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Effects of Nitrogen Supply on Dry Matter Accumulation, Water-Nitrogen Use Efficiency and Grain Yield of Soybean (*Glycine max* L.) under Different Mulching Methods

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Abstract: In dryland agriculture, mulching methods and nitrogen application have been extensively adopted to improve water and nitrogen use efficiency and increase crop yield. However, there has been a scarcity of research on the combined effects of mulching types and nitrogen application on the growth and yield of soybean (*Glycine max* L.). In the present study, four nitrogen levels (N0: 0 kg N ha^{-1}, N1: 60 kg N ha^{-1}, N2: 120 kg N ha^{-1}, N3: 180 kg N ha^{-1}) and four mulching methods (NM: no mulching, SM: straw mulching, FM: film mulching, SFM: straw and film mulching) were set so as to evaluate the effects of mulching methods and nitrogen application on dry matter accumulation, grain yield, water-nitrogen use efficiency, and economic benefits of soybean in Northwest China from 2021 to 2022. The results show that the dry matter accumulation, yield formation, water and nitrogen use efficiency, and economic benefits of soybean were improved under different mulching methods (SM, FM, and SFM) and nitrogen applications (N1-N3), and that the effect is the best when the nitrogen application rate is N2 and the mulching method is FM. As such, a conclusion could be drawn that suitable nitrogen application (120 kg ha^{-1}) combined with film mulching was beneficial for the utilization of rainwater resources and soybean production in the dryland of Northwest China.

Keywords: soybean; nitrogen; mulching methods; water-nitrogen use efficiency; grain yield; economic benefit

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1. Introduction

Globally, soybean (*Glycine max* L.) is one of the most important crops, as it is an important part of global food security and a protein source for human food and animal feed [1]. The loess plateau is a critical grain production base in China [2]. Drought is the main factor leading to the instability of grain production in the region, and can be caused by abnormal climate, uncertain rainfall, and uneven distribution [3]. With the long-term shortage of water resources, there has been an increasingly prominent contradiction between the uses of agricultural water use [4]. Owing to the lack of irrigation water and facilities in planting areas, the growth of most farmland crops is completely dependent on rainfall. Since rain-fed agriculture is the primary mode of local farming [5], through appropriate agronomic measures (such as land cover) and more efficient use of limited rainwater resources, the rain-fed crop yield and water use efficiency can be improved, thereby allowing for a higher economic efficiency to ultimately be achieved [6,7].

Nitrogen is a significant factor in crop growth and promotes crop photosynthesis by increasing chlorophyll content in crop leaves, thereby increasing the crop leaf area index and aboveground biomass, which increases the yield [8]. In the growth stage of crops, the application of an appropriate amount of nitrogen fertilizer is a necessary condition for increasing yield [9]. A reasonable application of nitrogen fertilizer can promote the increase of soybean leaf area index and dry matter accumulation, and ultimately increase grain yield [10]. As revealed in previous research, because soybeans can provide nitrogen by nitrogen fixation through their root nodules, maintaining a normal growth of soybeans may not require excessive nitrogen application.Although the nitrogen fixed by the symbiotic nitrogen fixation of soybean and rhizobia accounts for more than half of the total nitrogen required for its life, however, this is due to the consumption of soil fertility by previous crops and the intensification of nutrient competition within and between crops. After nodule formation in soybean roots, rhizobia need to obtain carbon and nitrogen sources from plants for symbiotic nitrogen fixation. At the same time, during the reproductive growth period, the demand for soybean nutrients is large, and nitrogen deficiency is prone to occur. Therefore, it is necessary to apply sufficient nitrogen to soybean [11]. Excessive nitrogen application will adversely affect the growth of soybean [12], with studies confirming that excessive nitrogen application inhibits soybean growth, reduces nitrogen use efficiency, and ultimately reduces soybean yield [13]. At present, there is growing concern among scholars with regard to the decrease in nitrogen use efficiency and the corresponding environmental problems caused by the unreasonable application of nitrogen fertilizer [14,15].

Due to the pressure of topography and climate in the Loess Plateau of China and the pressure of agricultural harvest, it is impossible to achieve conservation tillage like the arid areas of the United States, so most of them will use various farmland coverage methods as field management methods [6]. In dryland agricultural areas (with an annual precipitation of 300–600 mm), land cover is effective in improving water use efficiency and increasing crop yields [16,17]. Relevant studies have demonstrated that flat straw mulching on dryland farmland can increase soil water storage by means of non-productive evaporation to a certain extent [18]. Other scholars have highlighted that ridge-furrow film mulching can maximize the use of rainwater. Plastic film was used to cover ridges and furrows, and crops are planted in ridges and furrows [19]. By collecting rainwater from ridges and furrows, such mulching method can fully inhibit soil evaporation and promote water infiltration while also significantly improving the water absorption capacity of crop roots [20,21]. Through such means, the raw materials of crop photosynthesis are increased, the crop nutrient absorption, growth, and development are promoted, and the goal of improving water and nitrogen use efficiency and yield is ultimately achieved.

The independent effects of nitrogen application and mulching on soybean growth and yield have been extensively explored [22,23]. However, there is a scarcity of research on the interaction of mulching type and nitrogen application on soybean growth and yield, especially in continuous experiments in different years. The present authors speculate that nitrogen application and surface mulching, as well as the interaction effects thereof, can significantly affect the growth and yield of soybean, and the internal relationship needs to be further clarified. The aim of the present study was to explore the comprehensive effects of nitrogen application and surface mulching and the interaction effects thereof on dry matter accumulation, soil water storage, evapotranspiration, water and nitrogen use efficiency, grain yield and the components thereof and economic benefits of dryland soybean, and then to obtain soybean nitrogen application management decisions suitable for Northwest China. To achieve such an aim, a two-year field experiment was conducted by setting four mulching methods and four nitrogen application levels to explore the optimal combination of soybean mulching methods and nitrogen application rates in the area.

2. Materials and Methods

2.1. Research Area

In the present study, a two-year (2021–2022) soybean field experiment was conducted at the Institute of Water-saving Agriculture in Arid Areas of China (34°18′ N, 108°24′ E, 521 m a.s.l.) (Figure 1). The average annual rainfall of the pilot station is 632 mm and the potential evaporation is 1500 mm (1991–2020). The soil properties of 0–20 cm are shown in Table 1, and the determination methods of each index are detailed in a study by Guo et al. (2022) [24]. Daily temperature and precipitation during the two-year soybean growing season were recorded by a national meteorological station located 20 m away from the experimental field (Figure 2). The average maximum and minimum temperatures from June to October in 2021 were 30.3 °C and 20.0 °C, respectively, and 31.3 °C and 21.2 °C in 2022. The levels of precipitation during the planting periods in 2021 and 2022 were 432.6 mm and 279.5 mm, respectively. Compared with the average precipitation of 345 mm in soybean season in the past 30 years (1991–2020), 2021 is a wet year and 2022 is a dry year. Precipitation year type is divided according to precipitation anomaly. The boundary between wet years and dry years is ±15% of average precipitation.

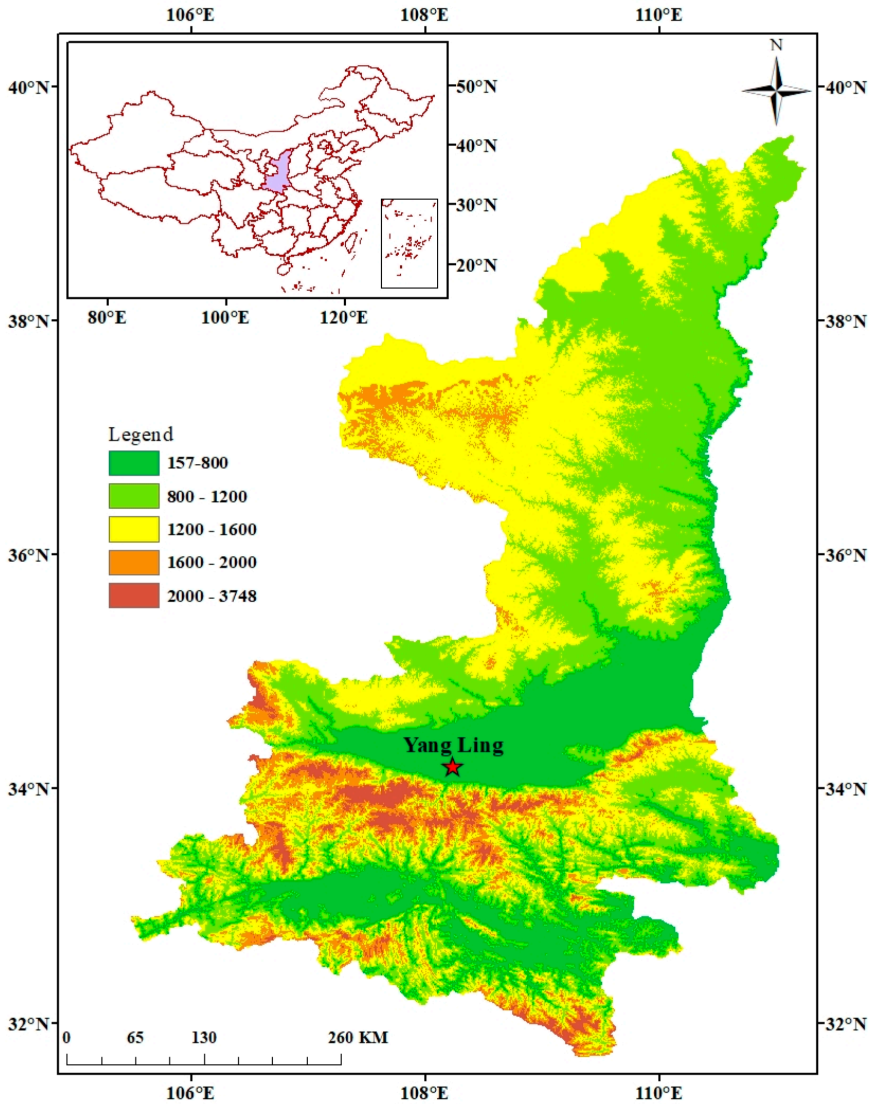

Figure 1. Study area.

Table 1. Basic soil properties of the plough horizon soil layer at the experimental site in Yangling, China (sampled on 17 June 2021).

Soil Property	Value	Measurement Method
Soil texture	silty clay loam	Laser particle size analyzer
Bulk density	1.41 g cm^{-3}	Core sampling method using ring knife
pH	8.14	Acid-Alkali indicator method
Field capacity soil moisture	0.248 m^3 m^{-3}	Ring knife method
Soil organic matter	11.3 g kg^{-1}	Walkley and Black
Electric conductivity	0.18 ds m^{-1}	DDS-11 Conductivity Meter
Nitrogen nitric	10.1 mg kg^{-1}	Kjeldahl digestion
Total carbon	112.5 mg kg^{-1}	Vario PYRO cube Element analyzer
Total nitrogen	0.91 g kg^{-1}	Kjeldahl digestion
Available nitrogen	27.5 mg kg^{-1}	Colorimetric method by 2 mol/L cold KCL extractable
Available phosphorus	19.8 mg kg^{-1}	Olsen method by 0.5 mol/L $NaHCO_3$ extractable
Available potassium	124.3 mg kg^{-1}	Colorimetric method by 2 mol/L cold HNO_3 extractable

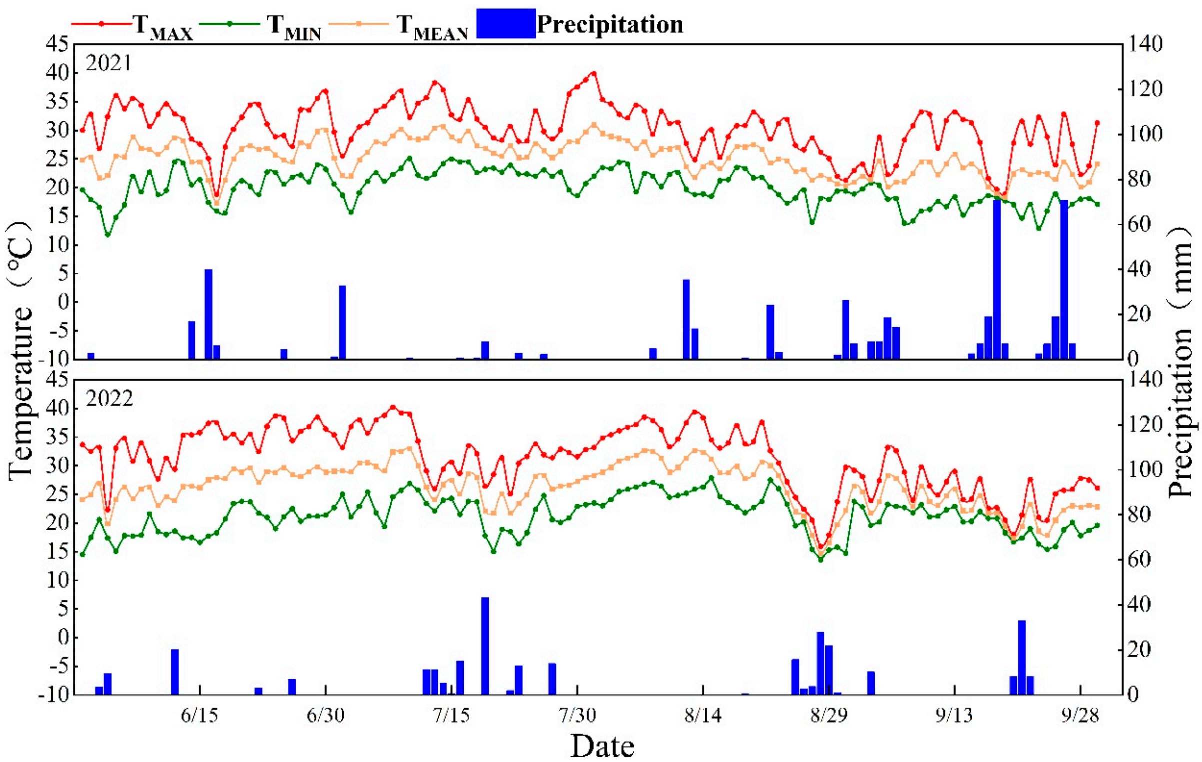

Figure 2. The daily precipitation, maximum, minimum, and average temperature of rain-fed soybean growing season in 2021 and 2022.

2.2. Test Design, Measurements, and Methods

2.2.1. Soybean Field Test Design

The experimental design was as shown in Table 2. Based on the nitrogen application rate of 180 kg ha^{-1} by most local farmers, four nitrogen application levels (N0: 0 kg N ha^{-1}, N1: 60 kg N ha^{-1}, N2: 120 kg N ha^{-1}, N3: 180 kg N ha^{-1}) and four mulching methods (NM: no mulching, SM: straw mulching, FM: film mulching, SFM: straw and film mulching) were set. There was a total of 16 treatments, which were repeated twice for a total of 32 test areas, and a completely randomized design was adopted for the test, with each area having a length of 6 m and a width of 4 m. A protective belt with a width of 2 m was set between the plots to reduce the impact between treatments.

Table 2. Basic information regarding field experiment.

Treatment	Mulching Method	Nitrogen Application Rate
NMN0 NMN1 NMN2 NMN3	No mulching	0 kg ha^{-1} 60 kg ha^{-1} 120 kg ha^{-1} 180 kg ha^{-1}
SMN0 SMN1 SMN2 SMN3	Straw mulching	0 kg ha^{-1} 60 kg ha^{-1} 120 kg ha^{-1} 180 kg ha^{-1}
FMN0 FMN1 FMN2 FMN3	Film mulching	0 kg ha^{-1} 60 kg ha^{-1} 120 kg ha^{-1} 180 kg ha^{-1}
SFMN0 SFMN1 SFMN2 SFMN3	Straw and film mulching	0 kg ha^{-1} 60 kg ha^{-1} 120 kg ha^{-1} 180 kg ha^{-1}

Notes: N3 is the level of nitrogen applied by local farmers; N2 is 33% N fertilizer reduction treatment; N1 is 67% N fertilizer reduction treatment; N0 is no N application treatment.

The application amount of phosphorus and potassium fertilizer in each plot was 30 kg ha^{-1}. The nitrogen fertilizer was urea (46% N), the phosphorus fertilizer was calcium superphosphate (16% P), and the potassium fertilizer was potassium chloride (62% K). Each fertilizer was applied in a ditch at 25 cm from the crop before sowing, and the straw mulching amount was 9000 kg ha^{-1}. The soybean planting mode under the FM treatment was ridge film furrow sowing, that is, the ratio of ridge to furrow was 1:1, the width of ridge and furrow was 50 cm, and the height of ridge was 30 cm. The ridge was raised before sowing, and two rows of soybean were planted at the base of ridge. Soybeans were covered with straw within seven days after sowing, and the material was the whole wheat straw harvested in the previous crop. SFM treatment covered the ridge with film and the furrow with straw. Further, the soybean planting density was 300,000 plants ha^{-1}, with a row spacing of 50 cm and a plant spacing of 10 cm. Soybean was sown on 18 June 2021 and 10 June 2022, respectively, and harvested on 30 September 2021 and 20 September 2022.

2.2.2. Dry Matter Accumulation

The aboveground biomass was measured at the four-node stage (V4), full bloom stage (R2), full pod stage (R4), full seed stage (R6), and full maturity stage (R8) of soybean. In the present study, six representative plants were randomly selected from each plot, the soybean roots were completely removed by the traditional root digging method and the soybean dry to constant weight, and then the aboveground biomass of soybean was measured by means of electronic balance.

2.2.3. Soybean Yield and the Components Thereof

At R8, the middle 2 rows of 1 m were taken from each plot to calculate the yield, and the soybean seeds were air-dried. At 14%, the mass fraction of the converted grain moisture could be calculated as the standard yield (kg ha^{-1}). At the same time, 10 representative plants were taken to determine the number of main stem nodes, the number of pods per plant, and the 100-grain weight. The soybean grains were dried to constant weight in an oven at 75 °C to determine the 100-grain weight.

2.2.4. Soil and Plants Sampling and Analysis

After harvesting, soil samples were taken at 10 cm intervals between the two wide rows of soybeans and next to the soybean plants to a depth of 100 cm. In addition, the residual NO_3^--N in soil was analyzed by means of an AA3 continuous flow analyzer (Bran Luebbe, Germany). At the same time, the Kjeldahl method was used to determine the total nitrogen uptake of dried soybean plant samples of R8 [25]. The number of samples collected in all plots was repeated 6 times.

2.2.5. Soil Water Storage, Evapotranspiration, and Water Use Efficiency

Evapotranspiration (ET) and water use efficiency (WUE) were determined using the soil water balance method [24]:

$$\mathrm{ET} = \mathrm{P} + \mathrm{I} + \mathrm{U} + \mathrm{R} + \mathrm{D} + (\mathrm{SWS}_2 - \mathrm{SWS}_1) \tag{1}$$

$$\mathrm{WUE} = \frac{GY}{\mathrm{ET}} \tag{2}$$

where ET represents the soybean water consumption (mm); P represents the rainfall (mm); I represents the irrigation amount (mm); U represents the groundwater recharge (mm); R represents the surface runoff (mm); D represents the deep drainage (mm); SWS_1 and SWS_2 are the soil water storage in the 0–100 cm soil layer at the beginning and end of the experiment, respectively (mm). Due to the deep groundwater depth, flat terrain, and shallow infiltration depth, I, U, R, and D were ignored, and Equation (1) could be simplified as: $\mathrm{ET} = \mathrm{P} + (\mathrm{SWS}_2 - \mathrm{SWS}_1)$.

2.2.6. Nitrogen Use Efficiency

The total nitrogen uptake results obtained in the previous step were calculated to obtain the following nitrogen use efficiency values [25]:

$$\text{N utilization efficiency}\left(\text{NUE, } kg\ \text{kg}^{-1}\right) = \frac{GY}{N_{uptake}} \tag{3}$$

$$\text{N partial factor productivity}\left(\text{NPFP, } kg\ \text{kg}^{-1}\right) = \frac{GY_N}{N} \tag{4}$$

$$\text{Soil NO}_3{}^- - \text{N residual}\left(\text{kg ha}^{-1}\right) = \sum_{i=0}^{100} C_{NO_3-N} \times h_i \times \gamma_i \times 100\% \tag{5}$$

where GY_N represents the grain yield with N applied (kg ha^{-1}); N_{uptake} represents the total N uptake (kg ha^{-1}); C_{NO_3-N} represents the soil NO_3^--N concentration (g kg^{-1}); h_i represents the soil thickness (m); and γ_i represents the soil bulk density (g cm^{-3}).

2.2.7. Economic Benefits Analysis

The value of the economic benefits (E_b) was calculated as follows [26]:

$$\mathrm{E_b} = \mathrm{p} \times \mathrm{GY} - \mathrm{F_w} - \mathrm{S_w} - \mathrm{O} \tag{6}$$

where p represents the soybean price (CNY kg^{-1}); GY represents the grain yield (kg ha^{-1}); F_w represents the fertilizer cost (CNY ha^{-1}); S_w represents the seed cost (CNY ha^{-1}); and O represents the other input costs (CNY ha^{-1}). According to the survey, the soybean price was 5 CNY kg^{-1}, while the fertilizer costs of N0-N3 were 581 CNY ha^{-1}, 831 CNY ha^{-1}, 1081 CNY ha^{-1}, and 1331 CNY ha^{-1}, respectively. Since the planting density of each treatment was the same, the seed cost was calculated to be 1000 CNY ha^{-1}. Adding labor costs, the other costs under NM, SM, FM, and SFM treatments were 8000 CNY ha^{-1}, 9500 CNY ha^{-1}, 9000 CNY ha^{-1}, and 10,000 CNY ha^{-1}, respectively.

2.3. Data Analysis and Verification of the Prediction Accuracy of the Models

One-way analysis of variance (ANOVA) was conducted using the SPSS software. ANOVAs were conducted using the influence of different years on each index (Y), the influence of different mulching methods on each index (M), and the effects of different nitrogen application on each index (N), and included the two/three-way interaction of Y&N, Y&M, M&N, and Y&M&N. Multiple comparisons of mean annual values were performed using the least significant difference (LSD) at $p < 0.05$. Origin was used to create the Figure.

Figure 3 is the technical roadmap of this study.

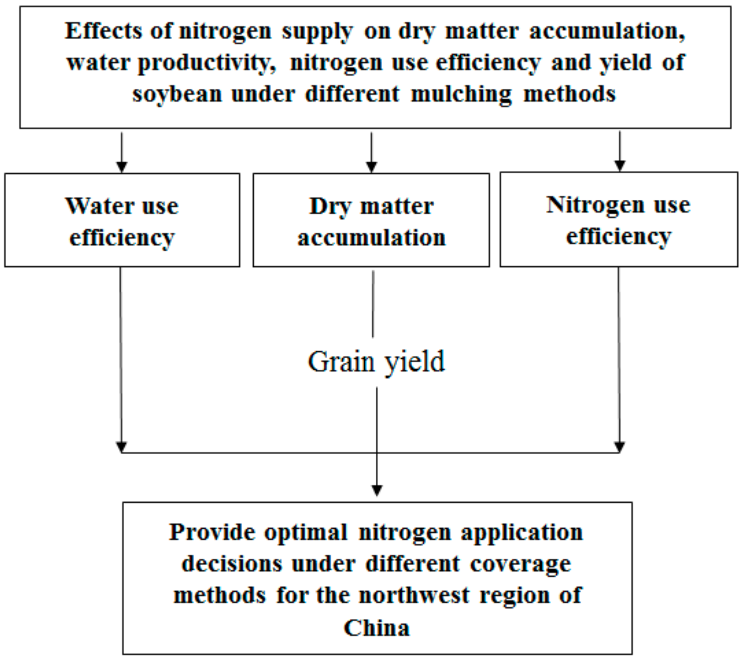

Figure 3. Diagrams of architectures used in the experiments.

3. Results

3.1. Analysis of Meteorological Data

We found that the difference between the maximum and minimum temperatures in the two years is not large, but the interannual variation of precipitation in the soybean growing season is very large, that is, 2021 is much higher than 2022. The precipitation in 2021 is mainly concentrated in the reproductive growth period (Figure 2).

3.2. Effects of Nitrogen Supply on Dry Matter Accumulation of Soybean under Different Mulching Methods

The effects of different mulching methods and different nitrogen applications on the dry matter accumulation of soybean are shown in Figure 4a–h. Under the same treatment, the dry matter accumulation in 2021 was higher than that in 2022 ($p < 0.05$). The dry matter accumulation of soybean was significantly affected by different mulching, nitrogen application, and the interaction between the two ($p < 0.05$). The aboveground biomass of soybean in 2021 was higher than that in 2022. The dry matter accumulation of different treatments increased with the growth of soybean and reached the maximum at harvest (R8). The results show that the increase in nitrogen application rate could significantly promote the growth of soybean in the range of 0–120 kg ha^{-1} (N2). However, when the nitrogen application rate exceeded 120 kg ha^{-1}, the dry matter accumulation decreased significantly. When the nitrogen application rate was N2 for 2a, the levels of dry matter accumulation at the harvest stage (R8) under the NM, SM, FM and SFM treatments were 6.3–36.4%, 5.3–43.6%, 13.5–53.4%, and 11.1–34.9% higher than those under other nitrogen treatments, respectively. When the nitrogen application was N2 and the mulching method was FM, the maximum dry matter accumulation was 18,471.5 kg ha^{-1} in R8, which was 32.1%, 11.9%, and 23.3% higher than NMN2, SMN2, and SFMN2, respectively.

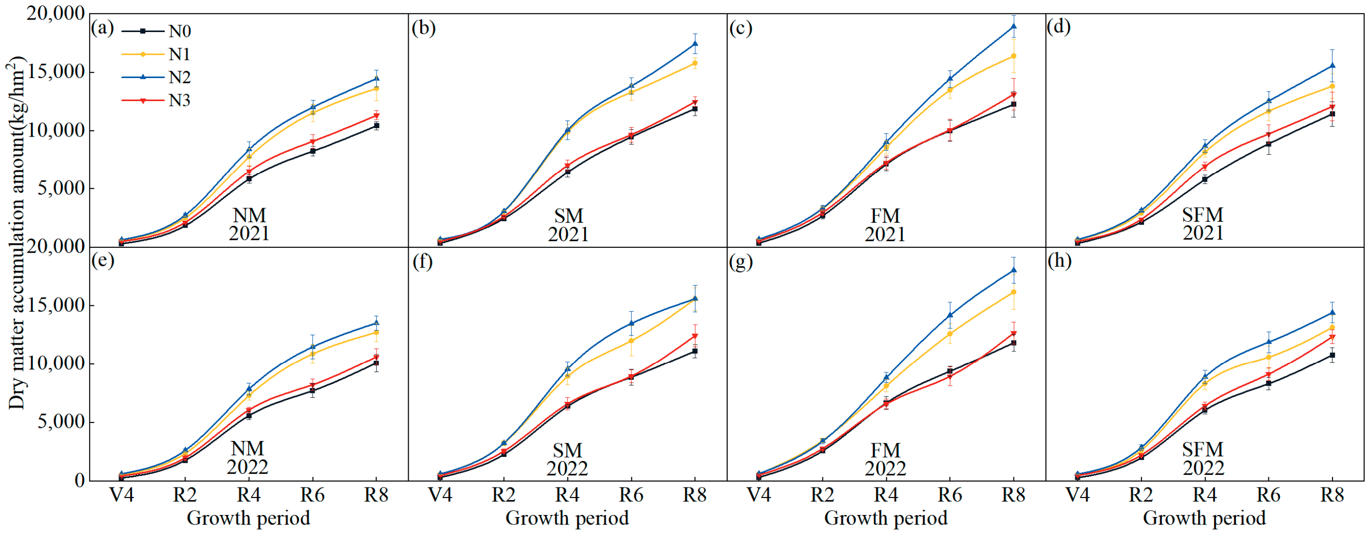

Figure 4. The effects of nitrogen application and mulching treatments (NM, SM, FM, SFM) on soybean above-ground biomass at different growth stages in 2021 and 2022 (**a**–**h**). Vertical bars indicate the LSD values at $p = 0.05$ level.

3.3. Effects of Nitrogen Supply on Water Use Efficiency of Soybean under Different Mulching Methods

The observation can be made from Table 3 that for the effects of nitrogen application and different years on soil water storage, ET and WUE, soybeans reached a significant level at the harvest stage of 2 ($p < 0.05$). For the effects of mulching on soil water storage and WUE at the harvest stage of 2, soybean also reached a significant level ($p < 0.05$). The interaction between nitrogen application and different years had a significant effect on soil water storage and ET at the harvest stage of 2a soybean ($p < 0.05$) but did not have a significant effect on WUE ($p > 0.05$). The interaction between mulching methods and different years on soil water storage, ET, and WUE at the harvest stage of soybean 2 a reached significant level ($p < 0.05$). The effects of mulching methods and nitrogen application interaction had no significant effect on soil water storage and ET at the harvest stage of soybean 2 a ($p > 0.05$) and had a significant effect on WUE ($p < 0.05$). However, under the combined effects of mulching methods and nitrogen application in different years, the effects of soil water storage, ET and WUE, were not significant ($p > 0.05$).

Under the same mulching method, the soil water storage in the harvest period decreased first and then increased with the increase in nitrogen application. When the nitrogen application was 120 kg ha^{-1}, the soil water storage reached the lowest value, indicating that appropriate nitrogen application could promote the absorption of soil water by soybean. Under the same nitrogen application, findings were made that the soil water storage under SFM reached the highest level, which was 4.9%, 3.4%, and 2.6% higher than that of NM, SM, and FM, respectively. Because the initial soil water storage and precipitation of each treatment were the same, the rule that the change of ET of each treatment was inversely proportional to the rule of soil water storage at the harvest time could be easily obtained from the calculation formula of ET.

Table 3. Effects of different mulching methods and different nitrogen application on water use efficiency of soybean. The soil water storage before sowing and after harvest was calculated by drilling 0–100 cm soil before sowing and after harvest in each year. The calculation formula is detailed in Liao et al. (2022) [10].

Year	**2021**					**2022**				
Treatment	**Soil Water Storage before Sowing (mm)**	**Soil Water Storage after Harvest (mm)**	**Precipitation during Planting Period (mm)**	**ET (mm)**	**WUE (kg·ha^{-1}·mm^{-1})**	**Soil Water Storage before Sowing (mm)**	**Soil Water Storage after Harvest (mm)**	**Precipitation during Planting Period (mm)**	**ET (mm)**	**WUE (kg·ha^{-1}·mm^{-1})**
NMN0	163.77	180.39 ab	432.6	415.98 hi	7.21 j	154.33	115.00 bcd	279.5	318.83 ab	8.23 k
NMN1	163.77	165.81 fgh	432.6	430.56 bcd	8.93 fgh	154.33	105.70 ghi	279.5	328.13 ab	9.97 h
NMN2	163.77	155.65 i	432.6	440.72 a	9.13 fg	154.33	99.23 j	279.5	334.60 a	10.36 g
NMN3	163.77	172.40 cdef	432.6	423.97 defg	8.05 i	154.33	109.91 defg	279.5	323.93 ab	8.97 j
SMN0	163.77	181.56 ab	432.6	414.81 hi	8.59 ghi	154.33	115.74 bc	279.5	318.09 ab	9.43 i
SMN1	163.77	167.87 efgh	432.6	428.50 bcde	10.99 c	154.33	107.02 fghi	279.5	326.81 ab	11.90 d
SMN2	163.77	160.55 hi	432.6	435.82 ab	12.03 b	154.33	102.35 ij	279.5	331.48 ab	13.46 a
SMN3	163.77	174.96 bcde	432.6	421.41 efgh	10.05 de	154.33	111.54 cdef	279.5	322.29 ab	11.44 e
FMN0	163.77	182.35 ab	432.6	414.02 hi	9.52 ef	154.33	116.25 bc	279.5	317.58 ab	10.88 f
FMN1	163.77	169.08 defg	432.6	427.29 cdef	11.80 b	154.33	107.79 fgh	279.5	326.04 ab	13.06 b
FMN2	163.77	162.52 ghi	432.6	433.85 abc	12.83 a	154.33	103.61 hij	279.5	330.22 ab	13.72 a
FMN3	163.77	175.58 bcd	432.6	420.79 fgh	10.58 cd	154.33	111.93 cdef	279.5	321.90 ab	11.95 cd
SFMN0	163.77	183.41 a	432.6	412.96 i	8.36 hi	154.33	122.77 a	279.5	311.06 b	9.38 i
SFMN1	163.77	169.36 defg	432.6	427.01 cdef	10.12 de	154.33	113.37 cde	279.5	320.46 ab	11.52 e
SFMN2	163.77	162.95 ghi	432.6	433.42 abc	10.54 cd	154.33	109.07 efg	279.5	324.76 ab	12.26 c
SFMN3	163.77	178.29 abc	432.6	418.08 ghi	8.82 gh	154.33	119.34 ab	279.5	314.49 ab	10.01 h
	Significant level (F value)									
Y	/	*	/	*	*	/	*	/	*	*
N	/	*	/	*	**	/	**	/	*	**
M	/	**	/	**	**	/	**	/	ns	**
Y*N	/	*	/	*	ns	/	*	/	*	ns
Y*M	/	*	/	*	*	/	*	/	*	*
N*M	/	ns	/	ns	*	/	ns	/	ns	**
Y*N*M	/	ns	/	ns	ns	/	ns	/	ns	ns

Notice: Y: the influence of different years on each index; M: the influence of different mulching methods on each index; N: the effect of different nitrogen application on each index; Y*M: the influence of the interaction between mulching methods and year on each index; Y*N: the effect of interaction between year and nitrogen application on each index; N*M: The effect of the interaction between mulching and nitrogen application on each index. Y*N*M: the effect of year, mulching methods and nitrogen interaction on each index. Different alphabets indicate the significance within the same year at 5% level by LSD test. ns: not significant, ($p > 0.05$); *, Significant at $p < 0.05$; **, Significant at $p < 0.01$.

The interaction between nitrogen application and mulching methods had a significant effect on the WUE of 2a soybean ($p < 0.05$), and the highest WUE values of 2a were obtained under the FMN2 treatment, being 12.83 and 13.72, respectively. The WUE values of FMN2 in 2021 and 2022 were 6.6–78.0% and 1.9–66.8% higher than those of the other treatments, respectively.

3.4. Effects of Nitrogen Supply on Nitrogen Use Efficiency of Soybean under Different Mulching Methods

Nitrogen uptake, soil nitrogen residue, NUE, and NPFP were significantly affected by nitrogen application, mulching methods, and the interactions between them ($p < 0.05$) (Table 4). At the same time, the nitrogen uptake, soil nitrogen residue, NUE, and NPFP were significantly affected by different years and the interaction between different years and nitrogen application ($p < 0.05$). However, the interaction between different years and mulching, and the interaction between nitrogen application and mulching in different years, had no significant effect on nitrogen uptake and soil nitrogen residue ($p > 0.05$), but had a significant effect on NUE and NPFP ($p < 0.05$). The NUE and NPFP in 2021 were higher than that in 2022 under the same treatment ($p < 0.05$).

Table 4. Effects of different mulching methods and different nitrogen application on nitrogen use efficiency of soybean. Y: the influence of different years on each index; M: the influence of different mulching methods on each index; N: the effect of different nitrogen application on each index; Y*M: the influence of the interaction between mulching methods and year on each index; Y*N: the effect of interaction between year and nitrogen application on each index; N*M: The effect of the interaction between mulching and nitrogen application on each index. Y*N*M: the effect of year, mulching methods and nitrogen interaction on each index. Different alphabets indicate the significance within the same year at 5% level by LSD test. ns: not significant, ($p > 0.05$); *, Significant at $p < 0.05$; **, Significant at $p < 0.01$.

Year	2021				2022			
Treatment	**N Uptake (kg ha^{-1})**	**NUE (kg kg^{-1})**	**NPFP (kg kg^{-1})**	**Soil N Residual (kg ha^{-1})**	**N Uptake (kg ha^{-1})**	**NUE (kg kg^{-1})**	**NPFP (kg kg^{-1})**	**Soil N Residual (kg ha^{-1})**
NMN0	68.77 j	/	/	25.88 gh	68.80 i	/	/	27.83 f
NMN1	86.98 hi	44.19 e	64.06 d	27.97 fg	80.39 gh	40.71 de	54.53 d	28.67 f
NMN2	95.15 fg	42.28 f	33.52 h	31.26 e	102.40 cd	33.82 g	28.87 g	32.36 e
NMN3	117.44 bc	29.06 j	18.96 j	45.24 a	111.18 b	26.12 j	16.14 i	46.92 a
SMN0	85.74 hi	/	/	21.08 ij	77.75 h	/	/	21.60 gh
SMN1	96.16 f	49.00 b	78.51 b	20.35 j	91.13 ef	42.61 bc	64.73 b	21.07 h
SMN2	102.93 e	50.94 a	43.70 f	28.99 ef	103.52 bc	43.12 b	37.20 e	29.71 ef
SMN3	121.15 ab	34.95 h	23.52 i	38.83 c	124.38 a	29.64 i	20.48 h	40.19 c
FMN0	90.32 gh	/	/	19.78 jk	85.84 fg	/	/	20.24 h
FMN1	102.20 e	49.35 b	84.06 a	17.23 k	95.93 de	44.37 a	70.95 a	20.46 h
FMN2	110.30 d	50.47 a	46.38 e	23.43 hi	108.88 bc	41.66 cd	37.77 e	24.44 g
FMN3	124.44 a	35.78 g	24.74 i	35.53 d	120.40 a	31.95 h	21.37 h	36.64 d
SFMN0	82.30 i	/	/	23.38 hi	83.00 gh	/	/	24.11 g
SFMN1	89.92 gh	48.06 c	72.02 c	26.16 g	92.93 ef	39.72 e	61.52 c	27.98 f
SFMN2	99.88 ef	45.75 d	38.07 g	34.13 d	105.84 bc	37.69 f	33.20 f	35.19 d
SFMN3	114.44 cd	32.23 i	20.49 j	42.03 b	110.45 b	28.51 i	17.50 i	43.39 b
Significant level (F value)								
Y	*	*	*	*	*	*	*	*
N	**	**	**	**	**	**	**	**
M	**	**	**	**	**	**	**	**
Y*N	*	*	*	*	*	*	*	*
Y*M	ns	*	*	ns	ns	*	*	ns
N*M	*	**	**	*	*	**	**	*
Y*N*N	ns	*	*	ns	ns	*	*	ns

The soil nitrogen residue increased with the increase in nitrogen application rate. Compared with other mulching methods, the soil nitrogen residue under ridge-furrow film mulching was significantly lower. The soil nitrogen residue values of N0, N1, N2, and N3 under the FM treatment were 6.6–34.2%, 9.9–50.3%, 22.6–44.8%, and 9.5–27.7% lower than those under other mulching methods, respectively. The N_{uptake} of soybean increased with the increase in nitrogen application rate, and reached the maximum value under the N3 treatment, being 46.9%, 28.3%, and 13.9% higher than that under the N0, N1, and N2 treatments, respectively. At the same time, the N_{uptake} of the FM treatment was 14.7%, 4.4%, and 7.6% higher than that of the NM, SM, and SFM treatments under the same nitrogen application rate. In the two years, NUE and NPFP were the highest when the nitrogen application was N1. At the same nitrogen application rate, NUE and NPFP performed better under FM, that is, the highest NUE and NPFP values were obtained under FMN1.

3.5. Effects of Nitrogen Supply on Grain Yield and the Components Thereof of Soybean under Different Mulching Methods

In the two years, different mulching methods and different nitrogen applications had significant effects on soybean yield and the components thereof ($p < 0.05$), and the interaction of different mulching methods and different nitrogen application had significant effects on soybean pods per plant and seeds per plant ($p < 0.05$). In 2021, the interaction of different mulching methods and different nitrogen applications had a significant effect on soybean grain yield ($p < 0.05$). In 2022, the interaction of different mulching methods and different nitrogen applications had a significant effect on soybean grain yield ($p < 0.05$). The seed yield and components in 2021 were higher than those in 2022 under the same treatment ($p < 0.05$).

The effects of different mulching modes and nitrogen application rates on soybean yield, and the components thereof are shown in Figure 5. In 2021 and 2022, the number of main stem nodes increased first and then decreased with the increase in nitrogen application rate, and the maximum values were obtained under N2, which were 14.03 and 13.28 per plant in 2018 and 2019, respectively. At the same time, when the mulching method was furrow mulching, the highest number of main stems was obtained, which increased by 4.5–18.6% in 2021 and 4.7–18.7% in 2022 compared with other mulching methods. Under different mulching methods, the number of pods per plant also showed a trend of increasing first and then decreasing with the increase in nitrogen application rate. The maximum value was obtained under the N2 nitrogen application rate. The average values were 72.1 in 2021 and 66.9 in 2022, being 8.9–53.2% and 9.3–49.5% higher than the other three nitrogen application rates. Similar to the number of main stems, the highest pod numbers per plant were obtained in 2021 and 2022 under FMN2, which were 78.8 and 76.0, respectively. The variations of grain number per plant and 100-grain weight in 2021 and 2022 were the same as those of main stem number and pod number per plant, and the highest values were obtained under FMN2.

There were significant differences in soybean grain yield under different treatments. With the increase in nitrogen application, soybean grain yield increased first and then decreased. Under the same mulching method, the values of the average grain yield within 2 years reached the maximum under the N2 nitrogen application rate, being 4850.0 kg ha^{-1} and 4110.8 kg ha^{-1} in 2021 and 2022, respectively, and 8.3~39.0% and 8.9~37.1% higher than the other three nitrogen application rates, respectively. The results of the present experiment show that increasing the nitrogen application rate could effectively increase soybean grain yield, but when the nitrogen application rate exceeded 120 kg ha^{-1}, the continuous increase in nitrogen application rate would not have a significant effect on the increase in soybean grain yield, and could even have a negative impact on the yield reduction. The results show that suitable mulching methods (SM and FM) could promote the increase in grain yield, but such promotion effects would be slowed down with the increase in mulching amount (SFM). In 2021 and 2022, the average grain yields of ridge-furrow mulching were the highest, being 4751.0 kg ha^{-1} and 4022.5 kg ha^{-1}, which were 7.1~33.1% and 7.0~31.2% higher than the other three mulching methods, respectively.

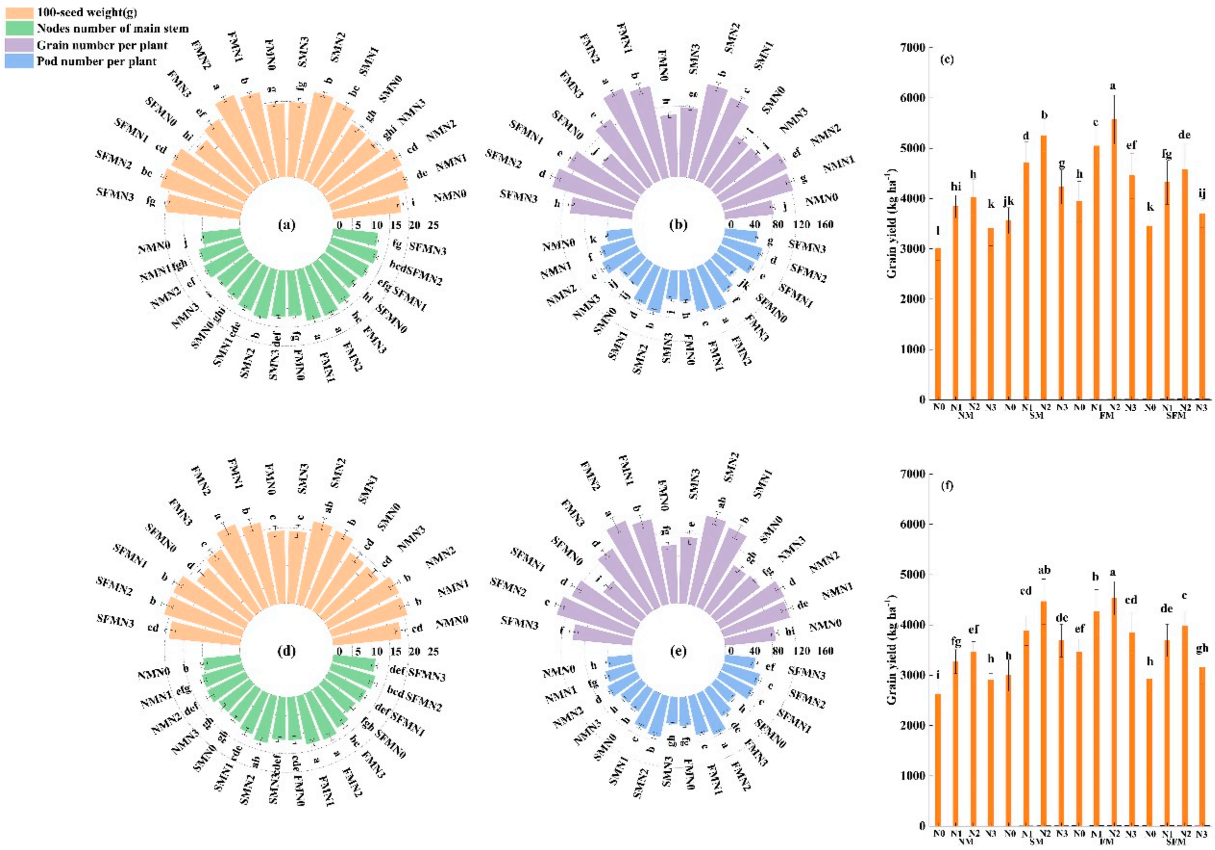

Figure 5. Effects of nitrogen application and mulching treatments (NM, SM, FM, SFM) on soybean yield and its components in 2021 and 2022. (**a**–**c**) represent the data for 2021, and (**d**–**f**) represent the data for 2022. The vertical line represents the LSD value at the p = 0.05 level. Different lower cases indicate significant differences among treatments.

3.6. Effects of Nitrogen Supply on Economic Benefit of Soybean under Different Mulching Methods

In different years, the effects of nitrogen application rate and mulching methods on soybean net income were significant ($p < 0.05$). The interaction between different years and nitrogen application rate and the interaction between different years and mulching methods were significant ($p < 0.05$). The interaction between nitrogen application and mulching had a significant effect on the net income of soybean in 2021 ($p < 0.05$) but had no significant effect on the net income of soybean in 2022 ($p > 0.05$). In different years, the interaction of nitrogen application and mulching methods had no significant effect on the net income of 2a soybean ($p > 0.05$).The economic benefit in 2021 is higher than that in 2022 under the same treatment ($p < 0.05$). The effects of different mulching methods and different nitrogen application on economic efficiency can be seen in Table 5.

Table 5. Effects of different mulching methods and different nitrogen application on economic efficiency. According to the survey, the soybean price was 5 CNY kg^{-1}, while the fertilizer costs of N0-N3 were 581 CNY ha^{-1}, 831 CNY ha^{-1}, 1081 CNY ha^{-1}, and 1331 CNY ha^{-1}, respectively. Since the planting density of each treatment was the same, the seed cost was calculated to be 1000 CNY ha^{-1}. Adding labor costs, the other costs under NM, SM, FM, and SFM treatments were 8000 CNY ha^{-1}, 9500 CNY ha^{-1}, 9000 CNY ha^{-1}, and 10,000 CNY ha^{-1}, respectively. Y: the influence of different years on each index; M: the influence of different mulching methods on each index; N: the effect of different nitrogen application on each index; Y*M: the influence of the interaction between mulching methods and year on each index; Y*N: the effect of interaction between year and nitrogen application on each index; N*M: The effect of the interaction between mulching and nitrogen application on each index. Y*N*M: the effect of year, mulching methods, and nitrogen interaction on each index. Different alphabets indicate the significance within the same year at 5% level by LSD test. ns: not significant, ($p > 0.05$); *, Significant at $p < 0.05$; **, Significant at $p < 0.01$.

Year	2021					2022				
Treatment	Fertilizer Cost (CNY ha^{-1})	Seed Cost (CNY ha^{-1})	Other Cost (CNY ha^{-1})	Total Income (CNY ha^{-1})	Net Income (CNY ha^{-1})	Fertilizer Cost (CNY ha^{-1})	Seed Cost (CNY ha^{-1})	Other Cost (CNY ha^{-1})	Total Income (CNY ha^{-1})	Net Income (CNY ha^{-1})
NMN0	581	1000	8000	14,991.92 l	5410.92 g	581	1000	8000	13,117.86 i	3536.86 e
NMN1	831	1000	8000	19,217.25 hi	9386.25 e	831	1000	8000	16,359.28 fg	6528.28 d
NMN2	1081	1000	8000	20,111.71 h	10,030.71 de	1081	1000	8000	17,319.67 ef	7238.67 bcd
NMN3	1331	1000	8000	17,062.10 k	6731.10 f	1331	1000	8000	14,524.55 h	4193.55 e
SMN0	581	1000	9500	17,819.05 jk	6738.05 f	581	1000	9500	14,992.04 h	3911.04 e
SMN1	831	1000	9500	23,553.70 d	12,222.70 c	831	1000	9500	19,419.98 cd	8088.98 b
SMN2	1081	1000	9500	26,217.60 b	14,636.60 b	1081	1000	9500	22,318.45 ab	10,737.45 a
SMN3	1331	1000	9500	21,170.46 g	9339.46 e	1331	1000	9500	18,436.16 de	6605.16 cd
FMN0	581	1000	9000	19,712.98 h	9131.98 e	581	1000	9000	17,270.60 ef	6689.60 cd
FMN1	831	1000	9000	25,216.92 c	14,385.92 b	831	1000	9000	21,285.26 b	10,454.26 a
FMN2	1081	1000	9000	27,826.60 a	16,745.60 a	1081	1000	9000	22,660.60 a	11,579.60 a
FMN3	1331	1000	9000	22,262.50 ef	10,931.50 d	1331	1000	9000	19,234.29 cd	7903.29 bc
SFMN0	581	1000	10000	17,267.88 k	5686.88 g	581	1000	10000	14,597.42 h	3016.42 e
SFMN1	831	1000	10000	21,606.10 fg	9775.10 e	831	1000	10000	18,457.09 de	6626.09 cd
SFMN2	1081	1000	10000	22,843.30 de	10,762.30 d	1081	1000	10000	19,917.45 c	7836.45 bcd
SFMN3	1331	1000	10000	18,441.92 ij	6110.92 fg	1331	1000	10000	15,748.74 gh	3417.74 e
Significant level (F value)										
Y	/	/	/	**	**	/	/	/	**	**
N	/	/	/	**	**	/	/	/	**	**
M	/	/	/	**	**	/	/	/	**	**
Y*N	/	/	/	*	*	/	/	/	*	*
Y*M	/	/	/	*	*	/	/	/	*	*
N*M	/	/	/	**	**	/	/	/	ns	ns
Y*N*M	/	/	/	ns	ns	/	/	/	ns	ns

By analyzing the experimental data of 2a, findings were made that when the coverage mode was FM, the highest net income could be achieved, being 65.5%, 21.5%, and 65.0% higher than NM, SM, and SFM, respectively. Similarly, the optimal net income was obtained under N2, and the net profit of FMN2 was 79.0%, 14.0%, and 50.4% higher than that of FMN0, FMN1, and FMN3, respectively.

4. Discussion

The main sources of crop water in semi-arid areas are soil moisture and precipitation, and ridge-furrow rainwater harvesting and planting allow for the accumulation of rainfall. We found that in different hydrological years, wet years (2021) have better seed yield and economic benefits than dry years (2022). In the context of rain-fed agriculture, precipitation is the decisive factor in determining crop yield [10], and the interaction between year and nitrogen application and mulching methods had a significant effect on soybean growth indicators. We found that the interaction between mulching and nitrogen application had a significant effect on nitrogen use efficiency and other indicators. This is because the nitrogen application rate will directly affect the nitrogen use efficiency, while the interaction between mulching and nitrogen application has no significant effect on water use efficiency and net income, which may be because the results caused by the two treatments will balance each other to a certain extent [26]. Ridge mulching inhibits soil evaporation, thereby increasing soil water storage [19]. At the same time, plastic film mulching increased the surface soil temperature on the ridge at the early stage of soybean growth by receiving more long-wave radiation and reducing the latent heat and sensible heat exchange between the soil and the surrounding air. Plastic film mulching is considered to be an effective strategy to promote early seed germination and accelerate crop growth and development due to the improvement of soil thermal conditions, especially in the early growth stage [10]. As reported by Bai et al. [27] in a study on the soil moisture status of ridge mulching farmland, ridge mulching soil could increase the soil moisture content of crops compared with bare land. At the same time, straw mulching can also reduce soil temperature and evaporation to increase soil water storage [28]. In the present study, the soil water storage under SFM treatment was found to be the highest, because the surface coverage area was larger than that of the SM and FM treatments, reducing water evaporation. In the harvest period, the soil water storage of FM treatment was higher than that of SM treatment, probably because many straws were degraded during the harvest period, which reduced the coverage area and resulted in a weaker ability to inhibit water evaporation compared with the film mulching treatment [29]. The effect of nitrogen application on soil water storage reached a significant level due to the amount of nitrogen applied determining the growth status of soybeans. Soybeans do not need too much water supply in the absence of nitrogen or excessive nitrogen, which can be attributed to the aforementioned nitrogen supply. Under the background of stress, the growth of soybeans is also limited, and the water absorption and water consumption capacity of soybeans are also limited. Appropriate fertilization can promote the growth of crop roots, thereby promoting the absorption of soil moisture by crops to reduce soil water storage, resulting in different soil water storages under different nitrogen applications [30].

Soybean yield in two years was significantly affected by mulching methods, nitrogen application rate, and their interaction. Soybean yield depends on the accumulation of dry matter, which comes from photosynthesis. The supply of water in soybean photosynthesis is mainly derived from root water absorption, which determines the formation of final yield. Nitrogen affects soybean yield by affecting plant growth and development. Ridge-furrow plastic mulching systems improve rainwater collection and utilization efficiency, reduce soil water loss, and produce a good soil thermal state during key growth periods, thereby increasing crop growth and yield [20], which has great potential for increasing the yield of cereal legumes and ensuring food security around the world, especially in rain-fed areas. All factors affect population yield by affecting yield components per plant, such as 100-grain weight per plant and pods. However, due to the uniform distribution of rainfall and the increase of soil temperature under ridge-furrow mulching, it increased soybean yield. In the present study, because the capacity of reducing soil water loss of FM treatment was higher than that of the NM and SM treatments [31], the soil water storage of FM treatment was stable. As such, the FM treatment with appropriate nitrogen application (N1 and N2) could achieve higher dry matter accumulation and grain yield. However, due to the combined effect of ridge-furrow film mulching and straw mulching, the soil water storage of SFM treatment was improved. Despite such findings, due to the unreasonable increase in farmland coverage area and unreasonable farmland coverage ratio, the distribution of farmland ground temperature was unbalanced, and the community structure of farmland soil microorganisms was destroyed to a certain extent [32]. At the same time, the soil compaction and soil permeability were reduced, which inhibited the growth and yield of soybean.

Findings were made that the ET under NM treatment was higher than that under other mulching treatments, which could be attributed to the large bare area of soil, and the soil moisture was mainly caused by the loss of soil evaporation, resulting in a higher total water loss under NM treatment [33]. Due to the significant anti-evaporation performance thereof, FM treatment increased the proportion of water consumption for actual growth of soybean under such treatment, and thus the ET value under the FM treatment was relatively low. Combined with the high yield under such mulching method, a higher WUE could obviously be obtained under such treatment, at the same time, due to the appropriate amount of nitrogen and the use of mulching treatments, the growth of soybean leaves will be promoted to a certain extent, thereby reducing soil evaporation [10]. Crop yield and nitrogen use efficiency can be improved by understanding the process and mechanism of crop nitrogen uptake and regulating crop growth and development with effective fertilization measures [34]. In the present study, an appropriate amount of nitrogen application combined with furrow mulching treatment could obtain higher grain yield and nitrogen utilization efficiency. For field crops, excessive nitrogen application will lead to overnutrition and nitrogen loss, which will reduce nitrogen use efficiency. Thus, appropriate fertilization is needed to avoid such risk [35]. Specifically, through the appropriate amount of nitrogen and furrow mulching treatment by increasing the absorption of total nitrogen, the residual nitrogen in the soil can be reduced to a certain extent, and the efficiency of nitrogen use goals can be ultimately improved. Such findings can be attributed to the fact that soybean can obtain a better root growth environment and more photosynthetic raw materials under such growth conditions, thereby promoting soybean to absorb nitrogen more effectively [19].

In the analysis of economic benefits, findings were made that the performance of net income was FM > SM > SFM > CK, which is consistent with the performance of yield. First of all, because the yield determines the total income, under the premise of the same soybean price, a higher yield can allow for a higher total income to be obtained, and the net income is determined by the total income and the total input. Comparing different coverage methods, the NM treatment and SFM treatment had low yield and high cost, and thus the economic benefit is considerably poor. The cost of SM treatment was slightly higher than that of the FM treatment, but the yield of SM treatment was not as good as that of FM treatment, and thus the net profit of FM treatment is higher [27]. For the amount of nitrogen application, the economic benefit under N2 nitrogen application is the most ideal. Compared with N1 nitrogen application, N2 nitrogen application can achieve more yield profits than the nitrogen application cost [26]. As such, based on the consideration of net income, the recommended nitrogen application amount in the present experiment is N2.

5. Conclusions

In this study, all farmland mulching methods (SM, FM, and SFM) and nitrogen application can increase soybean yield. Among them, furrow mulching provides a better soil environment for the growth and development of rain-fed soybeans, and obtains higher seed yield, water and nitrogen use efficiency, and net income. Compared with soybean with high nitrogen application rate, reduced nitrogen application (33% reduction) can improve seed yield, water use efficiency, and net income. Among all treatments in the two years, reducing 33% N fertilizer combined with mulching treatment(FMN2) had the highest dry matter accumulation, seed yield, and net income, which were 18,471 kg ha^{-1}, 5048.7 kg ha^{-1}, and 14,162.6 CNY ha^{-1}, respectively. Therefore, in the Loess Plateau of China, ridge-furrow mulching and reduced nitrogen application are an efficient soil and crop management strategy to meet the challenges of sustainable development and economic benefits of rain-fed soybeans.

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