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Fertigation and Carboxymethyl Cellulose Applications Enhance Water-Use Efficiency, Improving Soil Available Nutrients and Maize Yield in Salt-Affected Soil

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Abstract: Conventional organic soil amendments and drip irrigation are insufficient for mitigating soil salinization. The development of a more potent soil amendment with higher water retention capability is critical. Carboxymethyl cellulose (CMC) has excellent water retention and adsorption properties and is suitable for soil water retention and amendment; however, its effects on water and salt distribution, soil nutrients, and maize yield have not been clearly investigated. We set up five treatments with flood irrigation (CK), drip irrigation (W), drip irrigation combined with 100 kg CMC ha^{-1} (WC1), drip irrigation combined with 200 kg CMC ha^{-1} (WC2), and drip irrigation combined with 300 kg CMC ha^{-1} (WC3). Our findings demonstrate that the application of CMC in conjunction with drip irrigation led to a significant surge in soil water content within the 0–40 cm layer, ranging from 3.73% to 16.46%, while simultaneously inducing a reduction in salt content of 4.08% to 16.61%. Consequently, this resulted in a desalination rate spanning from 10.32% to 12.93%. The salt was gradually washed down and formed a desalination area with the drip emitter as the center, and the salt distribution characteristics shifted from a surface accumulation type to a bottom deposition type. The drip irrigation and CMC application also increased the content of available nutrients, reduced surface evaporation, underground water loss, and maize evapotranspiration, and improved water-use efficiency, thus increasing the aboveground biomass and grain yield. In summary, CMC had a significant effect on water retention, desalination, and yield increases. It can serve as a novel soil amendment for salt-affected soil.

Keywords: drip irrigation; carboxymethyl cellulose; water and salt transport; available nutrients; maize

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1. Introduction

Soil salinization is a global environmental issue, resulting in a vast expanse of land becoming infertile due to salt accumulation, which has become an increasingly severe problem worldwide [1]. The total land area with varying degrees of salinization is estimated to be approximately 9.5 × 10^8 hm^2 globally, accounting for about 22% of global agricultural land [2]. This area continues to grow at a rate of 1–2.5 × 10^6 hm^2 per year [3]. Based on projections, it is anticipated that by 2050, around 40–50% of the world's arable land will be adversely impacted by salinization [4]. In China, there are approximately 3.67 × 10^7 hectares of salt-affected soil, mainly distributed in the Northeast, North China, Northwest, and coastal areas [5]. Northern Ningxia, located in the semi-arid region of northwestern China, boasts flat terrain, has good soil quality, and benefits from irrigation from the Yellow River, making it a vital agricultural area and a base for commodity grain production in China. For centuries, people have relied on diverting water from the Yellow River, which has allowed for agricultural prosperity and cultural development in the Yellow River basin of ancient China despite an average annual precipitation of only

200 mm. However, due to the evaporation of up to 2000 m from the surface of the area and the long-term irrigation by the Yellow River, the groundwater level rises and the salts in the groundwater move up and gather at the surface, resulting in particularly severe secondary soil salinization in the region [6]. Extensive salt-affected soil has been abandoned, further shrinking arable land resources, reducing crop yields, and severely hindering local sustainable agricultural development [7].

Soil salinization is the result of the joint action of water and salt, which is closely related to factors such as irrigation, tillage patterns, climatic conditions, and soil types. In salt-affected soils, effective soil improvement measures aim to regulate the transport of water and salt, facilitate the leaching of soil salts downward, and impede the upward salt migration induced by transpiration towards the soil surface [8,9]. Traditional hydraulic engineering improvement measures often use flood irrigation to wash away salt, which not only wastes precious water resources but also increases the risk of environmental pollution [10]. In contrast, water and fertilizer integrated drip irrigation (fertigation) technology achieves high frequency and precise irrigation and allows water and fertilizer to evenly seep into the soil. This technique reduces soil solution infiltration and surface runoff while maintaining a high soil moisture content, promoting root growth and development of plants, and increasing water-use efficiency and crop yields [11]. Fertigation also creates a desalination zone near the dripper, characterized by ample water supply and low salt concentration, establishing a favorable microenvironment for cultivating crops in salt-affected soil [12]. Thus, drip irrigation has emerged as a highly effective strategy for rehabilitating low-yield agricultural lands impacted by salinization, garnering national and international recognition and adoption [8]. Previous research has shown that the comprehensive effects of water and fertilizer interaction in fertigation can increase water-use efficiency by 22–27% and crop yields by 10–15% while reducing water consumption by 40–50% [13]. However, a single-drip irrigation mode is no longer effective in suppressing the increasingly serious soil salinization. In large-scale intensive agricultural production, drip irrigation often needs to be combined with soil amendments for comprehensive management of salt-affected soil in order to achieve the desired water-saving and salt-suppression effects.

Several studies have indicated that the application of organic soil amendments in salt-affected soil can effectively enhance agricultural productivity [14,15]. Notably, humic acid and biochar have emerged as prevalent choices due to their profound impact on soil structure enhancement, facilitation of soil aggregate formation, elevation of soil organic carbon levels, enrichment of soil organic matter content, reduction of soil salinity, and stimulation of crop growth [16]. However, with global warming and the increasing occurrence of extreme weather events in arid and semi-arid regions, the surface evaporation rate has further increased, and the process of soil salinization has accelerated. Conventional soil amendments are no longer sufficient to address the increasingly severe soil salinization process, and there is an urgent need to develop water-retaining agents with stronger capabilities to cope with this challenge.

Carboxymethyl cellulose (CMC) exhibits a multitude of beneficial properties when dissolved in water. Notably, its aqueous solution demonstrates commendable attributes such as thickening, film-forming, suspension, adhesion, and, most notably, water-retention properties [17], making it particularly suitable as a water retention and soil conditioner for salt-affected soils. When applied to soil, CMC can change soil infiltration characteristics and infiltration model parameters by forming a gel-like structure, improve soil water infiltration performance [18], increase soil water holding capacity and salt leaching efficiency, and thus improve plant water utilization [19]. CMC can also act as a binder, which helps to aggregate soil particles, reduces soil compaction, increases soil pore space, improves soil non-capillary porosity, and improves water infiltration into the soil [20]. In addition, the negatively charged carboxymethyl group on the main chain of CMC can interact with the cations of the soil solution through electrostatic attraction, thus inhibiting soil salt stress [21]. However, research on the impact of CMC as a soil amendment on soil water and salt transport, nutrient distribution, and crop growth is currently lacking. Therefore, there is an urgent need to investigate the impact of CMC application on soil and crops, particularly in conjunction with fertigation for improving the soil quality of salt-affected soil. Such research will provide a theoretical basis for the selection and development of soil-improvement agents in comprehensive water-saving and salt control models for salt-affected soil in the future.

To fully understand the integrated effect of CMC on salt-affected soil, it is necessary to have a good understanding of the strong spatial and temporal variation of soil moisture and salinity and crop water use efficiency, and to improve the theory of water and salt transport regulation of CMC combined with fertigation. Therefore, the main focus of this study is on: (1) the vertical and horizontal distribution of soil moisture and salinity; (2) the availability of vital soil nutrients; and (3) the plant response to different application rates of CMC combined with fertigation. We expect that the expected results of this research work have the potential to greatly benefit salt-affected soils around the world. Additionally, they will help to choose suitable soil amendments for salt-affected soil, protect water resources, suppress salt deposition, and improve land productivity in salt-affected soil.

2. Materials and Methods

2.1. Description of the Study Site

The trial site was situated in Jiaoji Village, Pingluo County, Shizuishan City, Ningxia Hui Autonomous Region (36°15′ N, 106°15′ E, 1100 m above sea level), with a temperate continental semi-arid climate. An overview of the specific field trial areas is shown in Table 1.

Table 1. Overview of the field trial area.

Temperature and Rainfall Conditions in the Field Trial Area	
Annual average temperature	8.7 °C
Effective accumulated temperature	3100–3300 °C
Diurnal temperature range	10–15 °C
Annual average sunshine duration	2800–3000 h
Sunshine rate	68%
Average annual precipitation	190–210 mm
Average annual evaporation	1900–2000 mm
Frost-free period	165–170 d

The physical and chemical properties of the initial soils are summarized in Table 2. The soil textures are medium-textured saline alluvial soils with basic sand and loamy sand within 0–70 cm and loamy within 70–100 cm. Prior to the experiment, the average depth of the groundwater table was measured to be 1.38 m. The soil's pH value was determined to be 8.25, while the electrical conductivity (EC) measured 15.22 dS m^{-1}.

Table 2. Physical and chemical properties of the initial soil.

Soil Layer (cm)	**Bulk Density (g cm^{-3})**	**Organic Matter (g kg^{-1})**	**pH**	**EC [1] (dS m^{-1})**	**ESP [2] (%)**
0–10	1.36	15.79	8.72	2.80	23.46
10–20	1.46	14.31	8.77	2.59	22.29
20–30	1.46	12.51	8.68	2.32	21.16
30–40	1.55	12.02	8.65	2.65	22.65
40–50	1.54	10.15	8.60	2.53	21.68
50–60	1.53	9.36	8.38	2.41	20.91
60–70	1.55	7.19	8.58	2.33	20.52
70–80	1.56	5.78	8.23	2.22	19.90
80–90	1.55	5.21	8.54	2.22	19.91
90–100	1.55	5.18	8.14	2.10	19.24

[1] EC: electrical conductivity, [2] ESP: exchange sodium percentage.

2.2. Experimental Design

The experiment was initiated on 10 April 2022, and lasted for a period of 130 days, during which the maize variety tested was Da Jing Jiou 26. The experimental design embraced a wide-narrow row planting scheme, as illustrated in Figure 1B, characterized by a row width of 60 cm and an inter-row spacing of 40 cm. Within this arrangement, individual plants were meticulously positioned at intervals of 22 cm. A drip irrigation system was implemented, comprising key components such as electromagnetic valves, pressure gauges, flow meters, filter screens, and fertilizer tanks. Each treatment field was equipped with an independent drip irrigation field control system to regulate water application rates within each plot. Within the narrower rows, drip irrigation belts were installed at intervals of 20 cm, with each emitter delivering a flow rate of 1.28 L/h. Five treatments were established: (1) CK (traditional flood irrigation with an irrigation quota of 900 mm); (2) W (fertigation with an irrigation quota of 450 mm); (3) WC1 (fertigation with an irrigation quota of 450 mm and a CMC application rate of 100 kg ha^{-1}); (4) WC2 (fertigation with an irrigation quota of 450 mm and a CMC application rate of 200 kg ha^{-1}); (5) WC3 (fertigation with an irrigation quota of 450 mm and a CMC application rate of 300 kg ha^{-1}). Each experimental treatment was subjected to three replications, resulting in a total of 15 plots that were allocated within each block in a randomized manner. The spatial extent of each plot encompassed an area of 20 × 20 m^2, accommodating a profusion of 38 rows of maize plants, thereby culminating in a substantial trial area of 6000 m^2.

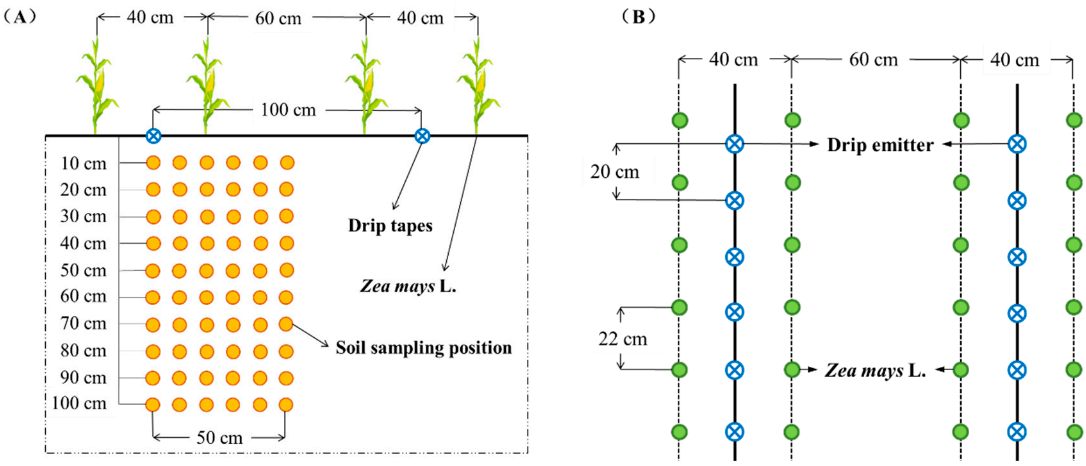

Figure 1. Field trial planting arrangements and soil sampling locations. (**A**), cross-sectional view; (**B**), aerial view.

2.3. Field Management of the Experiment

Field management was consistent with the local conventional irrigation and fertilization schedule. Prior to planting, 1500 kg of mature cow manure was applied per hectare to all plots as a basal fertilizer. The traditional flooding treatment (CK) used urea, ammonium phosphate, and ternary compound fertilizers. The inorganic fertilizer dosages were 400 kg N ha^{-1}, 200 kg P_2O_5 ha^{-1}, and 225 kg K_2O ha^{-1}, of which 65% N was used as a base fertilizer and 35% as a follow-up fertilizer. The fertilizer was immediately incorporated into the soil by rotary tillage to a depth of 20–25 cm after application. During the maize growing season, the remaining urea was applied twice according to the nutrient requirements of maize. We used water-soluble fertilizer (N-P_2O_5-K_2O = 24-12-14) for maize as fertilizer for the drip irrigation treatments (W, WC1, WC2, and WC3) according to the traditional local fertilization practices, and applied it by dissolving it in irrigation water during irrigation. Ten rounds of irrigation were carried out during the maize growth period, with seven rounds of fertilization applied by drip irrigation, and the total amount of fertilizer was consistent with that of the flood irrigation treatment. Additionally, WC1, WC2, and WC3 were applied by surface spreading 100 kg CMC ha^{-1}, 200 kg CMC ha^{-1}, and 300 kg CMC ha^{-1}

in the corresponding plots before planting and then rototilled into 20–25 cm of soil by rotary tillage. The irrigation flows were sourced through a stream linked to the Yellow River with conductivity, pH, and sodium adsorption rates of 0.43 dS m^{-1}, 7.98, and 1.87 $mmol^{0.5}$ $L^{-0.5}$, respectively. The specific irrigation and fertilization measures are shown in Table 3.

Table 3. Irrigation and fertilization during growing seasons of maize.

Treatment	Irrigation Amount (mm)					Fertilization Rates			CMC *
	Seedling	Jointing	Flowering	Maturation	Total	(kg ha^{-1})			(kg ha^{-1})
CK	260	250	190	200	900	N	P_2O_5	K_2O	0
W	135	135	90	90	450	400	200	225	0
WC1	135	135	90	90	450	400	200	225	100
WC2	135	135	90	90	450	400	200	225	200
WC3	135	135	90	90	450	400	200	225	300

* CMC: Carboxymethyl Cellulose.

2.4. Sample Collection and Analysis

2.4.1. Soil Sample Collection and Analysis

At the end of March, initial soil samples were collected from the test area, and after removing plant and animal residues and stones, the initial soil samples were air dried and then sieved (1 mm), and soil pH was gauged with a pH meter (Soil:Distilled Water = 1:5).

Exchangeable sodium percentage (ESP) was calculated as [22]:

$$ESP = Na^{+}/CEC \times 100\% \quad (1)$$

where Na^+ is the exchangeable sodium concentration (cmol (Na^+) kg^{-1}) and CEC is the cation exchange capacity (cmol kg^{-1}). The CEC was determined by the EDTA ammonium acetate exchange method [23], and the exchangeable Na^+ concentration was measured by flame photometry (Mettler Toledo, Shanghai Analytical Instrument Co., Ltd., Shanghai, China).

During the experiment, soil samples were collected at three time points during the entire maize growing season: on 15 April (A), 15 June (B), and 31 August (C). To obtain these samples, a random drip irrigation emitter was selected within each plot, and soil collection took place using a spiral drill measuring 4.0 cm in diameter and 15 cm in height. Soil sampling encompassed a range of horizontal and vertical distances from the drip emitter, as depicted in Figure 1A. Horizontal distances included 0, 10, 20, 30, 40, and 50 cm, while vertical distances spanned 10, 20, 30, 40, 50, 60, 70, 80, 90, and 100 cm. At each sampling instance, a total of 60 soil samples were collected. The soil sampling procedure for the CK treatment mirrored that of the other treatments, with the random collection of 60 soil samples within each plot.

Upon eliminating surface-level organic contaminants and fine roots, soil samples underwent air drying and were subsequently sieved through a 1 mm mesh to obtain particle size uniformity. Three replicates were then amalgamated into a composite sample. Soil moisture content was determined using the oven-drying method. Saturated soil paste extracts were then made by standard methods [24] with a water-to-soil mass ratio of approximately 3:5, and soil electrical conductivity (EC) was measured using a conductivity meter (DDS-12A, Shanghai Rex Instruments Factory, Shanghai, China).

The total soil salinity content was obtained by EC. The salt desalination rate (SDR, %) was calculated as follows:

$$SDR = \frac{S_0 - S_1}{S_0} \times 100\% \quad (2)$$

where S_0 is the initial soil salinity content (g kg^{-1}) and S_1 is the soil salinity content at the last sampling during the maize-growing season (g kg^{-1}).

The remaining soil samples were analyzed for their content of available nutrients. The alkali-hydrolyzed nitrogen (N) was measured by the NaOH hydrolysis method. Determination of available phosphorus (P) by molybdenum blue spectrophotometry using a UV–visible spectrophotometer (UV-9100, Beijing Ruili Analytical Instrument Co., Ltd., Beijing, China). Available P was measured by molybdenum blue spectrophotometry. Available potassium (K) was determined by a flame photometer (Mettler Toledo, Shanghai Analytical Instrument Co., Ltd., Shanghai, China) [25].

2.4.2. Plant Sample Collection and Analysis

During the maturation stage, when the maize grain moisture content reached approximately 20–22%, a random selection of three maize plants was made from each plot to assess their height and stem diameter. Subsequently, these entire plants, totaling 45 in number, were promptly transported to the laboratory and subjected to drying at 70 °C until reaching a constant weight. First, the aboveground parts of the dried single maize plants were weighed, then the grains were separated from the aboveground parts, and the weight of the retrieved single maize grains was weighed. Finally, the maize planting density per hectare was calculated based on the row spacing, and the aboveground biomass and grain yield per unit hectare were calculated based on the planting density.

Water-use efficiency (WUE, kg ha^{-1} mm^{-1}) was calculated using the following equation [26]:

$$WUE = Y/ET \tag{3}$$

where Y is the grain yield (kg ha^{-1}) and ET is maize evapotranspiration during the growth period (mm).

The soil water balance was calculated as follows [26]:

$$ET = I + P + \Delta S + G - R - L - E \tag{4}$$

where ET refers to the amount of evapotranspiration (mm), I represents the irrigation amount (mm); P was measured using a field rain gauge (mm); the variation in soil water storage ΔS was estimated through spatially weighted averaging (mm); G denotes the contribution of groundwater (mm), R signifies surface runoff (mm), L is the amount of groundwater leakage determined using a soil seepage monitoring device (mm), and E represents the amount of surface water evaporation monitored using a micro-evaporimeter (mm). However, due to the flat nature of the experimental area and the maize roots' average depth being shallower than the groundwater, the effects of R and G were disregarded in this investigation.

2.5. Statistical Analyses

The data obtained in this study was meticulously organized and recorded using Microsoft Office Excel 2016. Graphical representations were generated employing Origin 2018 (Origin Lab Co., Northampton, MA, USA). To assess the significance of differences among treatments, an analysis of variance (ANOVA) was conducted using IBM SPSS Statistics Version 19.0 (IBM Co., Armonk, NY, USA). Furthermore, Tukey's honestly significant difference (HSD) test was employed to perform pairwise comparisons between treatments, with a significance level set at $p < 0.05$. For the comparison of differences between two specific sampling times, an independent sample *t*-test was conducted. The levels of significance were denoted by *, **, and ***, indicating significant differences between two different sampling times at $p < 0.05$, $p < 0.01$, and $p < 0.001$, respectively.

3. Results

3.1. Soil Water Transport

Figure 2 shows the migration of soil moisture over time. The distribution of soil moisture varies significantly with irrigation and CMC application, indicating that the infiltration characteristics of soil moisture are significantly altered by irrigation and amendment application. Compared to the control treatment (CK), it can be observed that in drip irrigation treatments (W, WC1, WC2, and WC3), the wetted area of the soil gradually expands in the horizontal and vertical directions around the drip emitter as the maize grows. Conversely, the soil moisture content distribution under the flood irrigation treatment is extremely uneven, with low moisture content (14.75–15.19%) still present at a depth of 60–70 cm during the maize growth period (C). Compared to the drip irrigation treatment without CMC application (W), the application of CMC (WC1, WC2, and WC3) significantly increased the soil moisture content of each soil layer, and with an increase in the CMC application rate, the soil water content increased. By the C stage, the soil water content in the 10–40 cm soil layer of the WC1, WC2, and WC3 treatments increased by 3.73–6.19%, 6.54–8.92%, and 11.96–16.46%, respectively, compared to the W treatment, indicating that drip irrigation combined with CMC application has a good effect in maintaining soil moisture in the root zone (0–40 cm).

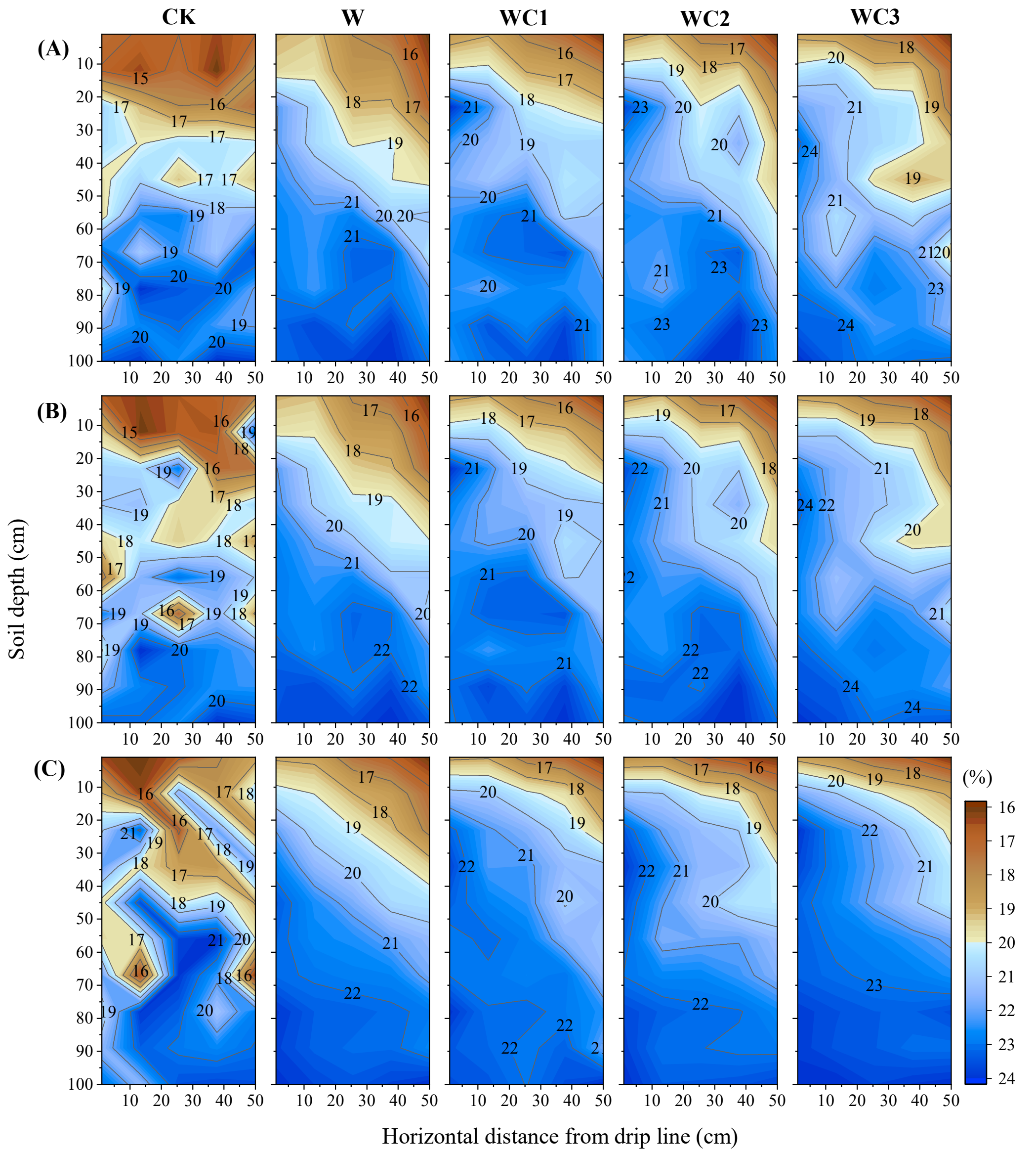

Figure 2. Spatial distribution of soil moisture. (**A**) Sampling time 15 April 2022, (**B**) Sampling time 15 June 2022, (**C**) Sampling time 31 August 2022.

3.2. Soil Salt Transport

Figure 3 depicts the temporal variations in soil salinity (EC). The movement of soil water plays a pivotal role in the redistribution of soil salinity. Notably, drip irrigation treatments (W, WC1, WC2, and WC3) resulted in a gradual downward leaching of soil salinity, forming a desalination zone centered around the drip emitter as the maize growth period progressed. By the mid-growth period of maize (B), compared with CK and W, WC1, WC2, and WC3 reduced the soil EC in the 0–20 cm soil layer by 1.17–3.12%, 3.62–3.99%, and 2.15–4.72%, respectively. At this stage, soil salinity was mainly concentrated in the 20–50 cm soil layer. By the late growth period of maize (C), with continued irrigation, soil salinity had further migrated downward and gradually leached into the deep soil layer. The salinity in the surface soil (0–30 cm) further decreased, and the desalination zone continued to expand. Its upper boundary moved from 20–30 cm to 40–50 cm. Moreover, the application of CMC demonstrated an enhanced desalination effect on the surface soil (0–40 cm). Compared to WC1, WC3 resulted in a 1.99% decrease in soil EC in the 0–40 cm soil layer.

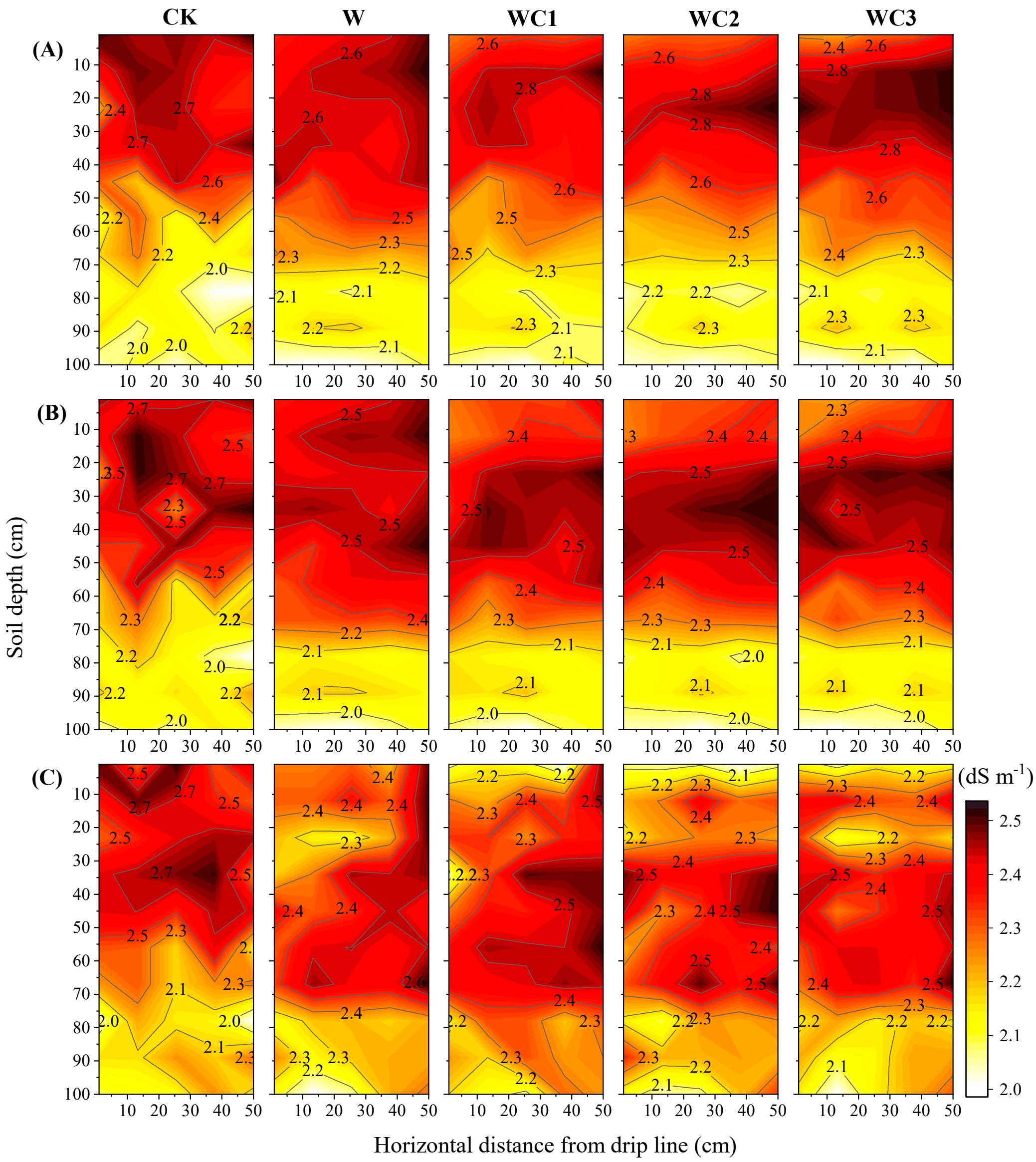

Figure 3. Spatial distribution of soil salinity. (**A**) Sampling time 15 April 2022, (**B**) Sampling time 15 June 2022, (**C**) Sampling time 31 August 2022.

3.3. Soil Desalination

Based on the results of the one-way analysis of variance (ANOVA) and subsequent multiple comparison analysis (Figure 4), it was observed that, with the exception of the CK, all treatments demonstrated a significant or highly significant reduction in soil salt content within the 0–40 cm soil layer in comparison to the initiation of the experiment on 15 April 2022. Over the course of the maize growth period, the average soil salt content in the 0–40 cm soil layer exhibited reductions ranging from 5.67% to 9.88%, 13.97% to 17.06%, 11.91% to 22.76%, and 13.67% to 24.60% for the W, WC1, WC2, and WC3, respectively. Furthermore, significant disparities in soil salt content were observed among the treatments during the maize growth period. Specifically, the combination of drip irrigation and CMC application led to a noteworthy reduction in soil salt content within the surface soil layer. In comparison to the CK, the soil salt content in the 0–30 cm soil layer was diminished by 4.80% to 9.62%, 6.98% to 15.57%, 9.25% to 20.56%, and 6.33% to 19.06% for the W, WC1, WC2, and WC3, respectively. However, no significant distinctions in soil salt content were observed among the drip irrigation treatments (W, WC1, WC2, and WC3) within each soil layer.

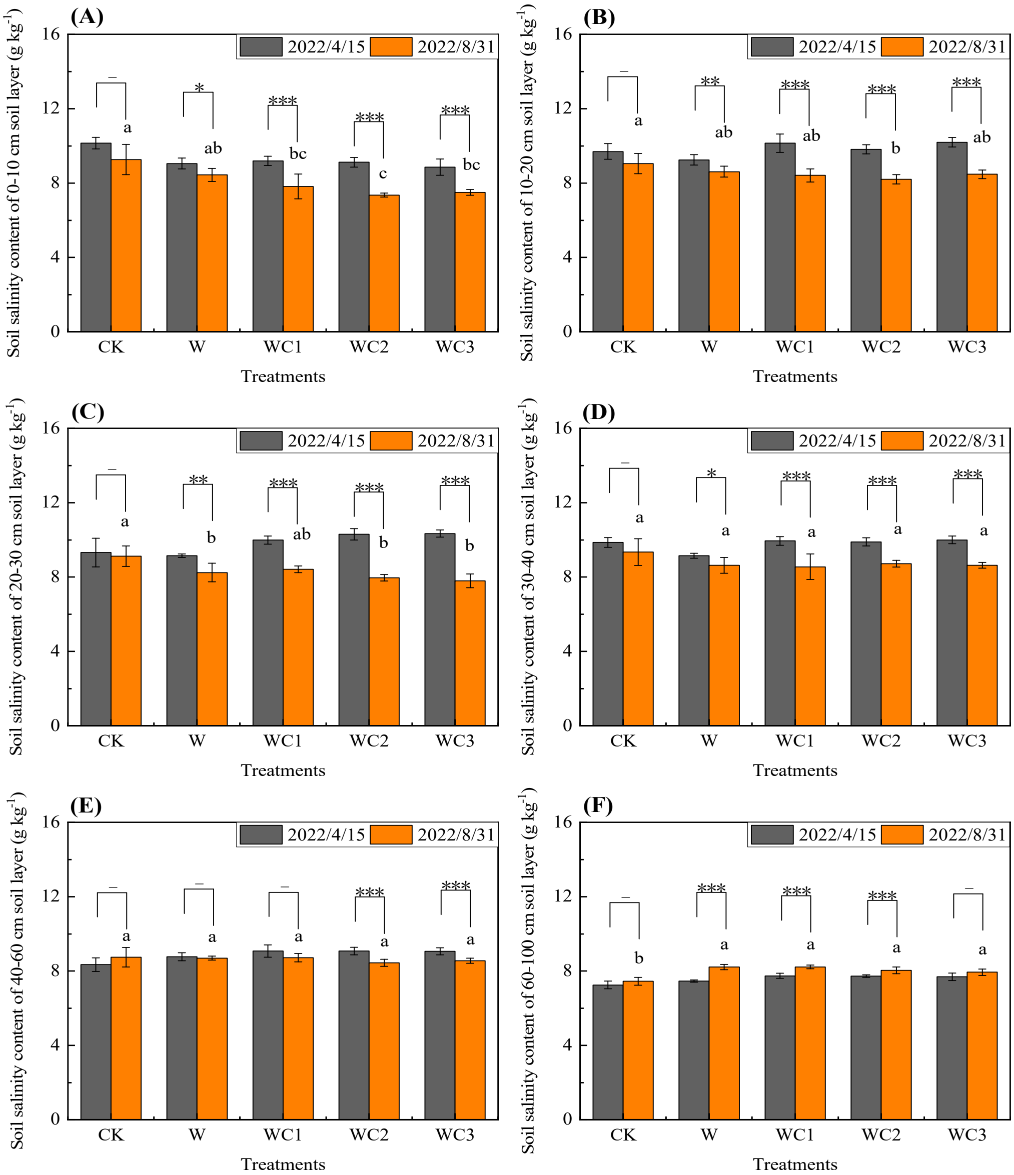

Figure 4. Effectiveness of soil desalination. (**A**) Salinity in 0–10 cm soil layer, (**B**) Salinity in 10–20 cm soil layer, (**C**) Salinity in 20–30 cm soil layer, (**D**) Salinity in 30–40 cm soil layer, (**E**) Salinity in 40–60 cm soil layer, (**F**) Salinity in 60–100 cm soil layer. Different lowercase letters indicate significant differences in soil salt content between different treatments on 31 August 2022; *, **, and *** indicate significant differences in soil salt content between two different sampling times (*t*-test, $p < 0.05$, $p < 0.01$, $p < 0.001$).

Upon comparing the initial soil salinity content, it was discovered through calculations of soil desalination rates during the late growth period of maize (Table 4) that the desalination effect of the 0–10 cm soil layer under the W, WC1, WC2, and WC3 treatments was significantly higher than that of the CK treatment. Particularly, WC2 and WC3 treatments exhibited desalination rates in the 0–10 cm soil layer that were 67.00% and 58.25% higher, respectively, compared to the W treatment. Overall, compared to the uneven desalination effect of the CK treatment, the desalination effect of the surface soil (0–40 cm) was significant for the other treatments, with the desalination rate of most soil layers in the deep soil (40–100 cm) being negative and ranging from –7.92% to 4.60%. This indicates that under high-frequency drip irrigation and CMC application conditions, soil salinity tends to gradually move down to the deep soil layer, accumulating in the process. Finally, the average desalination rate of each soil layer in the WC2 and WC3 treatments reached 4.40–4.54%, while the other treatments only reached 1.12–1.90%.

Table 4. Average soil desalination rate of each soil layer under different treatments.

Soil Layer (cm)	CK (%)	W (%)	WC1 (%)	WC2 (%)	WC3 (%)
0–10	7.84 cAB	16.00 bA	22.23 abA	26.72 aA	25.32 aA
10–20	2.55 aAB	7.31 aABC	9.43 aB	11.59 aB	8.83 aB
20–30	−9.11 bB	1.55 abBCD	−0.47 abAB	4.90 abBCD	7.06 aB
30–40	1.80 aAB	9.35 aAB	10.08 aB	8.52 aBC	9.36 aB
40–50	−3.81 aAB	3.43 aBCD	3.99 aAB	4.31 aBCD	4.60 aBC
50–60	3.84 aAB	−2.67 aCD	−3.77 aB	2.29 aBCD	−0.63 aBC
60–70	2.55 aAB	−7.92 aD	−7.17 aB	−5.35 aD	−5.02 aBC
70–80	10.00 aA	−3.64 aCD	−4.62 aB	−0.83 aCD	0.44 aC
80–90	1.51 aAB	−4.35 aCD	−4.22 aB	−3.00 aCD	0.14 aBC
90–100	1.85 aAB	−7.81 aD	−7.40 aB	−5.15 aD	−4.73 aC
Average SDR *	1.90	1.12	1.81	4.40	4.54

* SDR: soil desalination rate. Distinct capital letters within the same column indicate significant variations between different soil layers ($p < 0.05$). Different lowercase letters within the same row indicate significant distinctions among different treatments ($p < 0.05$).

3.4. Soil Available Nutrients

Alkali hydrolyzed N: The content of alkali hydrolyzed N exhibited a gradual decline as soil depth increased. Among the different treatments, the CK had the lowest alkali hydrolyzed N content, followed by the W, while the WC2 and WC3 had the highest content. The application of CMC significantly increased the content of hydrolyzed inorganic N and easily hydrolyzed organic N in the soil, thereby improving the content of alkali-hydrolyzed N.

Available P: In comparison to the control treatment, the availability of phosphorus in the 30–40 cm soil layer showed a significant increase in the WC1, WC2, and WC3, with no significant difference observed among the different drip irrigation treatments (W, WC1, WC2, and WC3). As soil depth increased, the available P content gradually decreased, with the overall trend being WC3 $\geq$ WC2 $\geq$ WC1 $\geq$ W > CK. These findings suggest that the application of the amendment can reduce the adsorption and fixation of soil colloids to P, thereby improving the effectiveness of soil P.

Available K: Similar to the patterns observed for alkali hydrolyzed N and available P, the availability of potassium in the soil exhibited a gradual decline with increasing soil depth. Significant differences in soil-available K content were observed within the 0–60 cm soil layer, with the order being WC3 $\geq$ WC2 $\geq$ WC1 $\geq$ W > CK. The WC1, WC2, and WC3 displayed potassium contents that were 12.90–31.74%, 16.92–38.92%, and 20.93–48.69% higher, respectively, than the CK. However, no significant differences were observed among the treatments in the 70–100 cm soil layer, with the soil-available K content ranging from 89.06–135.8 mg kg^{-1}.

Organic C: Overall, the content of organic C in soil demonstrated a gradual decrease with increasing soil depth. In the shallow soil layer (0–40 cm), the soil organic C content in the WC1, WC2, and WC3 treatments was significantly higher than that in the CK treatment by 27.84–36.06%, 35.44–45.13%, and 73.05–56.23%, respectively, indicating that CMC can significantly increase the soil organic C content in the shallow soil layer. However, as soil depth increased, the differences among the treatments gradually diminished, and no significant difference in soil organic carbon content was observed among the treatments in the 60–100 cm soil layer.

3.5. Water Utilization of Crops

As shown in Table 5, the ΔS values ranged from 35.41 to 69.28 mm throughout the growing season, and both the drip irrigation pattern and CMC application significantly increased soil ΔS. Compared with CK treatment, W, WC1, WC2, and WC3 increased soil ΔS by 11.29–97.59%, 26.54–91.56%, 41.76–121.5%, and 52.97–152.2%, respectively, with WC3 showing the highest increase, followed by WC2 and WC1, and W the lowest. The drip irrigation and CMC application (W, WC1, WC2, and WC3) also significantly reduced groundwater percolation (L), surface evaporation (E), and maize transpiration (ET), which were 19.72–47.37% (L), 56.70–71.04% (E), and 16.05–28.42% (ET) lower than the CK. In the soil treated with CK, L and E accounted for 41.01% of irrigation water (I) and rainfall (P), significantly higher than W, WC1, WC2, and WC3 treatments, which were 31.65%, 24.03%, 23.91%, and 23.70%, respectively. Finally, W, WC1, WC2, and WC3 treatments significantly increased the water-use efficiency (WUE) of maize, but there was no significant difference between them.

Table 5. Maize water use efficiency.

Treatment	I [1] (mm)	P [2] (mm)	ΔS [3] (mm)	L [4] (mm)	E [5] (mm)	(L + E)/(I + P) (%)	ET [6] (mm)	WUE [7] (kg ha^{-1} mm^{-1})
CK	900.0	166.7	35.41 c	18.84 a	418.3 a	41.01 a	664.9 a	16.39 b
W	450.0	166.7	52.98 b	14.25 b	180.7 b	31.65 b	474.7 b	26.03 a
WC1	450.0	166.7	56.92 ab	13.35 b	134.7 c	24.03 c	525.6 b	23.76 a
WC2	450.0	166.7	62.65 ab	12.45 b	135.0 c	23.91 c	531.9 b	23.68 a
WC3	450.0	166.7	69.28 a	11.52 b	134.6 c	23.70 c	539.9 b	23.42 a

[1] I: irrigation amount, [2] P: precipitation during the maize growing season, [3] ΔS: soil water storage variation within the 0–100 cm soil layer, [4] L: underground leakage, [5] E: evaporation of surface water, [6] ET: maize evapotranspiration during the growth period, and [7] WUE: water-use efficiency. Different lowercase letters within the same row indicate significant distinctions among different treatments ($p < 0.05$).

3.6. Crop Growth

According to Table 6, drip irrigation and CMC application did not significantly affect the height and stem diameter of maize. However, there were significant differences in the aboveground biomass and grain yield of maize under different treatments. Compared with the CK treatment, the aboveground biomass and grain yield of maize plants increased by 4.85–16.16% and 5.44–16.43%, respectively, under the application of high amounts of CMC (WC2 and WC3). The general pattern observed was that the WC3 and WC2 exhibited similar effects, followed by the WC1 and W, with the CK displaying the lowest impact. However, no statistically significant variation in yield enhancement efficacy was detected among the treatments.

Table 6. Maize growth indicators.

Treatment	Plant Height (cm)	Stem Diameter (mm)	Aboveground Biomass ($kg \cdot ha^{-1}$)	Grain Yield ($kg \cdot ha^{-1}$)	Aboveground Biomass Increase (%)	Grain Yield Increase (%)
CK	297.7	20.22	47,284 b	10,868 b	-	-
W	298.4	20.38	49,157 ab	12,356 ab	4.00	13.98
WC1	311.1	20.75	49,324 ab	12,474 ab	4.35	15.07
WC2	302.3	20.58	49,564 a	12,592 a	4.85	16.16
WC3	323.8	21.12	49,839 a	12,633 a	5.44	16.43

Different lowercase letters in the same column indicate significant differences between different treatments at $p < 0.05$. No lowercase letters following the data indicate no significant differences between treatments.

Table 7 presents the evaluation of maize grain quality, revealing no noteworthy distinctions among the treatments except for crude protein content. Notably, the adoption of drip irrigation coupled with higher CMC application rates (WC2 and WC3) demonstrated a substantial augmentation in maize grain crude protein content. In comparison to CK, the WC2 and WC3 exhibited an increase in crude protein content ranging from 2.52% to 5.35% and 3.08% to 7.60%, respectively.

Table 7. Maize grain quality.

Treatment	Soluble Sugar (%)	Crude Protein (%)	Crude Fat (%)	Starch (%)
CK	2.71 a	8.41 c	3.24 a	63.96 a
W	2.92 a	8.49 bc	3.32 a	65.08 a
WC1	2.96 a	8.66 abc	3.35 a	64.62 a
WC2	2.88 a	8.76 ab	3.23 a	65.30 a
WC3	2.94 a	8.82 a	3.36 a	65.33 a

Different lowercase letters in the same column indicate significant differences between different treatments at $p < 0.05$.

4. Discussion

4.1. Soil Water and Salt Transport

In this study, the soil water content varied significantly with time under different irrigation methods and CMC application rates. Compared to traditional high-volume flood irrigation, the soil wetting area under drip irrigation treatments (W, WC1, WC2, and WC3) gradually expanded in both horizontal and vertical directions around the drip emitter with increasing maize growth stage (Figure 2), while the soil water content distribution was extremely uneven under flood irrigation treatments. The observed outcomes indicate that under drip irrigation conditions, the uniform and consistent infiltration of irrigation water enhances soil moisture levels in deeper layers while sustaining optimal moisture content in regions characterized by high evaporation rates. In contrast, flood irrigation, which involves the application of a large amount of irrigation water at once, often leads to the accumulation of irrigation water on the soil surface, which is prone to uneven leakage and poor water infiltration, resulting in uneven soil moisture distribution. Furthermore, flood irrigation causes significant evaporative losses of water, increases field evaporation, reduces water use efficiency (Table 5), and wastes precious water resources. Consequently, the stark contrast in soil moisture content between the two methods can be attributed to the extensive application of low-frequency irrigation water in flood irrigation versus the high-frequency, uniform irrigation water in drip irrigation. It is noteworthy that the introduction of CMC (WC1, WC2, and WC3) significantly elevates the soil moisture content in the 0–40 cm soil layer when compared to drip irrigation without CMC application (W). Moreover, the soil moisture content demonstrates an upward trend corresponding to increased rates of CMC application. The causes of this phenomenon can be attributed to the following three reasons. Firstly, CMC can increase the water-holding capacity of soil due to its high water-retention ability. The presence of CMC can form a gel-like structure that can hold onto water, reducing the amount of water that is lost through drainage or evaporation. This can help maintain soil moisture levels and improve water availability for plants [19].

Secondly, CMC can improve soil structure, which can affect the movement of water in the soil matrix [18]. CMC can act as a binder that can help aggregate soil particles, reduce soil compaction, and increase soil pore space. This can improve water infiltration into the soil and reduce the potential for water runoff and erosion. Thirdly, CMC exerts an influence on the hydraulic conductivity of the soil, which denotes the ease of water movement within the soil matrix. Through the formation of a gel-like structure, CMC engenders a reduction in hydraulic conductivity, impeding the flow of water. As a consequence, water retention in the soil is enhanced, leading to improved water availability for plant uptake [19]. Therefore, the formation of CMC gel can block soil pores and reduce the movement of water, which can further improve water retention and reduce the leaching of salts in the soil.

When soil moisture is increased, the movement of water carries away ions from the soil solution, which helps to increase the leaching of many salts from the soil solution, including sodium, magnesium, calcium, and potassium salts [27,28]. Of these, sodium ions are weakly adsorbed, are usually present in exchangeable positions in the soil, and are usually carried away more readily than other ions. Hence, akin to the temporal dynamics observed in soil moisture, the infiltration of water engenders a progressive migration of soil salinity towards deeper layers. This phenomenon leads to a transformation in the salinity distribution pattern, transitioning from surface accumulation to subsurface accumulation. Consequently, there is a significant reduction in surface soil salt content, as demonstrated in Figures 3 and 4. Previous studies [29–31] have shown that biochar as a soil amendment can suppress soil greenhouse gas emissions, promote soil C sinks, and remediate contaminated soils, while humic acid application to soil can reduce soil pH and salinity, neutralize free OH^- ions, and improve the soil microenvironment. In this study, the effects of CMC on the distribution of soil water and salt are different from those of other soil amendments. With the progression of the maize growth period, a conspicuous phenomenon emerges whereby the soil salt content within the plot treated with CMC progressively descends in conjunction with the infiltration of soil water. Consequently, a discernible desalination zone materializes, primarily centered around the drip emitter. Moreover, compared with the drip irrigation treatment without CMC, the drip irrigation treatment with CMC significantly reduced the salt content in the surface soil (Figure 3C). As is well known, under drip irrigation conditions in arid and semi-arid areas, soil salt content is affected by the combined effects of the downward movement of high-frequency drip irrigation water and the upward movement caused by strong surface evaporation [13]. The high-frequency drip flow gradually washes the soil salt downward, and during the interval between each drip irrigation, the upward movement of soil solution caused by surface evaporation dominates. At this time, the powerful water absorption potential of CMC inhibits the surface soil salt accumulation process caused by evaporation [32,33], thus reducing the salt content in the surface soil. From a chemical point of view, CMC is a negatively charged polymer due to the presence of carboxymethyl groups ($-COO^-$) on its main chain. When CMC is applied to soil, the negatively charged carboxymethyl group on its main chain can interact with positively charged cations in the soil solution such as sodium (Na^+), potassium (K^+), calcium (Ca^{2+}), and magnesium (Mg^{2+}) through electrostatic attraction, thus reducing their mobility and availability in the soil solution [21]. In this way, on the one hand, the leaching of cations can be reduced, which can reduce the uptake of toxic ions by plants and promote their growth [34]. This may also be the reason why there is little difference in the salt content of the subsurface layers. Overall, under the conditions of CMC application (WC1, WC2, and WC3), the desalination effect of the 0–30 cm soil layer is significant (Table 4), but there is no significant difference in soil salt content between the 30–100 cm soil layers (Figure 4 and Table 4), indicating that while the salt is fully leached downward, CMC also hinders the upward movement of salt caused by surface evaporation, resulting in a significant decrease in soil salinity in the root zone and the inhibition of the soil salinization process [18,35].

4.2. Soil Nutrients

Numerous studies have demonstrated that soil amendments can effectively increase soil nutrients and enhance land productivity [36–38]. In this study, CMC was found to significantly increase available nutrient content in the 0–40 cm soil layer, despite its lack of nutrients such as N and P, which are present in organic soil amendments such as humic acid, amino acids, and decomposed manure (Figure 5). This is partly because CMC helps to maintain soil moisture levels over a longer period of time, thus enhancing the solubility of insoluble nutrients in the soil and improving the biological effectiveness of soil nutrients [39]. By increasing the water holding capacity of the soil, CMC can help reduce nutrient leaching losses from irrigation water due to leaching and form complexes with some ions, thus increasing the supply of nutrients available for plant uptake [40]. On the other hand, CMC, as a polycarboxylate polymer, has a high anion exchange capacity (CEC). Its application within the soil context elicits an increase in soil CEC, thereby augmenting the adsorption and retention proficiency of nutrients in the soil and consequently amplifying the availability of effective nutrients. Moreover, CMC, serving as a carbon source, stimulates the proliferation and reproduction of soil microorganisms. These microorganisms play a pivotal role in the decomposition of soil organic matter and subsequent release of nutrients, thereby rendering them more readily absorbable by crops [41]. At the same time, microorganisms are able to produce some growth factors and enzymes that help increase the soil's nutrient supply potential. Notably, the application of CMC yielded a significant elevation in the availability of P within the topsoil layer (Figure 5), which might be due to the formation of complexes between CMC and water-soluble P fertilizer in irrigation water, thus reducing the adsorption and fixation of water-soluble P in irrigation water in the soil [42]. During the process when irrigation water containing CMC drips into the soil with the drip irrigation system, the excellent ion adsorption properties of CMC can form binders with negative ions such as P, and these binders can slowly release phosphate and increase the available P content in the soil, thus improving the effectiveness and availability of P. In addition, CMC plays a pivotal role in enhancing the stability of soil aggregates and mitigating their fragmentation, thus reducing the contact between P and soil particles and reducing P adsorption and immobilization [43]. Therefore, in this study, CMC adsorbed inorganic nutrients (NO_3^-, PO_4^{3-}, and K^+) from water-soluble fertilizers applied via drip irrigation with integrated water and fertilizer management, thereby increasing the content of available nutrients in the surface soil and improving fertilizer utilization efficiency. Furthermore, the increased soil moisture content also enhanced the solubility of insoluble nutrients in the soil, indirectly activating soil nutrients and increasing their bioavailability. Hence, CMC has great potential as an amendment for soil fertility and salt-affected soil reclamation.

4.3. Crop Responses

Optimizing water-use efficiency in arid regions is a strategic approach for enhancing productivity, as soil moisture is a critical determinant of plant growth [44]. Surface evaporation and transpiration are important factors affecting soil water loss and salt transport in agricultural fields [45]. Surface evaporation causes soil solution and transpiration to move upward, thereby promoting salt transport to the root zone, exacerbating salt stress, and affecting normal crop growth [46]. In this study, we found that drip irrigation and CMC application can reduce the surface evaporation of field water and increase soil water storage and maize transpiration, thereby improving maize water use efficiency (Table 5). These effects occur because flood irrigation causes irrigation water to spread extensively on the surface of agricultural soil, and the frequent lateral flow of irrigation water greatly increases surface evaporation. Under drip irrigation treatment, irrigation water was applied to the soil in small amounts and at high frequencies, and there was no surface water accumulation, which maintained soil structure and reduced underground seepage. Secondly, the notable water-absorbing capacity of CMC enhances the soil's water-holding capacity, effectively mitigating the occurrence of water redistribution induced by surface evaporation and thereby ensuring optimal water retention within the soil [18,19]. However, it is worth noting that there was no significant difference in ET and WUE between drip irrigation with CMC application and without CMC application. This may be because, although CMC can enhance the retention of soil moisture in the rhizosphere, it may also increase the difficulty of plant absorption and utilization, and the specific mechanism requires further study.

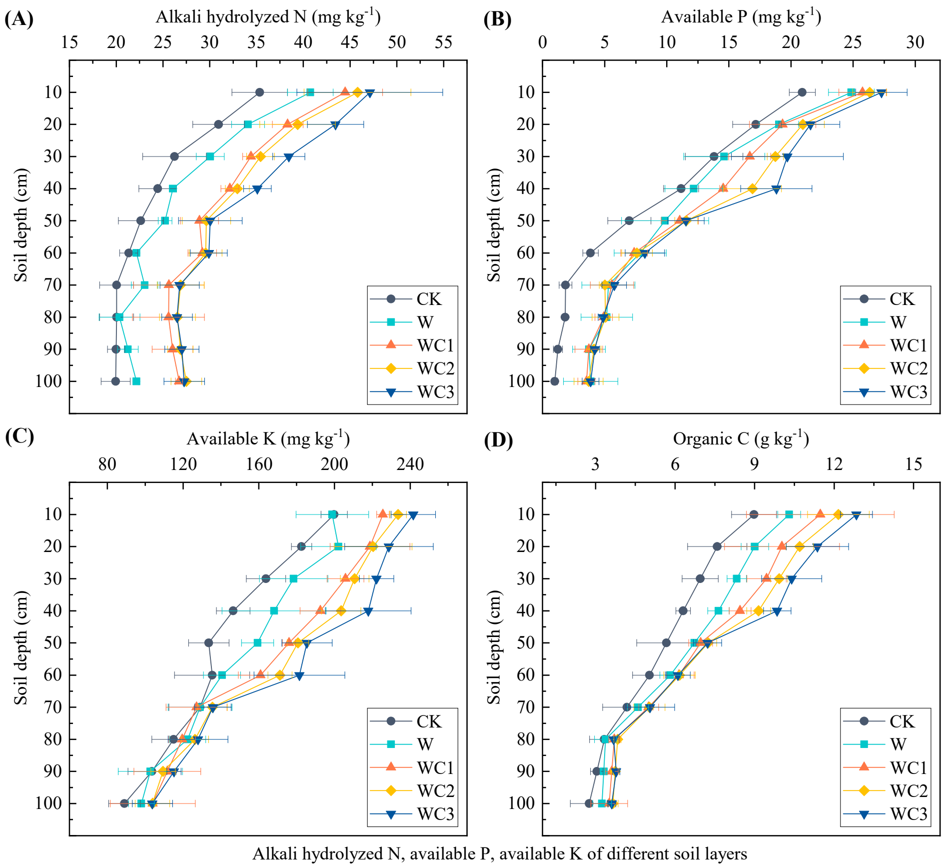

Figure 5. Spatial distribution of soil available nutrients. (**A**) Alkali hydrolyzed N content of each soil layer, (**B**) available P content of each soil layer, (**C**) available K content of each soil layer, (**D**) organic C content of each soil layer.

The variety of maize planted in our study was used for producing silage feed. Plant height and stem thickness are key growth characteristics of maize. Aboveground biomass is an important indicator of maize silage production [47]. Our findings indicate that while there were no significant differences in the height or stem diameter of maize plants among different treatments (Table 6), drip irrigation and the application of CMC helped to significantly increase the aboveground biomass and grain yield of maize, as well as elevate the crude protein content of the grain (Table 7). Furthermore, with increasing amounts of CMC applied, grain yield gradually increased. Based on the results of our studies on soil water and salt distribution and nutrient content, we hypothesize that CMC can promote corn growth and increase yield in several ways. First, CMC application significantly increased the available soil nutrient content (Figure 5), which is necessary to promote maize growth. Secondly, the exceptional water-retaining properties of CMC contribute to the amelioration of soil conditions, resulting in enhanced water stability within the soil matrix. This augmentation in water holding capacity (Figure 2) curtails water loss through evaporation from agricultural land, thereby facilitating optimal water absorption and utilization by plant root systems. Consequently, the water utilization efficiency of maize (Table 5) experiences improvements of noteworthy significance. Finally, CMC also has a certain chelating and ion exchange effect on the salts in the soil, and its combination with water and fertilizer-integrated drip irrigation has formed a desalination zone around the soil root system (Figure 3), improving the microenvironment of the maize root system and reducing the negative effects of salts on plants. In addition, the water-fertilizer integrated drip irrigation system made the irrigation frequency, fertilizer application amount, and irrigation water amount conform to the nutrient and water requirements of maize growth and development stages [13], providing sufficient nutrients and water for root uptake and promoting the accumulation of crude protein in the seeds, which is one of the important reasons for the increase in maize yield [48]. In summary, we conclude that CMC can be used as a new type of soil amendment for salt-affected soils, in combination with drip irrigation and other soil amendments, to supplement the water-locking ability of organic amendments. Of course, the effect of long-term CMC application on soil health requires continuous follow-up studies.

5. Conclusions

The use of drip irrigation and carboxymethyl cellulose significantly enhances surface soil water content, leading to the gradual infiltration of soil salts into the deep soil and forming a desalination zone centered on the drip irrigation head. This transformation in soil salt dynamics, transitioning from a surface aggregation pattern to a subterranean aggregation pattern, prominently curtails surface evaporation and augments water utilization efficiency. In addition, the application of carboxymethyl cellulose, owing to its robust adsorption capacity, resulted in a significant increase in the available nutrient content of the surface soil. Ultimately, this led to the creation of an inter-root microenvironment for maize with a high water content, low salt content, and high nutrient content, which significantly improved the maize underground biomass and yield. In summary, carboxymethylcellulose exhibits considerable promise as a novel soil amendment for salt-affected soils in conjunction with drip irrigation and other amendments. Future research should investigate the potential mechanisms underlying desalinization, yield increase, and quality improvement in salt-affected soils using different amendment combinations.

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References

1. Pitman, M.G.; Läuchli, A. Global impact of salinity and agricultural ecosystems. In *Salinity: Environment-Plants-Molecules*; Springer: Berlin/Heidelberg, Germany, 2002; pp. 3–20.
2. Zhou, Q.; Zhu, Z.; Shi, M.; Cheng, L. Growth and physicochemical changes of *Carpinus betulus* L. influenced by salinity treatments. *Forests* **2018**, *9*, 354. [CrossRef]
3. Mustafa, G.; Akhtar, M.S.; Abdullah, R. Global concern for salinity on various agro-ecosystems. In *Salt Stress, Microbes, and Plant Interactions: Causes and Solution*; Springer: Berlin/Heidelberg, Germany, 2019; pp. 1–19.

4. Kumar, P.; Sharma, P.K. Soil salinity and food security in India. *Front. Sustain. Food Syst.* **2020**, *4*, 533781. [CrossRef]
5. Luo, S.; Tian, L.; Chang, C.; Wang, S.; Zhang, J.; Zhou, X.; Li, X.; Tran, L.S.P.; Tian, C. Grass and maize vegetation systems restore saline-sodic soils in the Songnen Plain of northeast China. *Land Degrad. Dev.* **2018**, *29*, 1107–1119. [CrossRef]
6. Xiong, S.; Xiong, Z.; Wang, P. Soil salinity in the irrigated area of the Yellow River in Ningxia, China. *Arid Land Res. Manag.* **1996**, *10*, 95–101.
7. Munns, R.; Gilliham, M. Salinity tolerance of crops—What is the cost? *New Phytol.* **2015**, *208*, 668–673. [CrossRef] [PubMed]
8. Stavi, I.; Thevs, N.; Priori, S. Soil salinity and sodicity in drylands: A review of causes, effects, monitoring, and restoration measures. *Front. Environ. Sci.* **2021**, *9*, 712831. [CrossRef]
9. Guan, Z.; Jia, Z.; Zhao, Z.; You, Q. Dynamics and distribution of soil salinity under long-term mulched drip irrigation in an arid area of northwestern china. *Water* **2019**, *11*, 1225. [CrossRef]
10. Pimentel, D.; Berger, B.; Filiberto, D.; Newton, M.; Wolfe, B.; Karabinakis, E.; Clark, S.; Poon, E.; Abbett, E.; Nandagopal, S. Water resources: Agricultural and environmental issues. *BioScience* **2004**, *54*, 909–918. [CrossRef]
11. Rajak, D.; Manjunatha, M.; Rajkumar, G.; Hebbara, M.; Minhas, P. Comparative effects of drip and furrow irrigation on the yield and water productivity of cotton (*Gossypium hirsutum* L.) in a saline and waterlogged vertisol. *Agric. Water Manag.* **2006**, *83*, 30–36. [CrossRef]
12. Burt, C.M.; Isbell, B. Leaching of accumulated soil salinity under drip irrigation. *Trans. ASAE* **2005**, *48*, 2115–2121. [CrossRef]
13. Wang, Y.; Gao, M.; Chen, H.; Fu, X.; Wang, L.; Wang, R. Soil moisture and salinity dynamics of drip irrigation in saline-alkali soil of Yellow River basin. *Front. Environ. Sci.* **2023**, *11*, 345. [CrossRef]
14. Wang, X.; Wang, J.; Wang, J. Seasonality of soil respiration under gypsum and straw amendments in an arid saline-alkali soil. *J. Environ. Manag.* **2021**, *277*, 111494. [CrossRef] [PubMed]
15. D'Hose, T.; Debode, J.; De Tender, C.; Ruysschaert, G.; Vandecasteele, B. Has compost with biochar applied during the process added value over biochar or compost for increasing soil quality in an arable cropping system? *Appl. Soil Ecol.* **2020**, *156*, 103706. [CrossRef]
16. Tang, C.; Yang, J.; Xie, W.; Yao, R.; Wang, X. Effect of Biochar Application on Soil Fertility, Nitrogen Use Efficiency and Balance in Coastal Salt-Affected Soil under Barley–Maize Rotation. *Sustainability* **2023**, *15*, 2893. [CrossRef]
17. Rahman, M.S.; Hasan, M.S.; Nitai, A.S.; Nam, S.; Karmakar, A.K.; Ahsan, M.S.; Shiddiky, M.J.; Ahmed, M.B. Recent developments of carboxymethyl cellulose. *Polymers* **2021**, *13*, 1345. [CrossRef]
18. Zhang, J.; Wang, Q.; Shan, Y.; Guo, Y.; Mu, W.; Wei, K.; Sun, Y. Effect of Sodium Carboxymethyl Cellulose on Water and Salt Transport Characteristics of Saline–Alkali Soil in Xinjiang, China. *Polymers* **2022**, *14*, 2884. [CrossRef]
19. Olad, A.; Zebhi, H.; Salari, D.; Mirmohseni, A.; Tabar, A.R. Slow-release NPK fertilizer encapsulated by carboxymethyl cellulose-based nanocomposite with the function of water retention in soil. *Mater. Sci. Eng. C* **2018**, *90*, 333–340. [CrossRef]
20. Qiu, Z.; Zhang, R.; Qiu, H.; Gao, J. Effects of superabsorbents containing montmorillonite and polysaccharide on soil physical properties. *Soil Fertil. Sci. China* **2013**, *3*, 11–16.
21. Li, W.; Huang, S.; Xu, D.; Zhao, Y.; Zhang, Y.; Zhang, L. Molecular dynamics simulations of the characteristics of sodium carboxymethyl cellulose with different degrees of substitution in a salt solution. *Cellulose* **2017**, *24*, 3619–3633. [CrossRef]
22. Zhao, Q.; Tang, J.; Li, Z.; Yang, W.; Duan, Y. The influence of soil physico-chemical properties and enzyme activities on soil quality of saline-alkali agroecosystems in Western Jilin Province, China. *Sustainability* **2018**, *10*, 1529. [CrossRef]
23. Zhou, M.; Liu, X.; Meng, Q.; Zeng, X.; Zhang, J.; Li, D.; Wang, J.; Du, W.; Ma, X. Additional application of aluminum sulfate with different fertilizers ameliorates saline-sodic soil of Songnen Plain in Northeast China. *J. Soils Sediments* **2019**, *19*, 3521–3533. [CrossRef]
24. Robbins, C.W.; Wiegand, C.L. Field and laboratory measurements. In *Agricultural Salinity Assessment and Management*; Tanji, K.K., Ed.; ASCE: New York, NY, USA, 1990; pp. 201–219.
25. Pansu, M.; Gautheyrou, J. *Handbook of Soil Analysis*; Springer Science & Business Media: Berlin/Heidelberg, Germany, 2006.
26. Zhang, T.; Zhan, X.; He, J.; Feng, H. Moving salts in an impermeable saline-sodic soil with drip irrigation to permit wolfberry production. *Agric. Water Manag.* **2019**, *213*, 636–645. [CrossRef]
27. Qi, Z.; Feng, H.; Zhao, Y.; Zhang, T.; Yang, A.; Zhang, Z. Spatial distribution and simulation of soil moisture and salinity under mulched drip irrigation combined with tillage in an arid saline irrigation district, northwest China. *Agric. Water Manag.* **2018**, *201*, 219–231. [CrossRef]
28. Sun, G.; Zhu, Y.; Gao, Z.; Yang, J.; Qu, Z.; Mao, W. Spatiotemporal Patterns and Key Driving Factors of Soil Salinity in Dry and Wet Years in an Arid Agricultural Area with Shallow Groundwater Table. *Agriculture* **2022**, *12*, 1243. [CrossRef]
29. Motojima, H.; Yamada, P.; Irie, M.; Ozaki, M.; Shigemori, H.; Isoda, H. Amelioration effect of humic acid extracted from solubilized excess sludge on saline-alkali soil. *J. Mater. Cycles Waste Manag.* **2012**, *14*, 169–180. [CrossRef]
30. Mosa, A.; Mansour, M.M.; Soliman, E.; El-Ghamry, A.; El Alfy, M.; El Kenawy, A.M. Biochar as a Soil Amendment for Restraining Greenhouse Gases Emission and Improving Soil Carbon Sink: Current Situation and Ways Forward. *Sustainability* **2023**, *15*, 1206. [CrossRef]
31. Mosa, A.; Taha, A.A.; Elsaeid, M. In-situ and ex-situ remediation of potentially toxic elements by humic acid extracted from different feedstocks: Experimental observations on a contaminated soil subjected to long-term irrigation with sewage effluents. *Environ. Technol. Innov.* **2021**, *23*, 101599. [CrossRef]

32. Kim, B.; Kim, T.-H.; Lee, B. Optimal synthesis of carboxymethylcellulose-based composite superabsorbents. *Korean J. Chem. Eng.* **2021**, *38*, 215–225. [CrossRef]
33. Nie, H.; Liu, M.; Zhan, F.; Guo, M. Factors on the preparation of carboxymethylcellulose hydrogel and its degradation behavior in soil. *Carbohydr. Polym.* **2004**, *58*, 185–189. [CrossRef]
34. Davidson, D.W.; Verma, M.S.; Gu, F.X. Controlled root targeted delivery of fertilizer using an ionically crosslinked carboxymethyl cellulose hydrogel matrix. *SpringerPlus* **2013**, *2*, 1–9. [CrossRef]
35. Halidaimu, J.; Ning, S.; Wang, Q.; Zhang, J. Comparative analysis of the effects of PAM and CMC on soil infiltration and evaporation. *Soil Water Conserv.* **2020**, *34*, 121–127.
36. Singh, B.; Singh, B.P.; Cowie, A.L. Characterisation and evaluation of biochars for their application as a soil amendment. *Soil Res.* **2010**, *48*, 516–525. [CrossRef]
37. Lwin, C.S.; Seo, B.-H.; Kim, H.-U.; Owens, G.; Kim, K.-R. Application of soil amendments to contaminated soils for heavy metal immobilization and improved soil quality—A critical review. *Soil Sci. Plant Nutr.* **2018**, *64*, 156–167. [CrossRef]
38. Wu, H.; Lai, C.; Zeng, G.; Liang, J.; Chen, J.; Xu, J.; Dai, J.; Li, X.; Liu, J.; Chen, M. The interactions of composting and biochar and their implications for soil amendment and pollution remediation: A review. *Crit. Rev. Biotechnol.* **2017**, *37*, 754–764. [CrossRef] [PubMed]
39. Li, H.; Wang, Q.; Tao, W.; Chai, J.; Zhao, G. Effects of different amendments on the yield of surface runoff and loss of nutrients along loess slope soybean farmland. *Sci. Soil Water Conserv.* **2017**, *15*, 117–125.
40. Senna, A.M.; Botaro, V.R. Biodegradable hydrogel derived from cellulose acetate and EDTA as a reduction substrate of leaching NPK compound fertilizer and water retention in soil. *J. Control. Release* **2017**, *260*, 194–201. [CrossRef]
41. Dungait, J.A.; Hopkins, D.W.; Gregory, A.S.; Whitmore, A.P. Soil organic matter turnover is governed by accessibility not recalcitrance. *Glob. Chang. Biol.* **2012**, *18*, 1781–1796. [CrossRef]
42. Zhang, H.; Yang, H.; Shao, J.; Chen, Y.; Zhang, S.; Chen, H. Multifunctional carboxymethyl cellulose sodium encapsulated phosphorus-enriched biochar composites: Multistage adsorption of heavy metals and controllable release of soil fertilization. *Chem. Eng. J.* **2023**, *453*, 139809. [CrossRef]
43. Wu, J.; Tao, W.; Wang, H.; Wang, Q. Influence of sodium carboxyl methyl cellulose on soil aggregate structureand soil water movement. *Trans. Chin. Soc. Agric. Eng.* **2015**, *31*, 117–123.
44. Qu, W.; Tan, Y.; Li, Z.; Aarnoudse, E.; Tu, Q. Agricultural Water Use Efficiency—A Case Study of Inland-River Basins in Northwest China. *Sustainability* **2020**, *12*, 10192. [CrossRef]
45. Nachshon, U. Cropland soil salinization and associated hydrology: Trends, processes and examples. *Water* **2018**, *10*, 1030.
46. Li, Y.; Li, M.; Liu, H.; Qin, W. Influence of soil texture on the process of subsurface drainage in saturated-unsaturated zones. *Int. J. Agric. Biol. Eng.* **2021**, *14*, 82–89. [CrossRef]
47. Rüegg, W.; Richner, W.; Stamp, P.; Feil, B. Accumulation of dry matter and nitrogen by minimum-tillage silage maize planted into winter cover crop residues. *Eur. J. Agron.* **1998**, *8*, 59–69. [CrossRef]
48. Wang, D.; Mo, Y.; Li, G.; Wilkerson, C.J.; Hoogenboom, G. Improving maize production and decreasing nitrogen residue in soil using mulched drip fertigation. *Agric. Water Manag.* **2021**, *251*, 106871. [CrossRef]