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Cattle Manure Application and Combined Straw Mulching Enhance Maize (*Zea mays* L.) Growth and Water Use for Rain-Fed Cropping System of Coastal Saline Soils

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Abstract: Appropriate agronomic management is vital for the soil fertility and crop output of coastal salt-affected farmlands. Cattle manure incorporation and straw mulching are targeted as effective methods that can improve soil structure and stimulate crop growth, respectively. However, the combined application of manure and straw into salt-affected soils is less documented, especially with limited water supplement. In this study, a 3-year field experiment (2016–2018) was conducted in Binhai district, Tianjin, China to evaluate the effects of traditional tillage without manure and straw mulching application (TT), cattle manure incorporation (CM), straw mulching (SM), and CM combined with SM (CM + SM) on soil physiochemical properties, maize (*Zea mays* L.) growth, and water use efficiency. TT represented traditional cultivation in the study area without manure and straw application, as a control. All four treatments were carried out in a randomized block design with three replicates. The results demonstrate that CM treatment relieved salinity, decrease bulk density, and thereby stimulated root development. SM also has the advantage of improving salinity via 3-year implementation. Throughout the 3-year cultivation, CM + SM crop yields increased by >14.3% and grain water use index (GWUI) improved by >14.7% in comparison to TT treatment due to the improvement in soil properties. These benefits in soil properties, crop yield, and water use are important for minimizing salt constraints and realizing regional agro-ecological values.

Keywords: coastal soils; organic manure incorporation; straw mulching; salt accumulation; crop growth

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1. Introduction

Soil salinization has been a serious degradation issue, which is widely distributed in over 25 percent of the total land area around the world [1,2]. In China, salt-affected lands exceed 36 million ha, among which coastal soils occupy a significant ratio. Generally, coastal farmlands are undoubtedly vulnerable to climatic changes because of their poor permeability and the intrusion from marine water [3,4]. Therefore, it is critical to introduce diverse mechanisms for the reclamation of coastal salt-affected soils to minimize salt constraints and realize regional agro-ecological values.

In coastal farmlands, natural factors or anthropogenic activities such as the rise of sea level, and the over-consumption of groundwater, induce the invasion from salt water, resulting in secondary salinization [5]. Soil salinization, especially the accumulated salt in topsoil, suppresses crop growth mainly through the following aspects: Firstly, accumulated salt around the rhizosphere could inhibit seed germination and emergence. Secondly, excessive sodium ion restrains the absorption of nutrient ions such as iron, magnesium, and potassium. Thirdly, salt stress reduces the quality of grains, and simultaneously leads to a reduction in crop yield [6,7]. This study aims to explore feasible agronomic approaches that can obtain an acceptable soil environment and stimulate crop growth.

In previous studies, numerous theoretical and practical approaches have been implemented to ameliorate salt-affected soils for increasing their fertility and crop growth [8–10]. The ameliorant reclamation of saline soil mainly results from the removal of substituted sodium (Na^+) out of colloid cation exchange areas; in particular, the root zone [11]. Chemical amendment is a common approach to provide a source of calcium (Ca^{2+}) to substitute the exchangeable Na^+ from the cation exchange complex, and the replaced Na^+ is then leached from the root zone through irrigation [12,13]. In particular, gypsum is widely applied as an essential source of Ca^{2+} to decrease exchangeable sodium [14]. Simultaneously, soil quality variables such as aggregate, permeability, and chemical properties can be improved significantly with the addition of gypsum [15,16]. However, with the increasing usage by industry, natural gypsum is rarely used owing to the high cost of exploitation, transportation, and crushing [17]. Desulfurized gypsum, a by-product during combustion of coal in thermal power plants, has become an alternative source, because it is high yield, and easy to apply [18–20].

Recently, the application of organic amendments, e.g., manure, compost, and crop straw, has been widely used among researchers as a better restoration strategy [21–23]. Hammer et al. [24] demonstrated that organic materials enhance plant growth and improve soil fertility and structure by stimulating arbuscular mycorrhizal fungi in dry saline lands, which is unanimous with the results obtained by Tejada and Gonzalez [25]. However, it is worth noting that most ameliorant studies have focused on optimizing ingredient proportions and characterizing temporal variations in soil physiochemical properties rather than on applying strategy and investigating the role of water use, although it has been confirmed that water use efficiency also plays a critical role in soil reclamation [26].

Therefore, we hypothesized that crop growth would be facilitated through appropriate agronomic management under limited water supplement conditions. In this study, 3-year maize (*Zea mays* L.) cultivation experiments without irrigation were conducted in a rain-fed cropping system, and cattle manure incorporation into topsoil and straw mulching after maize harvesting were used to determine how they contribute to crop performance and water use. During the period of each cropping season, soil organic matter (SOM), electrical conductivity (EC), soil bulk density, volumetric soil water content (SWC), maize shoot biomass and root dry weight, and the thereby water use were measured to evaluate the farmland response treated by manure incorporation and straw mulching, compared with traditional tillage (without soil treatment). Accordingly, the objective of this study was to investigate the effects of cattle manure incorporation and straw mulching on soil physicochemical properties and crop growth, in particular to collect sufficient data to enable a quantitative assessment of the potential benefits, and to thereby enhance soil fertility, diminish salt accumulation in topsoil, and minimize salt constraints caused by secondary salinization.

2. Materials and Methods

2.1. Experimental Site and Soils

Field experiments were carried out during cultivation seasons from 2016 to 2018, at Binhai district (38°46′ N, 117°13′ E, altitude of 3 m) in Tianjin city, China. For decades prior to 2016, the site was farmed traditionally, and it is approximately 10 km to the coastline of West Bohai Gulf. The climate is warm temperate and characterized by semi-humidity and monsoons, with seasonal fluctuation in rainfall and temperature. According to Tianjin Meteorological Service, the long-term average annual rainfall from 2005 to 2015 was 594 mm, mostly concentrated during June to September. The mean monthly temperature and precipitation during the year of cultivation experiments are presented in Figure 1.

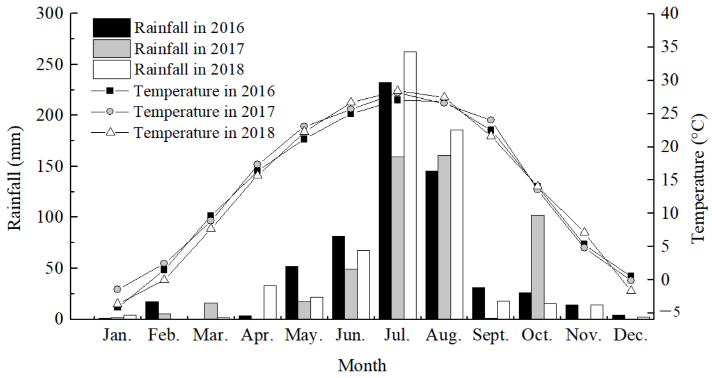

Figure 1. Variations in mean monthly temperature and precipitation of experimental site from 2016 to 2018.

Soils in the experimental region, originated from fluvial deposits, are highly argillaceous with poor permeability. Dry farming without irrigation is the prominent cultivation system due to the insufficient fresh water. The common crops include summer maize (*Zea mays* L.), soybean (*Glycine max* (L.) Merr.), and alfalfa (*Medicago sativa* L.). The soil in the top 0.30 m profile was defined as silty clay loam with 10.6% sand, 61.0% silt, and 28.4% clay. Before the experiment, original soil samples were collected and analyzed for chemical properties in May 2016 (Table 1).

Table 1. Soil properties of the top 0.30 m layer prior to experiments.

Items	Mean Value
Soil bulk density (g cm^{-3})	1.39
Field capacity (by weight, %)	28.4
Electrical conductivity (dS m^{-1})	2.04
pH	8.34
Na^+ (dry soil, mg kg^{-1})	2.67
Salt content (g kg^{-1})	7.08
Soil organic matter (g kg^{-1})	10.4
Alkaline-hydrolysable nitrogen (mg kg^{-1})	64.5
Available phosphorus (by Olsen, mg kg^{-1})	31.4
Available potassium (mg kg^{-1})	63.2

2.2. Experimental Design

Four treatments were selected for this study: (1) TT, traditional tillage without cattle manure application and no straw mulching, as the control group; (2) CM, cattle manure applied by mixing with the top 0.15 m soil layer uniformly; (3) SM, all maize straw returned by mulching after harvest; and (4) CM + SM, combined CM and SM treatments. For all the CM treatments, the amounts of cattle manure were equal at 10 t ha^{-1}, and some essential properties of cattle manure are presented in Table 2.

Table 2. Basic properties of cattle manure. Data were determined from mean values of 3-year experiments.

Items	Mean Value
Bulk density (g cm^{-3})	0.26
pH	8.21
Electrical conductivity (dS m^{-1})	6.72
Organic carbon (g kg^{-1})	327.46
Nitrogen (g kg^{-1})	11.98
Phosphorus (g kg^{-1})	11.35
Potassium (g kg^{-1})	13.54

The four treatments, TT, CM, SM, and CM + SM, were applied to 7.2 m wide and 9.0 m long field sections in a randomized complete block design, with three replicates, respectively. Each plot was ridged (a height of 0.20 m) against cross contamination.

2.3. Agronomic Arrangement

Before the cropping season of maize in 2016, the entire site was ploughed to a depth of 0.30 m to remove the existing plough pan. A no-till planter was used to sow and fertilize synchronously with individual planting mechanisms throughout the experiments. Each planting mechanism was equipped with an opener to provide an 80–120 mm-deep groove for fertilizer placement and a double-disc opener to place seed 40–50 mm above the fertilizer. The individual planting mechanisms were fitted with press wheels, which solidly planted maize in 0.60 m wide rows.

In detail, summer maize (cultivar: Zhengdan-958, germination rate: 90%, Hebei Xingnong Fumin seed sales Co., Ltd., Cangzhou City, Hebei, China) was planted at a rate of 30 kg ha^{-1} in accordance with local customs. Chemical fertilizer (N-P_2O_5-K_2O) was applied at 85 kg ha^{-1} of N, 45 kg ha^{-1} of p, and 40 kg ha^{-1} of K during maize sowing. Moreover, weeds were controlled by hand and plant protection was applied when needed based on traditional agronomic management. The agronomic schedules under different treatments are described in Table 3.

Table 3. Annual agronomic schedules for four treatments during crop season from 2016 to 2018.

Treatments	Agronomic Schedules
TT	Traditional tillage without manure and straw mulching application: rotary harrowing to 0.15 m deep for seedbed preparation, and no-till maize planting in early June; weed controlling in late June; and maize harvesting, with all maize residues removed manually, in late September. All the nutrients needed during the growing period were supplied by chemical fertilizers.
CM	During seedbed preparation, cattle manure was spread manually at the designed rate, with uniform distribution on soil surface. Then, manure was mixed with the upper 0.15 m of soil by rotary harrowing. Other agronomic schedules were the same as TT.
SM	After maize harvest, all the stubble was returned to the field, and spread on soil surface uniformly. Other agronomic schedules were the same as TT.
CM + SM	Agronomic schedules were the same as CM and SM.

2.4. Sampling and Measurement

2.4.1. Soil Water Content (SWC) and Bulk Density

Soil samples were collected at the start of the experiment in 2016 and for subsequent seasons until 2018. Soil cores were randomly collected from the cropping zones of each replicated treatment. The undisturbed soil cores (50 mm in height and 50.46 mm in diameter) were taken from different profiles to determine soil bulk density. The disturbed soil samples were air dried for at least 24 h in the laboratory for chemical properties measurements.

Soil bulk density and gravimetric water content were determined by oven drying method, which were initially weighed and oven dried at 105 °C for 48 h. The samples were taken before maize sowing, after harvesting, and during the key growth stages, respectively. Simultaneously, volumetric water content was determined by He et al. [27]:

$$\theta_v = \theta_m \times (\rho_b / \rho_w), \tag{1}$$

where θ_v is the volumetric water content, cm^3 cm^{-3}; θ_m is the gravimetric water content, g g^{-1}; ρ_b is the soil bulk density, g cm^{-3}; and ρ_w is the density of water, g cm^{-3}.

2.4.2. Soil Organic Matter (SOM) and Electrical Conductivity (EC)

As preparation for measurement, the air-dried soil samples were ground and then passed through a 2 mm mesh sieve, while visible roots, pebbles, and aggregates larger than 2 mm were screened out. Soil EC was measured by an EC meter (DDS-11A EC meter, Shang Hai Yoke Instrument Co., Ltd., Shanghai City, China) on the soil water suspension (1:5, w/v). The suspensions were prepared by 10 g sieved soil and 50 mL distilled water, before being centrifugally shaken for 15 min. Soil organic matter (SOM) was determined by dichromate oxidation [22].

2.4.3. Crop Growth and Water Use

Aboveground biomass and root samples were taken from three 1 m^2 areas per treatment at seeding stages. Root samples were collected to a depth of 0.40 m. All samples were oven dried at 65 °C to a constant weight to determine aboveground biomass and root dry weights.

Three crop rows of 3 m in length were selected randomly for each treatment to measure maize yields. Crop yields were determined at 12.0% moisture content. Grain water use index (GWUI) is the amount of grain field produced per unit of total water input. The total water input included seasonal rainfall, and total soil moisture consumption. Notably, dry farming was introduced without irrigation, i.e., irrigation was omitted in total water input.

Total water applied (TWA) was calculated from a simplified water balance equation:

$$\text{TWA} = P - \Delta W \tag{2}$$

where P is the total precipitation in cropping season (mm); and ΔW is the corresponding change in soil water storage in the 0 to 1 m profile from sowing to harvesting (mm). In this study, in-season upward capillary flow from groundwater to the rhizosphere was negligible because the ground water table was >3 m below the soil surface. Meanwhile, surface runoff was never observed in the field as the plots were protected by 0.2 m-high bunds.

Therefore, GWUI was calculated as the ratio of crop yield to seasonal total water applied [27]:

$$\text{GWUI} = \text{Crop yield} \div \text{TWA} \tag{3}$$

2.5. Statistical Method

Statistical analyses were performed with SPSS analytical software (International Business Machines Corporation, New York, NY, USA). Mean values were calculated for each measurement, and multiple comparisons of different treatments were made to assess the treatment effect based on least significant difference (LSD at p = 0.05). Origin 9.0 software (OriginLab Corporation, Northampton, Massachusetts, USA) was used to generate the graphs.

3. Results

3.1. Soil EC

As shown in Figure 2, mean soil EC fluctuated after maize harvesting from 2016 to 2018, and the value in 2017 appeared to be higher. This may be attributed to less rainfall during the mature stage in 2017. Additionally, the CM + SM treatment tended to have the least EC throughout the 3-year experimental period, while TT treatment had the highest value, i.e., TT > CM > SM > CM + SM. In 2018, mean soil EC under TT treatment were significantly higher (p = 0.05) than that in the treatments with cattle manure allocation, i.e., CM and CM + SM treatments. Mean EC in CM + SM treatment appeared to be less throughout the 0 to 0.30 m soil profile, which showed an overall improvement in EC by 32.7% when compared with TT treatment (p = 0.05). Meanwhile, SM decreased EC by 19.0% in comparison to TT (p = 0.05). Furthermore, there was no significant difference for EC between SM and CM + SM treatments.

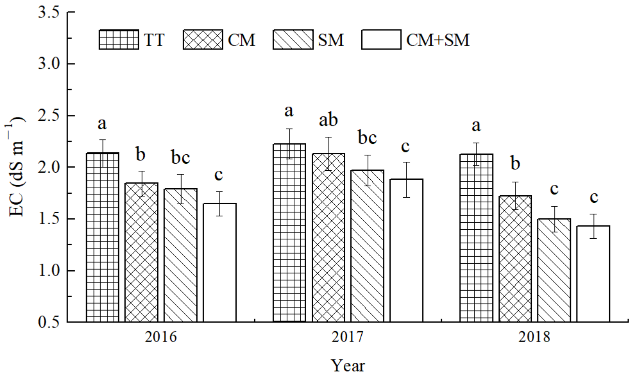

Figure 2. Mean soil electrical conductivity (EC) to the depth of 0.30 m for traditional tillage (TT), cattle manure mixing (CM), maize straw mulching (SM), and combined manure mixing and straw mulching (CM + SM) treatments from 2016 to 2018. Data were measured after maize harvesting. Means within same soil depth followed by the same letter are not statistically different according to least significant difference test (p = 0.05).

3.2. SOM

SOM in the top 0.30 m of the soil layer with cattle manure allocation, i.e., CM and CM + SM treatments, increased by 15.0–17.4 g kg^{-1} as compared with TT treatment throughout the whole experimental period (Figure 3, p = 0.05). Moreover, in comparison to the TT treatment, mean SOM showed an increasing tendency for SM treatment. In 2018, the third cropping season after maize harvesting, SM increased SOM by 55.4% compared with TT (p = 0.05). However, SOM values between CM and CM + SM treatments from 2016 to 2018 were not significantly different.

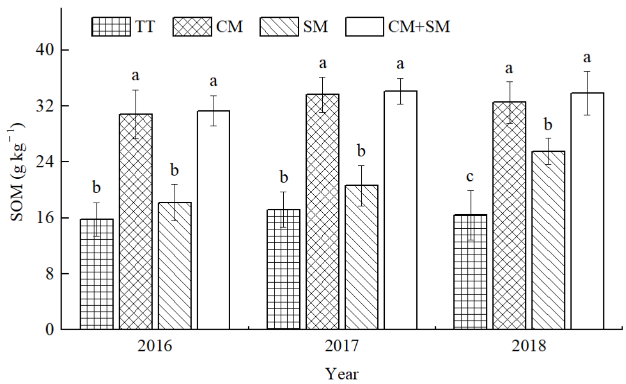

Figure 3. Mean soil organic matter (SOM) to the depth of 0.30 m for traditional tillage (TT), cattle manure mixing (CM), maize straw mulching (SM), and combined manure mixing and straw mulching (CM + SM) treatments from 2016 to 2018. The data were measured after maize harvesting. Means in the same year followed by the same letter are not statistically different according to least significant difference test (p = 0.05).

3.3. Soil Bulk Density

Contrary to SOM characteristics, cattle manure application tended to decrease soil bulk density in the upper 0.30 m of the soil profile (Figure 4). CM + SM treatment, with the lowest soil bulk density of 1280 kg m^{-3}, decreased by 5.4% in comparison to TT treatment significantly (p = 0.05). However, no significant difference was observed for soil bulk density between CM and CM + SM treatments from 2016 to 2018. Furthermore, despite that no significant difference was measured for bulk density between SM and TT treatment, the value appeared to be a consistent trend, and this value in SM was 1.2–1.8% less than that in the TT.

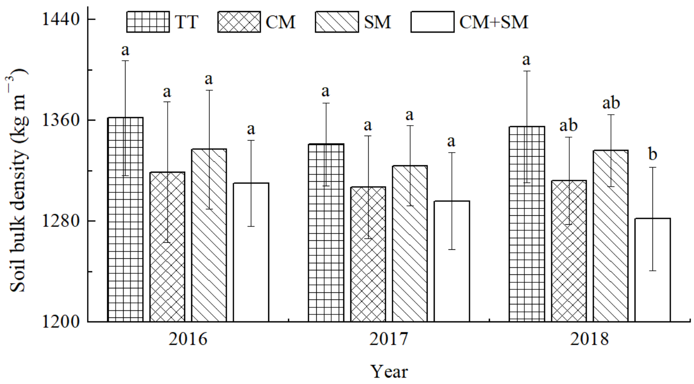

Figure 4. Mean soil bulk density to the depth of 0.30 m for traditional tillage (TT), cattle manure mixing (CM), maize straw mulching (SM), and combined manure mixing and straw mulching (CM + SM) treatments from 2016 to 2018. The data were measured after maize harvesting. Means in the same year followed by the same letter are not statistically different according to least significant difference test ($p = 0.05$).

3.4. SWC

Mean volumetric SWC at key growth stages was variable throughout the 3-year seasons from 2016 to 2018 (Figure 5). However, there was a consistent tendency in SWC improvement, which became increasingly obvious between treatments in the latter season. Generally, the CM + SM treatment tended to have the greatest SWC during the experimental period, while TT treatment had the least water contents, i.e., CM + SM > SM > CM > TT. Although no significant difference was found in the first cropping season, in 2016, mean volumetric SWC in the top 0.30 m soil layer of CM + SM treatment tended to be the greatest. In the third season, volumetric SWC in CM + SM at jointing and maturity stages was significantly greater, by 12.6% and 10.5%, compared with TT, respectively ($p = 0.05$). Improvement for SWC was observed in SM by comparison to TT. Despite no significant difference in the 2016 and 2017 cropping seasons, SM had greater SWC at the jointing and filling stages in the third season (2018), by 10.3% and 8.0%, respectively, than that in TT ($p = 0.05$).

3.5. Crop Growth

Table 4 compares shoot biomass and root dry weight of summer maize at seeding stage during the cropping period of 2016 to 2018. Cattle manure allocation, i.e., CM and CM + SM treatments, improved shoot biomass in salt-affected soils throughout the whole three seasons. Shoot biomass increased by over 240% for CM and 290% for CM + SM treatment ($p = 0.05$), respectively, as compared to TT treatment. Difference in root growth under manure application followed a similar pattern to shoot biomass. In comparison to TT treatment, improvement in root dry weight was over 141.7% in CM and over 175.0% in CM + SM at seeding stage, respectively ($p = 0.05$). In addition, enhanced crop growth was observed under SM treatment, and in the third season, SM demonstrated increased shoot biomass by 61.1% and root dry weight by 56.4% ($p = 0.05$).

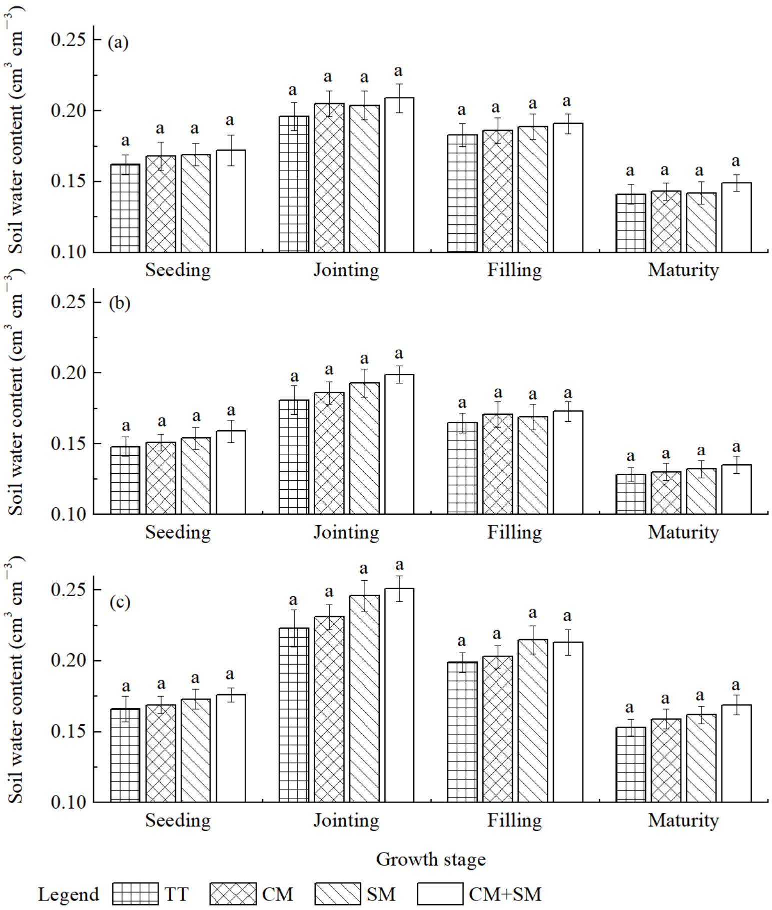

Figure 5. Mean soil volumetric water content in the upper 0.30 m of the soil profile under traditional tillage (TT), cattle manure mixing (CM), maize straw mulching (SM), and combined manure mixing and straw mulching (CM + SM) treatments at key growing stages in the 2016 (**a**), 2017 (**b**), and 2018 (**c**) seasons. Means within same key growing stage in the same year followed by the same letter are not statistically different according to least significant difference test ($p = 0.05$).

Table 4. Shoot biomass and root dry weight of maize at seeding stage for traditional tillage (TT), cattle manure mixing (CM), maize straw mulching (SM), and combined manure mixing and straw mulching (CM + SM) treatments during the cropping years. Means within a column in the same year followed by the same letter are not statistically different according to least significant difference test ($p = 0.05$).

Treatment Identifiers		Shoot Biomass (g/Plant)	Root Dry Weight (g/Plant)
Year	**Treatments**		
2016	TT	2.17 b	0.36 b
	CM	7.55 a	0.87 a
	SM	2.88 b	0.41 b
	CM + SM	8.64 a	0.99 a
		F-value = 59.1180 p-value = 0.0001	F-value = 31.1870 p-value = 0.0001
2017	TT	1.69 c	0.32 c
	CM	6.82 b	0.81 b
	SM	2.35 c	0.35 c
	CM + SM	10.97 a	1.21 a
		F-value = 86.6070 p-value = 0.0001	F-value = 35.5780 p-value = 0.0001

Table 4. *Cont.*

Treatment Identifiers		Shoot Biomass (g/Plant)	Root Dry Weight (g/Plant)
Year	Treatments		
2018	TT	2.44 d	0.39 d
	CM	8.71 b	1.19 b
	SM	3.93 c	0.61 c
	CM + SM	11.06 a	1.42 a
		F-value = 76.9250 *p*-value = 0.0001	F-value = 57.7500 *p*-value = 0.0001

3.6. Crop Yield and WUI

Yields of summer maize in these four treatments fluctuated widely within the 3-year cultivation (Table 5). Generally, the manure allocation treatment tended to have the greater crop yield, while TT had the lower water contents, i.e., CM + SM > CM > SM > TT. A yield advantage of cattle manure allocation over TT treatment appeared during the whole course of the seasons. Particularly, maize yield increased by more than 14.3% for CM + SM treatment, in comparison to TT treatment ($p = 0.05$). Moreover, compared with TT treatment, an increasing trend was observed for crop yield in SM treatment, and in the third cropping season, mean yield for SM was 7.7% greater than that of TT treatment (ns). However, no significant difference was observed for maize yield between SsM and CM treatments.

Table 5. Yield and water use efficiency of summer maize for traditional tillage (TT), cattle manure mixing (CM), maize straw mulching (SM), and combined manure mixing and straw mulching (CM + SM) treatments during the experimental years. Means within a column in the same year followed by the same letters are not statistically different according to least significant difference test ($p = 0.05$).

Treatments Identifiers		TWA [1] (mm)	Yield (kg ha^{-1})	GWUI (kg ha^{-1} mm^{-1})
Year	Treatments			
2016	TT	468.8 a	5423 b	11.6 b
	CM	466.1 a	5789 ab	12.4 ab
	SM	470.5 a	5691 b	12.1 b
	CM + SM	464.2 a	6197 a	13.3 a
		F-value = 1.8370 *p*-value = 0.1942	F-value = 4.6200 *p*-value = 0.0227	F-value = 5.4760 *p*-value = 0.0132
2017	TT	380.8 a	4362 b	11.5 b
	CM	378.4 a	4718 ab	12.5 ab
	SM	379.1 a	4536 b	12.0 b
	CM + SM	376.7 a	5124 a	13.6 a
		F-value = 0.7710 *p*-value = 0.5321	F-value = 4.6440 *p*-value = 0.0223	F-value = 5.2620 *p*-value = 0.0151
2018	TT	508.4 a	5627 b	11.1 b
	CM	507.8 a	6013 b	11.8 b
	SM	509.6 a	6059 b	11.9 b
	CM + SM	505.3 a	6650 a	13.2 a
		F-value = 0.7080 *p*-value = 0.5654	F-value = 7.8510 *p*-value = 0.0037	F-value = 8.5360 *p*-value = 0.0026

[1] TW A: total water applied.

GWUI followed a similar trend to crop yield, generally because TWA mainly came from the rainfall around the experimental site, which caused a difference of less than 10 mm (Table 5). Overall, GWUI in the CM treatment was 6.3% greater than that in the TT treatment, and the SM treatment was 4.3% greater than TT. Significant improvement in GWUI was observed in the CM + SM treatment, and the value was 14.7–18.9% higher than in the TT treatment ($p = 0.05$). Furthermore, an increasing trend for GWUI appeared in SM treatment, and the advantage was maintained at over 4.3% compared with TT.

4. Discussion

Coastal farmlands application has been practiced for decades in many countries. However, it was reported that the deficient organic matter, poor soil structure, and extremely high salinity were dominant factors threatening the reclamation of coastal salt-affected soils [3,4], particularly the domestic coastline of the west Bohai Gulf, along which the soils are vulnerable to climatic changes such as the periodical tidal activity, high evaporation-precipitation ratio, and salt accumulation in topsoil [28,29]. Around the experimental regions in the current research, local agronomic tradition tends to cultivate summer maize under a rain-fed cropping system, due to the intrusion of marine water and scarce fresh water (see Introduction).

Crop residues, e.g., maize or wheat straw applied to shade topsoil, have been demonstrated to enhance moisture retention and reduce water evaporation and salt accumulation [30–32]. In this research, as compared with TT treatment, maize SM slightly increased the volumetric SWC of the upper 0.30 m of the soil profile over the whole three growing seasons, and in particular, a significantly lower soil EC was observed under SM treatment in the third growing season ($p = 0.05$; Figure 2). This can be ascribed to the continuous straw mulching throughout our experimental period, because mulching impedes the exchange of water and vapor between topsoil and atmosphere, which could heighten the inhibition of moisture evaporation, and thereby reduce the upward migration of salt ions [30,33]. Furthermore, all the water replenishment in this study comes from rainfall events. Raindrop impact stimulates soil particles to plug the pores of topsoil, resulting in a surface seal which reduces soil permeability [34]. Therefore, the lower soil EC in SM treatment also may be due to the enhanced infiltration which improves salt leaching into deeper soil layers. The results reported here also show a relatively higher maize shoot biomass and root dry weight in SM treatment when compared with TT during the third growing season ($p = 0.05$; Table 4). This indicates that continuous mulch management can provide an improved soil environment in comparison to unmulched farmlands. Furthermore, despite the positive influence of straw mulching on soil physicochemical properties, some researchers concluded limited and even negative impacts on soil fertility and permeability [35,36]. Soil quality improvement associated with straw mulching is also affected by other natural or anthropogenic factors, such as soil texture, farming management, and climate change.

Cattle manure, rich in degradable organic carbon, could provide substrates as an organic source for farmland when added to the salt-affected soils. In this study, the input of cattle manure supplied from a 3-year incorporation resulted in a significant increase in SOM in comparison to unsupplied soils ($p = 0.05$; Figure 3). The incremental SOM appeared to be the direct consequence of cattle manure application, which was also reported by Meng et al. [37]. In general terms, soil EC is an important indicator that characterizes the soil salinity. In our study, the significantly decreased EC was associated with the increasing of SOM under cattle manure incorporation treatment. This may be due to the enhanced leaching of salt out from topsoil, and the subsequent removal of exchangeable Na^+ because of the improvement in soil porosity caused by persistent manure application [38–40]. Furthermore, the increase in SOM caused by seasonal manure incorporation can result in a decline in soil bulk density [41,42]. In this study, despite a slight decrease in soil bulk density in CM compared to that in TT treatment, a negative correlation between SOM and bulk density was observed in Figure 6. This is probably ascribed to supplementary binding agents from manure application, which resulted in the soil aggregation improving [37].

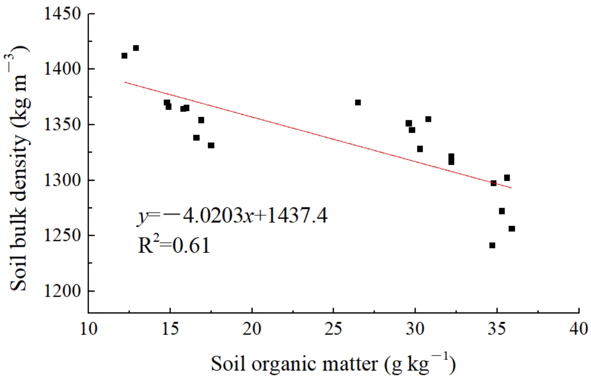

Figure 6. Relationship between soil organic matter (SOM) and bulk density under traditional tillage (TT) and cattle manure mixing (CM) treatments.

Cattle manure can be decomposed in the rhizosphere to improve its fertility, and to generate absorbable nutrients that can stimulate plant growth. The results reported here show a significant improvement in crop shoot biomass and root dry weight in CM treatment compared to that in TT treatment (p = 0.05; Table 4), in agreement with previous studies [14,37]. This could be explained by the reduced EC and increased SOM caused by manure application, which inhibit the salt damage from osmotic stress and ion toxicity, and thereby provide a suitable rhizosphere environment for crop root [43].

In this study, we focus on maize performance under limited water complement, thus appropriate land management is crucial for enhancing water use efficiency and facilitating crop growing. Overall, CM + SM treatment exhibited the most significant promoting influence on soil bulk density, EC, SOM, shoot biomass and root dry weight, and the ultimate maize yield and GWUI, which were followed by CM and SM treatments, particularly in the third cropping season. These positive results demonstrate that cattle manure incorporation combined with maize straw mulching appears as a feasible farming approach in coastal saline areas. It can be ascribed to the continuous soil cover and organic matter replenishment throughout this 3-year experiment.

Importantly, the hypothesis of this study aims to provide a low-input and feasible practical approach for agricultural production in coastal areas. However, soil salinity in coastal farmlands fluctuates seasonally. This is mainly because the transport of water and salt in topsoil is greatly dependent on local climate features such as precipitation, evaporation, and tidal intrusion. In this study area, the salinity tends to accumulate upward during drought season due to the limited rainfall and strong evaporation, while the rainy season actuates the salt leaching into deeper layers [44,45]. Based on the above, it is difficult for a single technology to achieve the expected output for researchers and farmers, because under the one-crop-per-annum system of coastal salt-affected areas, farmers inevitably need to manage salt fluctuations in topsoil during the fallow period (i.e., seasons without crop growing), not only concentrating on the improving rhizosphere environment during the growing season. In this study, all the stubble was returned to the field, and spread on the surface uniformly after maize harvest (SM treatment). This provides an isolation layer between the soil surface and atmosphere, which can inhibit moisture evaporation during fallow periods and weaken the salt accumulation upward root zone. However, straw mulching is constrained, because the cropland benefits such as SWC, yield, and GWUI are not immediately distinct within a short time, which is consistent with the results of He et al. [27].

Overall, cattle manure incorporated into salinized soils was corroborated to relieve salinity, decrease buck density, and stimulate root development. Straw mulching also has the advantage of improving salinity via 3-year implementation. Combined application of cattle manure mixing and maize straw mulching showed the most significant motivating impact on soil physicochemical properties, crop growth, and water use efficiency, followed by cattle manure and maize straw, respectively. Despite persistent farmland management for at least three years to obtain acceptable soil physicochemical properties, cattle manure application combined with the straw mulching method recommended in this study is low cost and reproducible, which is conducive to realizing coastal salinized soil reclamation and crop output on a larger scale. The results confirm our hypotheses and give a quantitative interpretation in comparison to local traditional agronomic practice.

5. Conclusions

In this study, the results indicate that manure incorporation and straw mulching application had individual and interactive influences on soil physicochemical properties, particularly in the top rhizosphere. Cattle manure incorporated into saline soil resulted in an increase in SOM and a decrease in soil EC. Straw mulching shaded soil and a significant decrease in EC was observed after 3 years of maize cultivation. The results demonstrate that straw mulching is not an immediate approach, and at least three years are required.

The combined application of cattle manure incorporation and straw mulching (CM + SM treatment), associated with the highest maize yield and water use efficiency, is recommended to popularize the coastal salt-affected lands. Firstly, the better integrated effects could make the CM + SM treatment more competitive, especially in areas with sufficient water or low salt stress. Secondly, straw mulching on the field surface can be completed efficiently by agricultural machinery during maize harvesting, which can eliminate the environmental problems caused by the evaporation via exposed soil and straw burning.

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