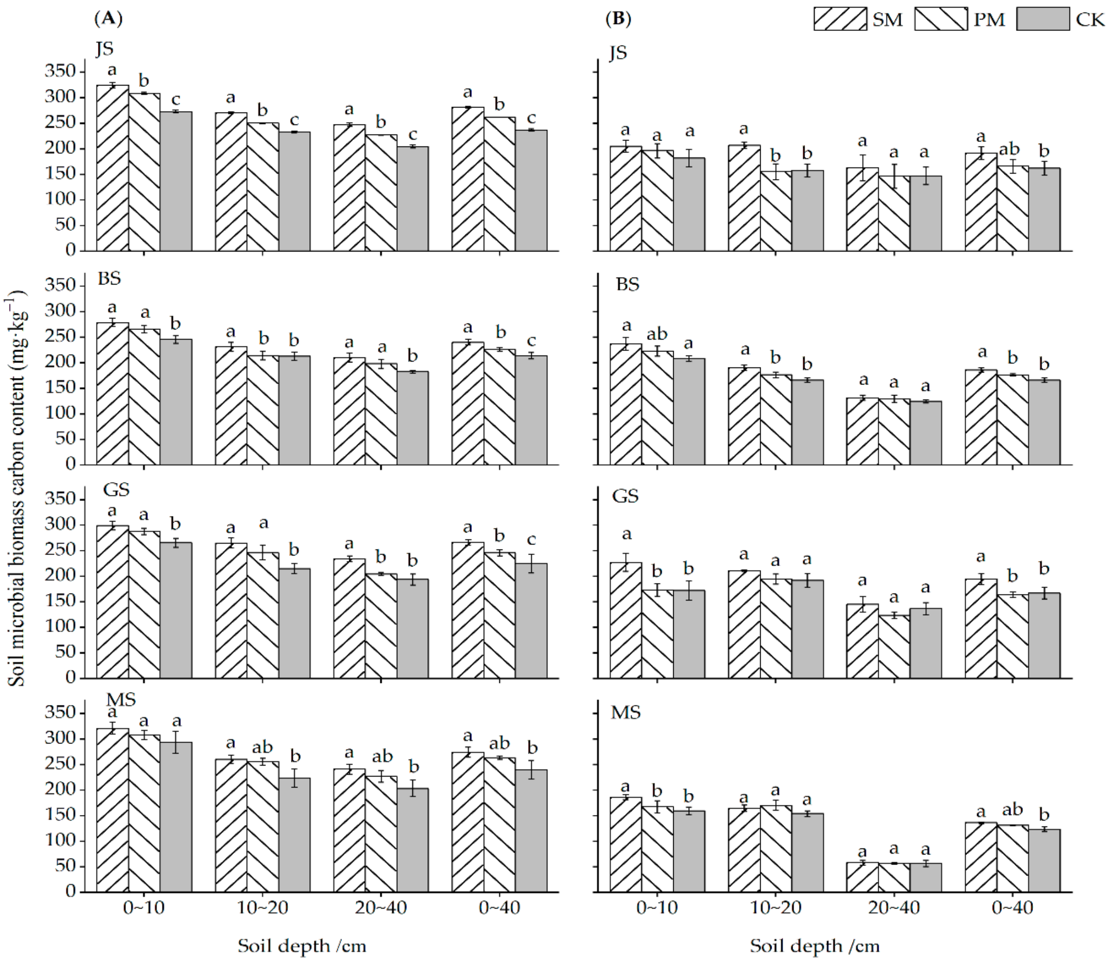

Figure 2. Soil microbial biomass contents (MBC) in different growing periods of winter wheat. (**A**) 2019–2020; (**B**) 2020–2021. Lowercase letters denote significance at 5% significance level among treatments. SM: corn straw strip mulching; PM: plastic film mulching; CK: no mulching; JS: jointing stage; BS: blooming stage; GS: filling stage; MS: maturity stage.

3.3. Differences in DOC Content under Different Mulching Treatments

Figure 3 shows that the DOC content in different soil layers in each treatment decreased with increasing depth. Compared with CK, the SM treatment increased the DOC content in the 0–40 cm layer by 3.73–9.79% in both growing seasons, with the greatest difference at GS. Among different soil layers, the increase was 3.16–9.55% in the 0–10 cm layer, with the highest rate of increase at GS, 4.61–11.23% in the 10–20 cm layer, with the highest rate of increase at BS, and 3.39–9.38% in the 20–40 cm layer, with the highest rate of increase at MS. The effect of the PM treatment on DOC differed between years, with a positive effect from 2019 to 2020 and a negative effect from 2020 to 2021 but with no significant difference compared with CK at the significance level of 5%. The effect of the PM treatment on the DOC content was generally less than that of the SM treatment, and differences were obvious in the 0–20 cm soil layer at JS, BS and GS from 2020 to 2021.

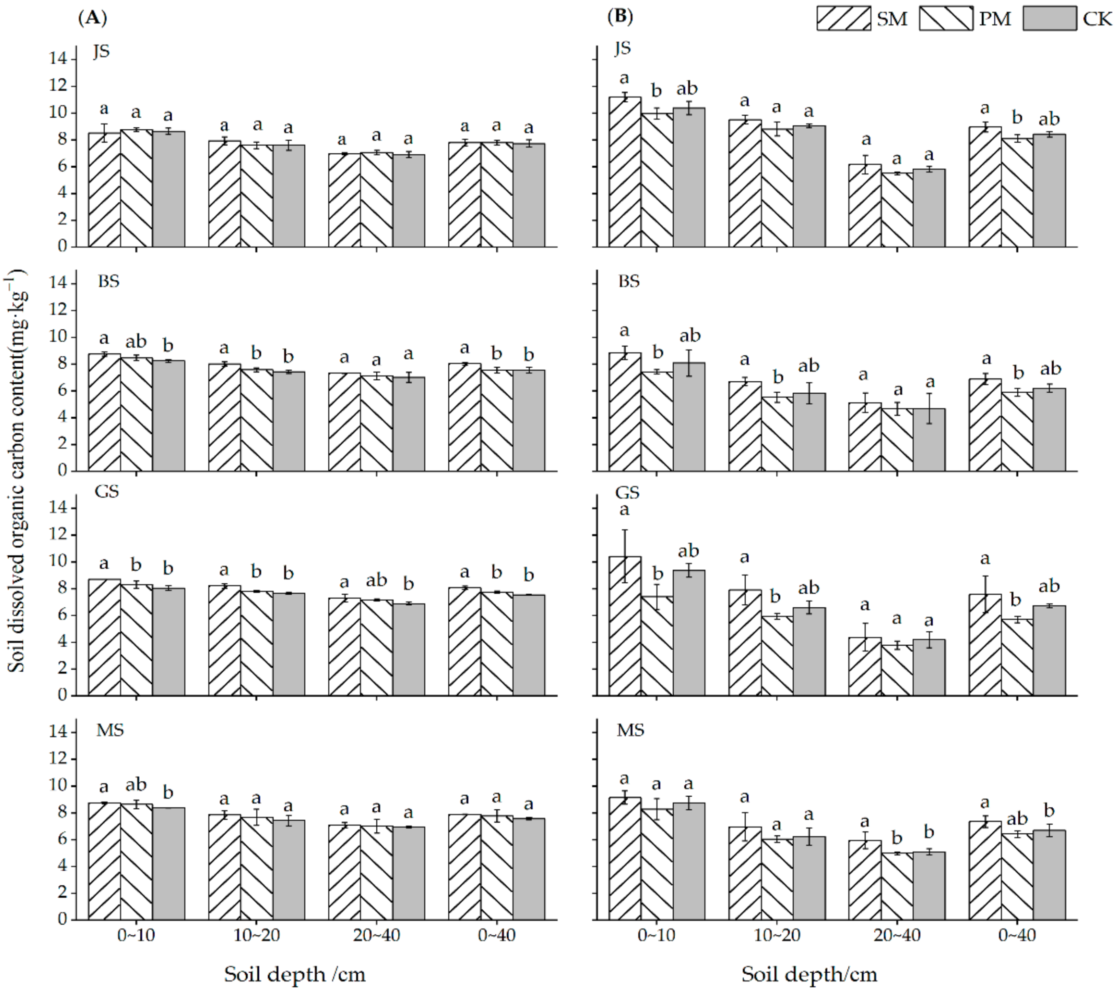

Figure 3. Soil dissolved organic carbon (DOC) in different growing periods of winter wheat. (**A**) 2019–2020; (**B**) 2020–2021. Lowercase letters denote significance at 5% significance level among treatments. SM: corn straw strip mulching; PM: plastic film mulching; CK: no mulching; JS: jointing stage; BS: blooming stage; GS: filling stage; MS: maturity stage.

3.4. Differences in PCM Content under Different Mulching Treatments

Figure 4 shows that the PCM content decreased with an increasing depth in different soil layers for different treatments. Compared with CK, the SM treatment promoted the PCM content in the 0–40 cm layer by 4.82–12.48% in both growing seasons, with the maximum at JS, followed by the MS. In different soil layers, the increase in the 0–10 cm layer ranged from 6.78% to 13.77%, with the highest at MS and with significant differences in all growth stages. The increase in the 10–20 cm layer ranged from 5.78% to 15.04%, with significant differences in all growth periods except for the BS from 2020 to 2021, and the increase in the 20–40 cm layer ranged from 0.93% to 8.86%, with no significant differences. The overall effect of the PM treatment on PCM was positive, and the PCM content in the 0–40 cm layer was significantly higher than that in CK at the JS and MS in both growing seasons, with larger differences in the 0–10 cm and the 10–20 cm layers. The PCM content of the SM was greater than that of the PM in each soil layers at whole growing periods, and significant differences in different soil layers existed in different growing seasons.

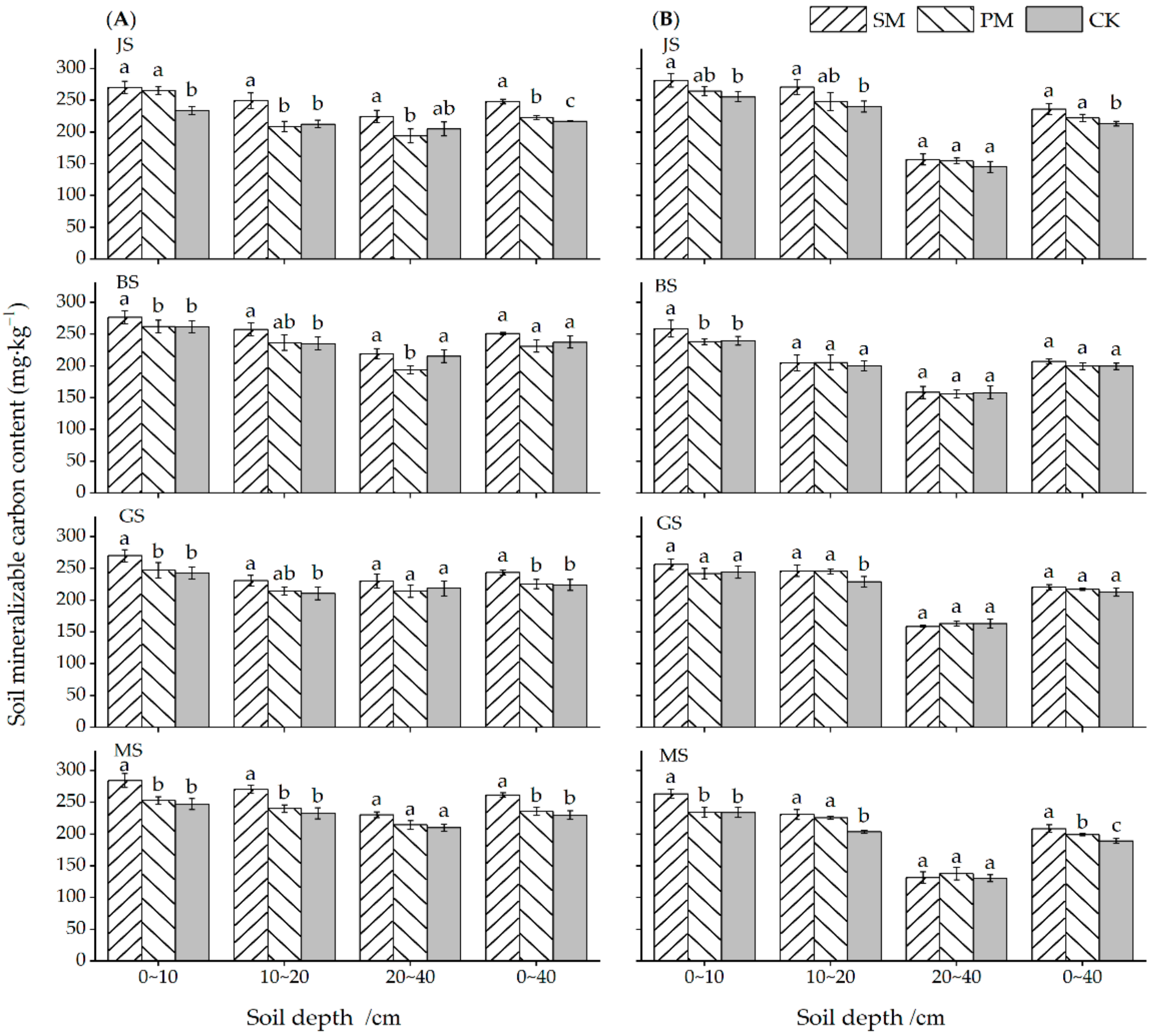

Figure 4. Soil mineralizable carbon contents (PCM) in different growing periods of winter wheat. (**A**) 2019–2020; (**B**) 2020–2021. Lowercase letters denote significance at 5% significance level among treatments. SM: Corn straw strip mulching; PM: plastic film mulching; CK: no mulching; JS: jointing stage; BS: blooming stage; GS: filling stage; MS: maturity stage.

3.5. Differences in EOC Contents under Different Mulching Treatments

Figure 5 shows that the EOC content of different soil layers decreased with increasing soil depth. Compared with CK, the SM treatment promoted the EOC content of the 0–40 cm layer by 6.01–11.68% in both growing seasons, with significant differences in all growth stages except at MS from 2019 to 2020. Among different soil layers, the increase in the 0–10 cm layer ranged from 5.80% to 9.76%, with the highest at GS and with significant differences in all growth stages; the increase in the 10–20 cm layer ranged from 8.09% to 12.39%, with the highest at JS, and the increase in the 20–40 cm layer ranged from 1.74% to 14.06%, with the highest at GS, and existing significant differences in different growth stages in two consecutive growing seasons. The effect of the PM treatment on EOC varied between years, with a positive and higher effect than the SM treatment from 2019 to 2020 and a negative and lower effect than the SM treatment from 2020 to 2021.

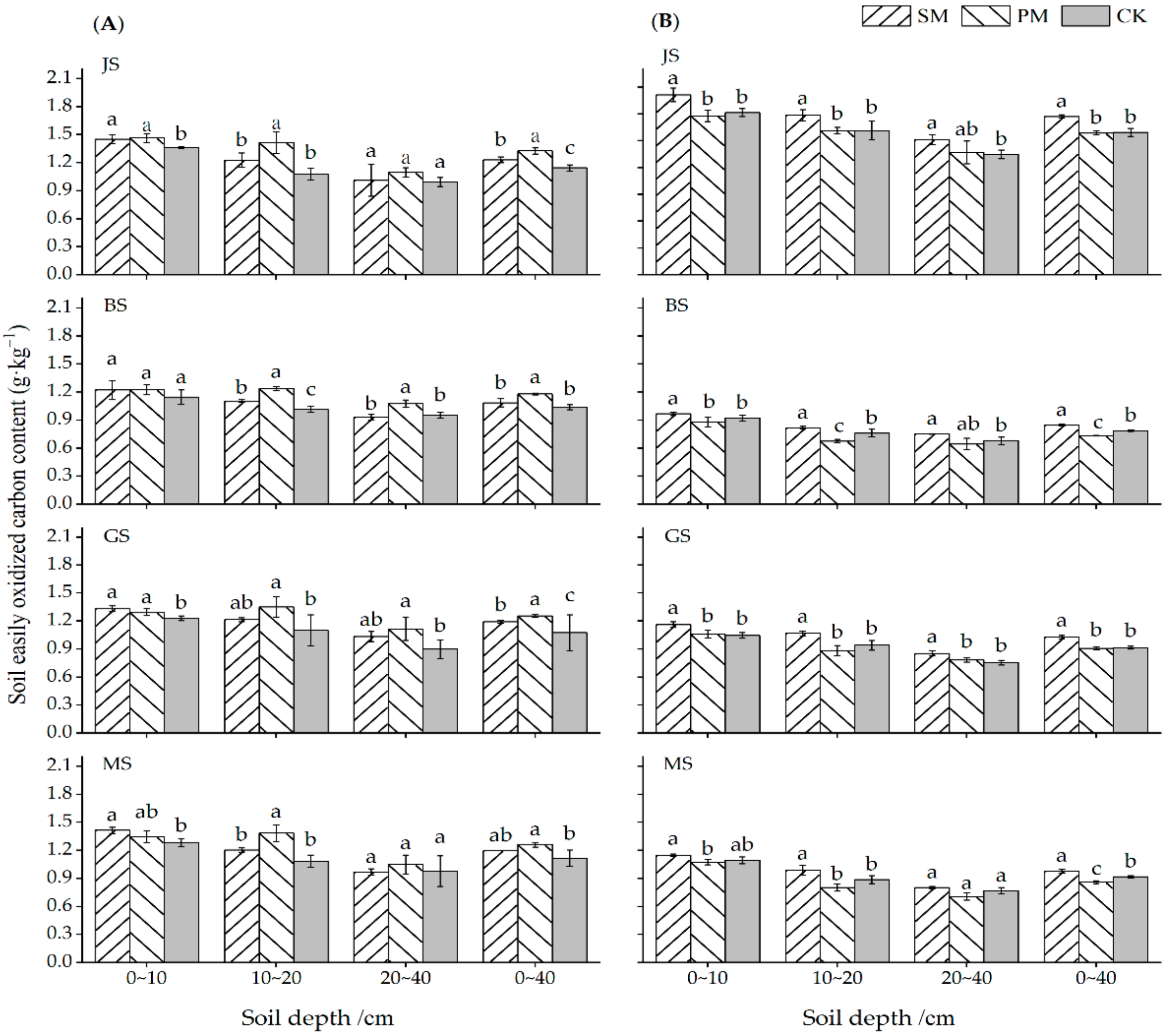

Figure 5. Soil easily oxidized carbon contents (EOC) at different growth stages of winter wheat. (**A**) 2019–2020; (**B**) 2020–2021. Lowercase letters denote significance at 5% significance level among treatments. SM: corn straw strip mulching; PM: plastic film mulching; CK: no mulching; JS: jointing stage; BS: blooming stage; GS: filling stage; MS: maturity stage.

4. Discussion

4.1. Effects of Mulching on SOC

The dynamic characteristics of soil SOC and active components in agricultural soils can reflect soil carbon input and mineralization processes. SM is more conducive to SOC accumulation than PM by improving soil environmental conditions, such as temperature and moisture [24]. The results of our work showed that the SM treatment promoted the SOC content in the 0–40 cm layer compared with CK, Fu et al. [25] also reached a consistent conclusion. SOC in the 0–10 cm and 10–20 cm layers showed the greatest increase and significant differences at MS, while no significant differences were found in the 20–40 cm layer. After the JS, wheat enters the vigorous growth stage, and the demand for nutrients increases, but the increase in air temperature accelerates the decomposition of straw to replenish the soil carbon pool loss at the harvest stage, and plant growth basically stops and the demand for soil nutrients is low, coupled with the plant root secretions and wither organ replenishment, which increases the soil SOC content. Wang et al. [26] concluded that the SOC content was significantly and positively correlated with the root input of winter wheat in the 10–20 cm layer. Unlike SM, PM did not have a significant impact on the SOC content, and Yu et al. [16] also obtained the same result. Although plastic film mulching is beneficial to promote wheat root growth [27], the warming and water retention effects of mulch facilitate the mineralization of soil organic matter [23] and reduce the SOC content [13,24], which causes the accumulation of organic carbon in shallow soil to decrease.

4.2. Effects of Mulching on MBC

Soil MBC is the crucial driving force of the soil carbon cycle, and seasonal changes in the soil microbial community are related to climate, management regimes and soil moisture [28]. In this study, both types of mulching promoted the MBC content in the 0–40 cm layer at different growth periods, and SM was better than the PM treatment, with significant differences in all growth periods under SM in the 0–10 cm layer, whereas significant differences due to PM occurred only at JS and GS. Significant differences in MBC were observed in all growth periods in the 10–40 cm layer from 2019 to 2020, but differences were not significant in 2020–2021, which may be related to the rainfall during the two cropping seasons, with effective rainfall of 243.4 mm at the whole growth stages from 2019 to 2020 and 176.6 mm from 2020 to 2021. Research has shown that soil moisture significantly affects the magnitude of the soil microbial load [29]. The moisture content in each soil layer between the SM and PM in different years and periods exhibited significant differences, which were greatly influenced by the precipitation during the reproductive period, and the moisture retention effect of the straw mulch treatment was greater than the moisture reducing effect, while the plastic film mulching showed a moisture retention effect at JS and a moisture reducing effect at BS [30]. Moreover, full plastic film mulching prevented the exchange of soil air with surface air, increased the soil CO_2 concentration and to some extent inhibited the activity of soil microorganisms [25], leading to a decrease in the MBC content.

4.3. Effects of Mulching on DOC

Soil DOC can be directly used by microorganisms and is the most active and variable part of SOC. In this study, compared with CK, SM treatment obviously improved the soil DOC content because the SM treatment improved the soil hydrothermal conditions, accelerated straw decomposition and crop root metabolism, increased the mass fraction of dissolved organic carbon and thus provided more carbon sources for microorganisms. Furthermore, the elevated microbial activity promoted the activation and decomposition of the insoluble state in the soil [31] and increased the DOC content. Among different soil layers, compared with CK, the DOC content of SM in the 10–20 cm layer increased the highest, that of the 0–10 cm layer was followed, and then that in the 20–40 cm layer. This is due to the fact that DOC mainly originates from plant apoplasts, root secretions and microbial metabolites, and the amount of reactive organic carbon decreases with depth at a certain soil depth. The impact of the PM treatment on DOC was positive from 2019 to 2020 and negative from 2020 to 2021, which may be related to the moisture reduction caused by plastic film mulching, especially the significant variation in soil moisture in the upper soil layer [29] and the decrease in the ability of soil microorganisms to decompose soil organic matter, which reduced the mass fraction of DOC. Moreover, the plastic film mulching increased the surface temperature, which increased the microbial population and soil respiration and increased DOC consumption.

4.4. Effects of Mulching on PCM and EOC

Soil PCM and EOC, the more reactive organic carbon in soils, are sensitive to early changes in the soil environment, and they are significantly correlated but differentially influenced by management practices [32]. Mclauchlan et al. [33] considered the soil carbon pool capacity as the most important factor in agricultural sustainability systems, with changes occurring mainly in the carbon susceptible pool. In our work, the PCM and EOC contents in the 0–40 cm layer was significantly greater in the SM treatments than in CK at JS, GS and MS in both growing seasons. However, the PCM in the 0–40 cm soil layer of the PM treatment was significantly higher than that in CK only at JS, which might be related to the warming effect of the plastic film mulching, where the increase in temperature accelerated the mineralization and decomposition of SOC, which would result in a decrease in the PCM content to a certain extent. The EOC content in the PM treatment showed variable performance between the years, with a positive effect in the 2019–2020 growing season and a negative effect in 2019–2020. Research has shown that the rate of change in PCM and EOC depends on the climate, tillage system, tillage practices and soil moisture [34]. The two mulching treatments differed in their effects on soil temperature and moisture retention, causing different soil microbial communities and root metabolism, which in turn affected the turnover of PCM and ROC.

5. Conclusions

SM can improve soil organic carbon and its component content in the 0–40 cm soil layer in the dryland area of the Loess Plateau in Northwest China. Compared with the control, SM treatment increased SOC, MBC, DOC, PCM and EOC contents in the 0–40 cm soil layer by 5.72%, 15.02%, 9.36%, 8.90%, and 9.49%, respectively, at the whole growth stage, especially in the 0–20 cm soil layer, which was more significant. PM has no significant impact on SOC and its components. Therefore, SM as a promising cultivation technology is superior to PM in maintaining soil carbon balance and improving soil quality, which is conducive to the sustainable management and efficient use of maize straw resources, and it has significant ecological benefits. However, research on SM as an alternative to PM needs to be compared across multiple regions and years in terms of economic benefits.

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