Effect of Sesbania and Triticale Rotation on Plant Characteristics and Soil Quality in Coastal Saline-alkaline Land: A Two-Year Field Experiment

Chunxiao Yu,[a,b] Guangmei Wang,[a,b,]* Xiaoling Liu,[a,b] Haibo Zhang,[a,b] Qian Ma,[a,b] Hanwen Liu,[a,b] Yi Zhang,[a,b] and Hongxiu Li [c]

Soil salinization and nutrient deficiency limit agricultural production in the Yellow River Delta region. This study investigates the green manure-forage grass rotation on soil quality and productivity. A two-year field experiment was conducted to investigate the effects of different varieties of *Sesbania cannabina* and x*Triticosecale* Wittm rotations on soil properties, biological characteristics, and adaptability in coastal saline-alkali land. Four cropping rotation systems were set: Gaoyuan 2 - Lujing 2 (G2L2), Gaoyuan 2 - Lujing 5 (G2L5), Gaoyuan 1640 - Lujing 2 (G1640L2), and Gaoyuan 1640 - Lujing 5 (G1640L5). The G2L5 rotation demonstrated superior enhancement of soil quality. The soil organic matter increased by 35.8%, and the soil electric conductivity (CEC) increased by 20.2%. Compared with *T.* Wittm, *S. cannabina* had a significant positive effect on soil physical and chemical properties. *S. cannabina* L5 showed improved performance in mass density, fresh weight of stem, leaf and aboveground part, *etc*. After *S. cannabina* returned to the field, *T.* Wittm G2 had greater plant height, thousand-grain weight, and stem weight, and the yield reached 322 kg per 667 m^2. In conclusion, G2L5 is the recommended planting model in saline-alkali soil. This research offers valuable insight for the efficient planting and sustainable development of coastal saline-alkali land.

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Contact information: a: CAS Key Laboratory of Coastal Environmental Processes and Ecological Remediation, Yantai Institute of Coastal Zone Research, Chinese Academy of Sciences, No. 17 Chunhui Road, Yantai Shandong 264003, China; b: Shandong Key Laboratory of Coastal Environmental Processes, No. 17 Chunhui Road, Yantai Shandong 264003, China; c: Shandong Saline-Alkali Land Modern Agriculture Company, No. 8 Zhihui Road, Dongying Shandong 257347, China;
** Corresponding author: gmwang@yic.ac.cn*

INTRODUCTION

Soil salinization is a global problem involving resources, environment, and ecology. It adversely affects plant growth and development. Most of the developed and utilized saline-alkali lands are medium-low production fields, and agricultural development faces severe challenges. There's an urgent need for innovative agricultural methods and utilization in saline-alkali lands (Setia and Marschner 2013). The coastal zone of the Yellow River Delta region (YRD) has specific characteristics, primarily including harsh environmental conditions, such as high salinity, shallow groundwater, a high evaporation-precipitation ratio, poor drainage, and secondary salinization (Xia *et al*. 2019). These factors limit plant growth in the YRD (Huang 2018). Consequently, restoring and utilizing salinized soil is imperative in the YRD. The forage grass-green manure rotation mode is a potential model in the development of saline-alkali land.

Sesbania cannabina is an annual herb of the Sesbanieae tribe within the Fabaceae family that forms a mutualistic symbiosis with root nodule bacteria and converts atmospheric nitrogen, which increases the humus content of soil and decreases the salt content (Becker and George 1995; Mahmood *et al*. 2008). *S. cannabina* is widely used as a green manure to improve rice yield and increase soil fertility (Rao *et al*. 2000; Zotarellia *et al*. 2012). *S. cannabina* as a fallow crop, then inorganic N fertilizer result in greater preseason topsoil nitrate-N than following unfertilized sole maize. The plant-based materials can decrease soil bulk density, which promotes soil drainage, and rinsing away some of the alkalinity by rainwater, thus providing a lower pH level (Ikerra *et al*. 2001; Ma *et al*. 2021). The residual effects of *S. cannabina* result in additional grain production of 1.2 t ha^{-1} of rice (+26.4%) and 0.5 t ha^{-1} of wheat (+24.1%) each year (Gill *et al*. 2000). Sesbania can grow in moderate and severe saline soil; it reduces the soil salt content and increases the soil organic matter, total N, available P, and available K contents (Zhu *et al*. 2021).

Triticale (x*Triticosecale* Wittm. ex A. Camus [*Secale* × *Triticum*]), is a new species artificially combined from species of *Secale* and *Triticum* by intergeneric sexual hybridization and hybrid chromosome doubling according to USDA plant database (https://plants.usda.gov/home/plantProfile?symbol=TRITI2); it is a potential dual-purpose crop for grain and forage, and it yields higher biomass than wheat (Royo *et al*. 1993). Triticale combines the high yield potential and good grain quality of wheat with disease and environmental tolerance of rye, which is particularly suitable for marginal environments, especially in acid-salinity or drought-prone soils (Mergoum *et al*. 2009). It has high biological yield, strong adaptability, and disease and saline resistance, and rarely needs pesticides during the whole growth period. Triticale is easy to realize green high-quality feed production and is now a well-established crop internationally, being used for food, feed, grazed or stored forage and fodder, silage, green feed, and hay (Anil *et al*. 1998). Yield varies with species and developmental stage at harvest, and a key factor influencing grain yield after early cutting is the number of spikes that develop (Royo *et al*. 1993). Drought and salt stress reduce the yield of *T*. Wittm, but increasing fertilizer improves its yield and quality (Fernandez-Figares *et al*. 2000). Given the performance of yield and feeding quality, it is recommended that the variety Zhongsi 237 be harvested as fresh or hay forage from the elongation stage to the booting stage (Zhu *et al*. 2010). However, the research of *T*. Wittm mainly focuses on the plant characters, rather than planting effect and applicability on saline-alkali soil.

S. cannabina and *T*. Wittm are two important crops suitable for coastal saline-alkali land. Forming an efficient rotation system would improve the productivity and physical condition of saline soil. *S. cannabina,* which serves as a pioneer crop in the improvement of saline soil, interplants green manure crops and grain fertilizer to augment soil fertility and grain crop yield*. T*. Wittm planting provides a novel approach to developing animal husbandry on saline-alkali lands. This study evaluated the effect of two kinds of *S. cannabina* and *T*. Wittm on fresh and dry mass and soil basal chemical properties. It is hypothesized that the rotation of different forage species and green fertilizer would affect their biological characteristics and soil improvement (Fig. 1).

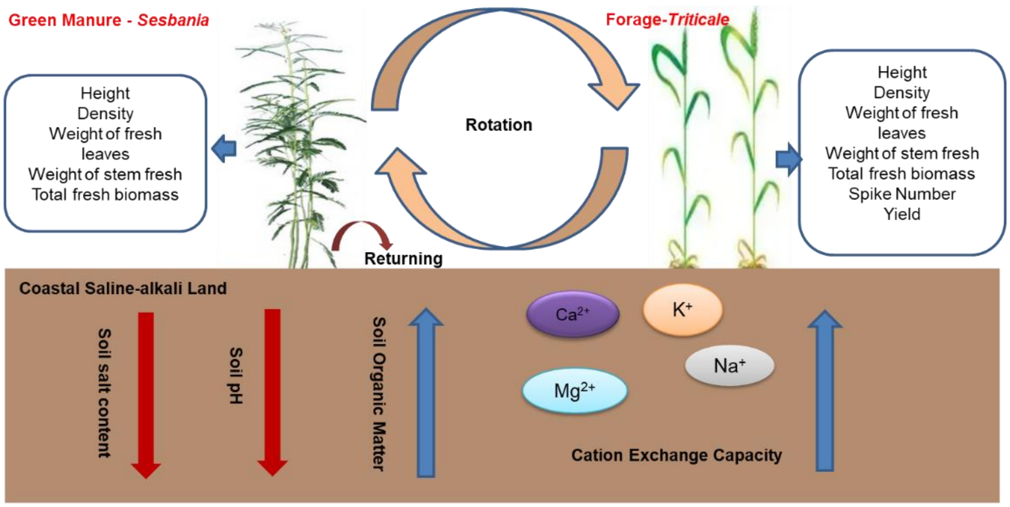

Fig. 1. Diagram showing the effect of *S. cannabina* and *T*. Wittm on soil properties

EXPERIMENTAL

Experimental Site

The experiment was conducted at the Saline-alkali Farmland Ecosystem Observation and Research Station in YRD, Yantai Institute of Coastal Zone, Chinese Academy of Sciences, in Dongying City, Shandong Province (37°32′ N, 118°65′ E), from 2019 to 2021 (Fig. 2).

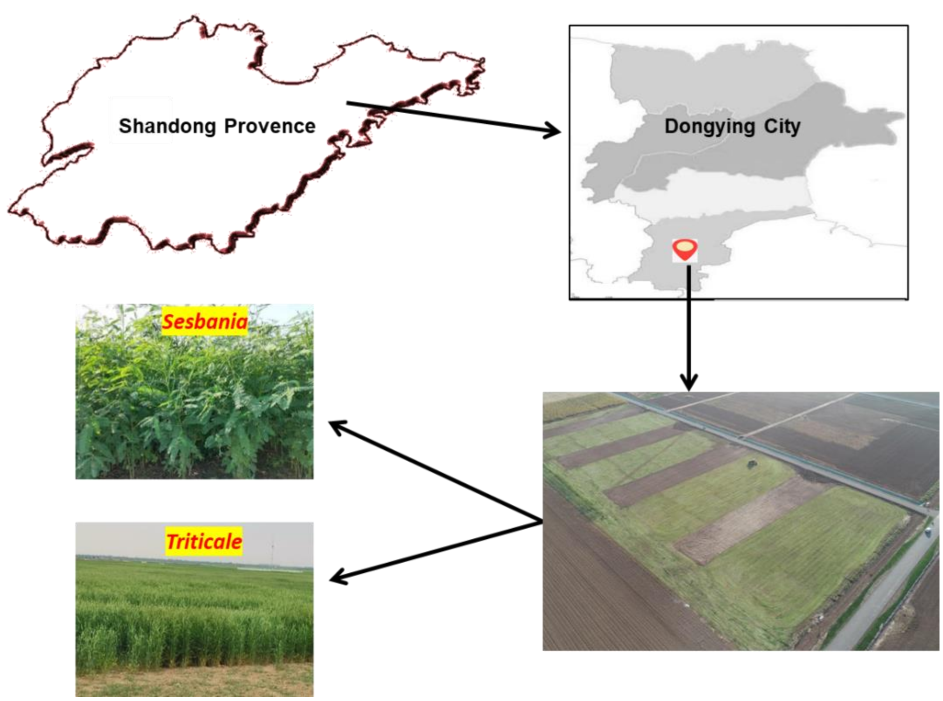

Fig. 2. Test site information

The research station is located in the Yellow River Delta, with a warm temperate monsoon climate. The average annual temperature is 13.5 °C and annual average precipitation is 700 to 800 mm, 80% of which falls concentrated from July to November (Fig. 3). The soil type is a silty loam texture (USDA classification), which is composed of 66.31% clay, 8.45% silt, and 25.24% sand. The experimental plot properties were as follows: soil electric conductivity (EC): 225.8 μS/cm, soil pH: 8.08, soil organic matter: 11.49 g kg^{-1}, and soil cation exchange capacity (CEC):13.29 cmol kg^{-1}.

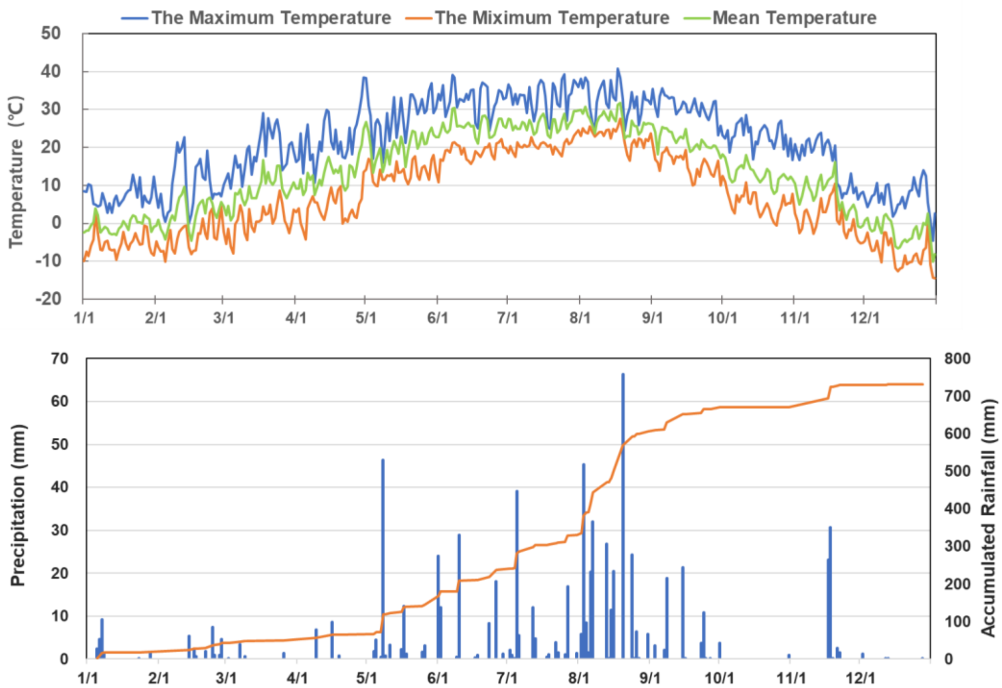

Fig. 3. The daily temperature and precipitation conditions in 2020

Experimental Design

Green manure *S. cannabina* and grass *T*. Wittm were chosen for crop rotation experiments. Two *T*. Wittm varieties of the Gaoyuan series (Gaoyuan 2 (G2) and Gaoyuan 1640 (G1640)), and two *S. cannabina* varieties of the Lujing series (Lujing 2 (L2) and Lujing 5 (L5)) were chosen. The selected *S. cannabina* and *T*. Wittm varieties have similar plant characters and certain salt tolerance. The two kinds of plant have a good connection for rotation and are suitable for growing in the Yellow River Delta region. There were four cropping rotation systems with four replicates: G2L2, G2L5, G1640L2, and G1640L5. Each plot was 60 m×20 m and spaced 1 m apart. The experiment was carried out at the Yellow River Delta Saline-alkali Farmland Ecosystem Observation and Research Station from 2019 to 2021.

T. Wittm (G1640 and G2) was sown on October 24, 2019 and October 19, 2020, with a sowing amount of 14 kg $667m^{-2}$, row spacing of 18 cm, depth of 3 to 4 cm, and diammonium phosphate was applied at 30 kg per 667 m^2 for basal application. The aboveground biomass of *T*. Wittm was harvested and removed all on June 19, 2020 and June 10, 2021. *S. cannabina* (L2 and L5) were sowed after *T*. Wittm was harvested in June 22, 2020 and June 20, 2021. The sowing amount was 1 kg $667m^{-2}$, row spacing was 60 cm, plant spacing was 30 cm, and sowing depth was 3 cm, *S. cannabina* (L2 and L5) was returned to the fields with 0-20 cm at the flowering stage on September 13, 2020 and September 15, 2021. Field management and planting practices was consistent with local practices.

Methods

Plant samples and aboveground biomass of *S. cannabina* and *T*. Wittm were taken with 1×1 m PVC pipes in each plot with four duplicates before harvest and returning to the field, on September 12, 2020, June 21, 2021, and September 14, 2021, especially, and the aboveground part of the plant was cut uniformly. After returning to the laboratory, the biomass and plant characteristics of *S. cannabina* and *T*. Wittm were measured, including plant height, density, weight of fresh leaves and stems, and the dried weight. Half of the fresh grass samples were dried at 105 °C for 30 min and then dried at 65 °C until the dry weight was constant. The dry weight of the fresh grass samples was obtained, and the fresh-dry ratio was calculated. The other half was air dried at room temperature, then weighed to obtain the yield. Meanwhile, 0 to 20 cm soil samples were taken in each plot before returning and harvesting on September 12, 2020 and June 21, 2021, and they were air-dried in the shade to determine the basic physical and chemical properties.

Soil pH and EC were measured in a 1:5 soil–water solution with a conductivity meter (DDS-11A) and pH meter (FE20K) after shaking for 1 h in an end-over-end shaker (Yu *et al*. 2014). Soil organic matter was determined by oxidizing organic matter in soil samples with $K_2Cr_2O_7$ in concentrated sulfuric acid for 30 min followed by titration of the excess $K_2Cr_2O_7$ with ferrous ammonium sulphate (Lu 2000). The cation exchange capacity (CEC) of soils was measured by the ammonium acetate method (pH=7), and the exchangeable base was measured by atomic absorption spectrophotometry (exchangeable Ca^{2+} and Mg^{2+}) and flame photometry (exchangeable K^+ and Na^+) (Lu 2000).

Statistical Analysis

All data collected were recorded and summarized using Microsoft Excel 2010 (Microsoft, Redmond, USA), and statistical analysis was conducted with SPSS 16.0 software (SPSS Inc., Chicago, USA). One-way analysis of variance (ANOVA) with Duncan’s method was performed for plant characteristics ($P < 0.05$), paired sample T test was used for soil analysis in different years ($P < 0.05$). Origin 2021 (Origin Lab Inc. USA) was used for graphs.

RESULTS AND DISCUSSION

Effects of Rotation on *Sesbania* Characteristics

The plant characteristics of Sesbania, specifically L2 and L5, exhibited noteworthy variation.

Table 1. Comparison of Plant Characteristics among Different *Sesbania* Varieties in 2019

Variety	Plant Height	Density	Weight of Fresh Leaves	Weight of Fresh Stem	Total Fresh Weight
Unit	cm	Plant m^{-2}	kg 667m^{-2}	kg 667m^{-2}	kg 667m^{-2}
L2	252.6±6.0 a	47.6±1.8 b	625.1±48.0 a	2330.7±85.9 a	2955.8±99.4 a
L5	236.2±4.5 b	84.9±4.9 a	482.5±26.9 b	2486.3±72.8 a	2968.8±64.0 a
Note: The data in the table represent the mean ± standard deviation. Lowercase letters represent different significance between Lujing 2 (L2) and Lujing 5 (L5) (*P* < 0.05).					

Plant height and fresh leaf weight of L2 were significantly lower than L5 (P < 0.05, Table 1); however, no significant difference was found in stem fresh weight and total fresh weight (Table 1). Interestingly, the fresh weight of L2 leaves was larger than L5, suggesting it might be more beneficial to use as green fertilizer on saline-alkali land.

The *S. cannabina* of L2 and L5's plant characteristics in 2020 are presented in Fig. 4. The G2L5 and G1640L5 treatments showed significantly higher *S. cannabina* density than G2L2 and G1640L2 (*P* < 0.05, Fig 4A). G2L2 showed significantly higher *S. cannabina* plant height than G1640L5 (*P* < 0.05, Fig 4B), but not significantly different from G2L5 and G1640L2 (Fig 4B).

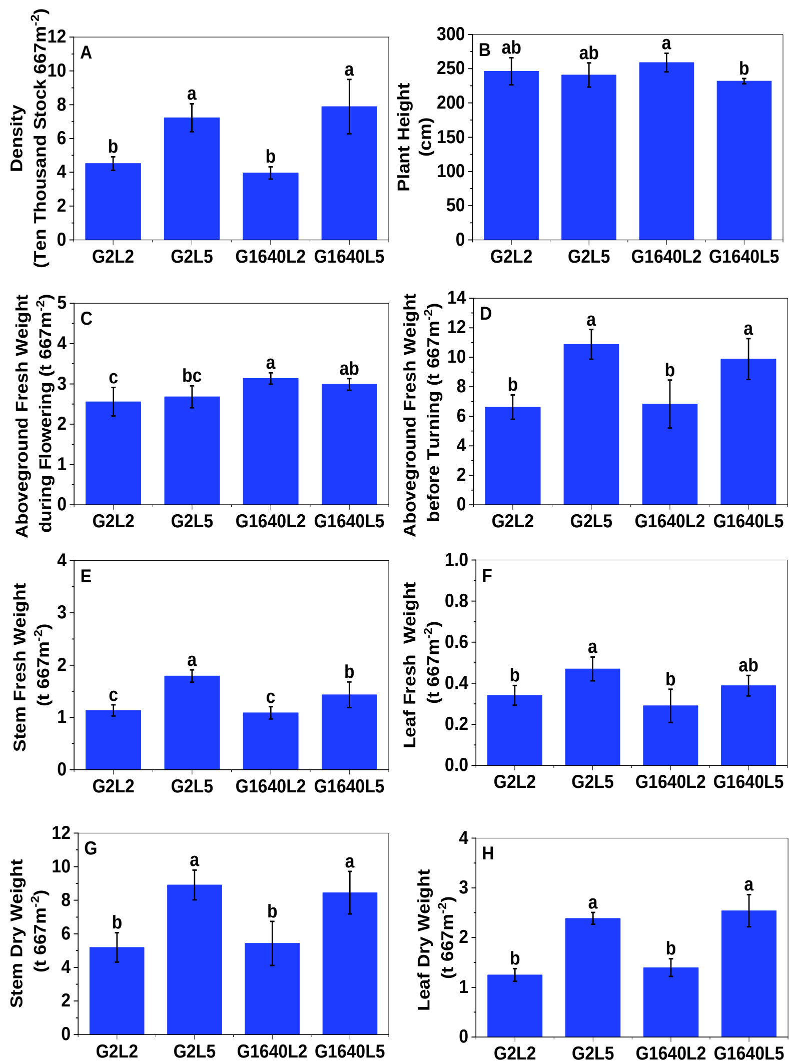

Fig. 4. *S. cannabina* plant characters in 2020. G2L2: Gaoyuan 2 and Lujing 2 rotation; G2L5: Gaoyuan 2 and Lujing 5 rotation; G1640L2: Gaoyuan 1640 and Lujing 2 rotation; G1640L5: Gaoyuan 1640 and Lujing 5 rotation. Lowercase letters represent the significant difference between treatments (P < 0.05).

The G1640L2 treatment demonstrated the greatest fresh weight of aboveground parts at the flowering stage, which was significantly higher than that of G2L2 and G2L5 (P < 0.05, Fig 4C), but there was no significantly difference with G1640L2 (Fig 4C). G2L5 and G1640L5 had the highest fresh weight of aboveground parts before tipping, with a significant difference compared with G2L2 and G1640L2 (P < 0.05, Fig 4D). The leaf fresh and dry weight of G2L5 was the highest and significantly higher than G2L2 and G1540L2 (P < 0.05), while G1640L5 were the second highest, and significantly higher than G2L2 and G1640L2 (P < 0.05), but there was no significant difference between them (Fig 4E, F). Stem fresh weight and stem dry weight showed the same trend, and G2L5 and G1640L5 were significantly higher than G2L2 and G1640L2 (P < 0.05, Fig 4G, H). Overall, L5's population density, fresh leaf and stem weight, fresh weight of aerial parts, and other traits were notably superior to L2, based on *S. cannabina* plant characteristics.

Effects of Rotation on *T*. Wittm Plant Characteristics

The plant height of *T*. Wittm G2L2 was significantly greater than *T*. Wittm G1640L5 and G1640L2 ($P < 0.05$, Fig. 5A), but was not significantly different from *T*. Wittm G2L5 (Fig. 5A). The thousand-grain weight of *T*. Wittm G2L5 was significantly higher than G1640L2 and G1640L5 ($P < 0.05$, Fig. 5B), but G2L2 and G2L5 did not reach significant differences (Fig. 5B). The G1640L5 treatment had the highest spike number, which was significantly higher than the other treatments ($P < 0.05$, Fig. 5C). The spike dry weight of *T*. Wittm G1640L5 and G1640L2 was significantly higher than G2L2 ($P < 0.05$), but there was no significant difference with G2L5 (Fig. 5D).

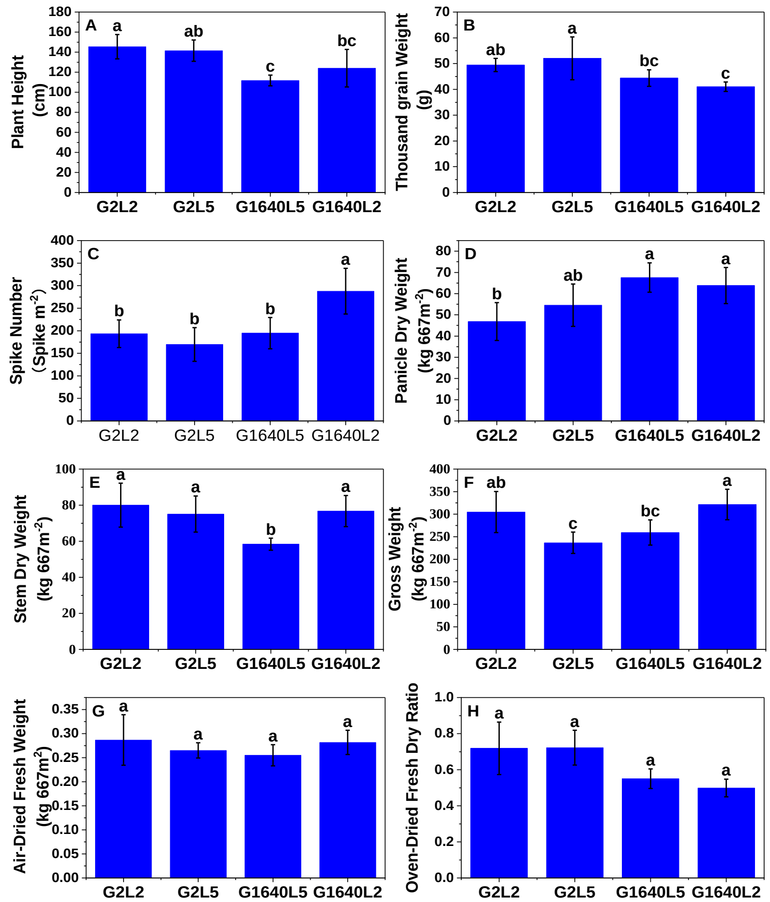

Fig. 5. Plant characteristics of *T*. Wittm in 2021. G2L2: Gaoyuan 2 and Lujing 2 rotation; G2L5: Gaoyuan 2 and Lujing 5 rotation; G1640L2: Gaoyuan 1640 and Lujing 2 rotation; G1640L5: Gaoyuan 1640 and Lujing 5 rotation. Lowercase letters represent different significance between treatments ($P < 0.05$).

Table 2. Comparison of Plant Characteristics and Yield of *T*. Wittm Varieties in 2019

Variety	Plant Height	Tiller Number	Density	Biomass per Plant	Number of Grains per plant	Hundred-grain Weight	Yield
Unit	cm	tillers plant^{-1}	m^2	g	spike plant^{-1}	g	kg 667m^{-2}
G1640	104.2 ±5.6 a	1.9 ±0.1 a	365 ±23 b	32.9 ±4.5 a	15.3 ±2.0 a	4.13 ±0.14 a	235.9 ±26.4 b
G2	108 ±3.5 a	1.7 ±0.1 a	447 ±32 a	25.5 ±2.3 a	14.3 ±1.2 a	3.99 ±0.09 a	413.1±70.3 a
Note: The data in the table represent the mean ± standard deviation. Lowercase letters represent different significance between Gaoyuan 1640 (G1640) and Gaoyuan 2 (G2) (P < 0.05).							

The stem dry weight of *T*. Wittm G1460L5 was the lowest, which was significantly lower than G2L2, G1640L2 and G2L5(P < 0.05, Fig. 5E). *T*. Wittm G1640L2 had the highest total weight, up to 321.51 kg 667m^{-2}, which was significantly higher than G2L5 and G1460L5 (P < 0.05), but there was no significant difference between G2L2 and G1640L2 (Fig. 5F).

There was no significant difference between *T*. Wittm G1640 and G2 in plant height, tiller number, number of grains per plant, hundred-grain weight (Table 2), However, G2's density and yield were significantly higher than G1640 (P < 0.05, Table 2), indicating G2's superior adaptability to coastal saline-alkali land based on *T*. Wittm plant traits in 2019. According to the plant characteristics of *T*. Wittm, G2 had better plant height, hundred-grain weight and stem weight, which was beneficial to the dry matter accumulation of the aboveground part of *T*. Wittm. G1640 was beneficial to the increase in *T*. Wittm's yield, with the highest panicle number, panicle dry weight and total panicle weight. There was no significant difference in the air-dried and oven-dried fresh drying ratio between the different *T*. Wittm varieties (Fig. 5G, H).

Effects on Soil Physical and Chemical Properties

Soil pH, electrical conductivity, organic matter, and CEC did not show significant differences among different *S. cannabina* and *T*. Wittm rotation treatments (P > 0.05, Fig. 6). Nevertheless, two years of soil samples revealed significant differences in soil pH (P < 0.05, Fig. 6A). Compared with 2020, G2L2, G2L5, G1640L5, and G1640L2 increased the soil pH by approximately 13.3%, 13.0%, 13.9%, and 12.7%, respectively; the soil electrical conductivity increased by 7.9%, 70.3%, 76.0%, and -6.0%, respectively; the soil organic matter increased by 7.6%, 35.8%, 10.0%, and 15.9%, respectively; and the soil CEC content increased by 0.9%, 20.2%, -8.6% and 8.4%, respectively. The G2L5 model demonstrated superior performance in terms of enhancing soil organic matter and CEC, but it also increased soil electrical conductivity. The G1640L2 treatment was the second best, which had a good effect on improving soil organic matter, soil CEC and a certain salty reduction effect. Nonetheless, the G1640L5 model is unsuitable for coastal saline-alkali land.

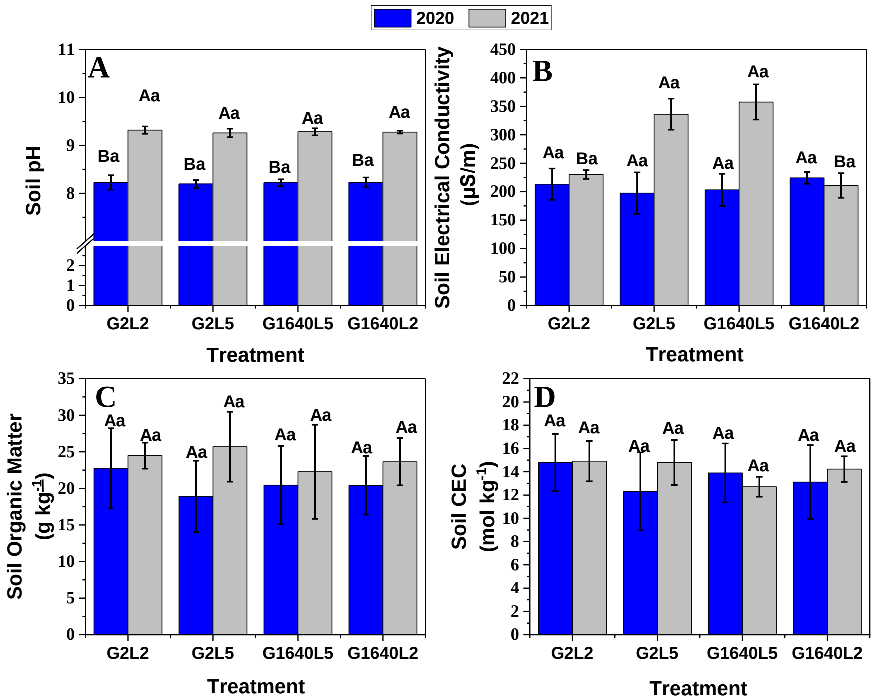

Fig. 6. Soil pH (A), electric conductivity (B), organic matter (C) and CEC (D) indicators after two years of planting. G2L2: Gaoyuan 2 and Lujing 2 rotation; G2L5: Gaoyuan 2 and Lujing 5 rotation; G1640L2: Gaoyuan 1640 and Lujing 2 rotation; G1640L5: Gaoyuan 1640 and Lujing 5 rotation. In the figure, uppercase letters represent the significant difference of soil indexes in different years under the same treatment (P < 0.05), and lowercase letters represent the significant difference between different treatments in the same year (P < 0.05).

Correlations between Plant Characteristics and Soil Indicators

Correlations of different *Sesbania* varieties on soil physical and chemical properties are shown in Fig. 7. The *Sesbania*'s gross dry weight was significantly positively correlated with soil pH and EC, and soil pH and EC were positively correlated (P < 0.05, Fig. 7), factors known to affects fertility in fields (Akgün *et al*. 2011). Studies also confirmed that applying agricultural organic wastes reduced soil's pH value, fostering a conducive environment for microbial activities, enhancing microorganism abundance, and accelerating the process of organic material decomposition, thereby increasing soil nutrients (Liang *et al*. 2005). Coupled with the interaction of the microorganism, *S. cannabina's* adaptability to salt stress environments is further heightened (Ren *et al*. 2018). Especially due to the appropriate supply of water and temperature in summer promoting *S. cannabina* growth and salt tolerance from July to September (Fig. 3), there was a positive correlation between soil CEC and soil organic matter (Fig. 6). EC was closely correlated with plant growth, especially with the total dry weight and stem dry weight of *Sesbania* (P < 0.05, Fig. 7). The variety of *S. cannabina* had a great influence on the plant characteristics (Fig. 7). Plant height was positively correlated with plant dry weight and stem dry weight. Plant dry weight was affected by plant height, thousand-grain weight and fresh weight, and then affected the fresh-dry ratio of *Sesbania*, but with spike dry weight, there was a significantly negative correlation. Panicle weight positively contributed to the total weight (P < 0.05, Fig. 7).

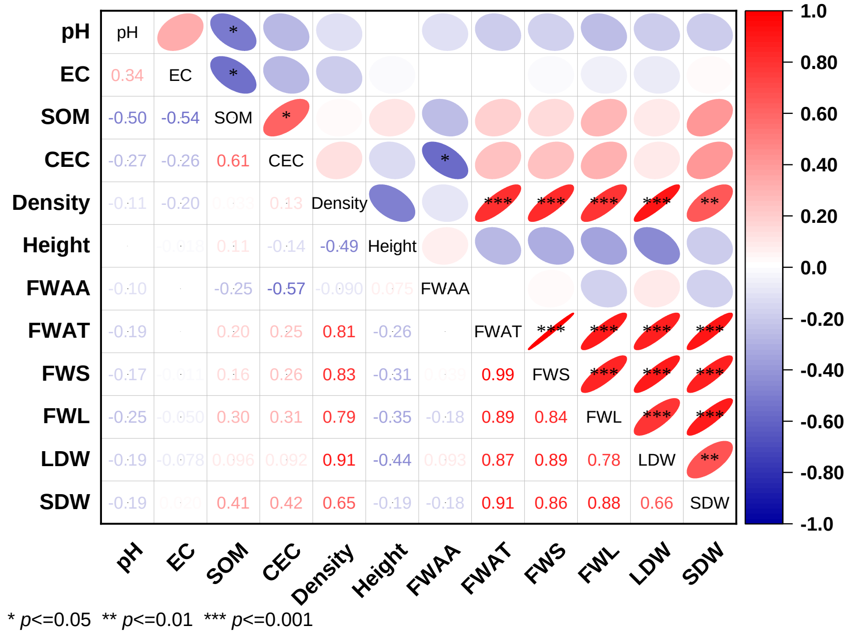

Fig. 7. Correlation diagram of *S. cannabina*'s plant characteristics and soil properties after *T*. Wittm planting in 2020. Note: EC: Soil electric conductivity; SOM: Soil organic matter; CEC: Cation exchange capacity; FWAA: Aboveground fresh weight during anthesis; FWAT: Aboveground fresh weight before turning; FWS: Stem fresh weight; FWL: Leaf fresh weight; LDW: Leaf dry weight; SDW: Stem dry weight. *, ** and *** represent the significant difference at 0.05, 0.01 and 0.001 level, respectively.

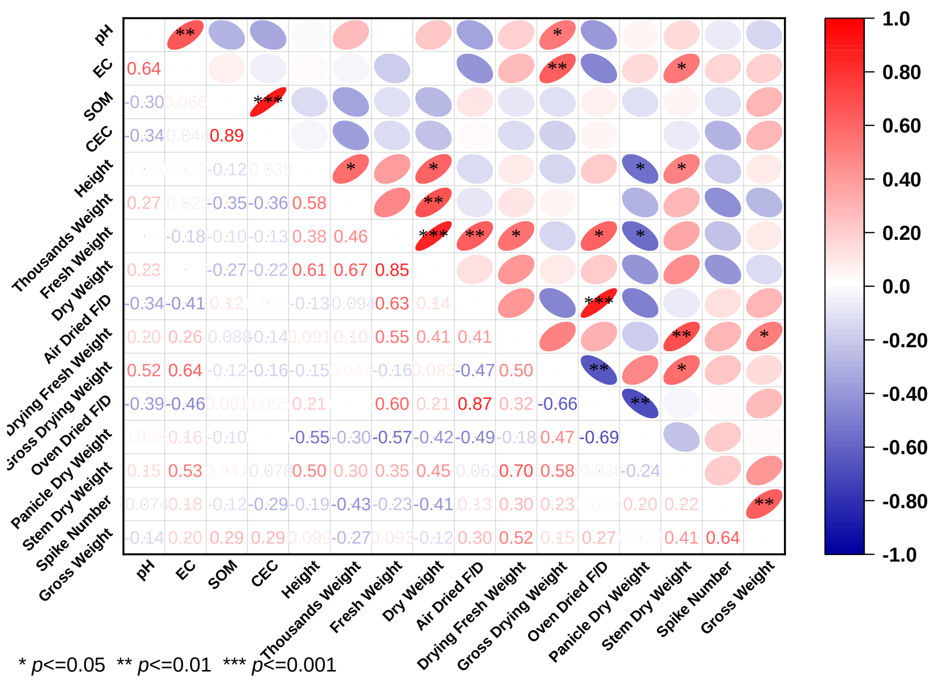

Fig. 8. Correlations between *T*. Wittm plant characteristics and soil properties after *Sesbania* returning in 2020. *, ** and *** represent the significant difference at 0.05, 0.01, and 0.001.

The effects of *T*. Wittm. planting on basic soil physical and chemical properties were investigated. As shown in Fig. 8, soil organic matter was significantly negatively correlated with soil pH and EC contents and significantly positively correlated with CEC, while CEC was significantly negatively correlated with aboveground fresh weight during anthesis. This means that the higher soil organic matter hindered soil pH and conductivity, while the increase in soil cation exchange capacity, which was beneficial for increasing biomass and soil amendment in the YRD saline-alkali soil. Research has shown that soil pH decreases, whereas soil cation exchangeable capacity increases, regardless of the type of organic material used (Yu *et al*. 2014). The increase in salinity and alkalinity hindered the activity of soil microorganisms and then reduced the decomposition of organic matter returned to the field, which is not conducive to the improvement of soil organic matter (Yan *et al*. 2015). *T*. Wittm density is the deciding factor and extremely influenced the fresh weight of aboveground parts before turning, fresh weight of stem, fresh and dry weight of leaf and stem dry weight, and biological indicators of crop plant character are significantly correlated. However, different *S. cannabina* returning to the field, *T*. Wittm planting did not affect soil properties significantly (Fig. 7, Fig. 8), while research showed that salinity decreased the net photosynthesis and transpiration rates of the cereals (Morant-Manceau *et al*. 2004), which was different from the present research. The mean reason may be influenced by sampling times, due to the rainy season, and salinity decreased with salt follows water running off.

Effects of *S. cannabina and T*. Wittm Varieties on Soil Physical and Chemical Properties

Soil pH is one of the basic soil-forming conditions that characterizes the chemical properties of soil and determines the fertility of the soil (Zhang *et al*. 2017; Chen *et al*. 2020). Two-factor variance analysis of soil pH, electrical conductivity, organic matter, and CEC showed that different cropping systems had significant effects on soil pH but had no significant effects on soil conductivity, organic matter and CEC (Table 3).

Table 3. Two-variate Test of Crop Species and Year on Soil Physical and Chemical Indexes

Dependent Variable	Mean Square	F	Significance
Soil pH	9.106	1.117E3	0.000***
Soil Electric Conductivity	1916.269	2.940	0.099
Soil organic matters	92.242	4.193	0.052
Soil CEC	3.200	0.602	0.445
Crop Variety	0.182	1.045	0.406
Year	75.120	3.944	0.000***
Crop Variety * Year	0.293	1.687[b]	0.187
Note: There were 4 replicates per treatment (n=16), and the Duncan method was chosen for the significant difference test (****P* < 0.001, ***P* < 0.01, * *P* < 0.05).			

Xiao *et al*. (2018) reported that the pH level is negatively correlated with soil nutrient availability. This may be because *S. cannabina* had a better N accumulation potential, especially NH_4^+-N and NO_3^--N (Becker and George. 1995). The change in growing season and precipitation affected the change in soil pH (Fig. 3). At the same time, the interaction analysis between cropping system and planting years showed that cropping system had no significant effect on soil properties, but different planting years had a significant effect on soil properties. The results showed that climate and other external factors have a greater influence on soil properties than planting varieties.

The optimization of the green manure-pasture model is beneficial for the sustainability of agricultural systems, and long-term study are necessary for saline-alkali soil improvement.

CONCLUSIONS

1. The *Sesbania cannabina* and *Triticale* Wittm (G2L5) rotation improved soil quality, especially in soil organic matter and soil cation exchange capacity, soil pH, and electrical conductivity (EC) was not significantly affected.
2. The variety Lujing 5 exhibited superior performance in population density, fresh weight of stem and leaf, fresh weight of aboveground part, *etc*.
3. When *S. cannabina* was used as green fertilizer and returned to the field, G2 had better plant height, thousand-grain weight and stem weight, facilitating the dry matter accumulation of *T*. Wittm, and achieving a yield of 321.51kg 667m^{-2}.
4. The G2L5 variety was preferable adaptability and deserved widely promoted in coastal saline-alkali land. And the impacts and potential benefits generated by improving saline-alkaline land through sustainable agricultural systems need to be further detected.

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