Response of Corn Yield to Water Retaining Agents, Inhibitors, and Corn Stalks Addition in Semi-arid Cropland

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Drought, excessive use of nitrogen fertilizer, and decline in soil organic matter threaten corn production. This study investigated the potential of water retaining agents, inhibitors, and corn stalks in enhancing soil physicochemical properties to bolster corn yield in semi-arid farmlands. In our study, polyacrylamide addition increased the content of ammonium nitrogen (NH_4^+-N) and nitrate nitrogen (NO_3^--N) in the seedling stage, exchangeable potassium (K) in the mature stage but decreased the content of available phosphorus (P) in the seedling stage. Potassium polyacrylate addition increased the content of NH_4^+-N and decreased the content of available P in the seedling stage. The addition of inhibitors decreased the content of NH_4^+-N and available P in the seedling stage, NO_3^--N and available P in the jointing stage, and NH_4^+-N in the mature stage, respectively. Corn stalks returning could maintain soil moisture, decrease the content of NH_4^+-N in the seedling stage and exchangeable K in the mature stage, and increase the content of available P and exchangeable K in the seedling stage. Combined application of inhibitors and corn stalks could increase soil organic carbon (SOC) and ensure corn yield, which was the best fertilization mode in semi-arid cropland.

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INTRODUCTION

Corn is one of the most important food crops in the world, providing at least 30% of food calories for 4.5 billion people in 94 developing countries worldwide (Tefera *et al*. 2016). China accounts for 21% of the world's corn production (Xia *et al*. 2020). Liaoning Province is one of the 13 major grain-producing areas in China. The planting area of spring corn is more than 2 million hectares, of which the northwest area of Liaoning Province accounts for more than 2/3, and the output accounts for more than 75% of Liaoning Province. Therefore, corn production in the region is crucial for China's food security (Zhe *et al*. 2020). However, this area belongs to semi-arid cropland with a record of water shortage, and long-term cultivation has led to the decline of soil organic matter, which restricts the production of corn (Meng *et al*. 2023; Rix *et al*. 2023). Therefore, measures need to be taken to alleviate the constraints of these factors on corn production.

Water retaining agents are substances that can be added to soil to alleviate crop loss caused by drought. Among these are polyacrylamide (PAM) and potassium polyacrylate (K-PAA), which are commonly used (Wu *et al*. 2018; Zhao *et al*. 2023). Moreover, water retaining agents have the characteristics of promoting plant growth and root secretion, increasing soil enzyme activity, *etc*., which may improve the transformation of nutrients in the soil and promote corn production (Zhang *et al*. 2020a). In addition to water limitation, nitrogen (N) is also one of the most critical elements affecting crop yield. However, excessive fertilization in production practices can lead to a serious imbalance between the available nutrients provided by soil and the actual needs of crops (Cui *et al*. 2022). To deal with this problem, urea inhibitors and nitrification inhibitors are added to fertilizers to regulate the transformation process of fertilizer N in soil (Scherer *et al*. 2014; Li *et al*. 2023). Urease inhibitors can delay urea hydrolysis by inhibiting urease activity. Nitrification inhibitors reduce the formation and accumulation of nitrate by inhibiting the conversion of ammonium (NH_4^+) to nitrate (NO_3^-) (Liu *et al*. 2023). The combined application of urease inhibitors and nitrification inhibitors is considered to have better yield increasing effects (Qi *et al*. 2022). However, maintaining high crop yields in the long term also requires fertile soil. To alleviate soil degradation and improve soil fertility, measures of returning straw to the soil (*i.e.* "straw returning") have emerged (Zheng *et al*. 2021; Meng *et al*. 2023). Straw contains a large amount of lignocellulose, soluble carbon, and other nutrient elements, and it has good porosity (Thíebeau *et al*. 2021; Lu *et al*. 2023). These characteristics of straw are often used to improve soil physicochemical properties, promote soil moisture and fertilizer retention, and ensure crop yield (Velthof *et al*. 2002; Wu *et al*. 2021). However, further clarification is needed regarding whether adding water retaining agents, inhibitors, and straw can promote corn production in this semi-arid cropland.

The cinnamon soil of western Liaoning was taken as the test object to explore the effects of water retaining agents, inhibitors, and corn stalks addition on corn yield, which provided scientific basis for rational utilization of corn stalks resources, promotion of high yield of corn and improvement of soil fertility.

EXPERIMENTAL

Field Site and Experimental Design

The field experiment was conducted at the field experimental station of the Liaoning Key Laboratory of Water-Saving Agriculture in Fuxin County, northeast China. The annual average temperature is 7.2 °C, the annual average precipitation is about 480 mm, and the average sunshine time is about 2865 h. The rainfall situation in 2021 is shown in Fig. 1. The test soil was cinnamon soil with an organic matter content of 13.4 g kg^{-1}, a total N of 1.0 g/kg, a total phosphate (P) of 0.4 g/kg, a total potassium (K) of 22.8 g/kg, an available P of 53.6 mg kg^{-1}, and an exchangeable K of 86.7 mg kg^{-1}. Soil bulk density (0 to 20 cm) was 1.51 g cm^{-3}, and the pH (H_2O) was 5.5. The field was set up in spring 2021. The farming system is continuous corn with one season per year. The split zone experiment design with three replicates was adopted, and the main division was divided into 3 treatments, which were natural rainfall (R), adding water retaining agent PAM (white small particle cationic polymer produced by Yunze Chemical Co., Ltd. for water retention), and adding water retaining agent potassium polyacrylate (K-PAA) (white small particle polyacrylate water retaining agent produced by Hairuida Co., Ltd). The subdivision was divided into 5 treatments, namely no fertilization control (CK), conventional fertilization (U), conventional fertilization + corn stalks (US), conventional fertilization + inhibitors (UI), and conventional fertilization + inhibitors + corn stalks (UIS). The dosage of PAM and K-PAA was 30 kg hm^{-2}. The conventional fertilizer used for fertilization were urea, superphosphate, and potassium chloride (KCl), and the application levels were N 156 kg ha^{-1}, P 26 kg ha^{-1}, and K 60 kg ha^{-1}, respectively. The inhibitors were NBPT (N-(n-butyl)thiophosphoric triamide) and DMPP (3,4-dimethylpyrazole phosphate), applied at a dosage of 1% and 2% of urea N, respectively. Corn stalks were crushed (5 to 10 cm) and returned to the field (9.0 tons ha^{-1}). All fertilizers were applied once during planting on May 10, 2021. The area of each plot was 40 m^2 (5 m × 8 m). The planting density of the corn was 55,000 plants ha^{-1}. The corn variety was "H188" spring maize (*Zea mays* L., a late maturing maize variety based on Food and Agriculture Organization of the United Nations (FAO) standards, with a 127 day growing period). Fertilizer was spread and rotary plowed to a depth of 15 to 20 cm before sowing. Plant protection and irrigation were not used. Weeds were pulled manually, and the corn was harvested manually.

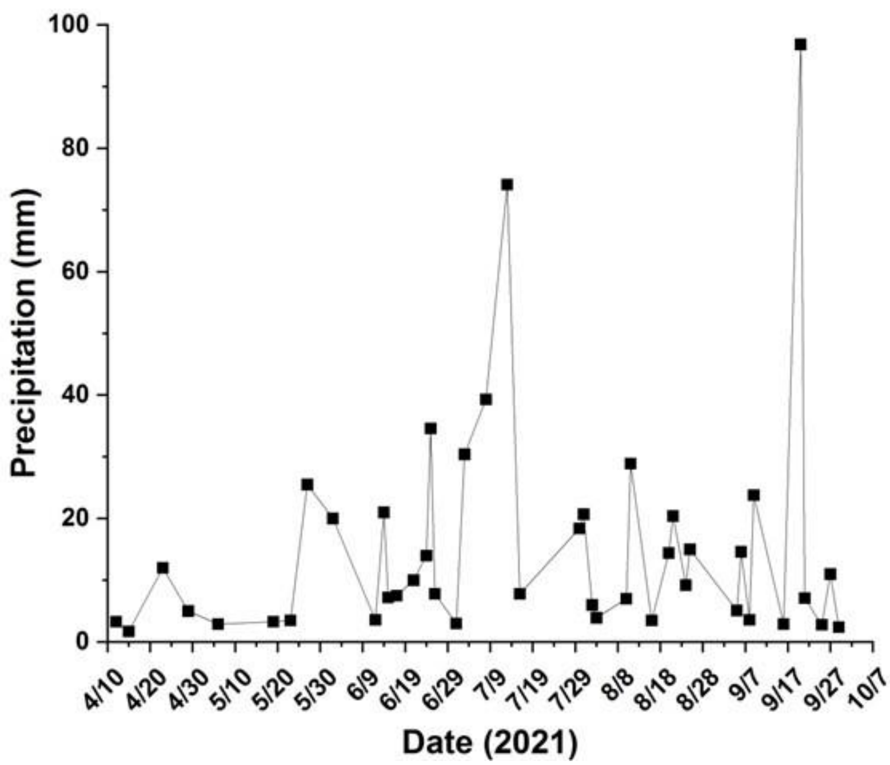

Fig. 1. Rainfall during the 2021 corn growing season

Sample Collection and Analysis

Three soil cores were randomly selected from each treatment plow layer (0 to 20 cm) during the corn seedling stage (June 16^{th}), jointing stage (July 16^{th}), filling stage (August 18^{th}) and mature stage (September 24^{th}). The soil samples were composited, sieved (2 mm), and stored at 4 °C until used for analysis. Soil moisture content was determined using the aluminum box drying method (105 °C). Soil moisture content is the percentage of water in the soil as a percentage of the weight of fresh soil. Soil ammonium nitrogen (NH_4^+-N) and nitrate nitrogen (NO_3^--N) were extracted with 2 M KCl solution (Meng *et al*. 2023), filtered, and analyzed with a continuous flow analyzer (AA3, Bran + Luebbe, Norderstedt, Germany). Available P was extracted using 0.5 mol/L $NaHCO_3$, and available K was extracted using neutral 1 mol/L ammonium acetate (NH_4Oac) (Zhao *et al*. 2004). Soil organic carbon (SOC) and total N contents were determined by dry combustion of the samples using an Elemental Analyzer (Vario EL III, Hanau, Germany) (Yang *et al*. 2017). The corn yield was measured after air drying.

Statistical Analysis

All analyses were performed using Statistical Package for the Social Sciences (SPSS) Statistics 16.0 (SPSS Inc., Chicago, IL, USA). One-way analysis of variance (ANOVA) was used for testing the treatment effects with Duncan analysis. Significance was $P < 0.05$. Pearson correlation analysis was used for the correlation between corn yield and soil physicochemical properties. The response of corn yield to the application of water retaining agents, inhibitors, and corn stalks was analyzed using univariate analysis of variance. Tables and figures were prepared with Excel 2016 (Microsoft Corp., USA) and Origin 8 (Origin Lab Corp., USA), respectively. The data in the figures and tables are the average value ± standard error.

RESULTS AND DISCUSSION

Soil Moisture Content

The variation range of soil moisture content in different corn growth periods was 13% to 18% (Table 1). The mature stage had the highest soil moisture content (17% to 18%), followed by jointing stage (16% to 18%), filling stage (15% to 16%), and seedling stage (13% to 17%). The treatments with the highest soil moisture content during the corn seedling stage were AUIS (17%), BUIS (17%), AUS (16%), RUS (16%), BUS (16%), and RUIS (16%), while the lowest treatment was RU (13%). There was no significant difference in soil moisture content among all treatments in other periods. Corn stalks returning was able to significantly reduce soil moisture loss in corn seedling stage (Table S1).

Soil Ammonium Nitrogen

The content of NH_4^+-N in soil was the highest at the corn seedling stage, and then it decreased rapidly. The content of NH_4^+-N remained stable at the corn filling stage and maturity stage (Table 2). The addition of water retaining agents, inhibitors and corn stalks significantly affected the soil NH_4^+-N content in corn seedling stage, among which the application of PAM increased the soil NH_4^+-N content, and the addition of inhibitors and corn stalks decreased the soil NH_4^+-N content (Table S2). The addition of water retaining agents and inhibitors also significantly affected the soil NH_4^+-N content at corn mature stage, in which the application of K-PAA increased the soil NH_4^+-N content, and the addition of inhibitors decreased the soil NH_4^+-N content (Table S2).

Table 1. Soil Moisture Content in Topsoil at Different Growth Stages of Corn

Treatments		Seeding stage	Jointing stage	Filling stage	Mature stage
R	CK	14% ± 0%bcC	17% ± 0%aA	16% ± 1%aB	18% ± 0%aA
	U	13% ± 0%cD	16% ± 0%aB	15% ± 0%aC	17% ± 0%aA
	US	16% ± 0%abBC	17% ± 0%aAB	15% ± 1%aC	18% ± 0%aA
	UI	14% ± 1%bcC	17% ± 0%aAB	15% ± 0%aBC	18% ± 0%aA
	UIS	16% ± 1%abcAB	17% ± 0%aA	15% ± 1%aB	18 ± 0%aA
PAM	CK	14% ± 1%bcC	17% ± 0%aA	16% ± 0%aB	18% ± 0%aA
	U	14% ± 1%bcB	17% ± 0%aA	15% ± 1%aAB	17% ± 1%aA
	US	16% ± 1%abA	17% ± 1%aA	15% ± 0%aA	17% ± 0%aA
	UI	14% ± 1%bcB	18% ± 1%aA	16% ± 1%aAB	18% ± 0%aA
	UIS	17% ± 1%aA	18% ± 1%aA	16% ± 1%aA	17% ± 1%aA
K-PAA	CK	14% ± 0%bcC	17% ± 1%aA	16% ± 0%aB	17% ± 0%aA
	U	14% ± 1%bcC	17% ± 0%aBC	15% ± 0%aAB	18% ± 1%aA
	US	16% ± 1%abcA	17% ± 1%aA	15% ± 1%aA	17% ± 0%aA
	UI	14% ± 1%bcB	17% ± 1%aA	16% ± 0%aAB	17% ± 1%aA
	UIS	17% ± 0%abB	17% ± 0%aA	16% ± 0%aC	18% ± 0%aA
R: Natural rainfall, PAM: Polyacrylamide addition, K-PAA: Potassium polyacrylate addition, CK: control check with no fertilization, U: urea application, US: urea application + corn stalks returning, UI: urea application + inhibitors, UIS: urea application + inhibitors + corn stalks returning					
The lowercase letters in columns indicate significant differences between different treatments during the same period, while the uppercase letters indicate significant differences between different periods of the same treatment at *P* < 0.05 according to the Duncan's test (n = 3), the same below					

Table 2. NH_4^+-N (mg kg^{-1}) in Topsoil at Different Growth Stages of Corn

Treatments		Seeding stage	Jointing stage	Filling stage	Mature stage
R	CK	17.57 ± 0.13bcA	4.7 ± 0.25cB	2.67 ± 0.36aC	2.01 ± 0.19cC
	U	17.51 ± 0.6bcA	5.9 ± 0.2abcB	2.44 ± 0.06aC	2.85 ± 0.87bcC
	US	17.25 ± 0.83bcA	5.29 ± 0.4abcB	3.04 ± 0.63aC	3.76 ± 0.43abBC
	UI	17.08 ± 0.84bcA	6.04 ± 0.63abcB	2.97 ± 0.53aC	2.99 ± 0.15bcC
	UIS	15.54 ± 0.33bcA	5.32 ± 0.43abcB	2.82 ± 0.41aC	2.04 ± 0.15cC
PAM	CK	15.61 ± 0.49bcA	7.4 ± 0.83aB	2.67 ± 0.22aC	2.16 ± 0.4cC
	U	52.39 ± 1.49aA	4.72 ± 0cB	2.31 ± 0.32aB	3.83 ± 0.82abB
	US	12.94 ± 1.04bcA	5.96 ± 0.54abcB	2.69 ± 0.17aC	2.47 ± 0.34bcC
	UI	19.84 ± 4.59bA	5.13 ± 0.29bcB	2.66 ± 0.14aB	3.12 ± 0.14bcB
	UIS	17.04 ± 2.06bcA	5.96 ± 0.56abcB	3.16 ± 0.54aB	2.22 ± 0.09cB
K-PAA	CK	11.22 ± 3.01cA	5.56 ± 0.68abcB	2.68 ± 0.27aB	3.04 ± 0.56bcB
	U	14.84 ± 3.61bcA	5.2 ± 0.5bcB	2.91 ± 0.46aB	3.33 ± 0.6abcB
	US	18.6 ± 4.3bcA	6.53 ± 0.27abcB	3.01 ± 0.05aB	4.75 ± 0.22aB
	UI	12.96 ± 0.51bcA	6.39 ± 0.98abcB	2.54 ± 0.23aC	3.3 ± 0.5abcC
	UIS	12.22 ± 0.45cA	7.27 ± 1.46abB	2.48 ± 0.24aC	3.47 ± 0.11abcC

Soil Nitrate Nitrogen

The content of NO_3^--N in soil was the highest at corn seedling stage, and then it decreased rapidly. The content of NO_3^--N remained stable at corn mature stage (Table 3). The addition of water retaining agents significantly affected soil NO_3^--N content at the seedling stage and jointing stage, and the addition of PAM significantly increased soil NO_3^-

-N content. The application of inhibitors significantly reduced the soil NO_3^--N content in the corn jointing stage (Table S3).

Table 3. NO_3^--N (mg kg^{-1}) in Topsoil at Different Growth Stages of Corn.

Treatments		Seeding stage	Jointing stage	Filling stage	Mature stage
R	CK	18.6 ± 3.02cdA	4.2 ± 1.18eB	3.77 ± 0.01cdB	2.24 ± 0.49abB
	U	16.51 ± 3.05cdA	8.51 ± 0.8bcB	5.19 ± 0.62abcB	2.68 ± 0.48abC
	US	17.12 ± 1.66cdA	5.35 ± 0.42eB	4.98 ± 0.61abcdB	2.57 ± 0.38abB
	UI	14.7 ± 3.24cdA	8.44 ± 0.62bcB	6.14 ± 0.71aBC	2.35 ± 0.14abC
	UIS	18.44 ± 0.02cdA	4.26 ± 0.6eB	3.67 ± 0.16cdB	1.73 ± 0.21bC
PAM	CK	9.17 ± 2.73dA	4.88 ± 0.7eAB	3.82 ± 0.2cdB	1.63 ± 0.22bB
	U	39.66 ± 3.91bA	6.37 ± 0.78cdeB	3.43±0.38dB	2.4 ± 0.19abB
	US	13.53 ± 3.03cdA	10.75 ± 0.24aA	4.86 ± 0.65abcdB	2.04 ± 0.32abB
	UI	19.45 ± 2.66cA	5.88 ± 0.38deB	5.18 ± 0.29abcB	2.22 ± 0.57abB
	UIS	48.33 ± 0.79aA	8.19 ± 1.23bcdB	5.79 ± 0.63abB	2.66 ± 0.28abC
K-PAA	CK	13.34 ± 3.85cdA	5.51 ± 0.22eB	3.71 ± 0.56cdB	1.85 ± 0.01bB
	U	14.81 ± 2.74cdA	5.99 ± 0.57deB	4.17 ± 0.51bcdB	2.14 ± 0.12abB
	US	18.64 ± 5.78cdA	9.73 ± 1.15abAB	4.49 ± 0.66abcdB	3.06 ± 0.59aB
	UI	11.73 ± 2.22cdA	7.88 ± 0.64bcdB	5.15 ± 0.2abcBC	2.5 ± 0.33abC
	UIS	12.01 ± 0.48cdA	1.95 ± 0.02fB	4.81 ± 0.46abcdC	2.1 ± 0.01abC

Table 4. Available P (mg kg^{-1}) in Topsoil at Different Growth Stages of Corn

Treatments		Seeding stage	Jointing stage	Filling stage	Mature stage
R	CK	38.05 ± 3.68ghA	48.52 ± 8.32cdA	29.3 ± 1.28fA	41.84 ± 6.23defA
	U	73.36 ± 0.55aA	39.15 ± 2.24defC	58.43 ± 3.97aB	45.31 ± 4.82bcdeC
	US	67.27 ± 9.8abA	67.99 ± 0.51aA	30.87 ± 1.66fB	40.27 ± 4.62efB
	UI	53.45 ± 0.11cdeAB	47.69 ± 1.37cdeAB	44.15 ± 5.03deB	61.62 ± 7.14aA
	UIS	39.25 ± 0.2fghB	39 ± 1.88defB	48.11 ± 3.39bcdA	45.41 ± 1.03bcdeAB
PAM	CK	25.35 ± 1.64iC	36.85 ± 3.98efB	57.91 ± 0.54aA	29.22 ± 2.08fBC
	U	48.97 ± 4.8defgB	63.72 ± 1.56aA	46.34 ± 2.6cdeB	56.08 ± 4.66abcdAB
	US	65.56 ± 2.05abcA	52.63 ± 4.15bcBC	56.72 ± 0.59abB	46.62 ± 2.61bcdeC
	UI	44 ± 6.81efghA	42.44 ± 1.03cdefA	37.35 ± 3.03efA	39.38 ± 4.5efA
	UIS	50.05 ± 5.16defgAB	37.11 ± 2.68efB	45.44 ± 5.84cdeB	61.97 ± 3.54aA
K-PAA	CK	42.6 ± 4efghB	36.65 ± 1.79fB	41.36 ± 1.64deB	58.91 ± 3.69abA
	U	32.36 ± 0.24hiB	60 ± 1.95abA	58.39 ± 1.52aA	54.06 ± 5.56abcdeA
	US	52.04 ± 2.49defA	49.42 ± 0.91cdA	32.21 ± 1.28fB	43.13 ± 5.55cdefA
	UI	40.25 ± 0.96efghAB	43.19 ± 0.7cdefA	31.65 ± 2.39fB	38.85 ± 5.74efAB
	UIS	58.2 ± 2.75bcdA	32.75 ± 5.57fB	54.37 ± 1.74abcA	57.36 ± 2.3abcA

Soil Available Phosphorus

The content of available P in soil changed little in different growing periods of corn (Table 4). The addition of water retaining agents, inhibitors, and corn stalks significantly affected the soil available P content in corn seedling stage, in which the application of corn stalks increased the soil available P content, and the addition of PAM, K-PAA, and inhibitors decreased the soil available P content. Only the addition of inhibitors reduced soil available P content in corn jointing stage (Table S4).

Soil Exchangeable Potassium

Soil exchangeable K content changed little during the growing period of corn (Table 5). Corn stalks addition significantly increased the exchangeable K content in corn seedling stage but decreased the exchangeable K content in corn mature stage. The addition of PAM significantly promoted the exchangeable K content in soil at corn mature stage (Table S5).

Table 5. Exchangeable K (mg kg^{-1}) in Topsoil at Different Growth Stages of Corn

Treatments		Seeding stage	Jointing stage	Filling stage	Mature stage
R	CK	85.84 ± 12.2deA	86.06 ± 2.4abA	67.84 ± 4.49aA	79.77 ± 5.02bcA
	U	102.9 ± 12.63bcdA	87.91 ± 5.69abAB	67.58 ± 2.48aB	72.4 ± 2.58bcB
	US	101.65 ± 5.59bcdA	68.57 ± 3.26bB	67.54 ± 6.27aB	72.88 ± 3.06bcB
	UI	79.45 ± 4.74deA	71.89 ± 5bAB	64.01 ± 0.75aB	79.38 ± 2.96bcA
	UIS	104.66 ± 13.68bcdA	84.81 ± 14.11abAB	63.66 ± 5.28aB	76.84 ± 2.31bcAB
PAM	CK	67.62 ± 1.35eB	67.11 ± 1bB	64.14 ± 1.42aB	87.69 ± 7.72bA
	U	117.23 ± 6.86bcA	102.44 ± 17.34aAB	76.88 ± 9.34aB	111.68 ± 3.06aAB
	US	86.03 ± 6deA	71.69 ± 2.12bAB	63.56 ± 0.86aB	85.54 ± 11.22bA
	UI	90.23 ± 13.91cdeA	70.86 ± 8.7bA	70.98 ± 5.74aA	74.47 ± 4.01bcA
	UIS	126.41 ± 13.65abA	82.61 ± 6.34abB	71.59 ± 3.7aB	78.77 ± 5.15bcB
K-PAA	CK	79.04 ± 4.95deA	73.09 ± 10.6abA	64.65 ± 4.22aA	73.7 ± 4.14bcA
	U	80.03 ± 0.2deA	75.68 ± 11.19abA	75.76 ± 3.51aA	76.11 ± 3.97bcA
	US	148.05 ± 5.63aA	70.64 ± 14.07bB	67.75 ± 4.4aB	68.96 ± 2.18cB
	UI	86.14 ± 6.35deA	77.31 ± 5.77abA	69.69 ± 4.25aA	76.97 ± 2.43bcA
	UIS	86.7 ± 6.1deA	75.85 ± 6.12abA	72.79 ± 0.3aA	73.56 ± 2.69bcA

Soil Organic Carbon and Total Nitrogen

As shown in Fig. 2A, the SOC content was about 8.5 g kg^{-1}, and there was no significant difference in all treatments except that AU treatment was significantly higher than RUIS and AUI treatments. The total N content of soil was about 0.9 g kg^{-1}, and there was no significant difference among all treatments (Fig. 2B). The addition of water retaining agents, inhibitors, and corn stalks had no significant effect on SOC and total N (Table S6).

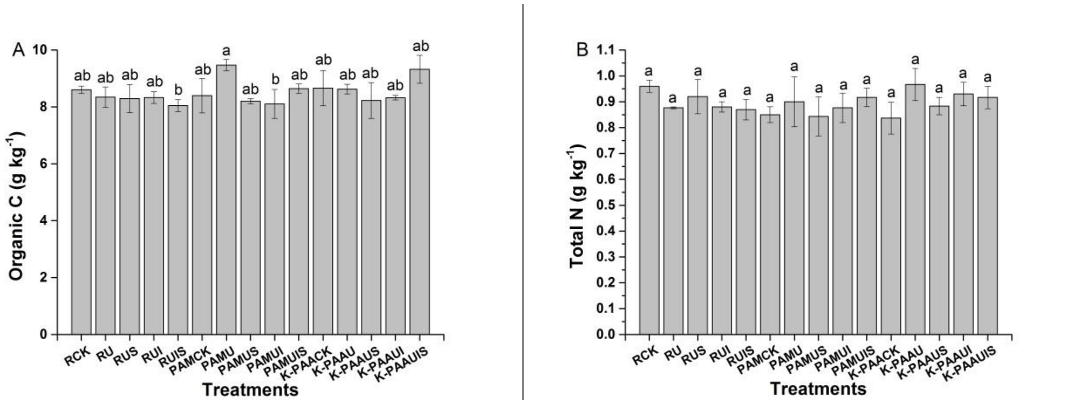

Fig. 2. Effects of water retaining agents and inhibitors application and corn stalks returning on SOC (A) and total N (B). R: natural rainfall, PAM: polyacrylamide addition, K-PAA: potassium polyacrylate addition, CK: control check with no fertilization, U: urea application, US: urea application + corn stalks returning, UI: urea application + inhibitors, UIS: urea application + inhibitors + corn stalks returning. Different letters indicate significant difference at $P < 0.05$. The same considerations apply to subsequent figures

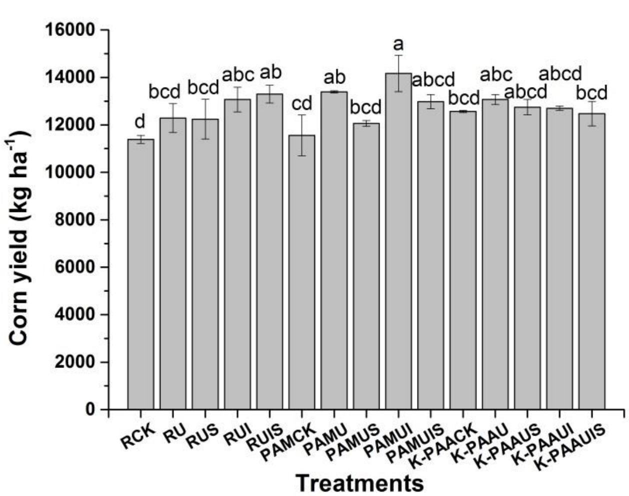

Fig. 3. Effects of water retaining agents and inhibitors application and corn stalks returning on corn yield

Corn Yield

The corn yield ranged from 11,400 to 14,200 kg hm^{-2}. The PAMUI treatment had the highest corn yield, significantly higher than K-PAACK, K-PAAUIS, RU, RUS, PAMUS, PAMCK and RCK treatments, but not significantly different from PAMU, RUIS, K-PAAU, RUI, PAMUIS, K-PAAUS and K-PAAUI treatments. The RCK treatment had the lowest corn yield, but was not significantly different from treatment PAMUIS, K-PAAUS, K-PAAUI, K-PAACK, K-PAAUIS, RU, RUS, PAMUS and PAMCK treatments (Fig. 3). Water retaining agents addition had no significant effect on corn yield, while inhibitors addition increased corn yield and corn stalks returning decreased corn yield (Table S6, $P < 0.1$).

Pearson Correlation Analysis of Corn Yield and Soil Physicochemical Properties

Through Pearson correlation analysis, it was found that there was no significant correlation between corn yield and other soil physicochemical properties except soil moisture content at filling stage (Table 6). There was a significant negative correlation between corn yield and soil moisture content at filling stage.

Table 6. Pearson Correlation Analysis of Corn Yield with Soil Moisture Content, NH_4^+-N, NO_3^--N, Available P, and Exchangeable K

		Soil moisture content	NH_4^+-N	NO_3^--N	Available P	Exchangeable K
Corn yield	Seeding stage	-0.163	0.276	0.152	-0.064	0.154
	Jointing stage	-0.234	-0.049	0.050	-0.017	-0.054
	Filling stage	-0.391**	-0.133	0.171	-0.042	-0.047
	Mature stage	-0.087	0.256	0.067	0.176	0.075

The values in the table are Pearson correlation coefficients (n = 3), **The correlation is significant at $P < 0.01$

Effects of Water Retaining Agents, Inhibitors and Corn Stalks Addition on Soil Physicochemical Properties and Corn Yield

The corn yield is known to be influenced by the soil physicochemical properties and climate. Fertile soil and suitable climate are conducive to high yield of corn (Zhang *et al*. 2020b; Zhao *et al*. 2023). The addition of water retaining agents, inhibitors, and corn stalks can affect soil physicochemical properties. Polyacrylamide addition increased the content of NH_4^+-N (38.7%, Table 2 and Table S2) and NO_3^--N (52.4%, Table 3 and Table S3) in seedling stage, and the content of exchangeable K (14.9%, Table 5 and Table S5) in mature stage, but decreased the content of available P (13.8%, Table 4 and Table S4) in seedling stage. Potassium polyacrylate addition increased the content of NH_4^+-N (31.1%, Table 2 and Table S2) in mature stage and decreased the content of available P (16.9%, Table 4 and Table S4) in seedling stage (Table S2, S4). This may be due to the fact that PAM contains ammonium ion, which directly increases soil inorganic N, and polyacrylates water retaining agents have the characteristics of slow release of water, which stimulates the growth of soil microorganisms and urease activity (Zhang *et al*. 2020a). In addition, the water retaining agents generally contain micropores. These can allow some small molecules or ions to diffuse into the water retaining agents' molecules and be wrapped by the agents in their water-swollen condition. Alternatively, the nutrients can be temporarily fixed by cation exchange and adsorption within the agents (Li *et al*. 2014), resulting in the reduction of available P. The effect of PAM on exchangeable K and K-PAA on NH_4^+-N may be caused by the competition between NH_4^+-N and potassium ions on the 2:1 clay mineral interlayers (Scherer *et al*. 2014). Addition of inhibitors decreased the contents of NH_4^+-N (29.1%, Table 2 and Table S2) and available P (16.0%, Table 4 and Table S4) in the corn seedling stage, NO_3^--N (21.63%, Table 3 and Table S3) and available P (27.2%, Table 4 and Table S4) in the jointing stage, and NH_4^+-N (18.3%, Table 2 and Table S2) in the mature stage. The effect of inhibitors on inorganic N content may be mainly through the inhibition of urease activity by NBPT to delay the conversion of urea to NH_4^+-N. In addition, DMPP inhibits the conversion of NH_4^+-N to NO_3^--N and reduces the production and accumulation of nitrate (Rose *et al*. 2018; Cui *et al*. 2022). The effect of inhibitors on the content of available P may be due to inhibitors' application increasing the effective duration of inorganic N in soil and promoting the assimilation ability of crops to N and P (Cui *et al*. 2022). Corn stalks returning could increase soil moisture (18.1%, Table 1 and Table S1), reduce the content of NH_4^+-N (30.5%, Table 2 and Table S2) at seedling stage and exchangeable K (7.02%, Table 5 and Table S5) at the mature stage, and increase the content of available P (13.67%, Table 4 and Table S4) and exchangeable K (17.54%, Table 5 and Table S5) at the seedling stage. The effect of corn stalks addition on soil moisture may be due to: 1) reducing the evaporation loss of soil water; 2) increased soil porosity and improved soil water holding capacity; and 3) the corn stalks contains more pores that can absorb water (Zhang *et al*. 2020b; Thíebeau *et al*. 2021). Corn stalks have a high C to N ratio (54.6:1), which can accelerate microbial growth and improve N absorption, possibly leading to a decrease in NH_4^+-N (Chen *et al*. 2014). In addition, corn stalks also contain a large amount of nutrients, which may be the reason for the increase in available P and exchangeable K content in the soil (Liu *et al*. 2011).

Soil organic matter content is an important index to measure soil fertility (Bai *et al*. 2016). The study found that the addition of water retaining agents, inhibitors, and corn stalks had no significant effect on SOC and total N, but the combination of inhibitors and corn stalks significantly promoted the increase of SOC (Table S6). This may be due to the application of inhibitors increasing the effective duration of inorganic N in the soil (Cui *et al*. 2022), alleviating N scarcity caused by high C input (corn stalks addition) and promoting the fixation effect of microorganisms on corn stalks charcoal (Chen *et al*. 2014; Cheng *et al.* 2017). The addition of water retaining agents had no significant effect on corn yield (Table S6), which was consistent with Holt *et al*. (2023). This is likely due to a 36% increase in rainfall during the growing season (Fig.1, 655 mm), reducing water stress on corn growth. Inhibitors addition increased corn yield (Table S6, $P < 0.1$). Previous studies have also found that inhibitors application can have a good yield increase effect, especially the combination of urease inhibitor and nitrification inhibitor, through the regulation of fertilizer N conversion to achieve yield increase (Shi *et al*. 2015; Wu *et al*. 2019; Qi *et al*. 2022). The addition of corn stalk is considered to be conducive to the increase of corn yield (Qin *et al*. 2021; Wang *et al*. 2021), but the corn yield did not increase in the study (Table S6), which may be due to the fact that it may take a long time for corn stalk addition to show a positive effect on corn yield (Chang *et al*. 2020; Yang *et al*. 2020; Islam *et al*. 2022). Therefore, according to research results, the combination of inhibitors and corn stalks application can increase soil fertility and has the potential to increase corn yield, which is the best fertilization mode in this area. Whether water retaining agents are conducive to increasing corn yield needs to be verified in drought years.

CONCLUSIONS

1. Addition of the water retaining agent polyacrylamide (PAM) increased the content of NH_4^+-N and NO_3^--N in seedling stage, and the content of exchangeable K in mature stage, but it decreased the content of available P in the seedling stage. Addition of the potassium salt of polyacrylate (K-PAA) as a water retaining agent increased the content of NH_4^+-N and decreased the content of available P in the corn seedling stage. Inhibitors addition decreased the contents of NH_4^+-N and available P in the seedling stage, NO_3^--N and available P in the jointing stage and NH_4^+-N in the mature stage. Returning corn

stalks to the soil could maintain soil moisture, reduce the content of NH_4^+-N at the seedling stage and exchangeable K at the mature stage, and increase the content of available P and exchangeable K at the seedling stage.

2. The addition of water retaining agents (PAM and K-PAA) had no significant effect on corn yield. Combined application of inhibitors and corn stalks can increase SOC and ensure corn yield, which is the best fertilization mode in semi-arid cropland.

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APPENDIX

Table S1. Soil Moisture Content in Response to Water Retaining Agents, Inhibitors, and Corn Stalks Returning

Factors	Seeding stage	Jointing stage	Filling stage	Mature stage
Water retaining agent (W)	0.605	0.310	0.688	0.863
Inhibitors (I)	0.383	0.053	0.153	0.718
Corn stalks (S)	0.000***	0.423	0.921	0.742
W×I	0.931	0.714	0.797	0.801
W×S	0.809	0.836	0.864	0.457
I×S	0.749	0.902	0.917	0.856
W×I×S	0.738	0.931	0.987	0.198
The values in the table are *P* values (n = 3). *The correlation is significant at *P*<0.05, **The correlation is significant at *P*<0.01, ***The correlation is significant at *P*<0.001, the same below.				

Table S2. NH_4^+-N in Response to Water Retaining Agents, Inhibitors, and Corn Stalks Returning

Factors	Seeding stage	Jointing stage	Filling stage	Mature stage
Water retaining agent (W)	0.000***	0.129	0.901	0.028*
Inhibitors (I)	0.000***	0.267	0.863	0.022*
Corn stalks (S)	0.000***	0.194	0.294	0.642
W×I	0.001**	0.576	0.256	0.890
W×S	0.000***	0.107	0.725	0.021*
I×S	0.001**	0.662	0.549	0.105
W×I×S	0.000***	0.980	0.693	0.194

Table S3. NO_3^--N in Response to Water Retaining Agents, Inhibitors, and Corn Stalks Returning

Factors	Seeding stage	Jointing stage	Filling stage	Mature stage
Water retaining agent (W)	0.000***	0.021*	0.659	0.852
Inhibitors (I)	0.666	0.000***	0.057	0.278
Corn stalks (S)	0.275	0.256	0.727	0.915
W×I	0.022*	0.076	0.139	0.266
W×S	0.978	0.000***	0.014*	0.449
I×S	0.000***	0.000***	0.050	0.398
W×I×S	0.000***	0.000***	0.497	0.114

Table S4. Available P in Response to Water Retaining Agents, Inhibitors, and Corn Stalks Returning

Factors	Seeding stage	Jointing stage	Filling stage	Mature stage
Water retaining agent (W)	0.001**	0.304	0.590	0.628
Inhibitors (I)	0.001**	0.000***	0.056	0.246
Corn stalks (S)	0.011*	0.057	0.437	0.973
W×I	0.000***	0.069	0.044*	0.160
W×S	0.000***	0.000***	0.000***	0.033*
I×S	0.174	0.001**	0.000***	0.005**
W×I×S	0.748	0.000***	0.000***	0.004**

Table S5. Exchangeable K in Response to Water Retaining Agents, Inhibitors, and Corn Stalks Returning

Factors	Seeding stage	Jointing stage	Filling stage	Mature stage
Water retaining agent (W)	0.476	0.585	0.179	0.000***
Inhibitors (I)	0.057	0.683	0.696	0.089
Corn stalks (S)	0.005**	0.342	0.273	0.036*
W×I	0.042*	0.572	0.761	0.000***
W×S	0.055	0.865	0.642	0.313
I×S	0.406	0.026*	0.137	0.056
W×I×S	0.000***	0.340	0.526	0.035*

Table S6. Organic C, Total N, and Corn Yield in Response to Water Retaining Agents, Inhibitors, and Corn Stalks Returning

Factors	Organic C	Total N	Corn yield
Water retaining agent (W)	0.259	0.510	0.366
Inhibitors (I)	0.756	1.000	0.086
Corn stalks (S)	0.705	0.672	0.086
W×I	0.237	0.818	0.129
W×S	0.399	0.694	0.127
I×S	0.022*	0.549	0.757
W×I×S	0.114	0.583	0.990