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Investigation of Salt and Nitrogen Distribution under Belt Plastic Film Mulching in Surface- and Drip-Irrigated Maize Field in Hetao Irrigation District

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Abstract: Hetao Irrigation District (HID) is one of the main regions for maize and sunflower production in North China. However, water resource shortages and soil salinization greatly limit maize and sunflower production. The surface irrigation method is the main irrigation method in HID; however, now, the plastic mulching and drip irrigation area is increasing to reduce irrigation water and enhance crop yield. In this study, the soil water, salt, and nitrogen contents at the 0–100 cm soil layer under plastic mulching and non-mulching conditions with the surface irrigation—fertilizer broadcast practice and drip fertigation method were investigated at the maize elongation and maturation stages in the 2021 and 2022 seasons. The results show that the mulching practice and irrigation methods greatly influenced the soil salt and ionic nitrogen (NO_3^- and NH_4^+) distributions and, ultimately, the maize yield. Mulching reduced the soil salt content in the 0–20 cm soil layer by a mean of 35.7% under surface irrigation and by 18.6% under the drip irrigation condition. The NO_3^- content in the 0–20 cm soil layer with the drip fertigation system was approximately 8 times higher in mulching soil than that out of mulching. However under the surface irrigation condition, the NO_3^- content was 8–10 times lower under mulching than that out of mulching. The soil salt and NO_3^- contents were distributed uniformly at each soil layer deeper than a 40 cm depth, indicating minor effects of mulching. The soil NH_4^+ content decreased as the soil depth increased and distributed uniformly at each soil layer, indicating the insignificant influence of the mulching practice. As a result, the maize yield under the drip-mulching condition was approximately 11% (10.6~11.4%) higher than that under the surface-mulching condition in the two maize seasons. Given that surface irrigation is currently the primary irrigation method in the Hetao Irrigation District (HID), we have proposed three approaches aimed at enhancing maize production through the improvement of nitrogen levels in surface-mulching practices.

Keywords: Hetao Irrigation District; mulching practice; soil nitrogen status; maize production; salinized soil use

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1. Introduction

Mulching has been considered an effective agronomic method to reduce soil evaporation, inhibit weed growth, maintain high soil water content, enhance soil temperature in cold regions, and, lastly, improve crop growth and increase water use efficiency [1–7]. In China, the total plastic film used in agriculture was 2.4 million tons in 2019 and covers approximately 20 million ha arable fields, which consequently results in approximately 20~30% higher crop production [4,8–10]. Most greenhouses in North China use plastic film mulching to enhance soil temperature in the winter season and meanwhile reduce weed growth, based on our investigation [11]. In the arid region in North China, the mulching

method combined with drip irrigation has been regarded as the main agronomic practice to save water and promote agriculture development [12]. Similarly, the mulching–drip irrigation combined method is recommended to use in arid regions aiming to cope with water scarcity [13].

Mulching, especially plastic film mulching, could prevent water flux from the soil surface to air, which then reduces 40~60% soil evaporation and consequently 10~20% crop evapotranspiration [14]. Because of the soil evaporation reduction, the soil water content maintains at a high level, which is very beneficial to crop growth [15]. The literature reported that both crop yield and water use efficiency under mulching increased by 25~85% for potato and approximately 25~60% for wheat and maize compared to no mulching [2,15–17]. A meta-analysis using 1310 yield (wheat and maize) observations from 74 studies conducted in 19 countries reported that mulching significantly increased yields, water use efficiency, and nitrogen use efficiency by up to 60%, compared with no mulching, and the effects were larger for maize than wheat, and larger for plastic mulching than straw mulching [2].

Dissolved salt in soil water is generally transferred with the water movement [18]. A large amount of irrigation water is always used to leach extra soil salt down into the deep soil layer or groundwater, aiming to maintain a low salt level for crop growth [19]. In another side, soil water evaporation could enhance salt accumulation in the soil surface. Because of the soil evaporation reduction effectively caused by surface mulching, salt accumulation in the surface is consequently greatly reduced [18]. Straw mulching reduced the salt accumulation in the 0–30 cm soil layer by 20~25% [20]; biodegradable film also reduced salt accumulation by 19% compared to no mulching, but was 18% higher than plastic mulching [18].

Nitrogen (N) is one of the most important nutrient elements for plants' growth and yield production [21]. Maintaining high soil available nitrogen content by deep application could increase 8–12% crop yield and 19–26% nitrogen use efficiency, based on a global meta-analysis [22]. Available nitrogen ions in soil, mainly including NH_4^+ and NO_3^-, are always dissolved into soil water, then move with water flux. Mulching prevents water flux in the soil surface and then reduces soil evaporation. Soil NH_4^+ and NO_3^- move, generally following the water flow. Soil evaporation decrease under mulching prevents NH_4^+ and NO_3^- movement up into the soil surface; then, most NH_4^+ and NO_3^- can distribute into the soil layer for crop uptake, thus reducing soil nitrogen stress [23], and finally, resulting in higher crop yield and nitrogen use efficiency [24]. According to several studies [7,18,24,25], plastic mulching has shown superior performance in terms of promoting nitrogen uptake and crop yield compared to straw, gravel, and biodegradable film mulching methods. Hetao Irrigation District (HID), located in North China, is characterized by low precipitation (yearly mean ~105 mm) and high evaporation potential (mean yearly reference evapotranspiration ETo of 1095 mm) [26]. Traditional irrigation amounts of 600~900 mm water per year support the agricultural development in this arid region [27]. Due to the large irrigation amount and inefficient drainage system, salts in soil and groundwater are increasing. To date, the salinized soil accounts for approximately 68% of the total arable land in HID [28]. Because the allocated water amount for HID by the Yellow River administration is decreasing [29], a small water amount will be used for salt leaching, which consequently will increase the salt accumulation in soil and groundwater.

To cope with the decreasing irrigation amount, water-saving technologies have been recommended for use in this region [29]. Plastic mulching practice was first used in the 1980s and now covers approximately 70% of the cultivated fields of the total arable land, of 0.77 million ha, in HID (Hao, Yunfeng, director of the Institute of Resources and Environment in Bayannaoer City, personal communication). Further, drip irrigation also has been adopted in HID, mainly for maize and vegetable crops [12]. Previous studies have primarily focused on examining crop growth [12,30], yield [31–33], evapotranspiration [34–36], and water use efficiency [37–41] in relation to mulching and irrigation methods. Because the distributions of soil water, salt, and nitrogen are influenced by the mulching and drip

irrigation conditions, understanding the dynamics of soil salt and nitrogen under this agronomic practice may help improving the soil water and nitrogen management.

Therefore, the objectives of this study are to investigate the characteristics of soil salt and nitrogen distributions with and without mulching under surface and drip irrigations. Results in this study may guide how to apply fertilizers under mulching conditions with drip and surface irrigations.

2. Materials and Methods

2.1. Experimental Site Description

The experiment was carried out in two maize growth seasons from 2021 to 2022 at the experimental station of Hetao Irrigation District, Bayannaoer City, Inner Mongolia Autonomous Region (107°39′ E, 41°09′ N, altitude 1032~1050 m). The experimental area is located in Hetao Plain, characterized by a temperate continental climate with a large temperature difference between day and night. The annual average precipitation is approximately 138 mm, mainly concentrating from July to August, and annual average evaporation is about 2096 mm. Maize is the first main crop, and its area accounted for 42% of the total cropping land of 0.75 million ha in HID. Therefore, the research was conducted in the maize field. The rainfall amount in the maize growth period was 67.6 mm in the 2021 season (from 15 May 2021 to 9 October 2021) and 121.0 mm in the 2022 season (from 6 May 2022 to 30 September 2021) (Figure 1). The groundwater depth is shallow and varied within 0.84~1.87 m below the soil surface in the two experimental seasons. The soil texture in the soil layers at 0~100 cm is warped irrigated soil with sand, silt, and clay percentages of 40~55%, 39~56%, and 3~9%, respectively. The mean salt content before the maize sowing over the two seasons was 2.98 g·kg^{-1}. The soil salt, nitrate, ammonium nitrogen, and pH in the 0–100 cm soil layer measured before maize sowing in the 2021 season are listed in Table 1.

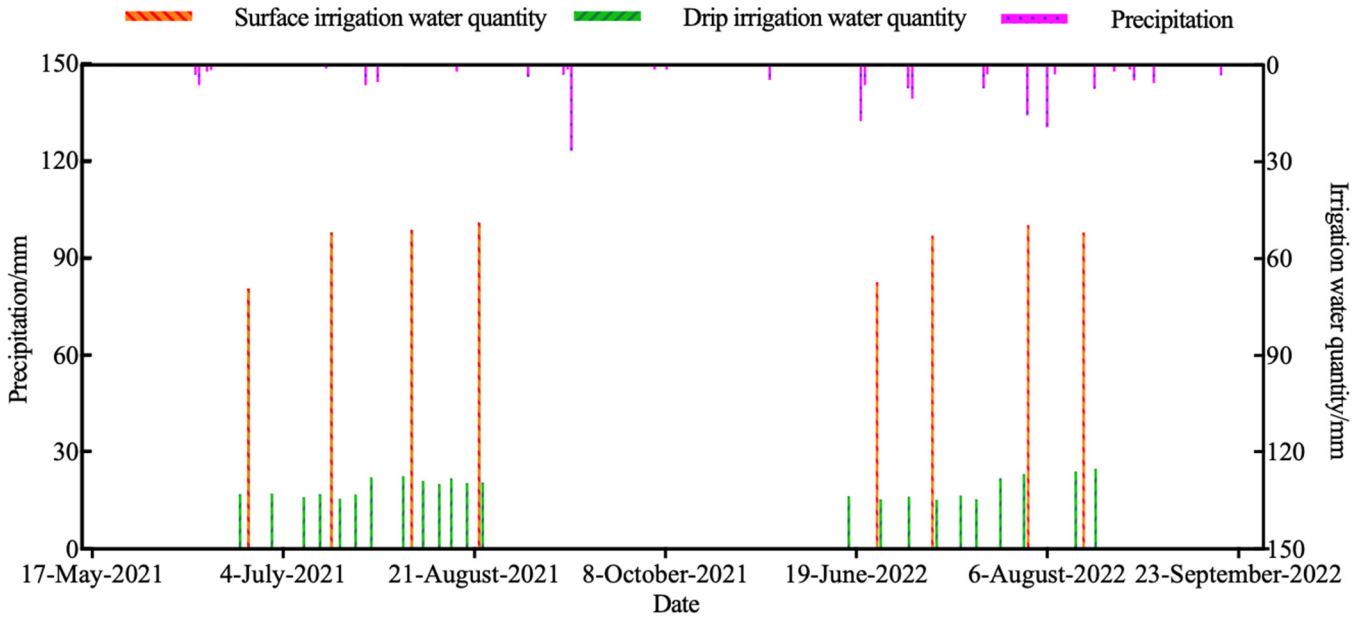


Figure 1. Rainfall and irrigation amount under surface and drip irrigation in the 2021 and 2022 seasons.

Table 1. The soil salt, nitrate, ammonium nitrogen, and pH in the 0–100 cm soil layer measured before maize sowing in the 2021 season.

Soil Depth/cm	Salt Content/ ($g \cdot kg^{-1}$)	Nitrate Nitrogen/ ($mg \cdot kg^{-1}$)	Ammonium Nitrogen/ ($mg \cdot kg^{-1}$)	Ionic Nitrogen/ ($mg \cdot kg^{-1}$)	pH
0–20	2.98	6.60	4.77	11.37	8.42
20–40	2.68	2.52	3.97	6.49	8.47
40–60	1.88	1.30	1.91	3.21	8.98
60–80	1.22	0.30	1.10	1.40	9.04
80–100	0.99	0.42	1.20	1.62	8.97

2.2. Experimental Design, Field Irrigation, and Nitrogen Management

The experiment was conducted with two treatments: plastic film mulching with surface irrigation (SM) and drip irrigation with plastic mulching (DM). Both treatments were carried out in two neighboring plots, with an area of 504 m^2 for SM and 360 m^2 for DM. The total field in the SM treatment was divided into 3 subplots. The size of each subplot is 12 m × 14 m, and ridges were formed between adjacent subplots to prevent irrigation water flowing from one subplot to another. The wide–narrow row planting mode was adopted for maize following the local practice; the wide and narrow rows were 70 cm and 45 cm, respectively (seeing Figure 2). The plant spacing was 30 cm. This planting mode resulted in a maize density of 60,540 plants ha^{-1}. Black plastic film with 0.008 mm thickness and 70 cm width was used. The plastic film was used to fully cover the narrow row (45 cm). There were four times of irrigation during the growth period, with a water depth of 80~100 mm each time. The total amount of irrigation was 380 mm. The four irrigations were carried out at the V6 and V12 stages, heading stage, and filling stage of maize growth (Figure 1).

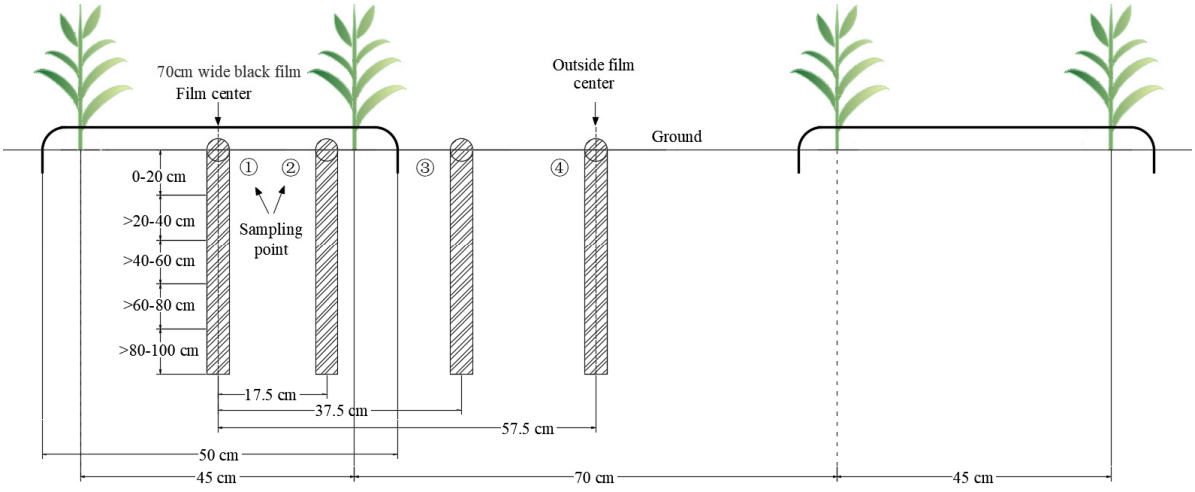


Figure 2. Schematic diagram to show the soil sample collection under surface irrigation and mulching treatment. Soil samples were taken at 20 cm intervals in the 0–100 cm soil depth, and four soil samples were collected at each soil layer, with the distances to the middle line of the narrow row of 0, 17.5, 37.5, and 57.5 cm. There were two soil sites (① and ②) under mulching and two (③ and ④) in bare soil.

Under the condition of drip irrigation, the maize planting mode and plastic film mulching were the same as that under surface irrigation. One drip tape was placed along the middle line in the narrow row and used to irrigate the two maize rows. The diameter of the drip tape was 16 mm, the emitter discharge was 3 L h^{-1}, and the distance between drippers was 25 cm. Drip irrigation started when the soil matric potential at 20 cm depth below drippers was close to −20 kPa [42]. Three tensiometers were used, and the water potential was read at 8:00 each day. Considering the small root system, the irrigation depth

before the tasseling stage was 15 mm each time, and the total irrigation times were 10 times. The irrigation depth from the tasseling to grain filling stage was 20 mm each time for a total of 5 times. The total irrigation amounts were 250 mm in the 2021 season and 187 mm in the 2022 season (Figure 1).

The total fertilizer amount of surface irrigation and drip irrigation was the same. Based on previous studies [27], the optimal total amount of nitrogen fertilizer (N) applied was 250 kg·ha^{-1}, phosphorus fertilizer (P_2O_5) was 150 kg·ha^{-1}, and potassium fertilizer (K_2O) was 60 kg·ha^{-1}. All of the phosphate fertilizer, potassium fertilizer, and nitrogen fertilizer (N) of 59 kg·ha^{-1} were used as base fertilizer. The rest of the nitrogen (191 kg·ha^{-1}) was used as topdressing, and the nitrogen fertilizer used was urea in both treatments. During the maize growth period under the surface irrigation treatment, the topdressing was carried out 4 times in total at the V6, V12, heading stage, and filling stage of maize growth. The topdressing time was consistent with the irrigation time (Table 2). Before the corresponding surface irrigation, the fertilizer was uniformly broadcasted to the field surface manually, and then with irrigation, the fertilizer was dissolved and infiltrated into the field soil along with water. The total topdressing was 5 times in the drip irrigation treatment at the V6, V12, heading stage, and filling stage of maize growth using a drip fertigation system deployed at the main pipe. All irrigation for both treatments was pumped from the groundwater at the experimental station. The irrigation and nitrogen applied are summarized in Table 2.

Table 2. Irrigation water quantity and nitrogen application rate during the two experimental periods.

Seasons	Surface Irrigation		Drip Irrigation	
	Date	Nitrogen Application Rate/ (kg·ha^{-1})	Date	Nitrogen Application Rate/ (kg·ha^{-1})
2021	1 July 2021	38.0	23 June 2021	33.6
	17 July 2021	39.0	9 July 2021	36.4
	5 August 2021	57.0	18 July 2021	43.1
	22 August 2021	57.0	26 July 2021	46.2
			12 August 2021	36.7
2022	25 June 2022	38.0	25 June 2022	30.6
	9 July 2022	39.0	2 July 2022	7.7
	1 August 2022	57.0	9 July 2022	38.0
	15 August 2022	57.0	25 July 2022	65.2
			13 August 2022	51.7

2.3. Measurement of Soil Water, Salt, Nitrogen, and Maize Yield

There were four times of soil sample collection under the surface irrigation conditions, two times at the elongation stage in July and two times at the maturation stage in September in both the 2021 and 2022 seasons. Under surface irrigation and mulching treatment, soil samples were collected at 20 cm intervals from 0 to 100 cm depth. At each soil layer, four soil samples were collected from the middle line in the narrow row (under mulching) to the middle line in the wide row (bare soil surface) (Figure 2). There were two times for soil sample collection under the drip irrigation condition, at the elongation stage and maturation stages in the 2021 season. Because there was a clear result for the salt and nitrogen distributions with the drip-mulching practice, there was no soil sample collection for measuring salt and nitrogen in the 2022 season. Considering the obvious difference in water status caused by drip irrigation, two soil sampling sites were chosen, at the middle lines in the narrow row (mulching region) and wide row (bare soil region). At each site, the soil samples were taken at 20 cm intervals in the 0–100 cm soil layer.

Each soil sample was divided into two parts. One part was used for soil water and nitrogen ions (NO_3^- and NH_4^+) measurement, and the other for soil salt measurement. The soil water content was determined by drying the soil samples in an oven at 105 °C for 24 h until a constant weight was reached. Both NO_3^- and NH_4^+ concentrations were measured using the UV-absorbance spectrophotometer method by a P4 ultraviolet-visible spectrophotometer (Shanghai Mapada Instruments Co., Ltd, Shanghai, China). The fresh soil sample was first extracted by shaking with a 2 M KCl solution (soil: solution ratio: 1:5) for 1 h on a rotary shaker (180 rev min^{-1}), followed by filtration; then, 1 mL of 1 M HCl solution was added to the extracts, and the mixed solution was directly analyzed to determine the concentration of NO_3^- and NH_4^+ [43]. For soil salt measurement, the fresh soil samples were first air-dried, then milled and screened with a 2 mm sieve. Soil water samples were extracted from a soil–water mixture with a soil: solution ratio of 1:5, then the electrical conductivity ($EC_{1:5}$, dS cm^{-1}) of the water sample was measured using an electrical conductivity meter (model DDSJ-308A, Shanghai Yidian Scientific Instrument Co Ltd., Shanghai, China). Lastly, the soil water $EC_{1:5}$ was converted into soil salt content ($Salt_s$, g·kg^{-1}) using the in situ calibrated relationship: $Salt_s = 3.688EC_{1:5} - 0.800\left(n = 47, R^2 = 0.99\right)$.

The maize grain yield was determined at harvest to evaluate the two mulching–irrigation modes' effects on crop yield. In each treatment, three 10 m row maize ears were collected at harvest, then placed on the ground for air drying. After approximately 10 days of air drying, the grains in each ear were collected, and their quality was measured using a 0.01 g resolution balance. Then, the water content of the maize grain after air-drying was measured using five grain samples. Lastly, the air-dried grain yield was converted to a standard yield with water content of 14%, which was taken as the final yield. The mean grain weight of all measured ears was calculated to standard values and then converted to the yield in a hectare.

2.4. Data Processes and Figure Preparing

All experimental data were processed using Microsoft Excel 2018. Figures were prepared using GraphPad Prism 9.0.0 (GraphPad Software, Boston, MA, USA), AutoCAD2020 (Autodesk Inc., San Rafael, CA, USA), and Surfer15 software (Golden Software, LLC, Golden, CO, USA).

3. Results

3.1. Climatic Condition and Maize Yield

The monthly mean climate conditions in the 2021–2022 maize growth seasons are shown in Table 3. Generally, the climatic condition in the 2021 season was close to that in the 2022 season. The daily average temperature during the two maize growth periods were in the ranges 12.58–27.84 °C and 9.46–31.53 °C, respectively, with averages of 21.62 and 21.78 °C, respectively. The variation ranges of relative humidity in the 2021 and 2022 seasons were 26.70–92.93% and 24.40–86.10%, respectively, with average values of 57.88% and 60.06%, respectively. The daily net radiation during the two maize growth periods were in the ranges 23.05–345.25 W m^{-2} (average 220.82 W m^{-2}) and 43.74–306.33 W m^{-2} (average 212.63 W m^{-2}), respectively. The average wind speed in the 2022 maize growth season was 1.80 m s^{-1}, which was a little higher than that (1.47 m s^{-1}) in the 2021 season. The total precipitation from June to September 2021 was 64.84 mm and was concentrated in September. The precipitation during the growth period in 2022 was 116.40 mm and was concentrated in June to August. The precipitation in the 2022 season was increased by 79.52% compared to that in the 2021 season.

Table 3. Monthly climatic condition in the 2021–2022 maize growth seasons.

Seasons	Month	Mean Temperature (°C)	Mean Relative Humidity (%)	Mean Net Radiation (W m^{-2})	Mean Wind Speed (m s^{-1})	Monthly Rainfall (mm)
2021	June	22.42	46.19	157.19	0.93	0.44
	July	26.79	65.65	269.56	1.76	16.20
	August	22.87	65.23	229.46	1.62	3.80
	September	20.38	64.70	185.87	1.58	44.40
2022	June	25.11	46.64	226.89	1.98	24.80
	July	25.38	62.67	200.81	1.86	28.80
	August	24.42	71.92	176.77	1.70	54.00
	September	19.26	55.53	173.27	1.67	8.80

In the 2021 and 2022 seasons, the grain yields of maize were 13.78 and 17.60, and 12.37 and 15.92 ton ha^{-1} under drip and surface irrigations, respectively. This shows maize yield was approximately 10.6~11.4% higher under drip irrigation condition than that under surface irrigation.

3.2. Soil Water Distribution within and out of Mulching

The spatial distribution of soil water content at the 100 cm depth under surface irrigation is shown in the Figure 3. It can be found that the soil water contents are distributed uniformly at each soil layer, especially in the upper 20 cm soil layer. This indicates that mulching did slightly effect the soil water content under the surface irrigation condition, whereas the soil water showed an obvious distribution at the soil depth. On the measurement days, the soil water was low (0.15~0.20 g g^{-1}) in the upper soil layer and increased with the soil depth. The highest SWs were measured at approximately 0.24 g g^{-1} at the 100 cm depth at the elongation stages in the 2021 season (Figure 3a) and 0.26~0.28 g g^{-1} in the 60–100 cm soil layer in the 2022 season (Figure 3b,c).

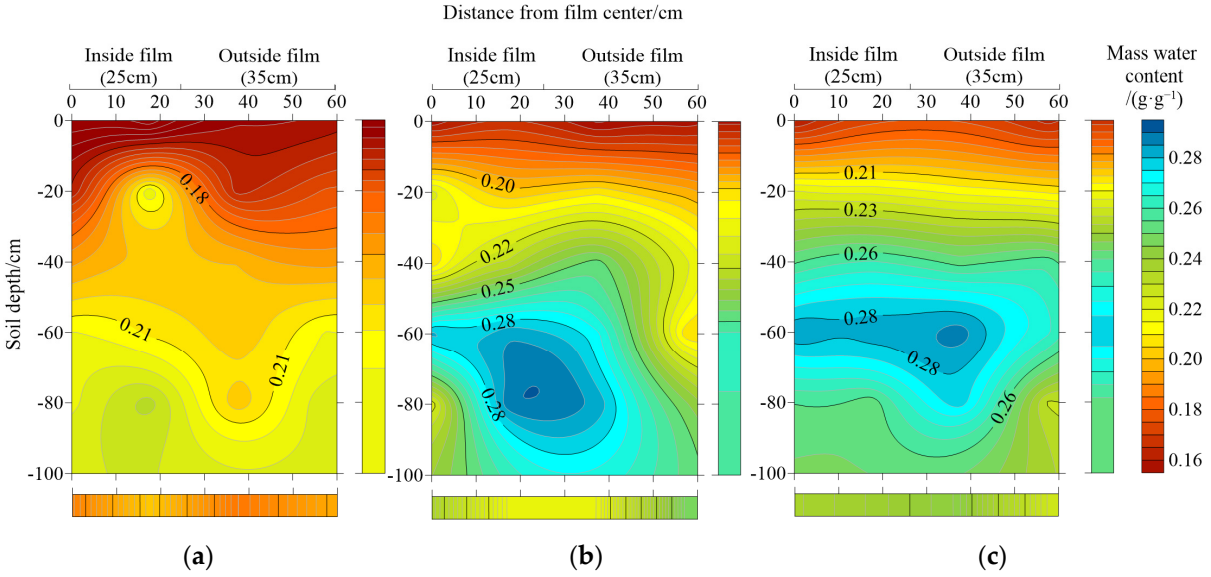


Figure 3. Spatial soil water (SW) distribution from the middle line of mulching in narrow row to the middle line of bare soil in the wide row at 100 cm depth at the elongation stage in the 2021 season (**a**), and elongation stage (**b**) and maturation stage (**c**) in the 2022 season under surface irrigation.

Soil water distributions at the 100 cm depth under mulching and bare soil regions under the drip-fertigation condition are shown in Figure 4. Under drip irrigation conditions, the soil moisture inside the mulching film was higher than that outside the mulching film, which was more obvious in the 0–20 cm soil layer. The mass water content of the 0–20 cm soil layer at the V6 stage and mature stage was 0.05 g g^{-1} and 0.03 g g^{-1} higher, respectively, than that outside the film. The average water content in the 0–100 cm soil layer was

0.026 g g^{-1} at the elongation stage (on 24 July) and 0.020 g g^{-1} at the maturation stage (on 24 September) higher than that outside of the film.

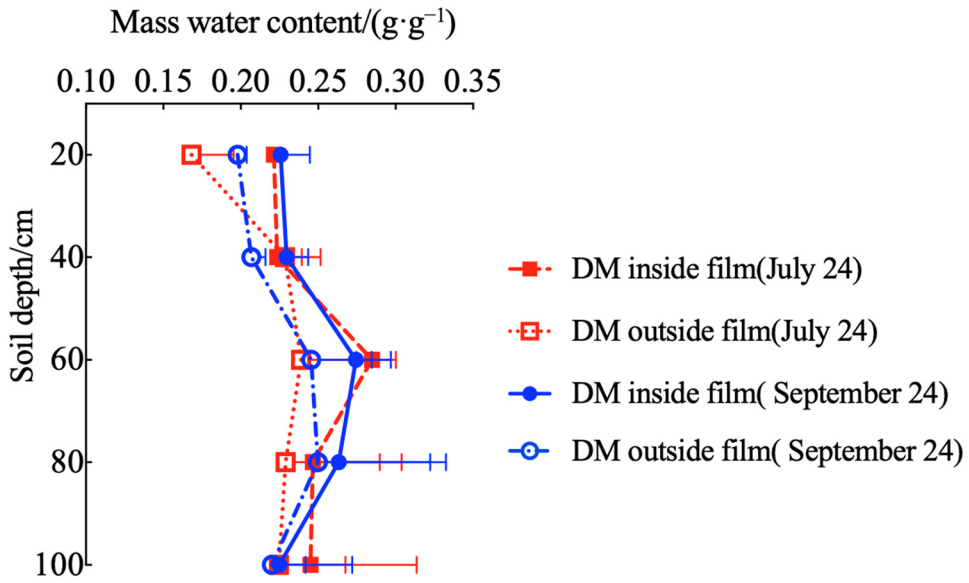


Figure 4. Soil water distributions in the 0–100 cm soil profile under mulching and bare soil with drip irrigation at the elongation (24 July) and maturation stages (24 September) in the 2021 season.

3.3. Spatial Distribution of Soil Salt within and out of Mulching

The spatial distribution of soil salt contents from the middle line of the mulching film to the middle line in the bare row in the 1 m soil depth under surface irrigation is shown in Figure 5. It can be seen that the soil salt content in the surface soil (0–20 cm) was the highest and changed greatly. With the increase in depth, the soil salt content gradually decreased. In the horizontal direction, the soil salinity showed a gradual increasing trend from the inside to the outside of the film, indicating the plastic film mulching greatly influenced the salt distribution in and out of the mulching regions.

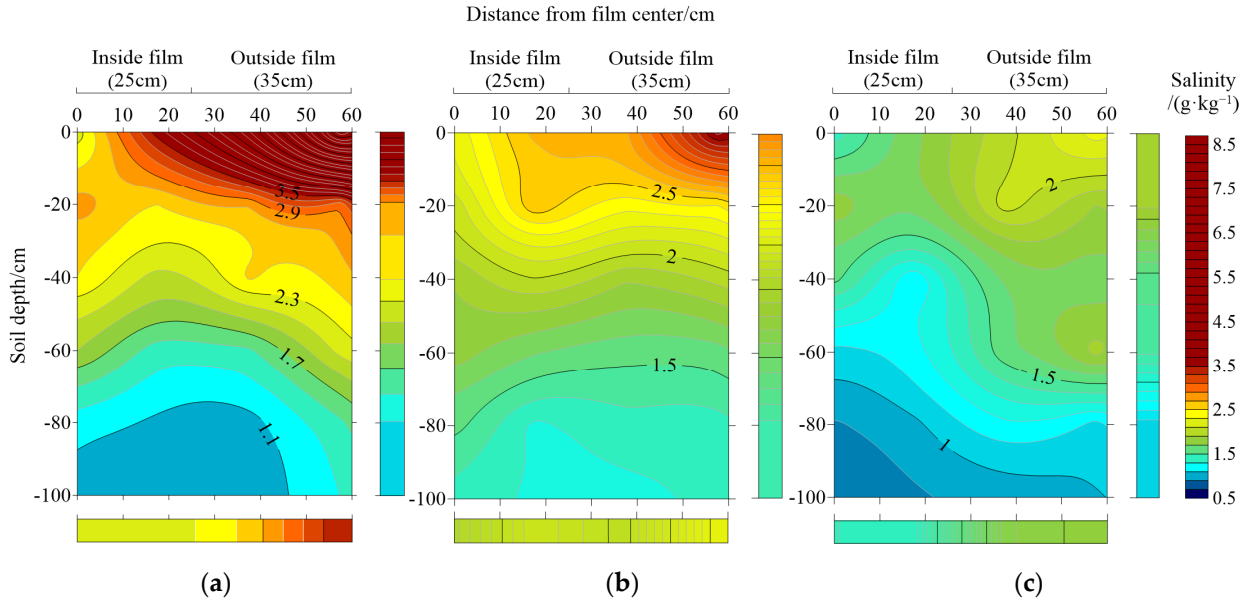


Figure 5. Spatial soil salt content distribution from the middle line of mulching in narrow row to the middle line of bare soil in the wide row at 100 cm depth at the elongation stage in the 2021 season (**a**), and elongation stage (**b**) and maturation stage (**c**) in the 2022 season under surface irrigation.

In the elongation stage of maize in the 2021 and 2022 seasons, the average salt contents in the 0–20 cm soil layer inside the film mulching region were 2.90 and 2.43 g·kg^{-1}, respectively, while the corresponding average salt contents in the same soil layer outside the film were 6.58 and 3.15 g·kg^{-1}, respectively. This shows the plastic mulching results in a 55.9% and 23.1% reduction in salt contents in the 0–20 cm soil layer. In the maize mature period of the 2022 season, the average salt content of the 0–20 cm soil layer inside the film mulching region was 1.51 g·kg^{-1}, and that outside the film was 2.10 g·kg^{-1}, also indicating a 28.1% reduction inside the film.

The difference in soil salt content between the mulching and bare soil region decreased greatly with the depth increasing. In the 20–40 cm soil layer, the soil salt content in the center of the film decreased by 5.62% and 14.57%, respectively, at the elongation stage in the 2021 and 2022 seasons, and by 1.66% in the mature stages in the 2022 season. In the soil layer below 40 cm depth till 100 cm, there is no obvious difference in soil salt contents in and out of mulching regions. This shows the effects of mulching on soil salt contents are significant in the upper 0–40 cm soil layer.

The soil salt contents in the 0–100 cm soil layer in and out of mulching at the two measurements under the drip irrigation–mulching treatment are shown in Figure 6. At the first measurement in the elongation stage (on 24 July 2021), the average salt content in the 0–20 cm soil layer in the center of mulching was 1.31 g·kg^{-1}, which was decreased by 18.63% compared with that outside the mulching (1.61 g·kg^{-1}). At the second measurement at the mature stage (on 16 September), the average soil salt content was 1.01 and 1.49 g·kg^{-1} in the center of the mulching and non-mulching regions, indicating a 32.21% decrease under mulching. In the 20–100 cm soil layer, the salt content in the mulching regions was close to that without mulching, indicating slight effects of mulching on the soil salt content after the 20 cm soil depth. With the soil depth increasing, the mean soil content decreased from 1.36 g·kg^{-1} in the 0–20 cm soil layer to 0.82 g·kg^{-1} in the 80–100 cm soil layer.

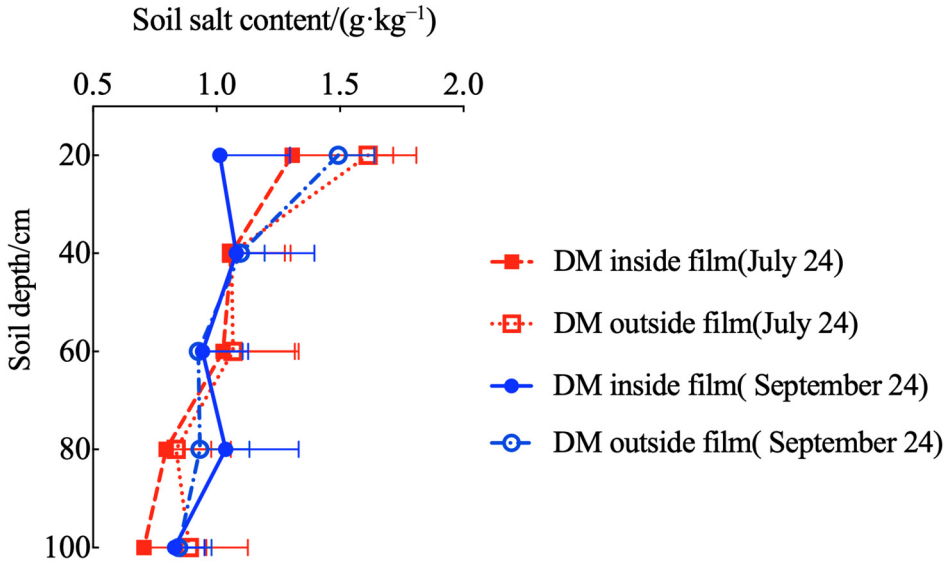


Figure 6. Distribution of soil salt content at the 1 m soil depth within and out of mulching under drip irrigation at the elongation (24 July) and maturation stages (24 September) in the 2021 season.

3.4. Spatial Distribution of Soil Nitrogen within and out of Mulching

The spatial distribution of NO_3^-, NH_4^+, and total ionic nitrogen (NO_3^- + NH_4^+) at the 0–100 cm soil layer in the mulching and bare soil regions upon the three measurements under surface irrigation are shown in the Figures 7–9. Generally, in the upper 20 cm soil layer, the NO_3^- contents were the lowest at the middle in the mulching region, then increased and reached to the highest at the middle in the bare soil region. Upon the two measurements at the elongation stage in the two maize seasons, the mean soil NO_3^-

contents in the upper 20 cm soil layer were 4.88 and 3.67 mg·kg^{-1}, and the corresponding ones in the bare soil region were 46.48 and 29.16 mg·kg^{-1}. This means NO_3^- in the mulching region was 10.2 and 7.9 times lower than that in the bare soil region. Upon the third measurement at the maturation stage in the 2022 season, the soil NO_3^- contents were 4.01 and 2.07 mg·kg^{-1} in the mulching and bare soil regions, respectively. The NO_3^- contents decreased greatly with the depth increasing. In the 20–40 cm soil layer, the NO_3^- contents in the mulching and bare soil regions were 8.09 and 13.23 mg kg^{-1}, respectively, at the elongation stage in the 2021 season, and 4.43 and 6.08 mg·kg^{-1} and 4.35 and 3.07 mg·kg^{-1} at the elongation and maturation stages, respectively. The soil NO_3^- contents in the 40–100 cm soil layer varied slightly with the soil depths and mulching conditions, within the range of 0.93–4.81 mg·kg^{-1}. This indicates the mulching practice did have slight effects on the soil NO_3^- contents in the soil layer below the 40 cm depth.

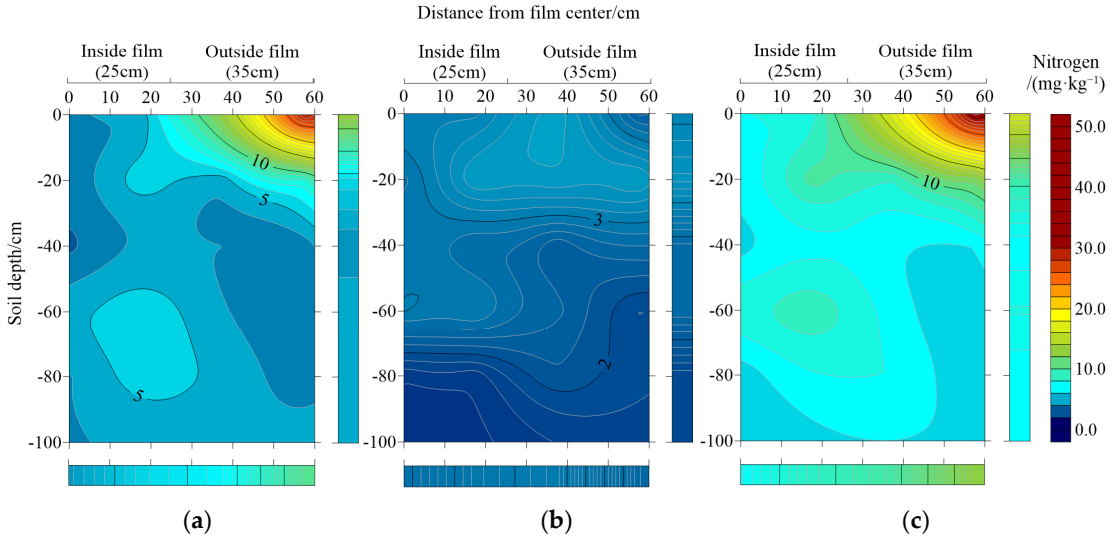


Figure 7. Spatial distributions of NO_3^- (**a**), NH_4^+ (**b**), and total ionic N (NO_3^- and NH_4^+) (**c**) in the 0–100 cm soil layer from the middle line of mulching in narrow row to the middle line of bare soil in the wide row at the elongation stage in the 2021 season under surface irrigation.

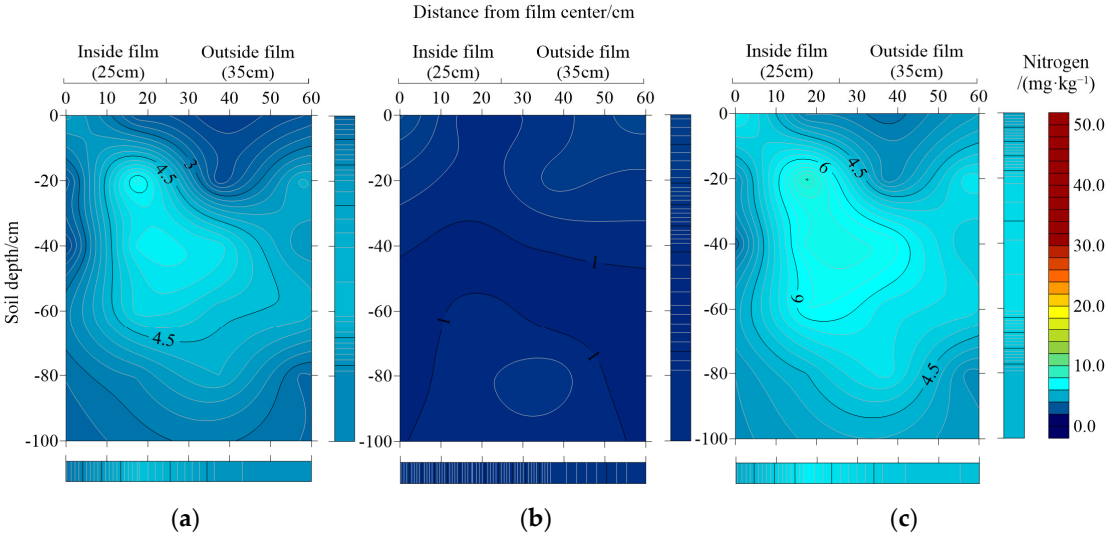


Figure 8. Spatial distributions of NO_3^- (**a**), NH_4^+ (**b**), and total ionic N (NO_3^- and NH_4^+) (**c**) in the 0–100 cm soil layer from the middle line of mulching in narrow row to the middle line of bare soil in the wide row at the elongation stage in the 2022 season under surface irrigation.

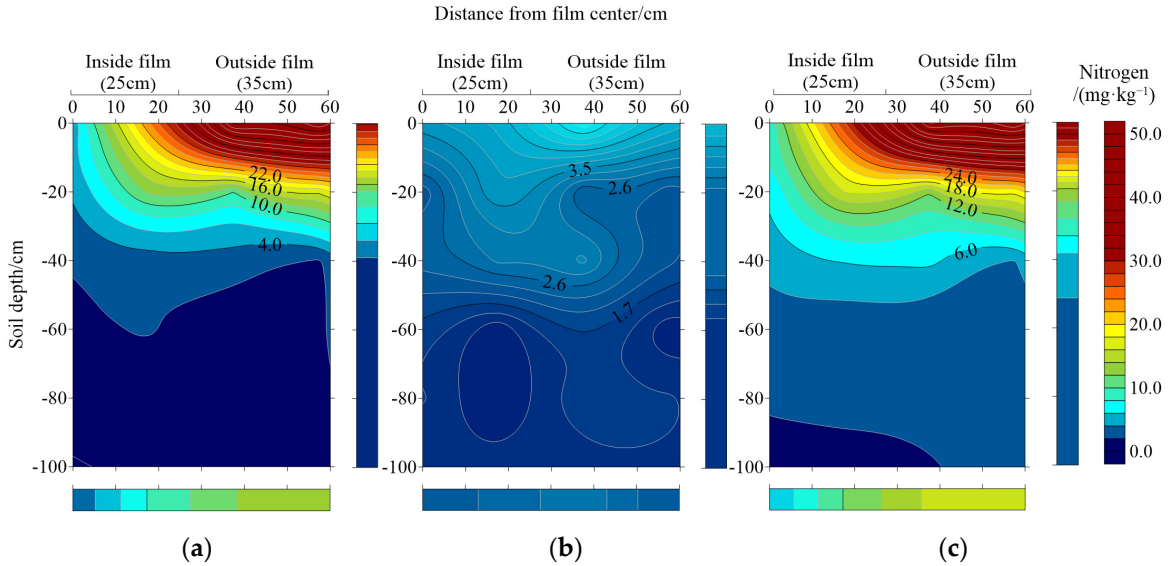


Figure 9. Spatial distributions of NO_3^- (**a**), NH_4^+ (**b**), and total ionic N (NO_3^- and NH_4^+) (**c**) in the 0–100 cm soil layer from the middle line of mulching in narrow row to the middle line of bare soil in the wide row at the elongation stage in the 2022 season under surface irrigation.

The soil NH_4^+ contents in each soil layer were close (Figures 7b, 8b and 9b), indicating the mulching practice slightly affects the NH_4^+ distribution. This result is greatly different from that for the NO_3^- distribution with the mulching condition (Figures 7a, 8a and 9a). The mean NH_4^+ contents generally decreased with the soil depth increasing, from 3.03 mg·kg^{-1} in the 0–20 cm soil layer to 1.36 mg·kg^{-1} in the 80–100 cm soil layer. The ionic nitrogen distribution was close to that of NO_3^- because the total NO_3^- amount accounted for 62.56–85.91% of the ionic nitrogen (Figures 7c, 8c and 9c).

Figure 10 shows the spatial distributions of soil NO_3^-, NH_4^+, and ionic nitrogen (sum of NO_3^- and NH_4^+) in the 0–100 cm soil layer at the middle points under mulching in the narrow row and bare soil in the wide row under the drip irrigation condition at the elongation and maturation stages in the 2021 maize season. It is clearly shown in Figure 10a that the soil NO_3^- contents (34.18 mg·kg^{-1}) in the 0–20 cm soil layer under mulching were greatly higher than that (4.06 mg·kg^{-1}) in the bare soil region, and correspondingly decreased to 5.75 and 5.44 mg kg^{-1} in the 20–40 cm soil layer. This indicates a minor difference in the NO_3^- content in and out of mulching regions. Further, close NO_3^- contents were found in the soil layer below the 40 cm soil depth. Similarly, the soil NH_4^+ contents in the 0–20 cm soil layer were much higher (5.36 mg·kg^{-1}) in the mulching region than that (2.45 mg·kg^{-1}) out of mulching, and in the 20–100 cm soil layer, the soil NH_4^+ contents ranged from 0.28 to 2.26 mg·kg^{-1} in and out of mulching regions (Figure 10b). Further, a similar spatial distribution at the soil depth in and out of mulching was found for the total ionic nitrogen (Figure 10c). Generally, it can be concluded that both irrigation and mulching result in higher nitrogen contents in the upper 20 cm soil layer in the mulching region than that out of mulching, and both nitrogen contents and these differences decreased quickly in the soil layer lower than 40 cm depth.

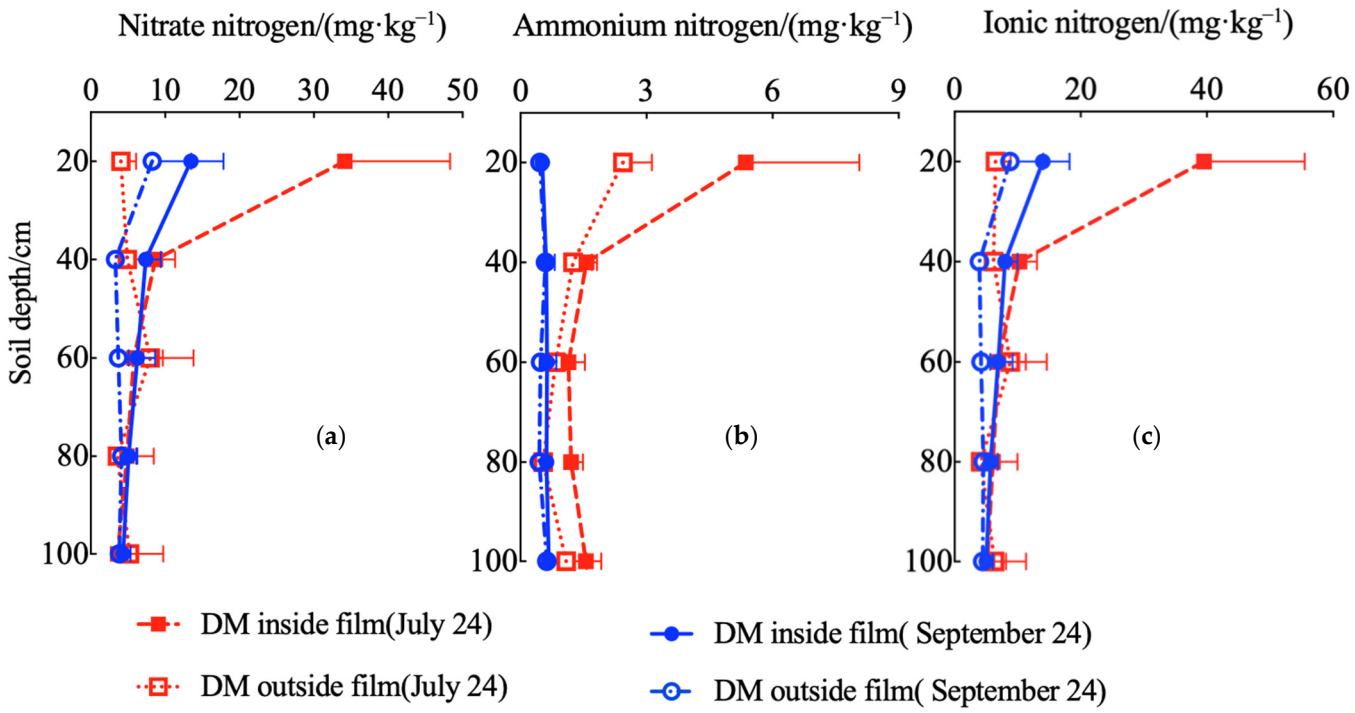


Figure 10. Spatial distributions of NO_3^- (**a**), NH_4^+ (**b**), and total ionic N (NO_3^- + NH_4^+) (**c**) in the 0–100 cm soil layer at the middle point of mulching in narrow row to the middle point of bare soil in the wide row at the elongation (24 July) and mature stages (24 September) in the 2021 season under drip-fertigation condition.

4. Discussion

Generally, there are two mulching patterns in the maize field; they are partial soil mulching and full soil mulching. Full soil mulching is always used in greenhouses to reduce soil evaporation and inside humidity, as well as to help farmers managing crops in a no-soil environment [11]. In most open fields, partial soil mulching is used. In this case, the crop row belt is covered and the spaces between row belts uncovered. Soil evaporation can lead to water stress, reduce the amount of moisture accessible to crops for their essential physiological processes, and induce salt accumulation in the soil surface [44–47]. Salt accumulation in the soil adversely affects crop growth by increasing the soil salinity, which impairs water uptake and nutrient absorption, leading to osmotic stress and reduced plant productivity [48,49]. Our study shows the soil salt content in mulching soil under both surface irrigation and drip irrigation was approximately 23~55% lower in the elongation stage and 28% lower in the saturation stages (Figure 5) in both experimental years. The low salt content (2~3 $g \cdot kg^{-1}$) under the mulching condition is beneficial for maize crop growth because maize is sensitive to salt [50]. Therefore, plastic mulching is a much better practice to maintain low salt content in the root zone, especially in arid regions where soil evaporation is high [18,20].

Nitrogen ions, mainly referring to NO_3^- and NH_4^+ [43,51], serve as building blocks for proteins and enzymes, promoting their synthesis, which is essential for various cellular functions, biochemical reactions, and synthesis of chlorophyll [52,53]. As a result, higher nitrogen ions in the root zone enhance crop growth [54]. We found the content of soil nitrogen ions in the 0–20 cm soil layer under mulching with surface irrigation was 8–10 times lower than that in the bare soil region (Figures 7a, 8a and 9a) in bother seasons. However, with drip irrigation, the nitrogen ions' content under mulching was approximately eight times higher than that in the bare soil region (Figure 10a). These different distributions of nitrogen ions are greatly influenced by the irrigation methods and nitrogen fertilizer application practice. In the HID, basal fertilizers, including 30~50% total nitrogen and all phosphorus and potassium fertilizers for maize, are always applied before soil preparation using a

machine. With the development of maize, top-dressing nitrogen fertilizers (generally using urea) are mostly applied manually on the soil surface under the surface irrigation condition. In this case, most of the dissolved nitrogen fertilizer infiltrates into the bare soil, and a small amount infiltrates into the soil with plastic mulching through plastic film cracks. Therefore, there are higher nitrogen ions in the bare soil layer than those under mulching. The nitrogen uptake by maize roots further reduces the nitrogen content under mulching. The high nitrogen content in bare soil could result in high NH_3 and N_2O emission [55,56], and lastly, cause low nitrogen use efficiency. The low nitrogen ions under mulching soil may cause nitrogen stress for plant growth, and finally results in low crop yield (11% reduction compared to drip irrigation in this study), while for drip irrigation, the dissolved nitrogen fertilizer is directly applied to the soil under mulching by the fertigation system and drip emitters. With optimized drip irrigation scheduling, most nitrogen applied could distribute in the root zone (Figure 10), then increase the nitrogen content and promote the maize growth, finally resulting in a higher yield (+11% compared to surface irrigation). Compared to surface irrigation, combining mulching with drip irrigation is a much better practice to apply nitrogen fertilizer to the root and enhance nitrogen use efficiency [23].

Mulching greatly affects the salt and nitrogen ions distribution in the top 40 cm soil layer. In the soil layer deeper than 40 cm, salt and nitrogen ions (NO_3^- and NH_4^+) distributed uniformly in each soil layer (Figures 7–9), regardless of the mulching and irrigation conditions in both seasons. This indicates mulching's effects on the salt and nitrogen distribution are mainly in the upper 40 cm soil layer. This result is important because most crops' roots are mainly developed in the upper 40 cm soil layer [57,58]. Chen, Li, Shi, Yan, Zhang, and Hu [23] modelled the nitrogen dynamics using the HYDRUS (2D/3D) model and found soil nitrate nitrogen in the upper 20 soil layer in the non-mulching region was higher than that under the mulching condition, and this difference was negligible in the soil layer deeper than 40 cm depth, which was in agreement with the results in this study.

Maize is very sensitive to the water, salt, and nitrogen content in the root zone [27,33,54,59–62]. Plastic mulching may maintain high soil water and nitrogen contents and reduce salt load in the upper 40 cm soil layer, which is very beneficial to maize growth [40,63]. The drip fertigation method can apply nitrogen solute directly into the root zone and, hence, enhance crop growth and finally result in higher yields (12.0%), water productivity (26.4%), and nitrogen use efficiency (34.3%) and low crop evapotranspiration (−11.3%), compared to farmers' practices, referring to traditional irrigation by furrow or flood and fertilization by broadcasting N fertilizer [64–66]. However, the low nitrogen ions in the mulching soil under the surface condition could cause nitrogen stress and, lastly, results in low yield production [67]. To increase the nitrogen content in the mulching soil, we suggest three practices:

(1) The first method is using slow-release nitrogen fertilizer and applying most or all fertilizer into the soil before sowing as basal fertilizers. Slow-release nitrogen fertilizer, especially combined with traditional fertilizers, can provide enough nutrients throughout the plant growth period to meet the crop nitrogen requirement and, finally, enhance crop growth and produce high crop production [68–70].

(2) The second method is to apply top-dressing fertilizer using a specified machine when crop growth is lower than 1.5 m. This machine works in the bare soil belt—firstly opens ditches along the side of plastic film, then applies fertilizer to ditches by devices, and lastly covers the ditches. This method is called the side-application method and now is increasingly recommended for use in the HID (Hao, Yunfeng, director of the Institute of Resources and Environment in Bayannaoer City, personal communication). In this method, the nitrogen is applied in the soil near the root and is suitable for root uptake. The drawback of the side-application method is it cannot be used when maize is heading, because high maize stems limit the machine working.

(3) The third method is to apply fertilizers at approximately 6–10 cm soil depth and mulch the soil surface. Compared to traditional broadcast N fertilizer with the mulching prac-

tice, the method of applying nitrogen fertilizer at the 6 cm soil depth causes 21–25% higher nitrogen uptake and a 15–20% higher grain yield of maize crops [32]. Similarly, deep application of urea increased the rice yield and straw mass by approximately 10~15% compared to the traditional broadcast application [71]. Meanwhile, mulching reduces the salt accumulation in the root zone and provides a low salt condition for crop growth.

In the future, we will focus on research on the dynamics of soil salt, water, and nitrogen when using different slow-release fertilizers, under side application and deep application conditions, and these effects on crops' growth and yield production. Crop models will be used to simulate the soil water, salt, and nitrogen distributions and crops response; then to evaluate the effects of plastic mulching on nitrogen balance, nitrogen use efficiency, nitrogen-related gas emission, and nitrogen leaching in deep soil; and, lastly, to propose optimal field management to improve the soil water, salt, and nutrient status and crop growth under the mulching condition.

5. Conclusions

In this study, we investigated the soil water, salt, and ionic nitrogen (NO_3^- and NH_4^+) distribution in the 0–100 cm soil layer under mulching and non-mulching conditions with surface and drip fertigation systems. The main results concluded are as follows:

(1) Under both irrigation conditions, soil salt contents under mulching regions were 20~50% lower than those in non-mulching regions, while these differences were negligible in the soil layer deeper than 40 cm depth, indicating mulching's effects on soil salt contents are concentrated in the upper 40 cm soil layer. The mulching's effects on soil salt are greater at the elongation stage than at the maturation stage.

(2) Under surface irrigation with the manual fertilizer-broadcast practice, the NO_3^- contents in the 0–20 cm soil layer under mulching was 8–10 times lower than those in bare soil in the wide row. On the contrary, the NO_3^- contents were approximately eight times higher under the mulching region than bare soil with drip fertigation system. Under both irrigation systems, there are unnoticeable differences in the NO_3^- contents in the soil layer deeper than the 40 cm soil layer. The soil NH_4^+'s distribution at each soil layer is uniform, regardless of mulching, and generally decreased with the soil depth increasing from 0–40 cm to 40–100 cm.

(3) Higher NO_3^- in the root zone under drip fertigation with the mulching practice finally results in an approximately 11% higher grain yield of maize than under surface irrigation. Considering surface irrigation is the main irrigation method in HID, three methods are recommended to enhance the nitrogen content in the mulching region; they are increasing the portion of basal fertilization application, using the side-application method during the crop growth period, and combining the use of slow-release and normal chemical fertilizers to maintain a relatively high nitrogen content throughout the crop growth season.

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