

Effects of Mulch and Planting Methods on *Medicago ruthenica* Seed Yield and Soil Physicochemical Properties (Postprint)

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Abstract

Medicago ruthenica (L.) Trautv., a wild grass species commonly cultivated as forage in arid and semi-arid regions of China, was studied to optimize seed production through mulch patterns and planting methods on the Loess Plateau of Gansu Province from 2017 to 2019. Six treatments were evaluated: (1) flat ground without mulch (F0, control); (2) flat ground with transparent white 0.008 mm thick plastic film mulch (FP); (3) flat ground with 4500 kg/hm² straw mulch (FS); (4) furrow with 10 cm ridges (R0); (5) furrow with plastic film mulch (RP); and (6) furrow with straw mulch (RS). Results demonstrated that harvested seed yield was highest under RP treatment, followed by FP and FS treatments. Soil moisture content from mid-May to mid-August 2017 was highest under RP and FP treatments, followed by RS and FS treatments. In 2018, soil moisture content peaked under RS and FS treatments. During 2017 and 2018, soil temperature was highest under FP and RP treatments, followed by F0 and R0 treatments. Total and available nitrogen, phosphorus, and potassium contents were highest under RS and FS treatments, followed by RP and FP treatments. Comprehensive analysis revealed that surface mulch improved the soil microenvironment and increased *M. ruthenica* seed yield. Straw mulch also effectively recycled excess crop straw, promoting sustainable agricultural development in the region. In conclusion, FS treatment was identified as the optimal mode for *M. ruthenica* seed production in this area.

Full Text

Preamble

Effects of Mulch and Planting Methods on *Medicago ruthenica* Seed Yield and Soil Physical-Chemical Properties

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Keywords: arid area; plastic film; straw mulch; soil moisture content; soil temperature; soil chemistry

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1 Introduction

Medicago ruthenica (L.) Trautv., a perennial herbaceous legume, is widely cultivated as forage in arid and semi-arid regions due to its high yield potential and tolerance to drought and cold (Shu et al., 2018). Its ability to thrive in barren environments makes it promising for forage cultivation and natural grassland reseeded, playing a substantial role in grassland animal husbandry and ecological restoration (Huang et al., 2007; Li et al., 2013; Xiao et al., 2018a). However, mature *M. ruthenica* plants exhibit natural seed dispersal, hindering large-scale seed collection for agricultural purposes. To date, seed production and collection have received limited scientific attention (Li et al., 2006; Li and Shi, 2006), and this difficulty prevents large-scale propagation of the species. Consequently, research on *M. ruthenica* seed production and collection is critically important.

In recent years, modifications to China's agricultural planting structure have

highlighted that forage seed is not only crucial for grassland industry development but also a key factor for forage production. Furthermore, continuous attention to ecological environment protection, animal husbandry development, and urban greening has increased demand for excellent grass varieties and high-quality forage seeds (Shao et al., 2014). These demands have revealed problems associated with low yield and poor benefits in Chinese forage seed production.

Water represents a major limiting factor for *M. ruthenica* seed production in arid and semi-arid areas due to low precipitation and high evaporation. Mulch can effectively maintain soil moisture and improve water utilization in these regions while reducing evaporation and compensating for inconsistent precipitation. Additionally, mulch improves soil environment and considerably increases seed yield (Zhao et al., 2012; Chen et al., 2015; Yang et al., 2018). Current water-saving measures include film mulch, straw mulch, and ridge-furrow systems (Han, 2018). Surface mulch combined with ridge-furrow treatment regulates soil temperature, moisture content, and air permeability, thereby supporting microbial communities and effectively promoting material transformation and nutrient decomposition in arid areas (Liu et al., 2014). Surface mulch with plastic film promotes soil organic carbon (SOC) and total nitrogen (TN) mineralization while effectively increasing available nitrogen (AN), phosphorus (AP), and potassium (AK) contents. However, soil water collected in shallow layers under plastic mulch is absorbed by crops from lower layers during growth, causing upward water movement from deep layers and reducing deep-layer water content (Zhou et al., 2012; Kader et al., 2017). In straw mulch systems, straw decomposes to produce organic compounds under favorable soil conditions. Combined with rainwater seepage, this leads to gradual mulch breakdown, increasing SOC and available nutrient contents. Thus, straw mulch serves as an important source of soil organic matter (SOM) (Tang, 2019). In wheat and maize straw mulch studies, SOC and TN contents at 0–10 cm soil depth increased by 16.9% and 7.7%, respectively, compared to control treatment (Shao et al., 2016). However, previous studies have observed that plants absorb excess soil AN, AP, and AK during growth and development, decreasing available soil nutrients (Hu et al., 2012; Yin et al., 2016).

The Longzhong Area, located in central Gansu Province and comprising 16.8% of the province's area, exhibits irregular and highly variable annual precipitation distribution, with most rainfall occurring from July to September. Due to concentrated rainfall during the plant growth season, Longzhong represents typical rain-fed agriculture (Liu and Wang, 2018). However, research on mulch treatment effects on *M. ruthenica* seed yield and soil nutrient contents has received limited attention in this region (Luo et al., 2014). Our objectives were to analyze the effects of different mulch treatments on *M. ruthenica* seed yield and soil physical-chemical properties in the arid Longzhong Area. These results may provide a theoretical basis for guiding forage cultivation and precision fertilization in similar regions.

2.1 Study Site

The study site was located in the Longzhong Area, Gansu Province, China (35°58'N, 104°62'E) at an altitude of 2000 m a.s.l. The dominant soil type is yellow soil, with average annual sunshine of 2409 h, average annual precipitation of 427 mm (extremely unevenly distributed), and average annual evaporation of 1510 mm. The annual average temperature is 6.3°C, with average annual active accumulated temperatures \$ 5.0°C and \$ 10.0°C of 2782.5°C and 2239.1°C, respectively. Temperature extremes range from -27.1°C to 34.3°C, and the average annual frost-free period is 141 d (Liu and Wang, 2017). Soil pH ranges from 7.0 to 8.2. SOM, TN, total phosphorous (TP), and total potassium (TK) contents are 47.81, 1.38, 1.10, and 8.36 g/kg, respectively. Furthermore, AN, AP, and AK contents are 36.32, 7.37, and 159.89 mg/kg, respectively. Average monthly temperature and precipitation from 2017 to 2019 are shown in Figure 1 [Figure 1: see original paper].

2.2 Experimental Design

The experiment comprised six treatments, each with 30 cm row spacing: (1) flat ground without mulch (F0, control); (2) flat ground with transparent white 0.008 mm thick plastic film mulch (FP); (3) flat ground with 4500 kg/hm² straw mulch (FS); (4) furrow with 10 cm ridge (R0); (5) furrow with plastic film mulch (RP); and (6) furrow with straw mulch (RS; Fig. 2 [Figure 2: see original paper]). In the ridge-furrow design, plants were grown in the furrow, not on the ridge. Each plot measured 2 m × 5 m, with 0.5 m between treatments. The experimental design was a randomized block with three replications. Seeds were sown on May 2, 2017, using hole seeding with appropriate supplementation or reduction of seedlings at 2–3 cm depth, with 5–10 seeds per hole to ensure 3–5 surviving plants per hole. Plant spacing was 10 cm and row spacing was 30 cm. Before sowing, *M. ruthenica* seeds were soaked in 98% concentrated sulfuric acid for 15 min, followed by washing with running water to break the hard seed coat.

2.3.1 Performance Seed Yield

Performance seed yield (kg/hm²) was calculated using Equation 1:

$$Y = \frac{P \times S \times W}{1000} \times 10$$

where Y is performance seed yield (kg/hm²), P is the number of pods per unit area (m²), S is the number of seeds per pod, and W is thousand-seed weight (g) (Xiao et al., 2018b).

2.3.2 Actual Seed Yield

Due to natural seed dispersal at maturity, actual seed yield was measured by selecting a 1-m² sample area away from plot edges during the seed maturity stage. This process was repeated three times per treatment to calculate the average value.

2.3.3 Soil Moisture Content, Soil Bulk Density, and Soil Porosity

Soil samples were collected monthly on sunny days during the *M. ruthenica* growing season (soil moisture from mid-May to mid-September in 2017 and 2018; bulk density and porosity from mid-May to mid-September in 2018 and 2019). Three soil profiles were assessed using randomly excavated soil from each treatment, with five samples collected from 10 cm increments (0–10, 10–20, 20–30, 30–40, 40–50, 50–60, 60–70, and 70–80 cm) using a 5-cm diameter soil ring knife. Each cylindrical sample was placed in a sample box and transferred to the laboratory. Samples were dried in an electric thermostatic air-blowing drying oven (GZX-GF101-3-BS-, Shanghai, China) at 105°C until constant weight was achieved for measurements and calculations.

Soil moisture content was calculated using Equation 2:

$$M = \frac{M_2 - M_0}{M_1 - M_0} \times 100$$

where M is soil moisture content (%), M_2 is wet soil mass in the aluminum box (g), M_1 is dry soil mass in the aluminum box (g), and M_0 is empty aluminum box weight after drying to constant weight (g) (Wilke, 2005).

Soil bulk density was calculated using Equation 3:

$$B = \frac{W_1 - W_0 \times (1 - M/100)}{V}$$

where B is soil bulk density (g/cm³), W_1 is total weight of ring knife and fresh soil (g), W_0 is total weight of ring cutter (g), M is soil moisture content (%), and V is soil core volume (100 cm³).

Soil porosity was calculated using Equation 4:

$$P = \left(1 - \frac{B}{G}\right) \times 100$$

where P is soil porosity (%) and G is soil specific gravity fixed at 2.65 g/cm³.

2.3.4 Soil Temperature

Soil temperature was determined on one sunny day in the middle of each month during the growing season. A curved-tube geothermometer measured temperature at 5-cm intervals from 5–25 cm depth. Measurements were recorded every 2 h from 08:00 to 18:00 (LST), with each measurement repeated three times to obtain average values (Zhou et al., 2017).

2.3.5 Soil Compactness

Soil compactness was measured using a soil compactness meter (SC-900, Spectrum, USA) up to 30 cm depth, with 20 measurements made per plot.

2.3.6 Soil Nutrients

Soil nutrients change gradually and were collected once during mid-October between 2018 and 2019. Soil cores were collected as described in Section 2.3.3 using a 3.5-cm diameter soil auger. After removing visible debris, samples were placed in zip-top bags and transported to the laboratory. Following natural drying, samples were passed through 0.25-mm and 1.00-mm sieves for nutrient analysis (Hou et al., 2018).

Following Bao (2000), SOM content was determined using potassium dichromate titration. Soil TN was determined using the Kjeldahl method. Soil TP was determined using the molybdenum blue method with an ultraviolet-visible spectrophotometer (SP-756P, Shanghai Guangpu Instruments Co., Ltd., China). Soil TK was determined using NaOH melt-flame photometry. Soil AN was determined using the alkali-hydrolyzed diffusion method. Soil AP was determined using the 0.5 mol/L NaHCO₃-molybdenum-antimony resistance colorimetric method. Soil AK was extracted using NH₄OAC with flame photometry.

2.4 Statistical Analysis

Microsoft Excel 2010 was used for data collation and visualization, with all values expressed as mean \pm standard error (SE). SPSS v.22.0 (SPSS Inc., Chicago, IL, USA) was used for one-way analysis of variance. Generalized linear model (GLM) analyzed the effects of planting years and mulch treatments on seed production and soil properties. Significance was determined at $P < 0.05$, with Duncan's method used for multiple comparison analysis.

3.1 Seed Yield of *M. ruthenica*

Performance and actual seed yields from 2017 to 2019 were highest under RP treatment and lowest under F0 treatment. Seed yield under FS treatment was consistently higher than under RS treatment. Furthermore, plastic mulch produced the highest seed yield, followed by straw mulch (Fig. 3 [Figure 3: see original paper]). Seed yields under R0 and F0 treatments were significantly

lower than other treatments from 2017 to 2018 ($P < 0.05$). No significant differences were observed between RP and FP, between RS and FS, or between R0 and F0 treatments for performance and actual seed yields ($P > 0.05$). The average actual seed yield during 2017–2019 ranged from 203–279 kg/hm² (Fig. 3b).

Under the same treatment, performance seed yield in 2018 was significantly higher than in 2017 and 2019 ($P < 0.05$), with no significant difference between 2017 and 2019 (Fig. 3a). Actual seed yield in 2018 was significantly higher than in 2017 for all treatments, with no significant difference between 2018 and 2019 under R0 and F0 treatments ($P > 0.05$; Fig. 3b).

3.2.1 Soil Moisture Content

In 2017, from mid-May to mid-August, soil moisture content at each depth followed the order: R (furrow) > F (flat ground), P (plastic film mulch) > S (straw mulch) > 0 (no mulch), with 0–10 and 10–20 cm depths showing slightly higher values than other depths (Fig. 4 [Figure 4: see original paper]). However, in mid-September, soil moisture under RS and FS treatments exceeded that under RP and FP treatments. Soil moisture under R0 and F0 treatments was significantly lower than other treatments ($P < 0.05$).

In 2018, from mid-June to mid-August, soil moisture content was highest under RS treatment and lowest under F0 treatment (Fig. 4). Under RP treatment, soil moisture was consistently higher than under FP treatment. Moreover, plastic mulch was more effective than straw mulch. Soil moisture in each treatment decreased with increasing soil depth.

From mid-June to mid-July, soil moisture under RS and FS treatments was significantly higher than under F0 treatment at 0–80 cm depth, while moisture at 40–80 cm under RS and FS treatments was significantly higher than other treatments ($P < 0.05$).

3.2.2 Soil Temperature

From mid-May to mid-September in 2017 and 2018, average daily soil temperature increased most rapidly with plastic mulch treatments, followed by control and straw mulch treatments (Fig. 5 [Figure 5: see original paper]). Soil temperature exhibited significant daily variation at 5–10 cm depth but not at 10–25 cm depth. Average soil temperature showed an inverse relationship with soil depth. From 08:00 to 18:00 daily, soil temperature at each depth first increased then decreased.

In mid-May, mid-June, and mid-September 2017, soil temperature peaked at 14:00 then gradually decreased. In contrast, temperature peaked at 16:00 in mid-July and mid-August 2017, and in mid-June, mid-July, and mid-August 2018.

From mid-May to mid-September 2017, soil temperature under RP treatment at 08:00 was highest, followed by FP treatment (Fig. 5). At 5 cm depth, from mid-May to mid-August, temperatures under RP and FP treatments were significantly higher than other treatments ($P < 0.05$), with FP treatment significantly exceeding RP at 10:00, 12:00, 14:00, 16:00, and 18:00. In mid-May, mid-June, and mid-August, temperature under RS treatment was significantly lower than under RP and FP treatments ($P < 0.05$). In mid-September at 5 cm depth, no significant difference was observed between RP and FP treatments ($P > 0.05$).

3.2.3 Soil Bulk Density, Soil Porosity, and Soil Compactness

In 2018 and 2019, soil bulk density was lowest under straw mulch and highest under control treatment (Fig. 6a [Figure 6: see original paper]). Bulk density at 0–20 cm depth was lowest under RP, FP, RS, and FS treatments. Analysis of variance showed that growth year did not significantly affect soil bulk density, but treatment effects were highly significant at 0–20 cm depth ($P < 0.01$).

In 2018 and 2019, soil porosity was highest under FS treatment and lowest under R0 treatment (Fig. 6b). Furthermore, porosity was consistently higher under flat ground than furrow treatments. Porosity peaked at 0–10 and 10–20 cm depths, then decreased with increasing depth. Growth year showed no significant effect on soil porosity, while treatment effects were highly significant at 0–10 and 10–20 cm depths ($P < 0.01$).

In 2018 and 2019, straw mulch treatments exhibited the lowest soil compactness, while control treatment showed the highest values (Fig. 6c). Compactness increased then decreased with depth, with maximum values at 10–20 cm depth ranging from 110–152 kPa. Growth year did not significantly affect soil compactness, but treatment significantly affected compactness at 0–10 cm depth ($P < 0.01$). Interaction between growth year and treatment had no significant effect on bulk density, porosity, or compactness ($P > 0.05$).

3.3.1 SOM, Soil TN, and AN

In 2018 and 2019, SOM content was highest under RS treatment and lowest under FP treatment, with straw mulch $>$ no mulch $>$ plastic film mulch ($S > 0 > P$; Fig. 7a [Figure 7: see original paper] and b). Compared to control, straw mulch increased SOM content while plastic film mulch reduced it. SOM content decreased with soil depth. At 0–10 cm depth, SOM under RS and FS treatments was significantly higher than under RP and FP treatments ($P < 0.05$). No significant differences were observed among treatments at 10–40 cm depth ($P > 0.05$). Growth year significantly influenced SOM content ($P < 0.01$), and treatment effects were highly significant at 0–10 cm depth ($P < 0.01$).

In 2018 and 2019, soil TN content was highest under straw mulch, followed by plastic film mulch ($S > P$), with lowest values under no mulch treatment (Fig. 7c and d). TN content showed an inverse relationship with soil depth. At

0–40 cm depth, no significant differences in TN content were observed among treatments in 2018 and 2019 ($P > 0.05$). Growth year, treatment, and their interaction did not significantly affect soil TN content ($P > 0.05$).

In 2018 and 2019, soil AN content decreased with increasing soil depth (Fig. 7e and f). In 2019, AN contents under RS and FS treatments were significantly higher than under F0 treatment ($P < 0.05$), but no significant differences were observed among other treatments. No significant differences in AN content were found among treatments at 10–40 cm depth ($P > 0.05$). Growth year did not significantly affect AN variation, while treatment had highly significant effects at 0–10 cm depth ($P < 0.01$).

3.3.2 Soil TP, AP, TK, and AK

In 2018 and 2019, soil TP content was highest under straw mulch, followed by plastic film mulch ($S > P$), decreasing with soil depth (Fig. 8a [Figure 8: see original paper] and b). Growth year did not significantly affect TP content, while treatment significantly affected TP at 0–10 and 10–20 cm depths ($P < 0.05$).

In 2018 and 2019, soil AP content was highest under RS treatment and lowest under F0 treatment (Fig. 8c and d). AP content under straw mulch exceeded that under plastic film mulch. In 2018, AP content under RS treatment at 0–10 cm depth was significantly higher than under F0 treatment ($P < 0.05$). In 2019, AP contents under RS and FS treatments were significantly higher than under R0 and F0 treatments ($P < 0.05$). No significant differences were observed at other depths ($P > 0.05$). Growth year did not significantly affect AP content, while treatment had highly significant effects at 0–10 cm depth ($P < 0.01$).

In 2018 and 2019, soil TK content was highest under straw mulch, followed by plastic film mulch, decreasing with soil depth (Fig. 8e and f). Growth year significantly affected TK content at 0–10 and 10–20 cm depths ($P < 0.01$), and treatment significantly affected TK at 0–10 cm depth ($P < 0.01$).

In 2018 and 2019, soil AK contents under RS and FS treatments were significantly higher at 0–10 and 10–20 cm depths than other treatments ($P < 0.05$; Fig. 8g and h). No significant differences were observed at 20–30 and 30–40 cm depths ($P > 0.05$). Growth year did not significantly affect AK content, while treatment effects were highly significant at 0–10 and 10–20 cm depths ($P < 0.01$). Interaction between growth year and treatment did not significantly affect TP, AP, TK, or AK contents ($P > 0.05$).

4.1 Effects of Mulch and Planting Methods on *M. ruthenica* Seed Yield

Our three-year experiment revealed that *M. ruthenica* seed yield was highest under plastic film mulch and lowest without mulch. Since surface cover treatment and ridge–furrow planting methods accumulated natural rainfall, seed yield

likely increased through improved plant water utilization efficiency. The ridge funnels rainfall into the furrow, and during early crop growth, plastic film mulch provided higher water retention than straw mulch (Fig. 4). Studies have shown that increased temperature and water availability enhance crop growth under mulch conditions. By increasing temperature and promoting water consumption, mulch cultivation can extend crop growth periods and increase dry weight per plant (Li et al., 2018; Chen et al., 2019). Consequently, *M. ruthenica* seed yield under plastic mulch exceeded that under straw mulch. In the first year (2017), plastic mulch produced the highest soil moisture content (Fig. 4) and soil temperature (Fig. 5), explaining the highest seed yields under FP and RP treatments. Additionally, seed yield peaked in the second year (2018).

A substantial gap existed between performance and actual seed yields. Results showed that potential seed yield of forage crops is extremely high, but actual seed yield is very low, with a gap of approximately 12%–20% (Han et al., 1996). Additionally, *M. ruthenica* exhibits a 93% splitting rate when seeds are fully mature, with a high proportion of splitting pods (Li et al., 2006). During harvesting, inconsistent seed pod splitting and maturity caused substantial losses and discrepancies between performance and actual seed yields.

All mulch treatments improved soil microenvironment compared to control, primarily by increasing soil moisture and nutrient contents. Although plastic film mulch produced high seed yield, moisture content, and temperature, plastic film remains in soil and degrades slowly, which is detrimental to crop emergence and normal growth (Yan et al., 2006). Plastic film is potentially harmful to soil physical and chemical properties, including white pollution from film residue that has become a soil pollution source (Qi et al., 2020; Xu et al., 2020). Straw mulch produced similar or equal effects on seed field and soil properties compared to plastic, and in some cases resulted in higher soil nutrient contents. Therefore, straw mulch methods should be prioritized for sustainable *M. ruthenica* development in the arid Longzhong Area.

4.2.1 Soil Moisture Content

Both plastic film and straw mulch effectively increased soil moisture content in this study. In 2017, RP and FP treatments produced the highest soil moisture, followed by RS and FS treatments. The higher moisture under ridge-furrow versus flat ground methods likely resulted from ridge planting effectively collecting rainfall and sheltering growth areas from wind evaporation, thereby improving water retention compared to flat ground methods. Soil moisture content and seed yield under plastic film mulch in 2017 were higher than other treatments. Plastic film mulch inhibits soil moisture evaporation, creating internal water circulation (Zhou et al., 2009). This circulation promotes soil water movement and accumulation from deeper depths to the surface, improving water retention (Liang et al., 1990). In this study, straw mulch produced higher soil moisture than plastic film mulch in 2018. Straw mulch inhibited soil water evaporation and ensured water demand was met during *M. ruthenica*'s later growth pe-

riod, thus promoting seed production. Additionally, the rough straw surface effectively intercepted rainfall, decreased surface runoff, and allowed water to infiltrate the soil, increasing soil moisture content (Li et al., 2013).

Due to high soil evaporation in the study area, soil moisture content first increased then decreased during the *M. ruthenica* growth period (Peng et al., 2018). Moreover, cool weather and increased rainfall in mid-September 2017 (Fig. 4) caused moisture content to decrease. We found that soil moisture under RS and FS treatments exceeded that under RP and FP treatments, and moisture under plastic film mulch decreased with soil depth. Therefore, plastic film mulch effects on increasing soil temperature and moisture were superior to straw mulch, significantly improving *M. ruthenica* growth in 2017. However, rapid *M. ruthenica* growth consumed more soil moisture, causing dehydration in the later growth period (Lu et al., 2016). Simultaneously, plastic film mulch encouraged water movement upward from deeper soil depths, depleting moisture at deeper layers. Therefore, plastic mulch is not conducive to long-term sustainable *M. ruthenica* development (Zaongo et al., 1997; Li et al., 1999).

4.2.2 Soil Temperature

Soil temperature directly affects plant development and seed emergence, and can be influenced by land cover materials and planting methods. In this study, daily soil temperature under plastic film mulch exceeded that under straw mulch, suggesting that plastic film effectively absorbs solar energy and transmits heat to the soil surface. When air temperature drops, retained heat from deeper soil depths moves toward the surface. Plastic mulch traps this heat at the surface, providing effective thermal insulation (Chen, 2012; Jiang et al., 2016). This thermal insulation benefited *M. ruthenica* seedling emergence, which was important for later growth and development. Straw mulch also delays soil heat emission into the atmosphere and effectively prevents daily temperature variations, thereby promoting root and stem system growth and increasing *M. ruthenica* seed yield (Fig. 3; Tang, 2019).

4.2.3 Soil Bulk Density, Soil Porosity, and Soil Compactness

Soil bulk density indirectly reflects crop root growth and SOM accumulation, with lower bulk density indicating looser soil. Soil porosity is also important for crop root growth because it controls soil moisture, fertility, aeration, and heat (Wang et al., 2015; Li et al., 2019). We found that plastic film and straw mulch decreased soil bulk density and compactness while increasing porosity, indicating that surface mulch effectively improved soil structure. Moreover, bulk density and compactness at 0–20 cm depth under all mulch treatments were significantly lower than under no mulch treatment, and bulk density under furrow-ridge treatment exceeded that under flat ground treatment. These results were associated with improved soil moisture and temperature conditions. Under mulch treatment, rainfall directly hitting the ground was blocked, pre-

venting compaction and promoting loose soil structure. However, Wang et al. (2015) found that during heavy rain, water collected in furrows eventually increased soil compactness and bulk density while decreasing porosity. In this study, bulk density under FS treatment was significantly lower than under R0 and F0 treatments, likely attributed to reduced porosity caused by long-term surface mulch. Straw mulch benefits soil aggregate structure and porosity formation, promoting proper plant root growth and spatial distribution (Bodner et al., 2015; Liao et al., 2021). Therefore, straw mulch can create an isolated buffer zone to reduce soil bulk density and compactness while increasing porosity (Mulumba and Lal, 2008; Xu et al., 2017).

4.3 Effects of Mulch and Planting Methods on Soil Chemical Properties

Soil nutrient contents increased under all mulch treatments compared to control, confirming that mulch effectively improved soil fertility and promoted crop growth (Dong et al., 2017). Moreover, SOM content under straw mulch exceeded that under plastic film mulch. Mulch maintenance of soil moisture and temperature accelerated straw decay and decomposition, releasing organic particles that infiltrated soil and increased SOM in shallow zones (Akhtar et al., 2018). Meanwhile, surface mulch and ridge-furrow treatments improved soil microenvironment. *M. ruthenica* might utilize soil fertility by accelerating nutrient conversion and utilization. As *M. ruthenica* absorbed soil nutrients, SOM content decreased with mineralization without additional fertilization. However, leguminous forage rhizobia nitrogen fixation can provide required nitrogen nutrients during legume plant growth, thereby reducing soil nitrogen use. Thus, planting legume forage did not significantly affect soil TN content. Meanwhile, nutrient contents decreased over time without additional fertilization, particularly under plastic film mulch where fast early growth consumed more nutrients than other treatments, reducing soil fertility in later growth stages (Pu et al., 2006). Therefore, successive years of plastic film mulch could eventually exhaust soil nutrients, which is not conducive to maintaining soil fertility or sustainable agriculture.

5 Conclusions

This study found that performance and actual seed yields of *M. ruthenica* were highest under plastic film mulch, followed by straw mulch. Soil moisture content in the first planting year was highest under RP and FP treatments, followed by RS and FS treatments. In the second year, moisture content under straw mulch exceeded other treatments. Soil temperature was highest under FP and RP treatments, followed by F0 and R0 treatments. Soil nutrient contents were highest under RS and FS treatments and generally decreased with soil depth. Meanwhile, mulch had negligible effects on soil total nutrient contents but significantly affected available nutrient contents. All treatments improved shallow soil physical-chemical properties compared to control, with straw mulch showing

the best effects. Comprehensive data analysis demonstrated that straw mulch is preferred for *M. ruthenica* seed production in the Longzhong Area and similar regions, with appropriate potassium and phosphate fertilizer supplementation.

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