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Returning Different Organic Materials to the Field: Effects on Labile Soil Nitrogen Pool under Drip Irrigation with Film Mulching in a Semi-Arid Soil

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Abstract: The purpose of this study was to observe the changes in soil nitrogen pools (active organic and inorganic nitrogen fractions) after applying organic materials under drip irrigation with film mulching in a semi-arid soil. The two-year field experiment included four fertilization treatments: maize straw, fodder grass, sheep manure, and a control treatment with no organic material applied (CK). The results showed that the application of maize straw and sheep manure significantly increased the soil total nitrogen content by 9.02~13.33% and 11.02~17.27%, respectively, while no significant improvement was found with the use of fodder grass. Compared with CK, returning organic materials to the field increased the soil active nitrogen pools, except for ammonium nitrogen content. Meanwhile, the content of particulate organic nitrogen was significantly increased by 42.11~78.85% under the application of organic materials, which took the highest proportion of active nitrogen pools and was sensitive to fertilization treatments. Among the three organic materials, maize straw and sheep manure increased the soil active nitrogen content the most. In conclusion, both maize straw and sheep manure are the optimum organic materials, which could be applied for improving soil nitrogen storage under drip irrigation with film mulching within semi-arid areas.

Keywords: organic fertilization; soil fertility; soil nitrogen management; sustainable agriculture

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Citation: Cheng, W.; Ma, X.; Wu, J.; Gu, Y.; Duo, X. Returning Different Organic Materials to the Field: Effects on Labile Soil Nitrogen Pool under Drip Irrigation with Film Mulching in a Semi-Arid Soil. *Appl. Sci.* **2024**, *14*, 2818. https://doi.org/10.3390/app14072818

Academic Editor: Rafael López Núñez

Received: 29 February 2024
Revised: 21 March 2024
Accepted: 25 March 2024
Published: 27 March 2024

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1. Introduction

Nitrogen (N) is one of the most important nutrients for securing crop production, which maintains the sustainability and economic viability of the world's agricultural systems [1]. The application of synthetic nitrogen fertilizer has become a major source of nitrogen for crop absorption, and nearly 50% of the world's population is dependent on synthetic fertilizers [2]. To meet the growing demand for food, China has applied more synthetic nitrogen fertilizer to their soils, accounting for more than a quarter of the total use amount globally [1]. However, the overuse of synthetic nitrogen fertilizer may cause nutrient runoff, biodiversity losses, land degradation, and increases in greenhouse gases emissions [3]. Thus, applying more efficient fertilization is essential for reducing synthetic nitrogen fertilizer consumption and optimizing nitrogen use efficiency.

Organic materials (e.g., compost manure, kitchen waste, and crop residue) could be used as substitutes for synthetic nitrogen fertilizers with relatively lower costs for sustainable agriculture [4,5]. The application of organic materials provides the necessary nutrients for crops and also improves soil water-holding capacity, soil aeration, organic matter content, and biological activity [6,7]. Unlike synthetic fertilizers, organic fertilization helps mitigate nitrogen loss by reducing the risk of nitrogen leaching into the groundwater

or volatilizing into the atmosphere as ammonia [8]. Furthermore, organic matter in these fertilizers enhances soil structure and microbial activity, promoting nitrogen retention through microbial immobilization and organic matter decomposition. This not only minimizes nitrogen runoff but also improves soil health and fertility over time, contributing to long-term sustainability in agricultural practices [9]. The nutrients in some organic materials could also be released more slowly, ensuring a long-term supply of nutrients to crops, and the application of different types of organic materials may have different effects on soil nutrient accumulation and crops performance [10].

Compared to the soil total nitrogen, the active organic nitrogen in soils is more sensitive to changes in fertilization practice and environmental factors, which could better reflect the quality of the soil nitrogen pools [11]. The soil active organic nitrogen (ATN) mainly includes particulate organic nitrogen (PON), soil microbial biomass nitrogen (MBN), and dissolved organic nitrogen (DON) [12]. Active inorganic nitrogen is also called mineralized nitrogen (N_{min}), including ammonium nitrogen (NH_4^+-N) and nitrate-nitrogen (NO_3^--N). Ammonium nitrogen is easily absorbed by colloids, while nitrate nitrogen is easily transported with water, which is the main nitrogen form absorbed and utilized by crops.

Generally, the soils in semi-arid regions have thin soil layers with an insufficient water supply and low nutrient contents, which is not conducive to organic matter improvement and nutrient storage [13]. The use of film mulch drip irrigation technology changes the water and heat conditions of soils, which helps preserve soil moisture and improve soil fertility under the application of organic materials. Therefore, this study aimed to explore the changes in the soil nitrogen pools in semi-arid chestnut soils by returning three different organic materials (maize straw, fodder grass, and sheep manure) to the field under drip irrigation with film mulching. The research results could help determine the most appropriate type of organic materials to be returned to the field and also provide a basis for the sustainable use of organic materials in a semi-arid soil. We hypothesized that the application of organic matter increases the content of soil total nitrogen (TN), active organic nitrogen fractions (DON, PON, and MBN), and active inorganic nitrogen fractions (NH_4^+-N and NO_3^--N), while different organic materials have divergent effects on improvements in soil nitrogen storage and soil fertility.

2. Materials and Methods

2.1. Experimental Site

The experiment was set up in Tumuji town (123°00′ E, 46°17′ N), which was part of a semi-arid region in Jalaid Banner, Hinggan League in Inner Mongolia, China. The average annual temperature is 4.0 °C, and the mean annual precipitation is 300–450 mm [14]. The soil was classified as Haplic Castanozem based on the soil classification system of China, with a pH of 7.8, 16.26 g kg^{-1} of organic carbon content, and 84.99, 22.66, and 61.36 mg kg^{-1} of available nitrogen, phosphorous, and potassium content, respectively. The water content and electrical conductivity within a 0–20 cm soil layer, which were measured in April 2018, were 11.3% and 0.26 ds m^{-1}, respectively.

2.2. Experimental Design

In this experiment, three types of organic materials were selected: maize straw (MS), fodder grass (FG), and sheep manure (SM). The basic chemical properties of each organic material are shown in Table 1. Among these organic materials, SM was obtained from the sheep farm in Tumuji Town, and FG was obtained from Zhaite Banner Ranch, mainly *Leymus Chinensis* L. species.

In this experiment, mechanized mulching and drip irrigation were used for maize cultivation. The white plastic mulching film (8 μm thick and 80 cm wide) was applied after the organic fertilization in spring and was recycled after the harvest of maize in the fall of each year. The experiment was conducted in 2018 and 2019. Organic materials were applied continuously for two years, and a total of four treatments were set up, including

MS, FG, SM, and a blank treatment without organic materials (CK). The experiment was arranged in a randomized block design, and the area of each plot was 5 m × 10 m with three replications. The organic materials were crushed before returning to the field. Ditches were created, followed by putting the organic materials in the ditches and lastly covering the ditch with soils. Three organic materials were applied with equal amounts of carbon input whereby the application rate of MS, FG, and SM was 31,800 kg ha^{-1}, 13,600 kg ha^{-1}, and 16,800 kg ha^{-1}, respectively. Due to the higher content of nitrogen in forage (i.e., FG), urea was used to adjust the nitrogen content for the other treatments of organic materials where 101,178 kg ha^{-1} and 38,589 kg ha^{-1} of urea was applied to MS and SM, respectively. Meanwhile, diammonium phosphate (18% N content) and compound fertilizer (N-P-K content: 15%-15%-15%) were also used before planting, with an application rate of 37.5 kg ha^{-1} and 450 kg ha^{-1}, respectively. After the application of basal fertilizers, maize (XianYu 027) was planted on the field, and urea (46% N content) was used for top dressing at the phenological stages of the jointing stage, bell mouth stage, and early tasseling, with an application rate of 90 kg ha^{-1} each time.

Table 1. The differences in basic properties of maize straw (MS), fodder grass (FG), and sheep manure (SM) (one-way ANOVA).

	MS	FG	SM
Organic C (g kg^{-1})	430.46 ± 70.37 a	346.29 ± 18.39 ab	272.95 ± 19.07 b
Total N (g kg^{-1})	6.25 ± 1.02 c	16.79 ± 0.89 a	9.73 ± 0.74 b
C:N ratio	68.89 ± 0.03 a	20.63 ± 0.02 c	28.09 ± 0.18 b
Lignin (%)	4.02 ± 0.66 a	3.23 ± 0.17 ab	2.55 ± 0.18 b
Cellulose (%)	25.52 ± 1.35 ab	31.72 ± 5.19 a	20.12 ± 1.41 b

Note: values represent mean ± standard error. Data with different letters within the same row are significantly different at 5% level.

2.3. Soil Sampling

Due to the slow and inadequate rate of decomposition after the organic materials were applied, the soils were collected four times (in April 2018, before the soil was frozen in October 2018, after the ablation period in April 2019, and finally before the next freezing in October 2019). During each time of sampling, five subsamples of soil in each treatment plot were collected from a 0–20 cm soil layer following the "S" sampling method, which were mixed to form one sample replication. Crop residues and gravels were removed from soil samples, and each soil sample was divided into two parts: one part was passed through a 2 mm sieve and stored at 4 °C for the determination of soil MBN, NH_4^+-N, and NO_3^--N; another part was air-dried, grounded, and passed through a 0.25 mm sieve to determine the content of TN, DON, and PON.

2.4. Determination of Soil Nutrient Content

The SOC content was determined by the $K_2Cr_2O_7$-H_2SO_4 oxidation method. The contents of TN and PON were determined by the Kjeldahl method [15]. The MBN content was measured using the chloroform fumigation extraction method [16]. The measurement on soil DON content was followed the method described by Jones and Willett (2006) [17]. The soil NH_4^+-N and NO_3^--N concentrations were measured using a flow analyzer (AA3, Bran-Luebbe, Norderstedt, Germany).

2.5. Statistical Analyses

There were three replications in each treatment, and 48 total soil samples with four amounts of sampling were involved in the analyses. All the experimental data were normally distributed. Significant differences among the treatments were determined by one-way ANOVA. The multiple comparisons of means ($p < 0.05$) were conducted using Fisher's protected least significant difference (LSD) test by SPSS software version 21. The

Pearson correlation analysis was performed to analyze the relationship among soil active nitrogen fractions. Graphics were prepared using Origin 2017.

3. Results

3.1. Effects of Different Organic Materials on Soil TN Content

Compared with the original starting point (April 2018), the application of organic materials increased the TN content (Figure 1). Compared with CK, adding organic materials significantly increased the TN content ($p < 0.05$). The application effects of different organic materials changed over time, the trends of which were significantly different. Among them, the TN content firstly declined and then increased under SM treatment. In contrast, the TN content showed an up-and-down tendency under FG treatment and a linear upward trend under MS treatment. The changes in TN content under each treatment in April 2019 (beginning of summer) were different from those in October 2018 (beginning of winter) as the TN content under SM treatment decreased by 2.21%, while it was increased by 4.96%, 6.92%, and 2.26%, respectively, under CK, FG, and MS treatments. Compared with October 2018, the TN content in October 2019 increased by 0.71~3.70%. Specifically, the TN content under MS, FG, and SM treatments increased by 9.02~13.33%, 4.10~6.92%, and 11.02~17.27%, respectively, compared to CK. SM had the highest TN content across the treatments ($p < 0.05$).

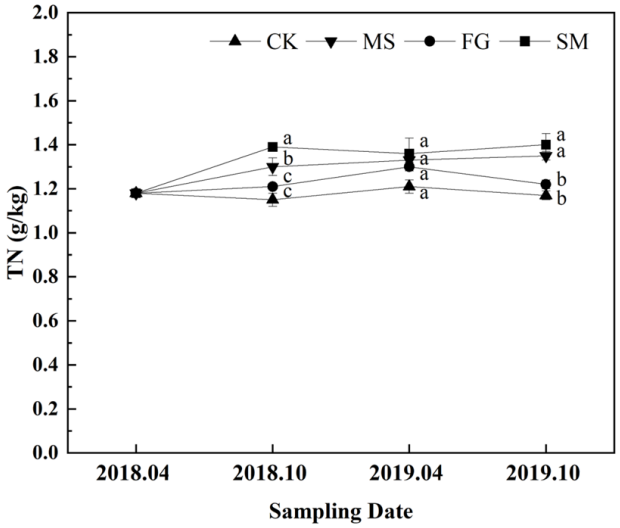


Figure 1. Application effects of different organic materials on soil total nitrogen (TN) content at different sampling dates. Lowercase and different letters indicate statistically significant differences at $p < 0.05$ between treatments.

3.2. Effects of Different Organic Materials on Soil DON Content

Compared with the original starting point (April 2018), the different treatments increased the DON content. However, that of the CK treatment dropped significantly in April 2019 (Figure 2). Compared with CK, the addition of organic materials increased the content of DON ($p < 0.05$). From 2018 to 2019, the changes in soil DON content after applying the different treatments followed the order MS > FG > SM > CK, and all showed a trend of firstly declining and then rising at the last sampling date. Compared with October 2018, the content of DON in April 2019 for MS, FG, SM, and CK decreased by 29.19%, 37.59%, 51.32%, and 23.88%, respectively. Compared with October 2018, the content of DON in October 2019 showed that the SM treatment increased by 4.94%, while FG, CK, and MS decreased by 2.91%, 0.85%, and 2.83%, respectively. In addition, from 2018 to 2019, the content of DON in the SM, FG, and MS treatments increased by 19.81~49.56%, 24.75~50.61%, and 26.75~56.72% respectively, compared with CK. This indicates that organic materials are

conducive to the storage of DON in soil. At the same time, the MS treatment was more conducive to the storage of DON in the short term ($p < 0.05$).

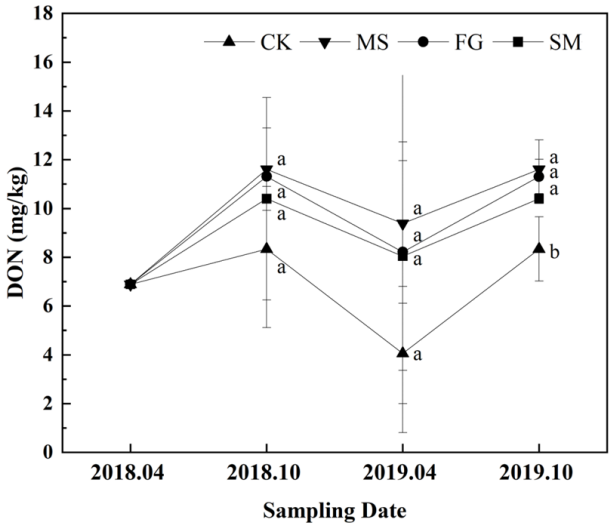


Figure 2. Application effects of different organic materials on soil dissolved organic nitrogen (DON) content at different sampling dates. Lowercase and different letters indicate statistically significant differences at $p < 0.05$ between treatments.

3.3. Effects of Different Organic Materials on Soil MBN Content

Compared with the original starting point (April 2018), the return of organic materials to the field increased the content of MBN (Figure 3). For the CK treatment, the accumulation of MBN occurred in 2019. The overall MBN content change from 2018 to 2019 followed the order MS > SM > FG > CK; however, each treatment had a different trend at different times. SM and FG followed the same trend of firstly rising and then falling, while MS and CK treatments showed an upward trend. The MBN content of each treatment in 2019 (April and October) was higher than that in October 2018, and the overall increase was 8.63~33.35%. In 2018 and 2019, the DOC content was increased by 13.97~49.40%, 33.35~52.38%, and 3.89~44.31%, respectively, under MS, SM, and FG treatments compared with CK, where MS recorded the highest MBN content.

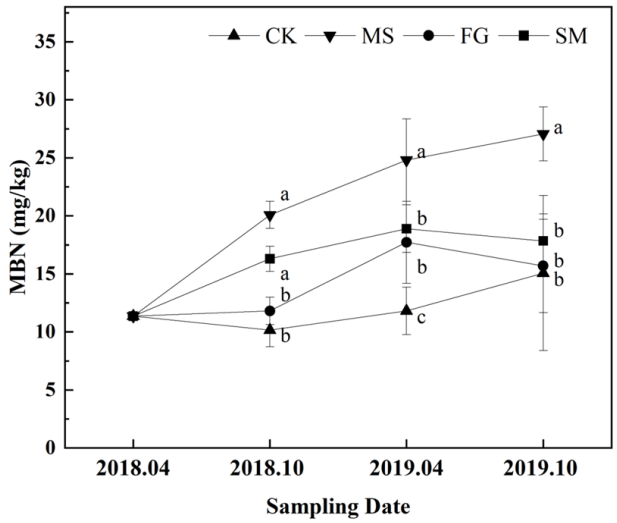


Figure 3. Application effects of different organic materials on microbial biomass nitrogen (MBN) content at different sampling dates. Lowercase and different letters indicate statistically significant differences at $p < 0.05$ between treatments.

3.4. Effects of Different Organic Materials on Soil PON Content

Compared with the original starting point (April 2018), the return of organic materials to the field increased the PON content (Figure 4). For the CK treatment, the accumulation of PON occurred in 2019. Compared with CK, the addition of organic materials increased the PON content ($p < 0.05$). In 2018 and 2019, the overall PON changes followed the order SM > MS > FG > CK; however, each treatment had a different trend at different times. MS showed a trend of firstly rising and then falling, while SM showed a gradually rising trend. FG and CK show a similar trend of firstly falling and then rising. Compared with 2018, SM and MS increased by 9.61% and 21.05%, respectively, in April 2019, while FG and CK decreased by 4.00% and 36.36%, respectively. Compared with CK, the organic material treatments increased the content of PON by 42.11~78.85% from 2018 to 2019. Meanwhile, the PON content under the application of organic materials was higher than that of CK, and the highest PON content was found under SM treatment.

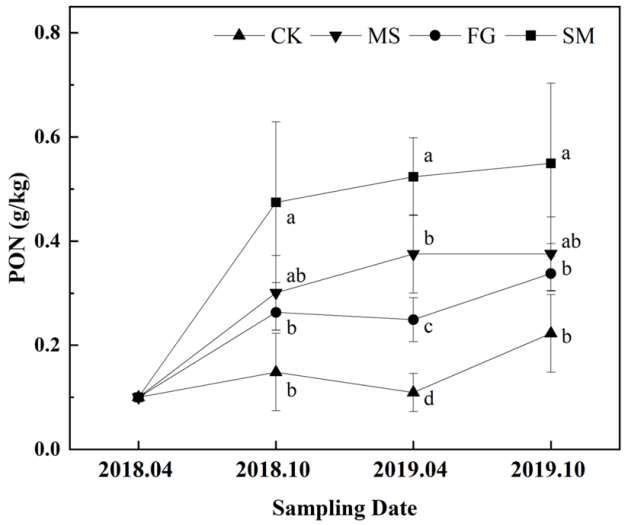


Figure 4. Application effects of different organic materials on soil particulate organic nitrogen (PON) content at different sampling dates. Lowercase and different letters indicate statistically significant differences at $p < 0.05$ between treatments.

3.5. Effects of Different Organic Materials on Soil ATN Content

The overall ATN changes followed the order SM > MS > FG > CK from 2018 to 2019, which was the same as that of the TN and PON content (Figure 5). Compared with October 2018, the content of ATN in April 2019 showed different trends. SM and MS increased by 8.89% and 18.89%, respectively, while FG and CK decreased by 4.08% and 33.46%, respectively. Compared with October 2019, all the treatments increased the content of ATN, which were 13.32%, 21.44%, 32.12%, and 19.79%, respectively. Compared with CK treatment, the ATN content under organic material treatments increased by 32.48~77.28% from 2018 to 2019. Among the organic material treatments, SM had the highest ATN content.

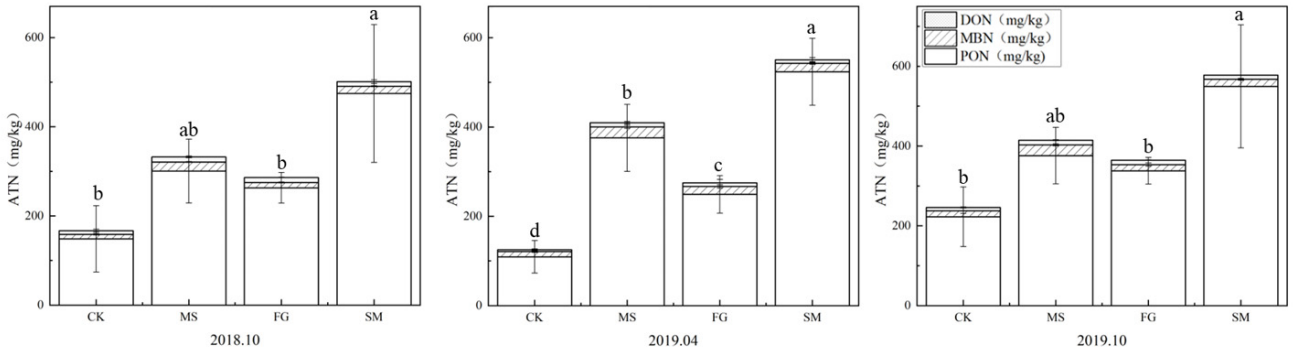


Figure 5. Application effects of different organic materials on soil active organic nitrogen (ATN) content at different sampling dates. Lowercase and different letters indicate statistically significant differences at $p < 0.05$ between treatments.

3.6. Effects of Different Organic Materials on Soil NH_4^+-N, NO_3^--N, and N_{min} Content

Compared with the original starting point (April 2018), the returning of organic materials to the field reduced the NH_4^+-N content in the soil, and the highest NH_4^+-N content was recorded under the CK treatment (Figure 6). In 2018 and 2019, the overall NH_4^+-N content followed the order CK > FG > SM > MS, and all the treatments followed a similar trend of firstly rising and then falling. Compared with 2018, the content of NH_4^+-N increased by 43.29~75.09% in 2019. From 2018 to 2019, the content of NH_4^+-N in the CK treatment was higher than SM, FG, and MS by 2.2~45.56%, 1.59~40.49%, and 26.92~57.05%, respectively.

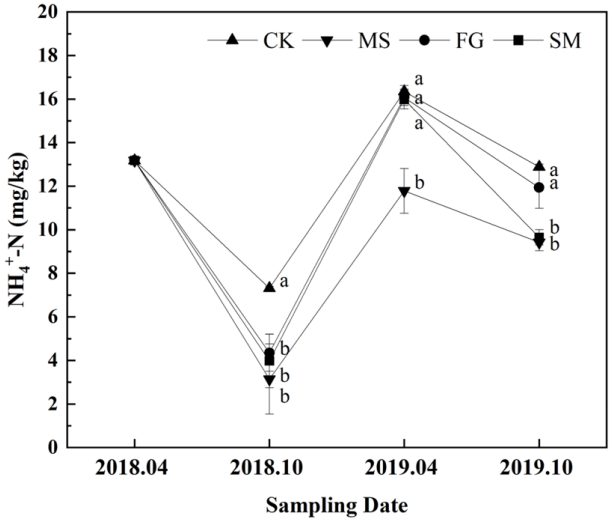


Figure 6. Application effects of different organic materials on soil NH_4^+-N content at different sampling dates. Lowercase and different letters indicate statistically significant differences at $p < 0.05$ between treatments.

Compared with the original starting point (April 2018), the returning of organic materials to the field increased the content of NO_3^--N in the soil, and the highest was recorded under MS treatment (Figure 7). From 2018 to 2019, the overall NO_3^--N content followed the order MS > SM > FG > CK, and all the treatments followed a similar trend of firstly rising and then falling. Compared with October 2018, the overall NO_3^--N content for April 2019 and October 2019 increased by 8.36~25.51% and 3.88~10.34%, respectively. Compared with the CK treatment, the NO_3^--N content of the organic material treatments increased significantly by 13.05~34.29% from 2018 to 2019. In these two years, MS application resulted in the highest NO_3^--N content compared with other treatments.

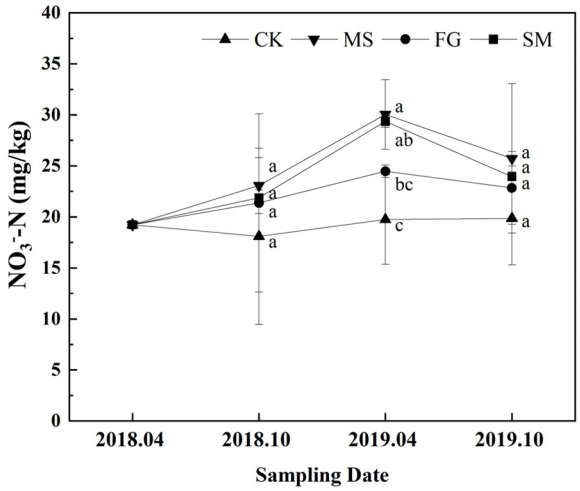


Figure 7. Application effects of different organic materials on soil NO_3^--N content at different sampling dates. Lowercase and different letters indicate statistically significant differences at $p < 0.05$ between treatments.

Generally, N_{min} content reflects the change in the total amount of inorganic nitrogen. The effects of different treatments on the overall N_{min} content from 2018 to 2019 showed a trend of firstly rising and then falling (Figure 8). In April and October 2019, the N_{min} content for the organic material treatments was 22.39~42.99% higher than that in October 2018. Compared with CK treatment, the N_{min} content in the organic material treatments increased by 1.7~20.4% from 2018 to 2019. Unlike the NH_4^+-N and NO_3^--N content, the N_{min} content followed a different trend and also varied in different periods.

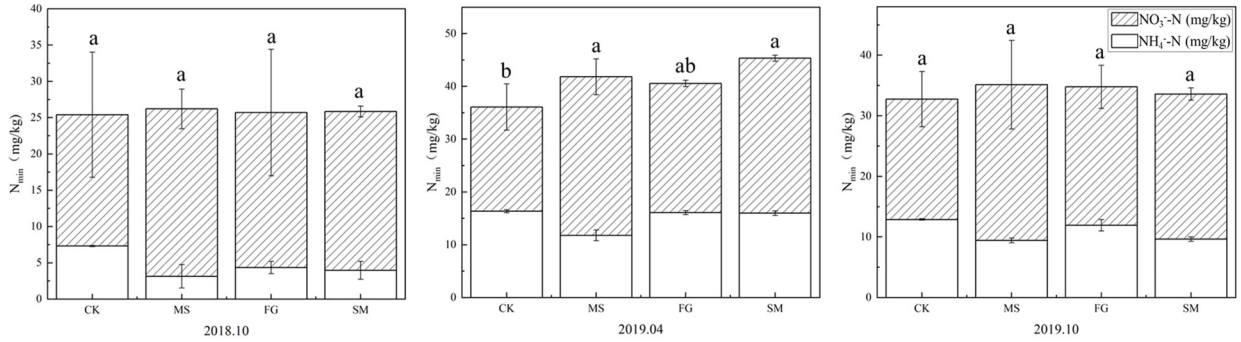


Figure 8. Application effects of different organic materials on soil N_{min} content at different sampling dates. Lowercase and different letters indicate statistically significant differences at $p < 0.05$ between treatments.

3.7. Distribution Ratio and Correlations of Soil Active Nitrogen Fractions

The application of organic materials changed the distribution of active nitrogen fractions in TN ($p < 0.05$), as shown in Table 2. Compared with CK, the application of organic materials reduced the distribution ratio of N_{min} in TN with the exception of April 2019, where the N_{min}/TN ratio was increased. In October 2019, the highest N_{min}/TN ratio was recorded under FG treatment; however, there was no significant difference in the N_{min}/TN ratio across the treatments. The application of organic materials increased the distribution ratio of ATN in TN by 29.43~74.70%. Moreover, the distribution ratio of PON/TN increased by 31.05~76.66%. The distribution ratio of DON in TN increased by 4.05~53.52%. The MBN/TN ratio for MS treatment was significantly different from the other treatments from October 2018 to April 2019 ($p < 0.05$); however, there was no significant difference between the treatments in October 2019. Within the same treatment, the proportion of soil active nitrogen fractions in TN was different, with PON taking the largest proportion, followed

by DON, N_{min}, and MBN, indicating that PON contributes the most to soil nitrogen and MBN the least. The proportion of the soil ATN content was higher than N_{min} in soil TN.

Table 2. Distribution ratio of soil active nitrogen fractions in total soil nitrogen.

Sampling Date	Treatment	MBN/TN	DON/TN	PON/TN	ATN/TN	N_{min}/TN
October 2018	SM	1.17 ± 0.08 b	0.74 ± 0.29 a	33.98 ± 6.23 a	35.89 ± 6.34 a	1.86 ± 0.09 a
	FG	0.98 ± 0.11 b	0.94 ± 0.04 a	21.77 ± 1.43 ab	23.69 ± 1.30 ab	2.12 ± 0.37 a
	CK	0.88 ± 0.13 b	0.71 ± 0.26 a	12.86 ± 3.60 b	14.45 ± 3.69 b	2.20 ± 0.41 a
	MS	1.56 ± 0.14 a	0.89 ± 0.12 a	23.07 ± 2.61 ab	25.52 ± 2.63 ab	2.03 ± 0.23 a
April 2019	SM	1.39 ± 0.07 b	0.57 ± 0.18 a	38.34 ± 2.13 a	40.60 ± 2.11 a	3.35 ± 0.21 a
	FG	1.36 ± 0.14 b	0.64 ± 0.34 a	19.19 ± 1.91 c	21.19 ± 1.97 c	3.12 ± 0.37 a
	CK	0.98 ± 0.13 b	0.33 ± 0.09 a	8.95 ± 1.50 d	10.27 ± 1.49 d	2.98 ± 0.18 a
	MS	1.87 ± 0.15 a	0.71 ± 0.11 a	28.36 ± 3.46 b	30.94 ± 3.44 b	3.15 ± 0.04 a
October 2019	SM	1.28 ± 0.14 a	0.78 ± 0.05 ab	39.66 ± 7.23 a	41.72 ± 7.37 a	2.41 ± 0.13 a
	FG	1.30 ± 0.22 a	0.90 ± 0.06 a	27.70 ± 1.36 ab	29.90 ± 1.18 ab	2.85 ± 0.16 a
	CK	1.30 ± 0.35 a	0.70 ± 0.01 b	19.10 ± 3.99 b	21.10 ± 4.28 b	2.78 ± 0.18 a
	MS	2.00 ± 0.08 a	0.84 ± 0.07 ab	27.74 ± 2.63 ab	30.58 ± 2.57 ab	2.61 ± 0.35 a

Note: values represent mean ± standard error. Data with different letters within the same row are significantly different at 5% level.

As shown in Table 3, there was a correlation between the active nitrogen components and TN. The Pearson correlation analysis showed that there was a significant positive correlation between soil ATN and TN ($p < 0.01$), indicating that the change in characteristics of ATN fractions was consistent with the changes in TN content. Moreover, TN had a significant positive correlation with PON ($p < 0.01$) and MBN ($p < 0.05$), while PON, DON, and MBN were positively correlated with each other. There was a significantly positive correlation between PON and ATN ($p < 0.01$), while soil N_{min} and TN was positively correlated but not significant. Similarly, N_{min} positively correlated with ATN; however, the correlation was not significant. Moreover, there was a correlation between organic and inorganic nitrogen fractions. There was a significantly positive correlation between MBN and NO_3^--N ($p < 0.01$) and PON and NO_3^--N ($p < 0.05$); however, DON and NH_4^+-N were significantly negatively correlated ($p < 0.05$). The correlation between the soil active nitrogen fractions and TN revealed that the effect of ATN fractions on TN was higher than that of the N_{min} fractions. Among the ATN fractions, PON largely contributed to the TN content in soils.

Table 3. Pearson correlation analysis among soil active nitrogen components.

	TN	MBN	DON	PON	ATN	NO_3^--N	NH_4^+-N	N_{min}
TN	1	0.669 *	0.357	0.868 **	0.872 **	0.683 *	−0.073	0.317
MBN		1	0.395	0.5532	0.547	0.791 **	0.047	0.459
DON			1	0.514	0.527	0.205	−0.701 *	−0.382
PON				1	1.000 **	0.658 *	−0.111	0.276
ATN					1	0.663 *	−0.121	0.272
NO_3^--N						1	0.287	0.740 **
NH_4^+-N							1	0.857 **
N_{min}								1

Note: ** stands for $p < 0.01$; * stands for $p < 0.05$.

4. Discussion

The long-term single application of film-mulched drip irrigation technology has been proven unfavorable to the storage of soil nutrients; however, several studies have shown that the addition of external organic matter can significantly increase the soil nutrients content. As such, people have advocated and practiced returning organic materials to the field to reduce the application of chemical fertilizers, improve soil fertility and increase

soil nitrogen storage [6]. The soil nitrogen pool is an important indicator of soil health. This study showed that returning organic materials to the field significantly increased the nitrogen content in the soil, which is consistent with the results of previous studies [9,18]. Organic materials are an important source of soil nitrogen that can reduce the nitrogen deficiency in crops, improve the soil organic carbon pools, and also increase the content of active nitrogen components in the soil [19–21]. Studies have shown that a single application of chemical fertilizers can increase soil nitrogen content to a certain extent, but the effect is not as good as the application of organic materials [20]. In this study, the application of organic materials significantly increased both the content of active nitrogen and TN, which was attributed to the decomposition of nutrients in organic materials over time [7]. The release of these nutrients can promote the growth of crop roots and promote the transformation of the active nitrogen pools. On the other hand, organic materials contain activity nitrogen-like components that can directly increase soil active nitrogen components after being applied to the soil [12,21]. From 2018 to 2019, the changes in TN content under the four treatments were insignificant, indicating that the TN is more stable than the active nitrogen pools under the changes in fertilization practice in a short term. Generally, when the TN content of the soil is less than 2 g kg^{-1}, the soil is considered to be nitrogen-deficient [22]. In this experiment, the TN content under different treatments at different times was between 1.15 to 1.40 g kg^{-1}, indicating that the soils at the test site were not high in nitrogen.

DON represents an unstable nitrogen source for soil microorganisms. In our study, the content of DON and the proportion of DON in TN under the organic material treatments were higher than that of CK, indicating that the application of organic materials is an efficient method to improve soil DON. Besides, the plant-based organic materials (MS and FG) were better at increasing the DON content than the animal-based organic material (SM). Many factors simultaneously affect the degradation and migration of DON content, including soil water content, temperature, litter and plant residues, soil physiochemical properties, and farming methods [18]. Studies have shown that during repeated freezing and thawing, the microorganisms in the soil gradually adapt to temperature changes, reducing the mortality rate, as the soil aggregates also tend to be stable. Therefore, the low content of soluble nitrogen in the soil during the freezing period (October 2018 to April 2019) could be attributed to the fact that most of the microorganisms did not die as soon as the freezing period began. Hence, they continued to consume soluble organic nitrogen in the soil [23,24]. During the thawing period, utilization of plastic mulching increased soil moisture and temperature, which promoted the release of soluble organic matter and might change the biological activities in the soil, thereby increasing the concentration of DON.

MBN is considered as an important indicator of soil quality, which can quickly respond to changes in soil management practice [2]. Although MBN only accounts for 2~6% of TN, it has a vital influence on the rate of nutrient cycling in agricultural ecosystems [25,26]. Due to the rapid generation of soil microbial biomass, MBN is considered to be the most unstable soil active nitrogen component, which represents the source of mineral nitrogen and the absorption of mineral nitrogen [27]. Our study found that the MBN content was increased from October 2018 to April 2019, which might a result of the dead microorganisms that were decomposed and released nitrogen to the soil, along with the destruction of soil aggregates and increased enzyme activities during the freeze–thaw cycle [28]. Moreover, the content of MBN and MBN/TN ratios under organic material treatments (MS, SM, and FG) were higher than that of the control treatment, indicating that returning organic materials to the field could efficiently increase soil microbial activity. The film-mulched drip irrigation technology created better water and heat conditions, which also helped optimize soil conditions for enhancing microbial activities.

Previous studies showed that returning organic materials to the field increased the content of stable organic matter in the soil, which was stored in the form of particulate organic matter [29]. The higher the stable organic matter content, the greater the nitrogen supply potential of the soil. The content of PON was significantly higher than the other

nitrogen fractions (MBN and DON), indicating that PON was more sensitive to fertilization practice and could be used to evaluate its impact on changes in soil active organic matter and soil quality [30]. Our study also found a higher PON content under the application of organic materials, which is in line with the results reported by Saninju et al. (2011) [31].

A larger part of the nitrogen in the soil is organic nitrogen, accounting for about 92~98% of the total soil nitrogen. However, organic nitrogen cannot be directly absorbed by crops and must be converted into inorganic nitrogen through mineralization for crops utilization [32]. The content of inorganic nitrogen affects the crop growth, and its dynamic changes are inseparable from the crop development [33]. The results of this study revealed that the application of organic materials significantly increased soil NO_3^--N content, while the soil NH_4^+-N content was very low. There are three reasonable reasons for explaining this: firstly, the organic material contains a certain amount of soluble organic matter, which provide exogenous nutrients for the multiplication of aerobic nitrifying bacteria and also effectively improve soil aeration for nitrification, thus significantly increasing the NO_3^--N content [34–36]. Secondly, organic materials could increase soil ion exchange sites and enhance ion adsorption capacity, which accumulate more NO_3^--N in soils [37,38]. Thirdly, the main inorganic form of nitrogen in dry farming soil is NO_3^--N [38]. From 2018 to 2019, the accumulation of both NH_4^+-N and NO_3^--N showed a similar trend that was firstly increased and then decreased, which was influenced by the microbial community involved in nitrification. The number of nitrifying microorganisms is generally inhibited by the alternation of freezing and thawing, but it does not completely cause fatal damage to them, and some bacteria are still highly active which promote nitrification [39]. Meanwhile, the litter and snow cover create an isolation layer between the soil surface (with low temperature) and the soils under the cover layer. This layer has a warm and anaerobic environment which also promotes nitrification [40,41]. Moreover, the number of denitrifying enzymes during the freezing period of the soil are decreased, resulting in a rapid increase in ammonia nitrogen after soil ablation, which promotes the denitrification process for reducing the ammonia nitrogen content in the soil.

Correlation analysis showed that soil TN had a significantly positive correlation with ATN but not with N_{min}, indicating that the changes in organic nitrogen fractions were more obvious than those in inorganic nitrogen fractions after the application of organic materials. A significant correlation was found between PON and TN, suggesting that the change in PON content could be a good indicator for the variation in soil nitrogen pools [42].

5. Conclusions

The two-year field study revealed that the return of organic materials to the field affected the content of TN, DON, MBN, PON, ATN, NO_3^--N, NH_4^+-N, N_{min}, and the distribution ratio. The application of organic materials had positive effects on soil fertility improvement under semi-arid drip irrigation with film mulching. Particularly, MS significantly increased the content of soil DON, MBN, NO_3^--N, and N_{min} content, while SM significantly increased the content of TN, PON, and ATN in the soil. With respect to the local environmental conditions in the study area, maize straw and sheep manure are the most suitable organic materials to be applied in a semi-arid soil under drip irrigation with film mulch, which help promote environmental quality and soil health in arid lands.

Author Contributions: Conceptualization, J.W.; methodology, J.W. and Y.G.; software, W.C., X.M. and X.D.; validation, X.M. and J.W.; formal analysis, W.C. and Y.G.; investigation, W.C., Y.G. and X.D.; resources, J.W.; data curation, W.C., X.M. and J.W.; writing—original draft preparation, W.C.; writing—review and editing, X.M. and J.W.; visualization, W.C. and X.M.; supervision, J.W.; project administration, J.W.; funding acquisition, X.M. and J.W. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China (42307438), the National Key Research and Development Program of China (2022YFD1500103), and the Jiangsu Basic Research Program (BK20230750).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available upon request from the first author. The data are not publicly available due to privacy.

Acknowledgments: The authors wish to thank Opoku-Kwanowaa Yaa for English writing and field investigation.

Conflicts of Interest: The authors declare no conflicts of interest.

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