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Responses of soil nutrients, enzyme activities, and maize yield to straw and plastic film mulching in coastal saline-alkaline

Zhen Liu[1,2], Mengkun Zhang[2], Zengjiao Wang[2], Ying Shen[2], Deheng Zhang[2], Shenghao Zhang[2], Xingchao Qi[1], Xuepeng Zhang[3], Tao Sun[4], Shenzhong Tian[4], Tangyuan Ning[2]**

[1]Shandong Key Laboratory of Eco-Environmental Science for Yellow River Delta, Shandong University of Aeronautics, Binzhou, P.R. China
[2]Key Laboratory of Crop Water Physiology and Drought-Tolerance Germplasm Improvement of Ministry of Agriculture, College of Agronomy, Shandong Agricultural University, Taian, P.R. China
[3]Crop Research Institute, Shandong Academy of Agricultural Sciences, Jinan, P.R. China
[4]State Key Laboratory of Nutrient Use and Management, Key Laboratory of Wastes Matrix Utilisation, Ministry of Agriculture and Rural Affairs, Institute of Agricultural Resources and Environment, Shandong Academy of Agricultural Sciences, Jinan, P.R. China
Zhen Liu and Mengkun Zhang have contributed equally to this work and share the first authorship.
**Corresponding authors: tiansz1616@163.com; ningty@163.com*

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Abstract: To address the issue of low soil nutrients and low crop yields in coastal alkaline salines, a field experiment of straw combined with plastic film mulching in coastal alkaline salines was conducted in this study to explore the effects of different treatments on soil nutrients, enzyme activities and maize yield. Four treatments, including no mulching (NM), straw mulching (SM), plastic film mulching (PM), and straw mulching combined with plastic film mulching (SP), were set up during 2019–2020. In the 0–20 cm soil layer, compared with NM, the soil organic carbon (SOC) and soil catalase activity (SCA) of SM significantly increased by 23.4% and 46.2%, respectively ($P < 0.05$). The soil total nitrogen (STN), soil available phosphorus (SAP), available potassium (SAK), sucrase activity, urease activity, alkaline phosphatase activity, and maize yield (MY) of SP significantly increased by 40.7, 26.8, 13.9, 34.6, 73.8, 36.2 and 19.0%, respectively ($P < 0.05$). SOC, STN, SAP, SAK and SCA were significantly correlated with MY. Therefore, straw mulching combined with plastic film mulching has the best effect on increasing soil nutrients, soil enzyme activity, and maize yield and is suitable for promotion and application in coastal alkaline salines.

Keywords: soil covering; soil salinisation improvement; soil fertility; land productivity

The area of saline alkali worldwide is 9.64×10^8 ha (Zhao et al. 2018). Coastal alkaline salines are an important reserve land resource for grain production and have attracted widespread attention. Soil salinisation is a typical factor restricting global land use efficiency and agricultural development (Ivushkin

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et al. 2019, Chang et al. 2023). The organic carbon in saline-alkali soil is 40% of that of nonsaline-alkali soil, and the crop yield is also lower than that of nonsaline-alkali soil (Pankhurst et al. 2001, Wang et al. 2004). Excessive soil salinity hinders the absorption and transportation of water, leading to a decrease in yield (Osman 2018). Maize is one of the most important cereal crops widely cultivated in the world and the third largest cereal crop in the world after wheat and rice (Mueller 2012). Maize is moderately sensitive to salt stress (Soothar et al. 2021). It plays an important role in the world economy, significantly contributing to the manufacturing industry and impacting the majority of the world's population (Andorf et al. 2019). Taking reasonable measures to increase the nutrient content of saline-alkali soil is very important to improve crop yield.

Mulching is an important ground-covering practice that can inhibit water evaporation in surface soil, increase moisture in the plough layer (An et al. 2015), reduce surface runoff and soil temperature in the summer season (Masciandaro et al. 2004, Adekalu et al. 2007), and increase soil enzyme activity (Masciandaro et al. 2004), soil nutrients and microbial biomass (An et al. 2015). Straw mulching can significantly increase soil alkali hydrolysable nitrogen, available potassium, soil total nitrogen (STN), total potassium, organic carbon, and enzyme activities (Akhtar et al. 2018). Long-term straw mulching can effectively delay the ageing of maize roots, improve the plant height of maize, and facilitate the absorption of nutrients and yield increases in maize (Hu et al. 2021). As straw decays and decomposes, it gradually produces a large number of nutrients in the soil, which can simultaneously increase the total and effective nutrient content, reduce the use of chemical fertilisers, save costs, and improve the ecological environment of farmland (Zhuang et al. 2020).

Plastic film mulching enhances soil nutrients by improving the "microclimate" of the soil below the plastic film. Plastic film mulching increases the water and heat conditions, reduces the soil organic carbon (SOC) in the soil (Li et al. 2004), controls soil moisture evaporation, accelerates the process of soil nutrient decomposition and crop nutrient absorption, improves soil biological activity, inhibits salt return and weed growth, and promotes crop growth and development (Sarkar et al. 2007). It can also reduce the pH value of the alkali soil and thus create a more suitable growth environment for soil microorganisms, ultimately increasing the efficiency and yield of crops (Liu et al. 2022, Wu et al. 2022). Soil enzymes participate in the material cycle, including various biochemical processes in soil, and their activities reflect the health level of the soil (Gil-Sotres et al. 2005, Yao et al. 2023). Enzyme activity in nutrient cycling is closely related to soil organic carbon and soil properties (Caravaca et al. 2002).

The improvement of soil quality and crop yield in saline-alkali soil is closely related to food security. However, there are few studies regarding straw combined with biodegradable plastic film mulching in coastal saline-alkali soil. To improve soil fertility and maize yield in coastal saline-alkali land, this study analysed the effects of straw and biodegradable plastic film mulching treatments on soil nutrients, enzyme activity, maize yield and their correlations.

MATERIAL AND METHODS

Trial site. This experiment was conducted in the Bohai Grain Warehouse (37°N, 118°E) of Wudi County, Binzhou City, Shandong Province, China, in 2019 and 2020. This area is characterised by a temperate continental monsoon climate, with an annual average temperature of 13 °C, annual average precipitation of 560 mm, annual average evaporation of 1 300 mm, and annual frost-free period of 202–210 days. The soil type was coastal salinised flavour aquic soil, classified as Cambisols (IUSS Working Group WRB 2006) by the WRB system. The soil texture was silty clay loam, moderately saline-alkali soil with a high salinity of approximately 10–40 g/L. The groundwater level was 1.0–1.5 m during the crop growth stage.

Trial design. The experiment adopted a random block design, repeated 3 times, with each plot area of 15 × 5 m. Four treatments, including no mulching (NM), straw mulching (SM), plastic film mulching (PM), and straw mulching combined with plastic film mulching (SP), were set up. After the straw was crushed, it was evenly spread on the ground surface with a dose of 1.2 kg/m^2 and a thickness of 1 cm. A transparent plastic film with a width of 1.5 m and a polylactic acid (PLA) material was selected. The straw and biodegradable plastic film costs were 65 $/ha and 250 $/ha, respectively. SP refers to covering straw first and then plastic film after sowing. The start and end of the experiment were June 18 and October 7 in 2019 and 2020, respectively. The sowing density of maize (cv. Zhengdan 958) was 66 000 plants/ha. The basic physical and chemical properties of the topsoil (0–20 cm) before the experiment are shown in Table 1.

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Table 1. Physical and chemical properties in the 0–20 cm soil layer before the experiment

Sand	Silt	Clay	Organic carbon	Total nitrogen	Phosphorus	Potassium	Saltiness (g/kg)	pH	Carbonates (g/kg)
(%)			(g/kg)		(mg/kg)				
40.77	58.99	0.24	7.13	0.82	17.52	132.60	3.62	8.82	8.80

Soil sample collection and determination. The 0–20 cm soil layer was collected, with three replications per treatment during the jointing (July 10), anthesis (August 3), filling (September 6) and maturity (October 6) stages of maize in 2019 and 2020. One part of the soil sample was dried, ground, and then passed through a 2 mm sieve for further determinations of chemical properties. The other sample was stored at 4 °C and used for enzyme activity analysis.

The soil samples were pretreated with 1 mol/L HCl to remove carbonate. Approximately 50 mg of dried soil after HCl treatment was wrapped in aluminium foil and combusted at 950 °C using a Vario TOC cube (Elementar Analysensysteme GmbH, Hanau, Germany) to determine the SOC. The semi-micro Kjeldahl method was used to determine the STN (Bremner 1960). The molybdenum antimony colourimetric method (0.5 mol/L $NaHCO_3$ extraction) was used to determine the soil's available phosphorus. The flame photometer method (1 mol/L NH_4OAC extraction) was used to determine the soil available potassium. Sucrase activity, urease activity, alkaline phosphatase activity, and catalase activity were determined by the 3,5-dinitro salicylic acid colourimetric method, indophenol blue colourimetry method, sodium diphenyl phosphate colourimetric method and $KMnO_4$ titration method, respectively (Guan 1986).

Maize yield determination. During the maize seedling stage, a ten-metre double-row survey was conducted in each plot to investigate the emergence rate. At the mature stage of maize, the ears of maize were collected from the middle double rows ten metres in length in each plot, repeated three times.

Statistical analyses. The significance of differences between NM, SM, PM, and SP and correlation analysis between soil nutrients, soil enzyme activities, and maize yield were carried out by ANOVA using SPSS statistical analysis system software (ver. 18.0, SPSS Inc., Chicago, USA) (Duncan's test at $P < 0.05$ and $P < 0.01$). The graphical analysis was conducted by Sigmaplot (ver. 12.5, Systat Software, Inc., San Jose, USA).

RESULTS AND DISCUSSION

Soil nutrients. In the 0–20 cm soil layer, the SOC of SM increased by 28.2% and 19.4% compared with that of NM in 2019 and 2020, respectively (Figure 1A). There was no significant difference between SM and SP in 2019 and 2020. In the 0–20 cm soil layer, the STN of SP was significantly higher than that of the other treatments. The STN of SP increased by 38.2% and 42.9% compared with that of NM in 2019 and 2020, respectively (Figure 1B). A buried straw layer combined with plastic film mulch significantly increased SOC in the 0–40 cm soil layer in saline soil after a 4-year experiment (Huo et al. 2017). In this study, straw mulching improved SOC and STN better

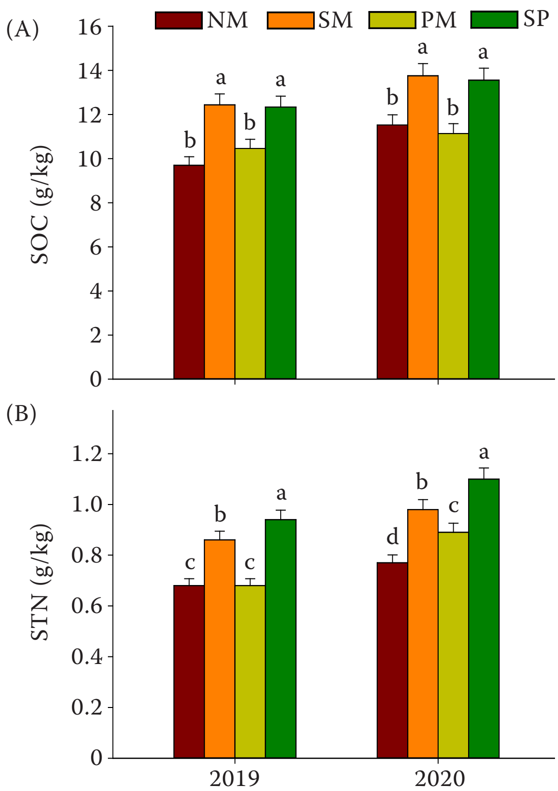

Figure 1. Effects of different treatments on (A) soil organic carbon (SOC) and (B) soil total nitrogen (STN). NM – no mulching; SM – straw mulching; PM – plastic film mulching; SP – straw and plastic film mulching

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Table 2. Effects of different treatments on soil available phosphorus (mg/kg) in the 0–20 cm soil layer

Year	Treatment	Jointing stage	Anthesis stage	Filling stage	Maturity stage
2019	NM	18.25^{b}	38.59^{b}	29.95^{b}	24.70^{b}
	SM	20.18^{ab}	41.58^{a}	35.57^{ab}	31.46^{a}
	PM	17.49^{b}	36.24^{b}	28.19^{b}	22.94^{b}
	SP	22.30^{a}	43.61^{a}	38.43^{a}	33.32^{a}
2020	NM	17.29^{b}	42.58^{b}	35.29^{c}	23.11^{b}
	SM	21.68^{ab}	50.81^{a}	41.93^{b}	24.97^{b}
	PM	16.37^{c}	43.87^{b}	36.14^{c}	25.17^{b}
	SP	23.56^{a}	52.74^{a}	44.84^{a}	32.62^{a}

NM – no mulching; SM – straw mulching; PM – plastic film mulching; SP – straw and plastic film mulching. Different letters in each column represent significant differences between different treatments ($P < 0.05$; Duncan's test)

than plastic film mulching. Because straw mulching increases the accumulation of effective nutrients in the soil and the storage capacities of SOC and STN (Yuan et al. 2014, Qin et al. 2022). The heat preservation and water retention function of film mulching improves the soil structure, increases microbial activity, promotes the release of soil nutrients, and increases the mineralisation rate of organic carbon (Zong et al. 2020), thereby reducing the contents of SOC and STN in the soil (Li et al. 2007).

In 2019, the soil-available phosphorus of SP increased by 22.2% and 27.5% compared with that of NM and PM during the jointing stage (Table 2). The soil available phosphorus of SP increased by 28.3% and 36.3% compared with that of NM and PM during the filling stage. The soil available phosphorus of SP and SM was higher than that of NM and PM during the anthesis and maturity stages. There was no significant difference between SP and SM during these four stages. In 2020, the soil available phosphorus during jointing and anthesis was consistent with the results in 2019. The soil available phosphorus of SP during filling and maturity was significantly higher than that of the other treatments.

In 2019, the soil-available potassium of SM, SP and PM increased by 9.4, 7.0 and 5.2% compared with that of NM during the jointing stage (Table 3). The soil available potassium of SM, SP and PM increased by 14.1, 10.8 and 3.7% compared with that of NM during the anthesis stage. Compared with NM, the soil-available potassium of SP, SM, and PM was increased by 20.8, 15.1 and 6.1% during the filling stage. During the maturity stage, the soil available potassium of SP and SM increased by 16.5% and 11.9%, respectively. In 2020, the soil-available potassium of SM, SP and PM increased by 15.1, 11.2 and 7.3% compared with that of NM during the jointing stage. The soil-available potassium of SP, SM and PM increased by 17.4, 13.0 and 6.7% compared with that of NM during the anthesis stage. The soil available potassium of SP increased by 15.4% compared with that of NM during the filling stage. The soil available

Table 3. Effect of different treatments on soil available potassium (mg/kg) in the 0–20 cm soil layer

Year	Treatment	Jointing stage	Anthesis stage	Filling stage	Maturity stage
2019	NM	115.39^{b}	156.28^{b}	138.45^{c}	117.47^{b}
	SM	126.23^{a}	178.29^{a}	159.36^{ab}	131.45^{a}
	PM	121.37^{ab}	162.14^{ab}	146.92^{b}	110.96^{c}
	SP	123.52^{a}	173.18^{a}	167.21^{a}	136.82^{a}
2020	NM	118.28^{c}	163.28^{c}	144.67^{b}	125.12^{c}
	SM	136.14^{a}	184.54^{ab}	154.42^{ab}	142.48^{a}
	PM	126.94^{ab}	174.25^{b}	148.25^{b}	135.17^{b}
	SP	131.58^{a}	191.63^{a}	166.88^{b}	138.62^{ab}

NM – no mulching; SM – straw mulching; PM – plastic film mulching; SP – straw and plastic film mulching. Different letters in each column represent significant differences between different treatments ($P < 0.05$; Duncan's test)

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potassium of SM, SP and PM increased by 13.9, 10.8 and 8.0%, respectively, during the maturity stage.

In this study, straw and plastic film mulching can compensate for the decline in soil fertility caused by a single mulching method and achieve an effective fertiliser effect because straw contains abundant nutrients such as nitrogen, phosphorus, and potassium (Hou et al. 2021). Straw mulching and plastic film mulching improved the soil's hydrothermal environment and accelerated the straw's decomposition. The decomposition of straw increases the content of soil available phosphorus and soil available potassium in the soil (Wang et al. 2023). Straw mulching transports rich fresh mineral nutrients and organic carbon to the soil, thereby increasing these nutrients (Lucas-Borja et al. 2020a). This study indicated that the nutrient content 2020 was higher than that in 2019. Potentially, with the increase in experimental years, the microbial activity in the soil increased, enhancing the ability to decompose straw and contributing to nutrient accumulation.

Soil enzyme activities. In the 0–20 cm soil layer, the soil sucrase activity of SP increased by 41.2, 23.4 and 15.3% compared with that of NM, SM and PM, respectively, in 2019 (Figure 2A). The soil sucrase activity of SP increased by 28.9, 16.2 and 13.1% compared with that of NM, SM and PM, respectively, in 2020. The soil sucrase activity reflects the change in SOC (Ge et al. 2010). In this study, single straw mulching and plastic film mulching increased soil sucrase activity, but the combination significantly increased soil sucrase activity. This was because straw mulching increased SOC, while plastic film mulching increased soil temperature and water content, effectively improving soil sucrase activity. The soil urease activity of SP increased by 75.6, 26.1 and 41.1% compared with that of NM, SM and PM, respectively, in 2019 (Figure 2B). The soil urease activity of SP increased by 72.2, 15.7 and 10.7% compared with that of NM, SM and PM, respectively, in 2020. Soil fertility affects soil urease activity. The lower the soil fertility is, the weaker the soil enzyme activity (Lucas-Borja et al. 2020a). Straw decompo-

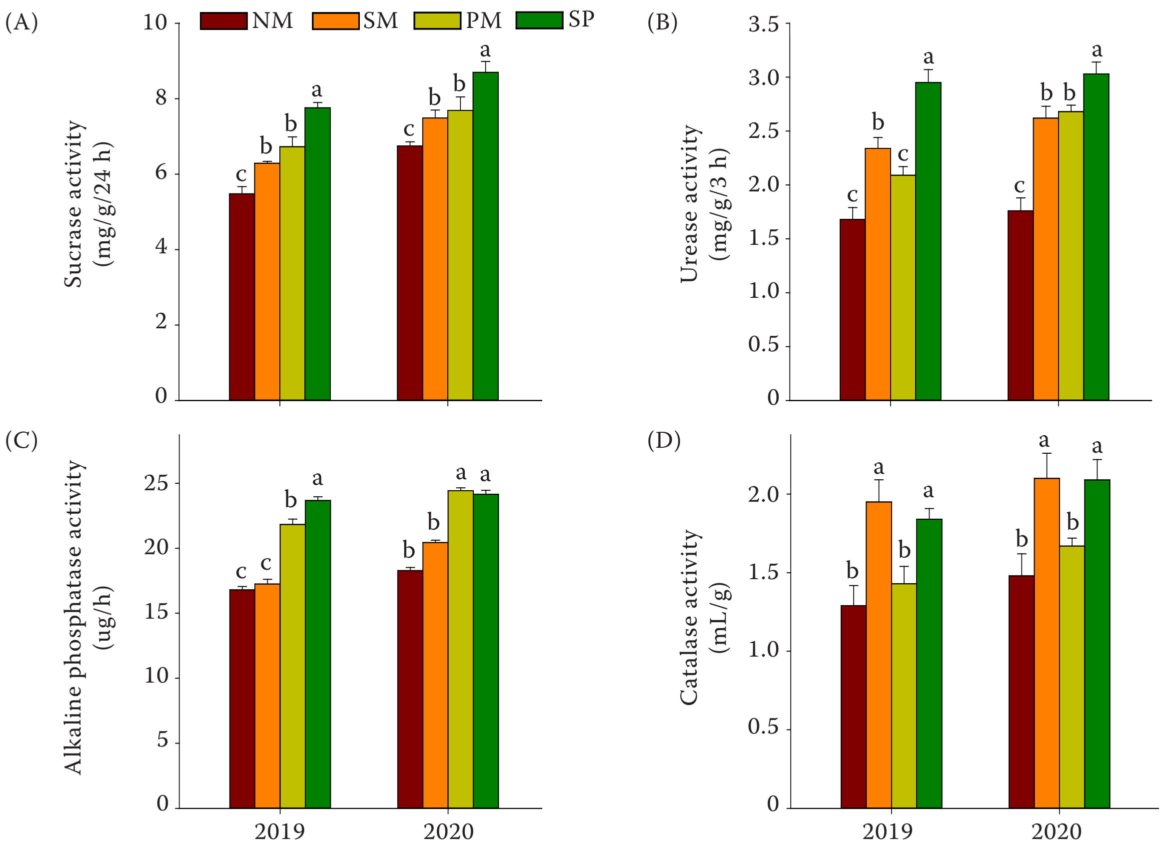

Figure 2. Effects of different treatments on (A) soil sucrase aktivity; (B) urease aktivity; (C) alkaline phosphatase activity, and (D) catalase activity in the 0–20 cm soil layer. NM – no mulching; SM – straw mulching; PM – plastic film mulching; SP – straw and plastic film mulching. Different letters in each group represent significant differences between different treatments ($P < 0.05$; Duncan's test)

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sition increases soil nutrient content, enhances soil fertility, and thus improves soil urease activity. SP's soil alkaline phosphatase activity obviously increased by 40.8% and 37.1% compared with that of NM and SM in 2019 (Figure 2C). PM's soil alkaline phosphatase activity increased by 33.6% and 19.5% compared with that of NM and SM, respectively, in 2020. There was no significant difference between PM and SP in 2019 and 2020. Straw and plastic film mulching increased soil available phosphorus in this study because an increase in soil available phosphorus can increase soil alkaline phosphatase activity (Lucas-Borja et al. 2020b). The soil catalase activity of SM increased by 51.2% and 36.4% compared with that of NM and PM, respectively, in 2019 (Figure 2D). The soil catalase activity of SM increased by 41.9% and 25.8% compared with that of NM and PM, respectively, in 2020. There was no significant difference between SM and SP in 2019 and 2020. Compared with no mulching, straw mulching significantly increased soil catalase activity, while plastic film mulching reduced soil catalase activity. Therefore, single-straw mulching can effectively improve soil catalase activity, while the combination of straw mulching and plastic film mulching has no significant difference from single-straw mulching.

The emergence rate and yield of maize. The poor physical and chemical properties of saline-alkali soil in the cultivated layer inhibit the growth of crops (Haque et al. 2008). The emergence rate of maize was the main manifestation of the differences in salt alkali stress under different treatments. SM and PM emergence rates were the highest and lowest, respectively, in 2019 and 2020 (Figure 3A). Compared with NM, the emergence rate of SM increased by 6.8%. Straw mulching was beneficial for improving the emergence rate, achieving seedling preservation, and ensuring the development of crop populations. This result occurred because the application of straw improves the soil structure, which is conducive to the growth of maize roots and improves the ability of crops to absorb water and nutrients. Due to the release of nutrients after straw decomposition, straw can enhance soil fertility and provide abundant nutrients for maize growth (Liu et al. 2020). The emergence rate of maize under plastic film mulching and straw and plastic film mulching was obviously lower than that under no mulching and straw mulching (Figure 3A). This was because plastic film mulching both reduces the evaporation of soil moisture and hinders the infiltration of rainwater during the rainy season, thus reducing the desalination effect of the soil (Zhang et al. 2013, Haque et al. 2018), causing salt stress in the early stages of maize growth and decreasing the field emergence rate of maize. The maize yields of SM and SP were significantly higher than those of NM and PM in 2019 (Figure 3B). Because plastic film mulching can cause soil temperature to exceed the appropriate range for root development, leading to a decrease in kernel number and thousand-kernel weight (He et al. 2017). The maize yield of SP was significantly higher than that of the other three treatments in 2020. Compared with that of NM, the grain yield of SP obviously increased by 18.8%. This result is contrary to the results of this study (Haque et al. 2018). Straw combined with plastic film mulching had the best effect on increasing soil fertility, soil enzyme activities and maize yield; it is a suitable agronomic measure for maize promotion in coastal alkaline salines.

Correlation analysis. SOC, STN, soil-available phosphorus and soil-available potassium had no significant correlation with soil alkaline phosphatase activity but were significantly correlated with maize yield (Table 4).

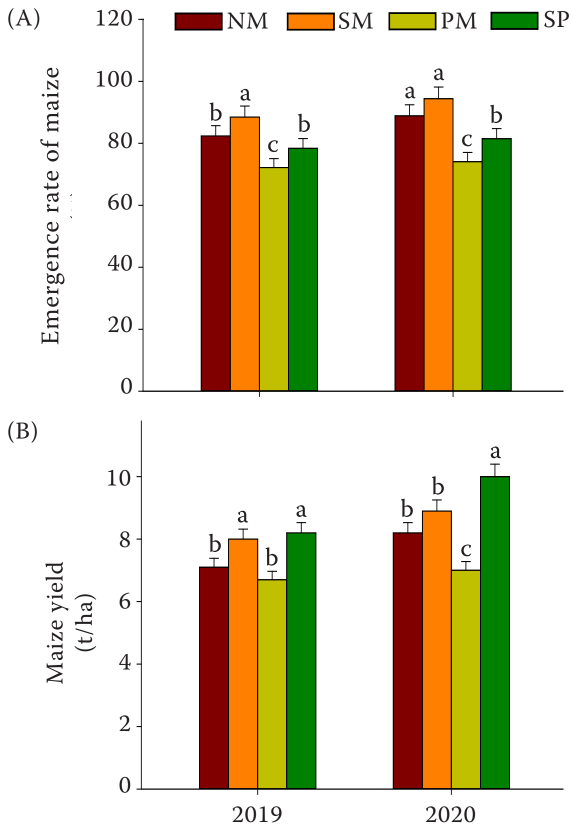

Figure 3. Effects of different treatments on (A) the emergence rate and (B) yield of maize. NM – no mulching; SM – straw mulching; PM – plastic film mulching; SP – straw and plastic film mulching. Different letters in each group represent significant differences between different treatments ($P < 0.05$; Duncan's test)

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Table 4. Correlation coefficients between soil nutrients, soil enzyme activities, and maize yield

Index	SOC	STN	SAP	SAK	SSA	SUA	SPA	SCA	MY
SOC	1	0.897**	0.907**	0.938**	0.699	0.722*	0.311	0.961**	0.878**
STN		1	0.970**	0.970**	0.861**	0.891**	0.575	0.915**	0.842**
SAP			1	0.939**	0.763*	0.816*	0.426	0.904**	0.916**
SAK				1	0.795*	0.894**	0.510	0.979**	0.787*
SSA					1	0.880**	0.869**	0.683	0.646
SUA						1	0.799*	0.811*	0.561
SPA							1	0.362	0.211
SCA								1	0.785*
MY									1

SOC – soil organic carbon; STN – soil total nitrogen; SAP – soil available phosphorus; SAK – soil available potassium; SSA – soil sucrase activity; SUA – soil urease activity; SPA – soil alkaline phosphatase activity; SCA – soil catalase activity; MY – maize yield. *$P < 0.05$; **$P < 0.01$

Only soil catalase activity significantly affected maize yield at the 0.05 level, while other enzyme activities were not significantly correlated with maize yield.

In addition, the extensive use of plastic film, with a low recovery rate and easy fragmentation, is the primary source of microplastics in soil, which can have adverse effects on plants, animals, and microorganisms in the soil (Wu et al. 2022). The cost of biodegradable plastic film and its potential negative impact on the soil environment also limit its widespread application. In summary, further in-depth research is needed to determine whether biodegradable plastic film can effectively address the issues of residual cover and microplastic pollution in farmland (Liu et al. 2023).

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