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Alfalfa Cultivation Patterns in the Yellow River Irrigation Area on Soil Water and Nitrogen Use Efficiency

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Abstract: Establishing lucerne field is an efficient way to protect natural steppes, alleviate conflicts between meadows and livestock, and promote the development of animal husbandry. However, problems such as extensive field management, valuing yield over quality, and low resource utilization are endemic in production. Exploring reasonable cultivation patterns can contribute to improving the current situation of artificial grassland production and promoting the high-quality development of husbandry and prataculture. Lucerne the field experiment was carried out in Jingtai, Gansu Province, China in 2021–2022; this study compared and analyzed the effects of three cultivation patterns—ridge tillage with plastic film mulching (PM), ridge tillage with biodegradable film mulching (BM), and traditional flat planting (FP)—on soil water, heat, and fertilizer, as well as lucerne growth, yield, quality, and water and nitrogen use efficiency. The results show that: (1) during the growth period of lucerne, PM and BM treatments augment the average moisture content of the soil layer of 0–120 cm by 31.19% and 24.03% compared to the FP treatment, respectively. In the soil layer of 0–40 cm, PM and BM treatments abate the soil moisture content of the ridges by an average of 19.29% and 7.89% compared to that in the ditches, respectively. In the soil layer of 40–120 cm, PM and BM treatments elevate the soil moisture content of the ridges by 4.40% and 4.65% on average compared to that in the ditches, respectively. The average soil temperature in a soil layer of 5–25 cm shows PM > BM > FP. In contrast with the FP treatment, PM and BM treatments increase the soil temperature of the ridges by an average of 1.87 °C and 0.96 °C and decrease that of the ditches by an average of 0.47 °C and 0.46 °C, respectively. After two years of planting, the three cultivation patterns all promote the soil nutrient content. Compared to the FP treatment, PM and BM treatments increase the organic matter content by 9.94% and 19.94%, respectively. (2) Ridge tillage with film mulching can evidently stimulate the growth of lucerne and enhance yield and quality. Compared to the FP treatment, PM and BM treatments enhance plant height by an average of 15.37% and 4.04%, stem diameter by an average of 34.14% and 14.58%, yield by an average of 21.20% and 14.77%, crude protein content by an average of 13.47% and 7.68%, and relative feed value by an average of 8.71% and 4.41%, respectively. (3) During the two-year growing period, the irrigation amount of lucerne was 508.60–615.30 mm, and the evapotranspiration was 563.70–761.80 mm. Compared to the FP treatment, PM and BM treatments hoist water use efficiency by an average of 43.50% and 17.56%, nitrogen partial factor productivity by an average of 21.20% and 15.22%, and net income by an average of 14.78% and 11.05%, respectively. In summary, in ridge tillage, both ordinary film mulching and biodegradable film mulching can create a favorable soil environment for lucerne growth and heighten production effect. The former has a better effect on advancing the lucerne production effect, and the latter exhibits superior performance in improving soil fertility.

Keywords: soil environment; cultivation pattern; biodegradable membrane; yield; water and nitrogen use efficiency; economic benefits

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1. Introduction

Due to the advantages of high yield, high quality, strong adaptability, and good economic benefits, lucerne (*Medicago sativa* L.) is known as the "king of pasture" [1]. It can increase land vegetation coverage, curb soil desertification and soil erosion, and fix nitrogen through its root nodules, playing a crucial role in improving regional eco-environments and soil fertility [2,3]. Lucerne is mainly grown in the United States, Canada, France, and Italy. As an artificial pasture, its planting area is the largest in the world. In recent years, China has attached great importance to the development of the lucerne industry and has successively formulated and implemented documents such as "coordinating and adjusting the planting structure of grain, economic, and forage crops", "expanding the pilot area of grain to forage conversion and accelerating the construction of a modern forage industry system", and "14th five-year national development plan for the forage industry". As of 2022, the lucerne planting area in China has reached 600,000 ha, accounting for 15% of the world's total planting area, second to the United States (36%) [4]. However, in the context of emphasizing agriculture and assisting animal husbandry in China, lucerne is mostly planted in arid and semi-arid areas with scarce water resources and soil nutrients. Moreover, multiple drawbacks exist in lucerne cultivation, such as single planting mode, extensive field management, and low productivity levels. There is a tremendous gap between China's lucerne production capacity and market demand. In particular, high-quality lucerne still relies on imports. Therefore, in response to the resource endowment characteristics of arid and semi-arid regions, investigating reasonable lucerne cultivation patterns to improve the soil micro-environment and stimulate the production potential of lucerne is of great significance for efficient lucerne production and the rapid development of grassland animal husbandry in China and worldwide.

Water is a primary environmental factor that limits crop growth [5]. Ridge tillage with film mulching integrates ridge tillage and film mulching, which can effectively suppress ineffective soil moisture evaporation, encourage the precipitation of the ridges to flow into the ditches, increase the infiltration depth and content of soil moisture in the ditches, and transform "ridge water" and "ditch water" into each other, making them serve as the source and sink mutually [6,7]. The soil moisture effect of ridge tillage with film mulching is closely related to factors such as ridge size and mulching material [8,9]. Research has shown that the rainwater collection efficiency of ridge tillage with film mulching is significantly higher than that of ridges, and the optimal effect can be achieved when the ridge-to-ditch ratio is 60 cm:60 cm [10,11]. Ridges mulched with ordinary films and biodegradable films can evidently enhance soil water storage. Because biodegradable films can gradually degrade with crop growth, the water storage effect in the later stage decreases compared to ridge tillage with ordinary film mulching [12–14]. Soil temperature is another major environmental factor that impacts crop growth [15]. Ridge tillage can expand the surface area of the soil receiving solar radiation and the temperature gap between day and night by altering microtopography. Mulching can elevate soil temperature on ridges by blocking solar long-wave radiation and absorbing more shortwave radiation [13,16,17]. However, the soil temperature effect of ridge tillage with film mulching varies with mulching material. It has been reported that the accumulated temperature of soil covered with ordinary films is significantly higher than that of soil mulched with black films [18,19]. The warming effect of novel mulching materials before degradation, such as biodegradable and liquid films, barely differs from that of ordinary plastic films [20–22]. The timely peeling of films during crop growth can effectively abate the phenomenon of crop premature senescence caused by high temperatures [23–25]. In addition to water and temperature, soil nutrients are another key environmental factor that affects crop growth [26]. Ridge tillage with film mulching affects soil water and thermal conditions, the soil's bacterial community structure, and soil enzyme activity, which further influences soil nutrient content and distribution [6,16]. Research has proven that mulching can significantly increase the abundance and variety of soil microorganisms, thereby decomposing more large particulate organic matter and returning it to the soil [23,27,28]. Compared with traditional flat cropping, the soil enzyme activity and the content of available nitrogen, phosphorus, and potassium in the plow layer of ridge tillage with rainwater harvesting are significantly promoted [10,29,30]. Under the condition of ridge tillage with film mulching, the optimal soil water, heat, and fertilizer can provide a favorable environment for crop growth, thereby improving crop production. It has been revealed that, when comparing flat planting with film mulching and ridge tillage without film mulching, ridge tillage with film mulching profoundly improves crop yield, quality, water and fertilizer use efficiency, and increases economic benefits. In ridge tillage, the improvement effects of ordinary film mulching and biodegradable film mulching surpass that of liquid film mulching [31–33]. The production effects of biodegradable membranes are tightly linked to the formula of the membranes and the environmental conditions of the experimental areas [34]. In high-altitude and low-temperature areas, using biodegradable films 0.008 mm thick are more conducive to improving the yield of crops mulched with biodegradable films [35].

To sum up, ridge tillage with film mulching can remarkably improve the soil environment and crop productivity. The effect varies with mulching material. Existing research on ridge tillage with film mulching mostly focuses on field crops [36,37] and cash crops [38–40]. There is a lack of studies on the soil environment and the production effect of the forage crop lucerne. Notably, systematically comparing the comprehensive response mechanism of lucerne with ordinary film mulching and biodegradable film mulching is insufficient. Gansu has developed into an essential production base of high-quality lucerne in China. As of 2023, the lucerne planting area in Gansu has reached 193,300 ha, accounting for 1/4 of the total planting area in China and ranking first in the country. The Yellow River Irrigation Area in Gansu Province is the second largest lucerne production area after the Hexi Corridor region. It has abundant light and heat resources and a wide temperature difference between day and night, which provide unique advantages in planting lucerne [41]. However, the region has sparse precipitation, severe soil salinization, a single lucerne planting pattern, and low and unstable productivity. In view of this, this study took lucerne from the Yellow River Irrigation Area in Gansu Province as the research object, aiming to (1) clarify the regulatory effects of ridge tillage with ordinary film mulching, ridge tillage with biodegradable film mulching, and traditional flat cropping on soil water, heat, and fertilizer; (2) quantify the impacts of the three cultivation patterns on the growth, yield, quality, and use efficiency of water and nitrogen and the economic benefits of lucerne; (3) obtain the planting model of lucerne with high yield, high quality, and high efficiency in the Gansu Yellow River Irrigation Area and similar ecological areas to provided a theoretical basis for the restoration of natural grassland and the high-quality development of animal husbandry.

2. Materials and Methods

2.1. Description of the Experimental Site

The experiment was conducted in 2021 and 2022, from April to October, at the Irrigation Test Station of the Jingtaichuan Electric Power Irrigation Water Resources Utilization Center in Gansu Province (37°23′ N and 104°08′ E, with an altitude of 1562 m). The average annual precipitation, evaporation, sunshine hours, radiation volume, temperature, and frost-free period in the area were 191.6 mm, 2761 mm, 2652 h, 6.18×10^5 J·cm^{-2}, 8.5 °C, and 191 days, respectively. The soil of the experimental land was sandy loam, with a dry bulk density of 1.45 g·cm^{-3}, a field water capacity of 24.1% (mass moisture content), and a pH of 8.11. The soil organic matter, total nitrogen, total phosphorus, total potassium, available nitrogen, available phosphorus, and available potassium in the soil layer of 0–40 cm were 1.32 g·kg^{-1}, 1.62 g·kg^{-1}, 1.32 g·kg^{-1}, 34.03 g·kg^{-1}, 74.51 mg·kg^{-1}, 26.31 mg·kg^{-1}, and 173 mg·kg^{-1}, respectively. The total precipitations during the growth period of lucerne in 2021 and 2022 were 147.43 mm and 170.46 mm, and the average temperatures were 19.07 °C and 18.77 °C, respectively (Figure 1).

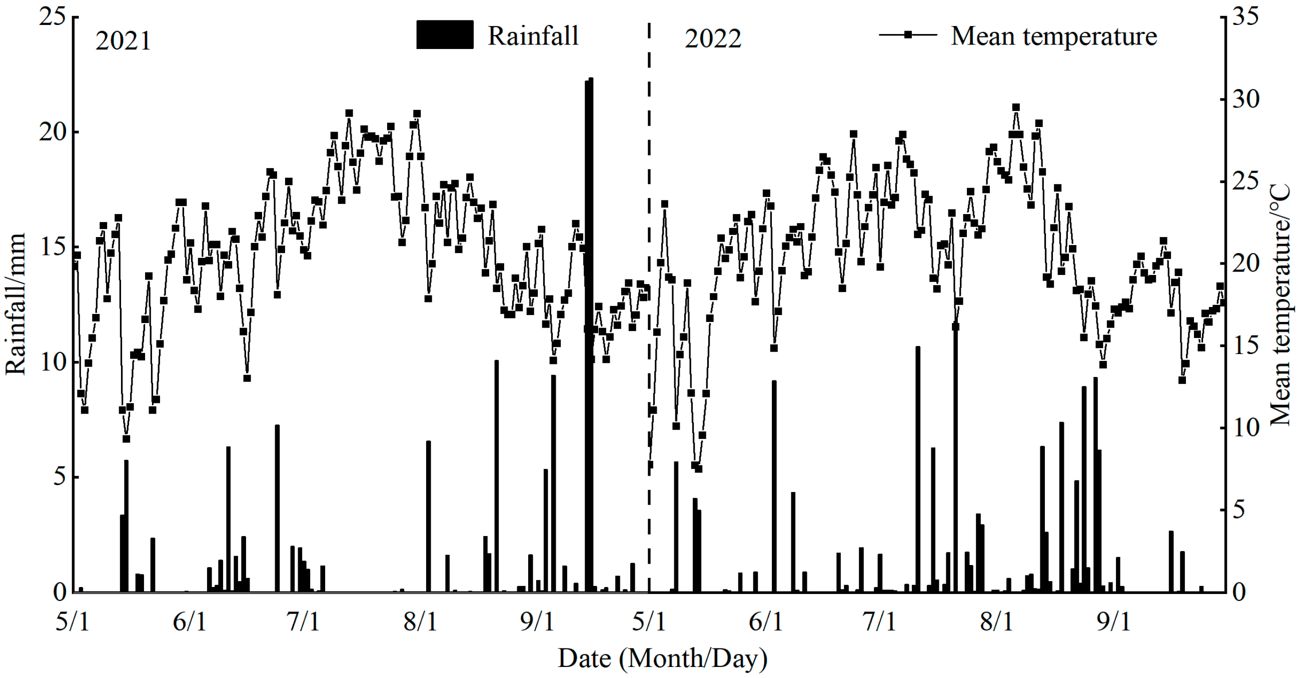

Figure 1. Meteorological characteristics of the experimental site from April to October in 2020.

2.2. *Experimental Design and Field Management*

Lucerne the tested lucerne variety in this study was Longdong lucerne, which has good drought resistance, strong adaptability, and high forage value. Its roots are developed and can fully absorb water. Its leaves are small with low stomatal density, which can effectively reduce transpiration water consumption. Therefore, it is suitable for planting in arid areas. The experiment set three cultivation patterns: ridge tillage with plastic film mulching (PM), ridge tillage with biodegradable film mulching (BM), and traditional flat planting (FP) (Figure 2). Each planting pattern had three repetitions, nine plots altogether, covering an area of 42.9 m^2 (5.5 m × 7.8 m). The ordinary plastic films (Fuyu Plastic Industry Co., Ltd., Lanzhou City, China) and biodegradable films (Tianzhuang Environmental Protection Technology Co., Ltd., Jinan City, China with an induction period of 90 days) had a width of 100 cm and a thickness of 0.008 mm. Ten days before sowing in 2021, the land was leveled. Strip sowing was adopted, with a sowing rate of 22.5 $kg \cdot ha^{-1}$. In the plots treated with PM and BM, after digging ditches and ridging, lucerne was planted on the ridge sides and inside the ditches. Each ridge was sowed with four rows of lucerne, with a row spacing of 20 cm. The row spacing in the plots treated with FP was 30 cm. Drip irrigation was used for fertilization. The spacing between drip irrigation belts in the plots treated with PM and BM was 40 cm, and that in the FP-treated plots was 60 cm. The designed flow rate of the drip head was 2 $L \cdot h^{-1}$. Valves and water meters (with an accuracy of 0.001 m^3) were installed on the water pipeline to adjust the amount of irrigation water. Fertilizers of nitrogen, phosphorus, potassium, controlled-release nitrogen fertilizer (Jinzhengda Ecological Engineering Group Co., Ltd., Linyi City, China; N mass fraction: 30%; nitrogen application rate: 160.0 $kg \cdot ha^{-1}$), superphosphate (40.0 $kg \cdot ha^{-1}$; P_2O_5 mass fraction: 16%), and potassium sulfate (19.2 $kg \cdot ha^{-1}$; K_2O mass fraction: 50%) were applied once before the first harvest turned regreen every year. Other field management measures were the same as those used in the general lucerne field in the local area. The lucerne was sown in April 2021. After germination, the germination rate of the lucerne was estimated by randomly selecting a one-square-meter area in each plot. After averaging all estimated values, the germination rate of lucerne reached over 80%, which met the experimental requirements. The lucerne plants were harvested on 16 July and 5 October in 2021 and 29 May, 29 July, and 13 September in 2022, respectively.

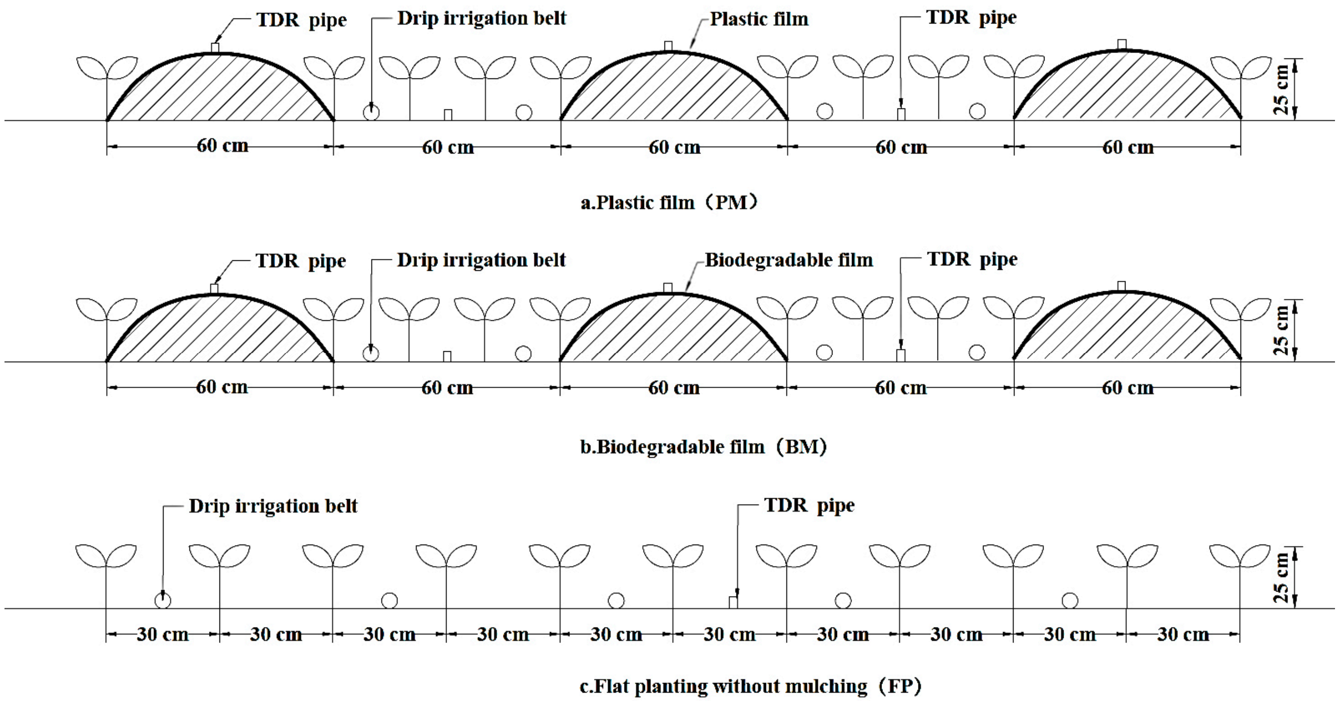

Figure 2. Schematic diagram of the test plot layout. TDR in the figure represents time-domain reflectometry.

2.3. Indicators and Methods for Measurement

2.3.1. Soil Moisture Content (%)

For PM and BM treatments, each adjacent ridge and ditch in the center of the plots was installed with one TDR (time–domain reflectometry, with a length of 150 cm) probe. For the FP treatment, one TDR probe was installed between the rows in the center of the plots. The PICO–BTTDR instrument (IMKO, Ettlingen City, Germany) was used to measure the volume of moisture content of the soil layer of 0–120 cm (with an interval of 20 cm) of the plots every 3–5 days.

2.3.2. Soil Temperature

The soil temperature (5 cm, 10 cm, 15 cm, 20 cm, and 25 cm) during the main growth period of lucerne was measured from 8:00 to 18:00 (every two hours) using a bent stem thermometer (Wuqiang Hongxing Instrument Factory, Hengshui City, China). For PM and BM treatments, bent stem thermometers were laid on adjacent ridges and ditches in the center of the plots; for the FP treatment, the bent stem thermometers were arranged between rows in the center of the plots.

2.3.3. Soil Nutrient

The root system of lucerne planted in the first year is relatively shallow, with a depth of about 30–50 cm. In the second year, the root system significantly deepens and expands, reaching a depth of around 80–100 cm. The soil surface layer from 0–40 cm is the most active area for lucerne roots. In this region, the density of lucerne roots is high and the absorption of nutrients is more frequent. Therefore, the soil nutrient content in the 0–40 cm soil layer was measured before lucerne planting in 2021 and after the third harvest of lucerne in 2022. For the FP treatment, three random soil samples from the 0–40 cm layer were taken from each plot to measure the nutrient content, and their average values were calculated. For the PM and BM treatments, three sets of soil samples from the 0–40 cm layer were randomly taken from the ridge and ditch in each plot to measure the nutrient contents, and their average values were calculated. The nutrient content in the soil layer of 0–40 cm was gauged before planting in 2021 and after the third harvest in 2022. The organic matter was determined by the potassium dichromate oxidation method, the total nitrogen was identified using a KjeltecTM8400 (FOSS Corporation, Gothenburg City, Sweden) automatic nitrogen analyzer, the total phosphorus was measured with the molybdenum antimony colorimetric method, the total potassium was determined by a flame spectrophotometer, the available nitrogen was gauged using the alkaline hydrolysis diffusion method, the available phosphorus was identified with the 0.5 mol·L^{-1} $NaHCO_3$ extraction colorimetric method, and the available potassium was measured by the NH_4OAc extraction flame photometric method.

2.3.4. Plant Height and Stem Diameter

In each harvest, 10 lucerne plants with uniform growth were selected from each plot. The vertical distances from the ground to the top of the plants were identified using a tape measure, and the stem thicknesses of the plants about 5 cm above the ground were determined with a vernier caliper.

2.3.5. Yield and Quality

(1) Yield (kg·ha^{-1})

The yield of lucerne was obtained using the quadrat method. When cutting each batch of lucerne, a 100 cm × 100 cm sample plot of evenly growing lucerne was selected from each plot. The lucerne plants were cut with scissors at a distance of 5 cm from the ground. Fresh grasses were weighed after eliminating other weeds. Then, they were put in an oven at 105 °C for green removal and dried at 75 °C until they reached a constant weight. The weight was converted into yield per unit area based on the area of the plot.

(2) Quality

The dried lucerne plants of each batch were crushed and passed through a 0.4 mm sieve for quality determination. The content of crude protein (CP, %) was determined using a fully automatic nitrogen analyzer (KjeltecTM8400), and the content of acidic detergent fiber (ADF, %) and neutral detergent fiber (NDF, %) was obtained by the Van Soest method with a semi-automatic fiber analyzer (F800).

The formula of relative feed value (RFV) is: [42]

$$RFV = (BMI \times DBM)/1.29 \quad (1)$$

$$BMI = 120/NDF \quad (2)$$

$$DBM = 88.9 - 0.799 \times ADF \quad (3)$$

2.3.6. Water-Nitrogen Use Efficiency [43]

(1) Evapotranspiration (ET, mm)

It can be obtained using the water balance method.

$$ET = 10\sum_{i=1}^{n} \gamma_i H_i(\theta_{i1} - \theta_{i2}) + I + P + K - R - D \quad (4)$$

In the formula, i is the soil layer number; n is the total number of soil layers; γi is the dry bulk density of the i-th soil layer in g·cm^{-3}; H_i is the thickness of the i-th soil layer in cm; θ_{i1} and θ_{i2} are the initial and final moisture content of the i-th soil layer, %, represented by a percentage of the dry soil mass; I is the irrigation amount in mm; P is the precipitation in mm; K is the replenishment amount of groundwater in mm; R is the surface runoff in mm; D is the amount of deep leakage in mm. The experimental land had a flat surface, the buried depth of groundwater was large, and the single precipitation was slight. Therefore, K, R, and D can be omitted.

(2) Water use efficiency (WUE, kg·ha^{-1}·mm^{-1})

$$WUE = Y/ET \quad (5)$$

(3) Irrigation water use efficiency ($IWUE$, kg·ha^{-1}·mm^{-1})

$$IWUE = Y/I \tag{6}$$

(4) Partial factor productivity of nitrogen ($PFPN$, kg·kg^{-1})

$$PFPN = Y/F \tag{7}$$

In the formula, F is the nitrogen application rate in kg·ha^{-1}.

2.3.7. Economic Benefits

(1) The formula for total revenue (TR, Dollar·ha^{-1}) is:

$$TR = Y \times P \tag{8}$$

In the formula, P is the price of lucerne in Dollar·ha^{-1}. The prices of lucerne in 2021 and 2022 were 290 and 304 Dollar·ha^{-1}, respectively.

(2) The calculation of net revenue (NR, Dollar·ha^{-1}) can be expressed as:

$$NR = TR - TC \tag{9}$$

In the formula, TC is the input cost in Dollar·ha^{-1}.

2.4. Data Analysis

This study used Microsoft Excel 2019 for data organization, Origin 9.0 and GraphPad 8.0.2 software for plotting, and IBM SPSS Statistics 26 software for analysis of variance, significance testing ($p < 0.05$), and multiple comparisons.

3. Results

3.1. The Impact of Cultivation Patterns on Soil Microenvironment

3.1.1. Soil Moisture Content

The cultivation pattern plays a significant role in the spatiotemporal distribution of soil moisture content (Figure 3). With the growth of lucerne, the soil moisture contents of the three cultivation patterns show a trend of first decreasing and then increasing, with the minimum value in the bud stage. Compared to the FP treatment, during the regreening, branching, budding, and early flowering stages, the PM treatment elevates the average soil moisture content by 27.99%, 29.98%, 23.20%, and 35.70%, and the BM treatment increases the soil moisture content by 22.20%, 28.41%, 18.66%, and 24.36%, respectively. As the depth of the soil layer increases, the soil moisture content of the FP treatment first grows, then decreases and finally stabilizes, similar to that of the ditches treated with PM and BM. By comparison, the soil moisture content of the ridges gradually elevates. In the soil layer of 0–40 cm, the PM and BM treatments abate the average soil moisture content of the ridges by 19.29% and 7.89% compared to that of the ditches, respectively. In the soil layer of 40–120 cm, the PM and BM treatments raise the average soil moisture content of the ridges by 4.40% and 4.65% compared to that of the ditches, respectively. During the two-year growth period, compared to the FP treatment, the PM and BM treatments increase the average soil moisture content in the soil layer of 0–120 cm by 31.19% and 24.03%, respectively.

3.1.2. Soil Temperature

Under the three cultivation patterns, the daily soil temperature drops with the soil depth. During the growth period, it augments initially, followed by a decrease, and reaches its peak in the branching period (Figure 4). In the two–year growth period, the average temperature in the soil layer of 0–25 cm presented as PM > BM > FP, and the PM and BM treatments promoted it by 0.70 °C and 0.25 °C compared to the FP treatment, respectively. The temperature in the soil layer of 5 cm was the highest, and the difference in soil temperature between treatments was the most significant. The PM and BM treatments raised the soil temperature of the ridges by an average of 3.46 °C and 2.78 °C compared to the FP treatment, respectively. The two treatments increased the soil temperature in the ditches by an average of 1.17 °C and 0.34 °C compared to the FP treatment, respectively. In the soil layer of 25 cm, the temperature was the lowest, and the difference in soil temperatures between treatments was the smallest. The PM and BM treatments elevated the soil temperature of the ridges by an average of 0.46 °C and 0.15 °C and dropped that of the ditches by an average of 1.25 °C and 1.10 °C compared to the FP treatment, respectively. During the regreening, branching, budding, and early flowering stages, compared with the FP treatment, the PM treatment increased the average soil temperature by 0.90 °C, 0.56 °C, 0.53 °C, and 0.80 °C, and the BM treatment promoted the average soil temperature by 0.18 °C, 0.03 °C, 0.26 °C, and 0.54 °C, respectively; the PM treatment augmented the soil temperature of the ridges by an average of 8.81%, 10.16%, 6.54%, and 9.59%, and the BM treatment elevated the average soil temperature by 6.03%, 4.01%, 3.47%, and 5.06%, respectively; the PM treatment decreased the soil temperature of the ditches by an average of 1.21%, 5.79%, 1.58%, and 1.49%; and the BM treatment abated the soil temperature by an average of 4.08%, 3.77%, 1.02%, and 0.35%, respectively.

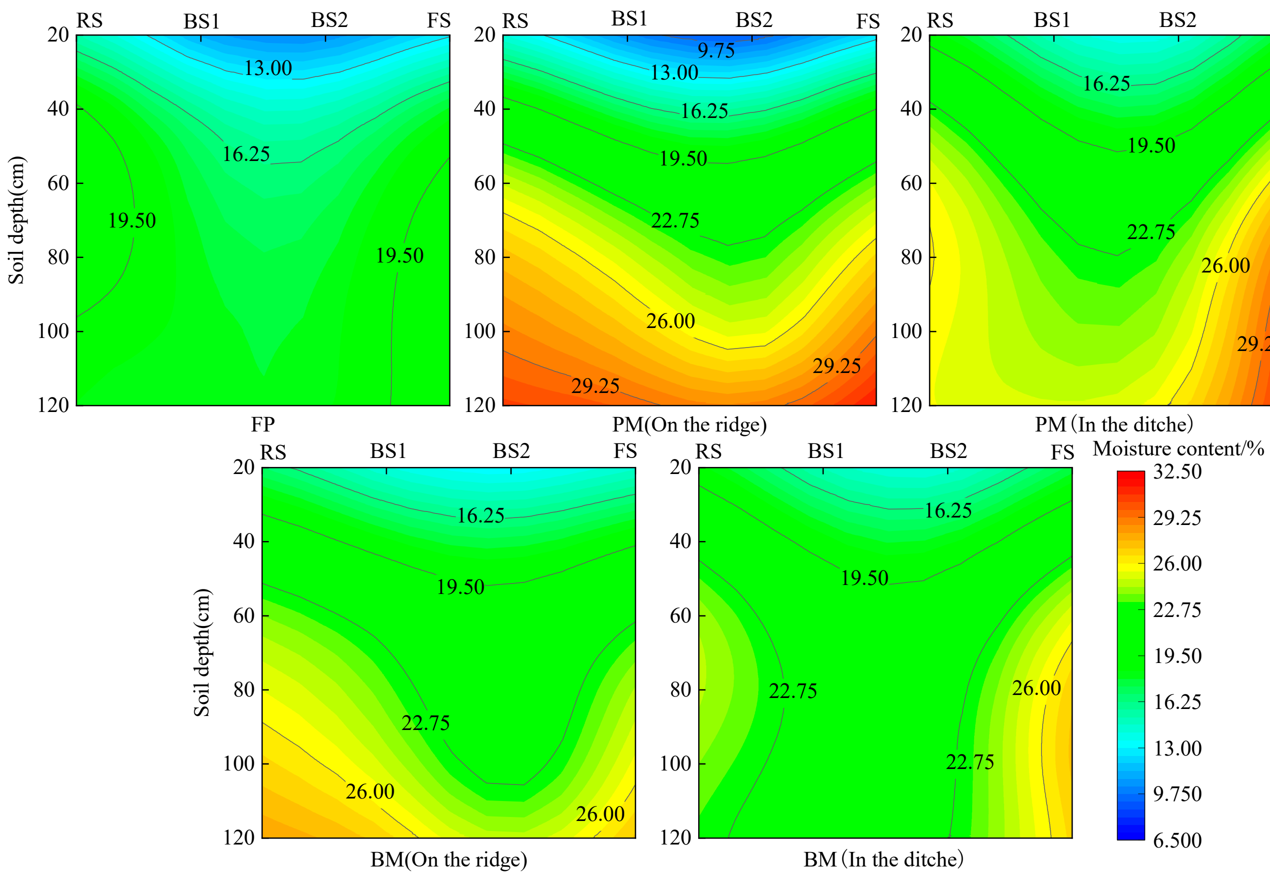

Figure 3. Temporal and spatial changes of lucerne soil moisture under different planting patterns. In the figure, regreening stage, branching stage, initiation of flowering stage and flowering stage were used respectively as RS, BS1, BS2 and FS. PM, BM, and FP represent ridge mulching with ordinary plastic film, ridge mulching with bio-degradable film, and traditional flat planting, respectively.

3.1.3. Soil Nutrients

Compared with before planting lucerne in 2021, the three cultivation patterns all enhanced the nutrient content in the soil layer of 0–40 cm after the third harvest in 2022, with the highest increment in organic matter content (375.00–469.70%), followed by the available nitrogen, available phosphorus, and available potassium content (3.17–22.88%), and the least in total nitrogen, total phosphorus, and total potassium content (0.26–1.11%) (Table 1). Compared with the FP treatment, the PM and BM treatments raised the soil nutrients by 0.09–9.94% and 0.26–19.94%, respectively. The differences in total nitrogen, total phosphorus, total potassium, and available nitrogen contents are minor. The BM treatment increased the content of organic matter, available phosphorus, and available potassium by 9.94%, 1.79%, and 4.07% compared with the PM treatment, and 19.94%, 3.26%, and 9.94% compared with the FP treatment, respectively.

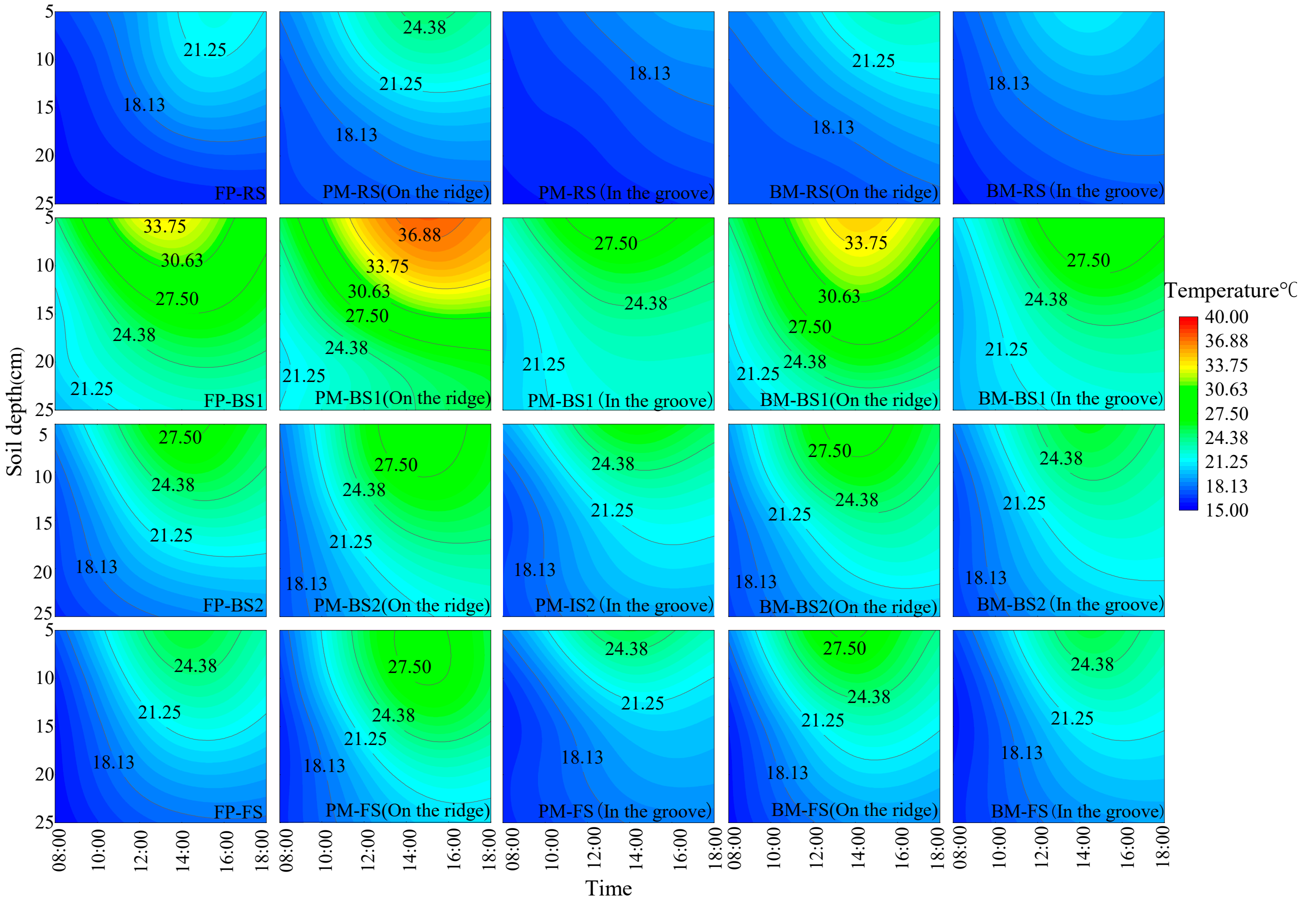

Figure 4. Temporal and spatial changes of lucerne soil temperature under different planting patterns. In the figure, regreening stage, branching stage, initiation of flowering stage and flowering stage were used respectively as RS, BS1, BS2, and FS. PM, BM, and FP represent ridge mulching with ordinary plastic film, ridge mulching with biodegradable film, and traditional flat planting, respectively.

Table 1. Average soil nutrient contents in 0–40 cm soil layer under different planting modes after the third crop lucerne cutting in 2022.

Treatments	**OM ($g{\cdot}kg^{-1}$)**	**TN ($g{\cdot}kg^{-1}$)**	**TP ($g{\cdot}kg^{-1}$)**	**TK ($g{\cdot}kg^{-1}$)**	**AN ($mg{\cdot}kg^{-1}$)**	**AP ($mg{\cdot}kg^{-1}$)**	**AK ($mg{\cdot}kg^{-1}$)**
PM	6.8 ± 0.1 b	1.8 ± 0.0 a	1.4 ± 0.0 a	34.2 ± 0.0 ab	90.2 ± 1.1 a	31.8 ± 1.0 b	188.6 ± 1.7 b
BM	7.5 ± 0.1 a	1.8 ± 0.0 a	1.4 ± 0.0 a	34.2 ± 0.0 a	91.0 ± 0.7 a	32.3 ± 0.8 a	196.2 ± 1.2 a
FP	6.3 ± 0.0 c	1.8 ± 0.0 a	1.4 ± 0.0 a	34.1 ± 0.0 a	89 ± 0.6 a	31.3 ± 0.6 b	178.5 ± 1.8 c

Note: Different lowercase letters indicated significant differences in soil nutrients between different treatments ($p < 0.05$). In the table, PM, BM, and FP represent ridge-covered ordinary film, ridge-covered biodegradable film, and traditional plain crop, respectively. The FP treatment is used as the control. The OM, TN, TP, TK, AN, AP and AK represent Organic Matter, Total Nitrogen, Total Phosphorus, Total Potassium, Available Nitrogen, Available Phosphorus and Available Potassium, respectively.

3.2. The Impact of Cultivation Patterns on the Growth of Lucerne

Plant height and stem diameter are prominent indicators that reflect the growth status of lucerne. The heights of the lucerne plants show an extending trend with planting years and a declining trend with harvests (Figure 5a). Compared with 2021, the average heights of lucerne plants under the three cultivation patterns increase by 23.45% to 25.10% in 2022. During the two-year growth, the overall heights of lucerne plants under the three cultivation patterns present PM > BM > FP, with an average increment of 15.37% and 4.04% under the PM and BM treatments compared to the average increment under the FP treatment. In the second harvest in 2021, the difference in the lucerne plant heights among the three cultivation patterns is the slightest. The PM and BM treatments elevate plant height by an average of 13.80% and 3.58% compared to the FP treatment, respectively. In the first harvest in 2022, the difference in lucerne plant heights is the greatest among the three cultivation patterns, and the PM and BM treatments augment plant height by an average of 16.12% and 5.61% compared to the FP treatment, respectively.

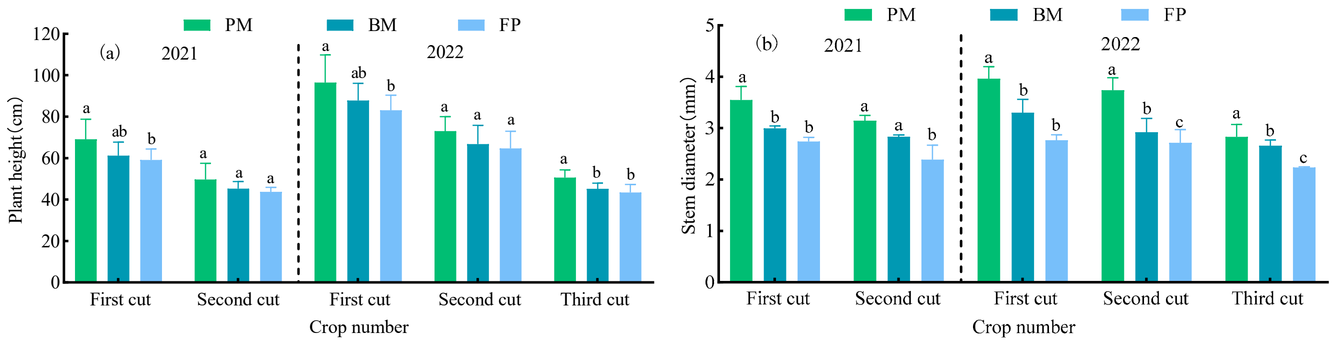

Figure 5. In the figure, (**a**,**b**) represent plant height and stem diameter, respectively. Effects of planting patterns on plant height and stem diameter of lucerne. PM, BM, and FP respectively represent ridge mulching with common plastic film, ridge mulching with biodegradable plastic film, and traditional flat cropping. Different lowercase letters of a, b and c indicated significant quality difference among different treatments ($p < 0.05$).The same hereinafter.

The stem thickness of lucerne enlarges with planting years and drops with harvests (Figure 5b). Compared with 2021, the stem diameters of lucerne under the three cultivation patterns increased by an average of 0.24–4.87% in 2022. During the two-year growth, the overall stem thicknesses of lucerne under the three cultivation patterns showed PM > BM > FP, and the PM and BM treatments promote the overall stem thicknesses by an average of 34.14% and 14.58% compared to the FP treatment, respectively. In the first harvest in 2021, the difference in stem thickness among the three cultivation patterns was the smallest; the PM and BM treatments augmented the stem thickness by an average of 29.55% and 9.43% compared to the FP treatment, respectively. In the first harvest in 2022, the difference in stem thickness among the three cultivation patterns was the most significant; the PM and BM treatments elevated the stem thickness by an average of 43.53% and 19.49% compared to the FP treatment, respectively.

3.3. The Impact of Cultivation Patterns on Lucerne Production

3.3.1. Yield

The yield of lucerne in the two-year growing exhibits a decreasing trend with harvests (Table 2). In the 2021 growing season, the first and second yields of the three cultivation patterns were 4713.03–5948.04 kg·ha^{-1} and 1955.79–2411.63 kg·ha^{-1}, accounting for 70.67–71.50% and 28.50–29.33% of the total annual yield, respectively. The total yields of the PM and BM treatments are similar. However, the yields significantly increased by 25.35% and 18.61% compared to that of the FP treatment, respectively. In the 2022 growing season, the first, second, and third crop yields of the three cultivation patterns were 10,234.07–11,954.32 kg·ha^{-1}, 5358.74–6269.64 kg·ha^{-1}, and 2053.60–2429.39 kg·ha^{-1}, accounting for 57.88–58.69%, 29.82–30.37%, and 11.64–11.76% of the total annual yield, respectively. The total yield of the PM treatment was remarkably higher than that of the BM treatment, and both grew by 17.04% and 10.94% compared to that of the FP treatment, respectively. This indicates that ridge tillage with film mulching, especially with ordinary films, has a satisfying effect on boosting lucerne yields.

Table 2. Impact of planting patterns and nitrogen levels on lucerne yield (kg·ha^{-1}).

Treatments	2021			2022			
	First Cut	Second Cut	Yearly Yield	First Cut	Second Cut	Third Cut	Yearly Yield
PM	5948 ± 18 a	2411 ± 137 a	8360 ± 245 a	11,954 ± 70 a	6270 ± 62 a	2429 ± 66 a	20,653 ± 134 a
BM	5655 ± 72 a	2255 ± 96 ab	7910 ± 166 a	11,489 ± 65 b	5837 ± 72 b	2251 ± 68 ab	19,577 ± 72 b
FP	4713 ± 73 b	1956 ± 95 b	6669 ± 46 b	10,234 ± 63 c	5359 ± 60 c	2054 ± 60 b	17,646 ± 57 c

Note: The data in the table are mean ± standard deviation. Different lowercase letters of a, b and c indicated significant quality difference among different treatments ($p < 0.05$). PM, BM, and FP represent ridge-covered ordinary film, ridge-covered biodegradable film, and traditional plain crop, respectively. The same is true below.

3.3.2. Quality

During the two-year growth period, the CP content and RFV content of the lucerne increased with the harvests, while the content of ADF and NDF dropped (Table 3). During the growing season of 2021, the contents of CP, ADF, NDF, and RFV under the three cultivation patterns were 15.48–16.50%, 32.62–35.05%, 52.70–56.44%, and 100.36–110.95% in the first cutting, and 16.44–18.65%, 27.04–32.03%, 47.02–49.11%, and 120.21–133.35% in the second cutting, respectively. The annual average values of the four quality indicators imply that the PM treatment enhances the CP content by 5.91% and 10.09% compared to the BM and FP treatments and reduces the ADF content by 11.06% compared to the FP treatment, the PM and BM treatments downgrade the NDF content by 5.53% and 3.13% compared to the FP treatment, and the PM treatment increases RFV by 10.75% compared to the FP treatment.

Table 3. Impacts of planting patterns and nitrogen levels on lucerne quality (%).

Index		2021			2022			
		First Cut	Second Cut	Average	First Cut	Second Cut	Third Cut	Average
CP	PM	16.5 ± 0.1 a	18.7 ± 0.4 a	17.6 ± 0.2 a	18.5 ± 0.7 a	18.7 ± 0.2 a	23.5 ± 0.4 a	20.3 ± 0.2 a
	BM	16.2 ± 0.5 a	17.0 ± 0.1 b	16.6 ± 0.2 b	17.9 ± 0.4 a	18.2 ± 0.3 ab	21.8 ± 0.5 a	19.3 ± 0.2 b
	FP	15.5 ± 0.7 a	16.4 ± 0.1 b	16.0 ± 0.4 b	16.0 ± 0.2 b	17.2 ± 0.5 b	19.0 ± 0.9 b	17.4 ± 0.4 c
ADF	PM	32.6 ± 0.4 a	27.0 ± 2.8 a	29.8 ± 1.2 b	32.6 ± 0.3 b	29.0 ± 1.6 a	26.7 ± 0.3 a	29.5 ± 0.5 b
	BM	34.0 ± 1.7 a	30.0 ± 0.2 a	32.0 ± 1.0 ab	34.5 ± 0.8 a	29.7 ± 1.1 a	27.0 ± 0.3 a	30.4 ± 0.3 ab
	FP	35.1 ± 1.0 a	32.0 ± 0.5 a	33.5 ± 0.8 a	34.6 ± 0.5 a	31.7 ± 0.6 a	28.3 ± 0.8 a	31.5 ± 0.2 a
NDF	PM	52.7 ± 0.5 c	47.0 ± 0.8 a	49.9 ± 0.1 c	51.7 ± 1.4 a	47.9 ± 0.7 a	45.0 ± 0.8 b	48.2 ± 0.4 a
	BM	54.4 ± 0.1 b	47.9 ± 0.3 a	51.1 ± 0.1 b	51.8 ± 0.2 a	48.4 ± 0.5 a	46.65 ± 0.6 ab	48.9 ± 0.0 a
	FP	56.4 ± 0.4 a	49.1 ± 1.5 a	52.8 ± 0.6 a	52.6 ± 1.2 a	49.9 ± 1.6 a	47.7 ± 0.7 a	50.1 ± 1.1 a
RFV	PM	111.0 ± 1.7 a	133.4 ± 6.6 a	122.2 ± 2.5 a	113.3 ± 3.4 a	127.7 ± 0.6 a	139.7 ± 3.1 a	126.9 ± 0.1 a
	BM	105.6 ± 2.0 ab	126.2 ± 1.3 a	115.9 ± 1.7 ab	110.2 ± 0.7 a	125.3 ± 0.4 a	134.3 ± 2.1 ab	123.3 ± 0.6 ab
	FP	100.4 ± 0.6 b	120.2 ± 4.5 a	110.3 ± 2.6 b	108.5 ± 3.0 a	118.7 ± 2.8 b	129.3 ± 3.2 b	118.8 ± 3.0 b

Note: Different lowercase letters of a, b and c indicated significant quality difference among different treatments ($p < 0.05$).. In the table, PM, BM, and FP represent ridge-covered ordinary film, ridge-covered biodegradable film, and traditional plain crop, respectively. CP, ADF, and NDF represent crude protein, acid detergent fiber, and neutral detergent fiber, respectively, while RFV stands for relative feeding value.

In contrast with the growth season of 2021, the quality of lucerne under the three cultivation patterns improved during the growth season of 2022. The contents of CP, ADF, NDF, and RFV of the three harvests of lucerne were 15.97–23.53%, 26.73–34.56%, 45.00–53.63%, and 108.47–139.74%, respectively. The annual average values of the four quality indicators show that the PM and BM treatments increased the CP content by 16.57% and 11.10% compared to the FP treatment and that the PM treatment abated the ADF content by 6.54% compared to the FP treatment; it also showed that there is no significant difference in the NDF content among the three cultivation patterns, and the PM treatment elevated the RFV by 6.81% compared to the FP treatment.

3.3.3. Water Use Efficiency

The ET, PFPN, IWUE, and WUE of lucerne all rise with planting years. Compared to traditional flat cropping, ridge tillage with film mulching significantly decreases ET and improves the PFPN, IWUE, and WUE (Table 4). During the 2021 growing season, in contrast with the FP treatment, the PM and BM treatments decreased the ET by 16.75% and 8.60% and augmented the IWUE, WUE, and PFPN by 25.34%, 49.49%, 25.36%, and 18.55%, 16.16%, and 18.62%, respectively. During the 2022 growth season, compared to the FP treatment, the PM and BM treatments lowered the ET by 14.87% and 12.98%, respectively; the PM treatment increased the IWUE, WUE, and PFPN by 17.04%, 37.50%, and 17.04%, and the BM treatment enhanced those by 10.99%, 18.97%, and 10.94%, respectively.

Table 4. Impacts of planting patterns on the water–nitrogen use efficiency of lucerne.

A Given Year	Handle	ET (mm)	IWUE (kg·ha^{-1}·mm^{-1})	WUE (kg·ha^{-1}·mm^{-1})	PFPN (kg·kg^{-1})
2021	PM	563.7 ± 7.2 c	2.8 ± 0.1 a	1.5 ± 0.1 a	52.3 ± 1.5 a
	BM	618.9 ± 7.9 b	2.6 ± 0.1 a	1.2 ± 0.0 b	49.4 ± 1.0 a
	FP	677.1 ± 23.3 a	2.2 ± 0.0 b	1.0 ± 0.0 c	41.7 ± 0.3 b
2022	PM	648.5 ± 23.4 b	5.2 ± 0.0 a	3.2 ± 0.1 a	129.1 ± 0.8 a
	BM	662.9 ± 21.2 b	5.0 ± 0.0 b	2.8 ± 0.1 b	122.4 ± 0.5 b
	FP	761.8 ± 15.8 a	4.5 ± 0.0 c	2.3 ± 0.0 c	110.3 ± 0.4 c

Note: Different lowercase letters of a, b and c indicated significant quality difference among different treatments ($p < 0.05$). In the table, PM, BM, and FP represent ridge-covered ordinary film, ridge-covered biodegradable film, and traditional plain crop, respectively. ET, WUE, IWUE, and PFPN represent evapotranspiration, water use efficiency, irrigation water use efficiency, and the partial factor productivity of nitrogen.

3.3.4. Economic Benefits

The net income of lucerne increases with planting years, and the overall performance presents as PM > BM > FP (Table 5). During the 2021 growth season, there was no significant difference in net income between the PM and BM treatments. However, compared to the FP treatment, the PM and BM treatments significantly increased in net income by 26.80% and 26.62%, respectively. During the 2022 growing season, there was a significant difference in the net income of lucerne among the three cultivation patterns. The PM and BM treatments promoted the net income of lucerne by 15.22% and 11.05% compared to the FP treatment, respectively.

Table 5. Impacts of planting patterns on lucerne's economic benefits.

Factors		2021			2022		
		PM	BM	FP	PM	BM	FP
Total revenue (Dollar·ha^{-1})		2425.2	2292.4	1932.1	6277.0	5950.2	5363.4
Input cost (Dollar·ha^{-1})	Seed	73	73	73	73	73	73
	Controlled release nitrogen fertilizer	133	133	133	133	133	133
	Rotary tillage	207	207	207	0	0	0
	Insecticide	117	117	117	117	117	117
	Mulching film	89	61	0	89	61	0
	Total input cost	619	591	530	412	384	323
Labor cost (Dollar·ha^{-1})	Mulching and residue removal	225	124	124	225	124	124
	Others (planting, fertilization, etc)	156	156	156	156	156	156
	Total labor cost	381	280	280	381	280	280
Net revenue (Dollar·ha^{-1})		1424.9 a	1422.9 a	1123.8 b	5485.4 a	5285.6 b	4759.5 c

Note: Different lowercase letters of a, b and c indicated significant quality difference among different treatments ($p < 0.05$). In the table, PM, BM, and FP represent ridge-covered ordinary film, ridge-covered biodegradable film, and traditional plain crop, respectively.

3.4. Correlation Analysis

Correlation analysis was conducted on the three cultivation patterns of lucerne during the two-year growth period, including plant height; stem diameter; yield; contents of CP, ADF, NDF, RFV, ET, IWUE, WUE, and PFPN; economic benefits; soil moisture content; soil temperature; and soil nutrients. Most of the correlation coefficients between the indicators are above 0.50 or below −0.50, indicating strong correlations between the selected indicators (Figure 6). Yield is significantly positively correlated with organic matter, available potassium, plant height, stem diameter, CP, RFV, IWUE, WUE, PFPN, and economic benefits. Meanwhile, it is negatively correlated with ADF and ET. RFV has significantly positive correlations with CP, IWUE, WUE, PFPN, yield, and economic benefits and significantly negative correlations with ADF, NDF, and ET. WUE is significantly positively correlated with organic matter, plant height, stem diameter, CP, RFV, IWUE, PFPN, yield, and economic benefits and significantly negatively correlated with ADF and ET. PFPN has significantly positive correlations with organic matter, available potassium, plant height, stem diameter, CP, RFV, IWUE, WUE, yield, and economic benefits and significantly negative correlations with ADF and ET.

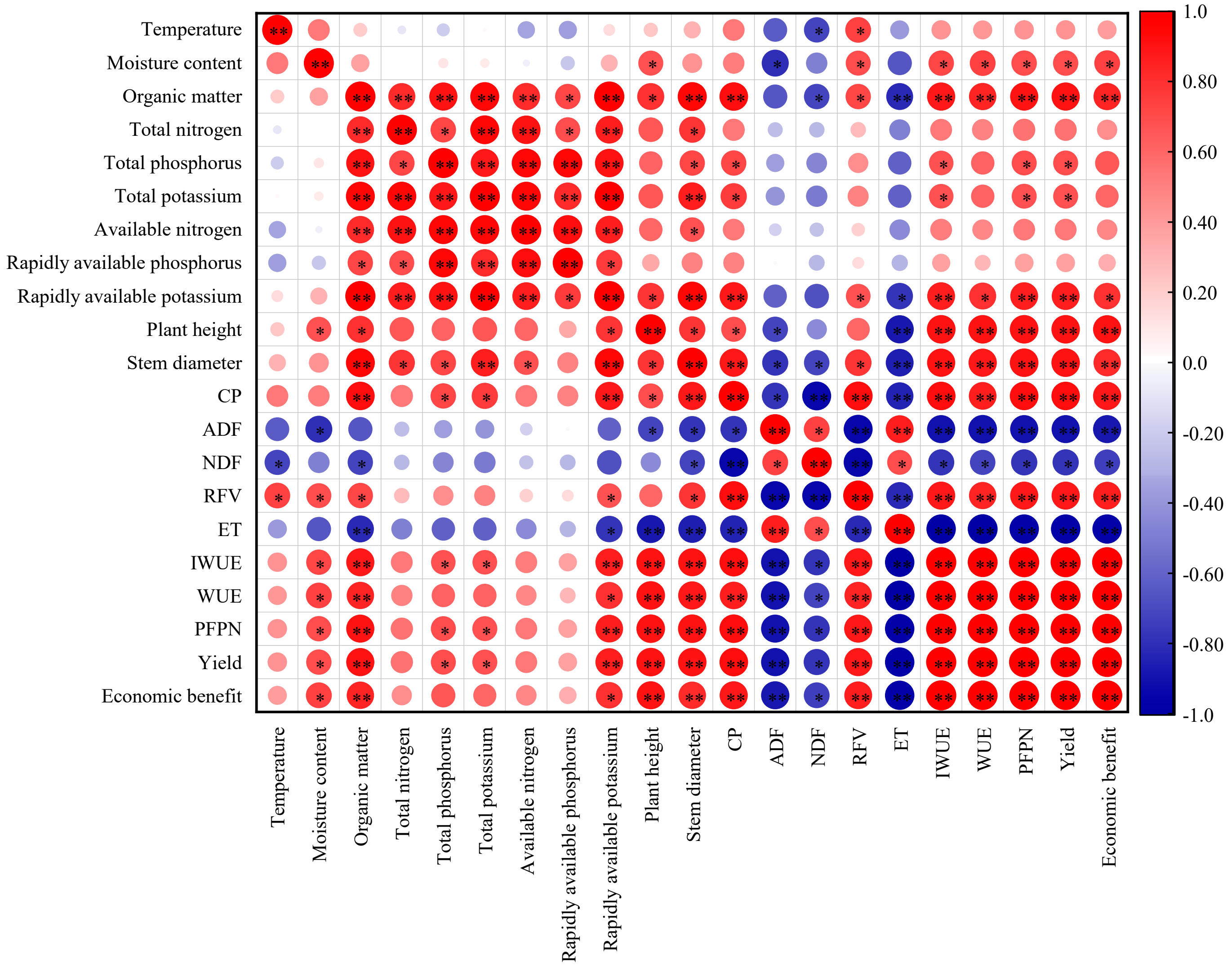

Figure 6. Correlation analysis of each index under different planting modes. * represents significant, ** represents extremely significant, red represents positive correlation, and blue represents negative correlation; the larger the circle, the higher the correlation.

4. Discussion

4.1. The Impact of Cultivation Patterns on Soil Microenvironment

Ridge tillage with film mulching can ameliorate the ecological microclimate of farmlands and coordinate the soil environments of water, fertilizer, air, and heat in the crop root system, which is crucial for sustainable agriculture development in arid and semi-arid areas [44].

Furthermore, ridge tillage can heighten soil water availability [5]. Similar to the research of Kou et al. [45] on lucerne and that of Jia et al. [46] on maize in the semi-arid region of northwest China on the Loess Plateau, this study discovered that the average soil moisture content and the ditch moisture content of the PM and BM treatments were significantly higher than those of the FP treatment. This is mainly attributed to the fact that ridge tillage with film mulching can superimpose rainfall in ridges and lessen surface soil evaporation, thereby improving soil moisture [47]. Meng et al. [48] proposed in their study on the Loess Plateau that the soil moisture content of ridge tillage with film mulching increased first and then dropped with soil depth, and it gradually declined with the growth period of lucerne. Meanwhile, this study found that the soil moisture content under the three cultivation patterns showed a trend of first decreasing and then increasing with the growth period of lucerne. This may be related to different irrigation management approaches. Meng et al. conducted the experiment under the rain–fed condition. The root system of lucerne continuously consumed the soil water stored in the root zone during the growth period, resulting in a gradual decrease in the soil moisture content. In contrast, this study consulted local production experience for irrigation during the growth period of lucerne. In the later growth stage of lucerne, the demand for water was relatively low. Moreover, the concentrated precipitation from July to September in the study area weakened the consumption of soil water by lucerne. In addition, this study found that the soil moisture content of the PM treatment was higher than that of the BM treatment; in the soil layer of 0–40 cm for PM and BM treatments, the soil moisture content in the ditches was greater than that of the ridges; it was converse in the soil layer of 60–120 cm. This is mainly because, under the gradual degradation of degradable films with the growth of lucerne and the long growing period, multiple instances of mowing in a year lead to an inferior soil moisture retention effect of degradable films compared to that of ordinary plastic films. For ridge tillage with film mulching, precipitation or irrigated water accumulates in the ditches, increasing the moisture content of the shallow soil in the ditches and infiltrating the adjacent ridges under the action of soil capillary. Lucerne is a deep-rooted crop that can absorb underground soil moisture, thus decreasing the moisture content of the deep soil in the ditches.

Another feature of ridge tillage with film mulching is regulating soil temperature [49]. Jing et al. [50] carried out their study in the high-altitude pastoral area of Tianzhu, Gansu Province, and believed that the temperature in the soil layer of 0–25 cm reached its peak between 14:00 and 16:00. This study disclosed that the soil temperatures of the three cultivation patterns all achieved their highest points during 12:00 and 14:00. This may be relevant to the solar radiation and light intensity in the study area. Similar to the research of Li et al. [51] on maize in the Weibei arid plateau, this study found that under the three cultivation patterns, the average soil temperatures in the soil layer of 0–25 cm during the growth period of lucerne presented as PM > BM > FP. The PM treatment exerts a warming effect through the entire growth of lucerne, while the BM treatment plays a warming role mainly in the early growth stage. This is because film mulching can allow short waves of sunlight to pass through the cover layer to the soil surface, and long waves reflected by the soil cannot get through the cover layer, thereby elevating the soil temperature under the films. Compared with ordinary plastic films, biodegradable films gradually degrade with the growth period of crops, and the insulation effect abates correspondingly. Generally, the degradation of biodegradable films in the later stage can effectively downgrade the premature senescence of crops caused by high temperatures, maintain soil fertility, and promote the sustainable development of agricultural ecosystems [52,53]. Meanwhile, this study found that, throughout the growth of lucerne, the soil temperatures of the PM and BM treatments on ridges were higher than in the ditches. On the one hand, this may be attributed to the fact that ridge tillage with film mulching abates solar radiation in the ditches. On the other hand, a good hydrothermal environment enables lucerne to quickly form an optimal canopy, enhancing the shading effect and declining soil temperature in the ditches [6].

Ridge tillage with film mulching not only affects soil, water, and heat conditions but also impacts the soil nutrient content and distribution [54]. Among them, soil organic matter content is one of the primary indicators for evaluating cultivation patterns [19]. Ren et al. [55] put forward in their research on summer maize in the Wei River Valley that compared to flat cropping, furrow-collecting rainwater cultivation remarkably enhanced the soil's available nitrogen, phosphorus, potassium, and organic matter contents in the plow layer. Similarly, this study also found that, after two years of planting lucerne, the soil nutrients of each treatment increased. The BM and PM treatments elevated the soil organic matter content by 469.70% and 418.18%, respectively. However, Song et al. [56] explored wheat in the Longzhong area of Gansu Province and discovered that the mulching duration had an enormous impact on the soil organic matter content. Compared with the initial stage of the experiment, the organic matter content of the entire mulching treatment declined by 21.2%, the content of the 60-day mulching treatment dropped by 17.2%, and the decline in the content of 30-day mulching and non-mulching treatments was relatively small. The reason may be that favorable water and heat conditions, abundant microbial populations, and strong enzyme activity in the lucerne planting area in the ditches covered with plastic films accelerate the decomposition of humus and allow plenty of organic matter to be returned to the soil [30]. Meanwhile, biodegradable films can restrict soil moisture evaporation, retain moisture, and have a strong adhesion ability, which can bind soil particles and form ideal aggregates, enhancing the capillary effect of soil particles and ameliorating soil permeability [57]. Additionally, after a certain period of degradation, biodegradable films become pollution-free small-molecule substances that participate in the biological metabolic cycle or are assimilated and absorbed by the soil, thereby promoting the soil nutrient content [58–60].

4.2. Effects of Cultivation Patterns on the Growth, Yield, and Quality of Lucerne

Reasonable cultivation patterns are essential for the good growth and development of plants and for yield formation [61]. Song et al. [62] reported in their research on the hilly areas of the Loess Plateau that the plant height and stem diameter of the lucerne from ridge tillage with ordinary and biodegradable film mulching were significantly higher than those on soil ridges and flat cropping. Zhang et al. [63] found in the semi-arid region of northwest China that ridge tillage with ordinary and biodegradable film mulching increased the heights of sainfoin plants by 56.6% and 47.7% compared to traditional flat cropping, respectively. Huo et al. [64] revealed in their study on the hilly areas of the Loess Plateau that, in contrast with traditional flat cropping, ridge tillage with ordinary and biodegradable film mulching increased lucerne hay yield by 5.2–12.0% and 2.0–9.9%, respectively. Similar to previous findings [62–64], this study found that, compared to the FP treatment, the PM and BM treatments promoted the average plant height of lucerne by 15.37% and 4.04%, the average stem diameter by 34.14% and 14.58%, and the average yield by 19.32% and 13.04%, respectively. The major reason for this is that ridge tillage with film mulching slows down the wind speed in the ditches and builds a suitable soil microenvironment for lucerne growth, thereby stimulating plant growth and yield formation [8]. In addition, this study discovered that the yields of lucerne under the three cultivation patterns decreased with harvests. This may be attributed to the fact that after lucerne is harvested, it will recover its growth by consuming the nutrients stored in the root. However, as the number of cuts increases, the nutrient supply in the root of lucerne cannot meet the plant's needs, resulting in a drop in yield. Additionally, under high temperatures, lucerne will grow too fast, and low temperatures can constrain the growth rate of lucerne.

The second and third crops of lucerne grew in hot summer and cold late autumn when biomass was insufficient, and the yield decreased.

The contents of CP, ADF, NDF, and RFV are key indicators for measuring the nutritional value of lucerne [41]. The higher the CP and RFV contents and the lower the contents of ADF and NDF, the better the feeding performance and the higher the nutritional value of lucerne [65]. Similar to the results of Meng et al. [48] 's research on the Loess Plateau, this study found that the PM and BM treatments evidently improved the quality of lucerne compared to the FP treatment, and the PM treatment achieved the best quality. The primary reason for this is that during the growth of lucerne, ridge tillage with film mulching can effectively collect rainwater and store water, which elevates the soil moisture content in the ditches, advances the activity of glutamine synthase, and depresses the activity of proteolytic enzymes, ultimately leading to an augmentation of the CP content [66]. Moreover, the increase in soil moisture in the ditches promotes root water absorption and plant moisture content, thereby inhibiting plant lignification and downgrading the content of ADF and NDF [67]. Sha et al. [68] discovered in the Ningxia Hui Autonomous Region that the contents of CP, ADF, and NDF in lucerne were greatly affected by planting years. The content of CP decreased with planting years, while that of ADF and NDF rose. However, this study found that the CP content of lucerne in the second year was remarkably higher than that in the planting year, and the contents of ADF and NDF were significantly lower. The reason for this may be that this study planted two lucerne crops in the same year, with a long growth cycle. During this period, affected by precipitation and wind, the lucerne plants incurred lodging from the bud stage to the early flowering stage. Lodged lucerne suffered from insufficient light, weakened photosynthesis, poor root and neck respiration, and decay, ultimately leading to a drop in quality.

4.3. Effects of Cultivation Patterns on Water and Nitrogen Use Efficiency of Lucerne

The WUE can characterize the efficiency of converting unit water volume into dry matter accumulation during the physiological activities of crops [69]; IWUE reflects the contribution of irrigated water to the dry matter in crops [70]; and PFPN refers to the increase in crop nitrogen yield per unit of land due to the application of a certain amount of nitrogen fertilizer [71]. Ridge tillage with film mulching can efficiently assemble precipitation, augment soil moisture content, enhance the soil absorption of water and nitrogen, promote plant growth and dry matter accumulation, and improve the WUE and PFPN [35]. Huo et al. [64] reported in their study on the semi-arid Loess Hilly Region in Gansu Province that ridge tillage with ordinary and biodegradable film mulching increased the average WUE of lucerne by 35.00% and 31.00% compared to traditional flat cropping, respectively. Wenhui Meng et al. [72] conducted a study on corn in the Loess Plateau and believed that, compared with traditional flat cropping, two years of ridge tillage with film mulching enhanced PFPN by 27.72% and 30.66%, respectively. Consistent with previous findings [8,72], this study found that, in contrast with the FP treatment, the PM and BM treatments downgraded the ET by an average of 15.81% and 10.79% and elevated the IWUE by an average of 21.19% and 14.77%, the WUE by an average of 43.50% and 17.56%, and the PFPN by an average of 21.20% and 14.78%, respectively. The reason is that in this study, the yield shows PM > BM > FP, and the water consumption exhibits FP > BM > PM, while the irrigation and nitrogen application rates are constant. Therefore, the water and nitrogen use efficiency of the PM treatment is the highest, and that of the FP treatment is the lowest.

5. Conclusions

During the entire growth cycle of lucerne, ridge mulching with ordinary plastic film and ridge mulching with biodegradable film significantly increased the average water content in the 0–120 cm soil layer. The average soil temperature in the 0–25 cm soil layer followed the order of ridge mulching with ordinary plastic film > ridge mulching with biodegradable film > traditional flat planting. Compared with traditional flat planting, ridge mulching with ordinary plastic film and ridge mulching with biodegradable film both increased the average soil temperature and decreased the soil temperature in the furrow. After two years of planting, the soil nutrient content in all treatments increased compared to traditional flat planting. In terms of promoting growth, enhancing yield, quality, and utilizing water and nitrogen, ridge mulching with ordinary plastic film was the most effective, followed by ridge mulching with biodegradable film, while traditional flat planting was the least effective. In summary, both ridge mulching with ordinary plastic film and ridge mulching with biodegradable film can create a suitable soil environment for lucerne growth and improve production efficiency. Among them, ridge mulching with ordinary plastic film is more effective in improving lucerne production efficiency, while ridge mulching with biodegradable film is more effective in improving soil fertility.

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