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Experimental Study on the Potential Use of Bundled Crop Straws as Subsurface Drainage Material in the Newly Reclaimed Coastal Land in Eastern China

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Abstract: Initial land reclamation of the saline soils often requires higher drainage intensity for quick leaching of salts from the soil profile; however, drainage pipes placed at closer spacing may result in higher cost. Seeking an inexpensive degradable organic subsurface drainage material may satisfy such needs of initial drainage, low investment and a heathy soil environment. Crop straws are porous organic materials that have certain strength and endurance. In this research, we explored the potential of using bundled maize stalks and rice straws as subsurface drainage material in place of plastic pipes. Through an experimental study in large lysimeters that were filled with saline coastal soil and planted with maize, we examined the drainage performance of the two organic materials by comparing with the conventional plastic drainage pipes; soil moisture distribution, soil salinity changed with depth, and the crop information were monitored in the lysimeters during the maize growing period. The results showed that maize stalk drainage and the rice straw drainage were significantly ($p < 0.05$) more efficient in removing salt and water from the crop root zone than the plastic drainage pipes; they excelled in drainage rate, leaching fraction, and lowering water table; and their efficient drainage processes lowered salt stress in the crop root zone and resulted in a slightly higher level of biomass. The experimental results suggest that crop straws may be used as a good organic substitute for the plastic drainage pipes in the initial stage land reclamation of the saline coastal soils.

Keywords: subsurface drainage; soil salinity; salt leaching; maize stalk; rice straw

1. Introduction

Development of the coastal mudflat area for agricultural use has been a continuing effort in eastern China. It has been an important regional practice to offset the negative impact of fast population growth and urbanization progress on farmland shortage [1–3]. However, the newly reclaimed coastal mudflat areas generally have brackish shallow groundwater table and high content of salt in the soils, which impede the growth of plants [4]. To make the soils suitable for crop production, land drainage is required to lower the water table and leach the soluble salts from the soil profile. Subsurface drainage with perforated plastic pipes has been a common practice worldwide to control groundwater table or to remove salts from soil profile through leaching irrigation and drainage [5–7]. By lowering water table, subsurface drainage also improves soil aeration at sub-layers and promotes water infiltration, leading to improved development of crop roots and higher crop yields [8,9].

The eastern coastal area of China generally has a humid climatic condition with annual rainfall above 800 mm [10]. Salt leaching in humid area can be accomplished by rainfall when proper drainage system is in place. In the initial stage of reclaiming the saline soils, however, higher drainage intensity, or closely spaced drainage pipes is often required to speed up the salt leaching, or the soil remediation process [11–14]. However, as the soil salinity decreases with the cultivation and the drainage leaching processes, drainage intensity should be lowered to encourage more rainfall storage in soil for improved water use efficiency [15] and prevent losses of soil nutrients from excessive leaching [16,17]. That is, when the soil salinity is lowered to a safe level, high intensity drainage becomes unnecessary. Additionally, the installed underground pipes may become redundant and wasteful considering the relatively high initial cost of subsurface drainage system construction. Therefore, seeking for an inexpensive material that can automatically degraded over time to replace the traditional subsurface plastic drainage facilities for initial land reclamation use may lower the cost for agricultural development and be more environmental friendly in the coastal region.

As byproducts of crop production, straws are traditionally burned after harvest to clear the limited crop fields more quickly with little cost. The smoke emissions from straw burning have been reported as a cause of air pollution in many developing countries [18–20]. It has been blamed as one of the causes for the heavy smog in China during the harvest season [21,22]. To explore their potentials uses, crop straws have been studied in many aspects to discover their applications, such as surface mulching to increase soil temperature and retard the loss of moisture from the root zone [23–25]. Crop straws/stalks are important organic fertility resources for soils [26]; straw interlayer, i.e., straw or mixture of straw and soil buried at different soil depth, has been studied as an agronomic measure to increase moisture storage and organic matter contents, and reduce soluble salt concentrations in the soil during the growing season [27].

Because crop straws are porous organic materials that have certain strength and endurance [28–30], they may be used as a temporary subsurface drainage material when buried underneath crop fields. For the above mentioned land reclamation of the saline coastal soils, crop straws might be an ideal candidate for the initial stage subsurface drainage material. The natural degradation of the organic material in later stage is desired when the soil salinity is under control through the leaching process. Existing research on the crop residue reuses mainly focused on using straws or stalks as isolation layers to reduce soil water loss or to avoid soil salinity buildup; little attention has been paid to the potential use of crop straw as an organic alternative for short term subsurface drainage material.

In this study, we explored the potential of using crop straw (maize stalk and rice straw) as subsurface drainage material. Our hypothesis was that the bundled crop straw buried underground may act like drainage pipes that remove soil water and the dissolved salts in the saline coastal soils in the initial land reclamation stage; their gradual decomposition would be desired, as the soils become salt free later and the field drainage intensity needs to be reduced. The decomposed crop straw may become soil amendments left in the crop fields. As the first step of the research, in this paper, we examined the drainage performance of the maize stalks by comparing it with the conventional corrugated plastic pipes through a lysimeter experiment. The specific objectives of this study were to:

(1) Compare the soil moisture distributions in saline soils as affected by subsurface drainage with bundled maize stalks, rice straws and perforated plastic pipes;
(2) Examine drainage effect of the bundled maize stalks and rice straws in lowering water table and discharge drainage water as compared to the perforated plastic pipes; and
(3) Compare the effects of the three drainage materials on maize yield and root growth to confirm applicability of the straw drainage in early stage of land reclamation of the saline coastal soils.

2. Materials and Methods

2.1. Site Description and Experimental Setup

The experimental study was conducted in 2016 at the testing ground of the Key Laboratory of Efficient Irrigation-Drainage and Agricultural Soil-Water Environment in South China, Ministry of Education in Nanjing, China (118°60′ E, 31°86′ N). The area has a mean annual temperature of 15.3 °C, and a subtropical monsoon climate with hot, wet summers and dry, windy winters [31]. An automated weather station at the experimental site recorded the daily air temperature, precipitation, wind speed, relative humidity, and solar radiation during the study period. Twelve lysimeters of 2.5 m × 2 m × 2 m (length × width × depth) were employed for the experiment. Figure 1 presents a sketch of the lysimeter system. As displayed in Figure 1c, there are multiple drainage outlets through the concrete wall of each lysimeter, subsurface drainage discharges were collected through these outlets using plastic measuring buckets (Figure 1g) in the underground gallery. The water table in each lysimeter can be observed in manometers (Figure 1b) that are attached to the lysimeter wall underground.

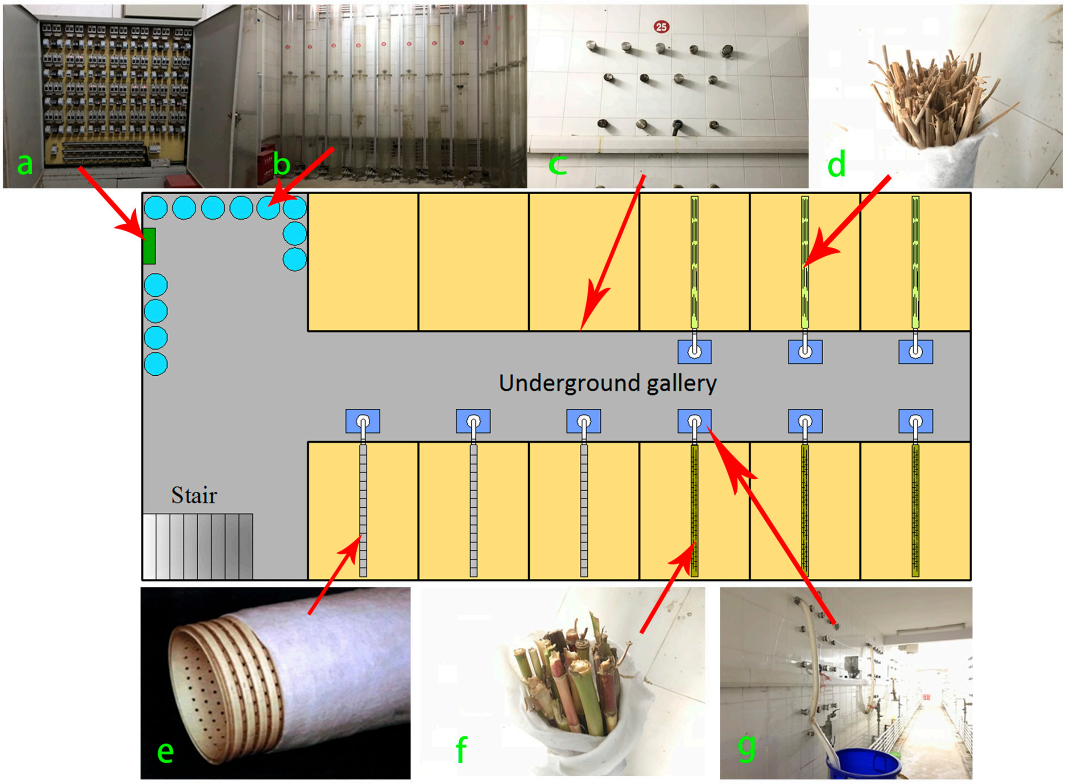

Figure 1. The experimental setup of the 12 drainage lysimeters (including three replicates for each treatment). The components are: (**a**) the regulating switch; (**b**) manometers; (**c**) drainage outlets; (**d**) the rice straw bundle; (**e**) the perforated plastic pipe; (**f**) the maize stalk bundle; and (**g**) the drain flow collection bucket.

During the experiment, the groundwater level was set at 1.2 m from the soil surface, which is based on the average condition of water table depth in the eastern coastal areas of China [32]. Figure 2 shows that the water table in each lysimeter was maintained using a Marriotte bottle system, and an electronic sensor detects water table fall and turns on the water pump automatically to replenish water to the lysimeter. When the water table depth in each lysimeter falls below 1.2 m as result of the crop evapotranspiration, the electronic sensor would turn on the pump to raise the water table up to 1.2 m from the soil surface and the amount of groundwater supply to the plots was recorded using a water meter.

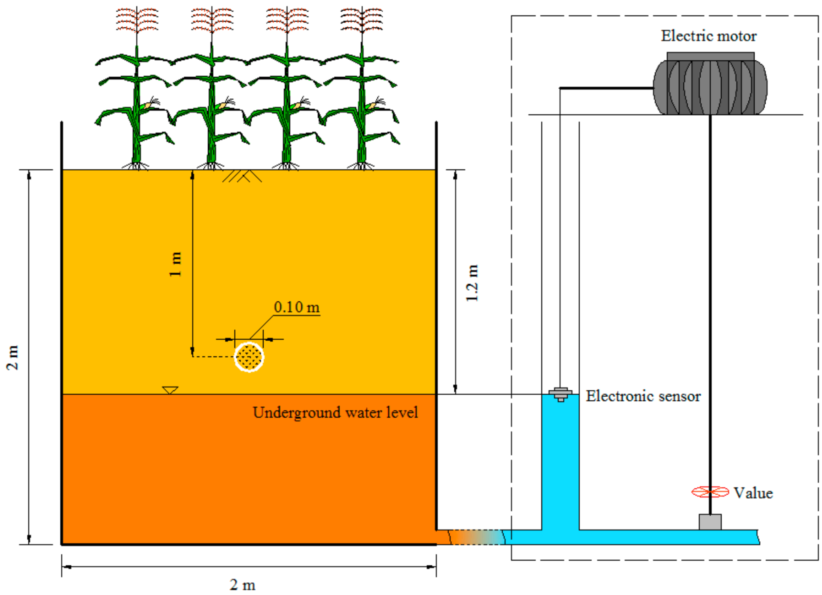

Figure 2. Sketch of the experimental lysimeter profile.

The lysimeters were filled with soil excavated from a newly reclaimed land area in eastern coast of China (Dongtai City, Jiangsu Province, China). The soil was air dried and passed through a 5-mm sieve before filling into the lysimeters. The soil particle analysis showed that the lysimeter soil consists of 22.47% clay (0–0.002 mm), 36.19% silt (0.002–0.02 mm) and 41.34% sand (0.02–2 mm). The soil can be classified as loam based on the USDA soil texture triangle. The measured average soil salinity ($EC_{1:5}$) was 2.07 dS/m and the soil pH was 8.11. The measured soil porosity was 47.54% and the bulk density was 1.34 g·cm^{-3}. The measured field capacity of the 0–60 cm root zone soil was 33%.

Perforated corrugated high-density polyethylene pipes were chosen as the conventional drainage facilities. The pipes were 10 cm in diameter and 180 cm in length, wrapped with nonwoven fabrics. Rice straws and maize stalks were both bundled into conduits of 10 cm in diameter and 180 cm long using plastic ties and enveloped with the same non-woven fabrics. As shown in Figures 1 and 2, all drainage pipes were laid in the middle of each lysimeter along the length at depth of 1.0 m, making the drain spacing as 2 m each.

Maize (*Zea mays* L.) is one of the most widely grown crops in the world. It has been classified as a drought-tolerant crop that is moderately sensitive to soil salinity [33]. Existing studies on maize cultivation showed that water use efficiency, yield and root growth of maize are negatively affected by the soil salinity [34,35]. The maize cultivar (Suyu 29) was sowed on 1 July and harvest on 21 October 2016. Each lysimeter had 24 maize plants with row spacings of 0.40 m and 0.38 m. Maize commonly requires 300–500 mm water during its life cycle under the climate conditions in southeastern China [36]. During the experiment, four fresh water (EC = 0.52 ms/cm) irrigations of 40 mm, 80 mm, 120 mm and 160 mm water were applied separately on 20 July, 16 August, 8 September and 30 September. Irrigation to the lysimeters was controlled by an electromagnetic valve and the amount of irrigation were recorded via a water meter. During the experiment, rainfall effect was excluded by a large automatic rain-shelter that kept all lysimeters free from rainfall. Consequently, the water supply to maize growth was from four irrigation events and groundwater contribution during the entire growing season.

There are four drainage treatments in the experiment, and each treatment was replicated three times, i.e., three lysimeters without subsurface drainage were kept as the control (CK), three lysimeters were installed with the conventional high-density polyethylene plastic drainage pipes (HPD), three lysimeters were installed with the bundled rice straw drainage (RSD) modules and three were installed with the bundled maize stalk drainage (MSD) modules. The irrigation and drainage conditions of all treatments were kept the same.

2.2. Sample Collection and Analysis

To reveal the differences in soil water distribution between the irrigation intervals (around 20 days), the soil water content was monitored 2–3 days after irrigation (i.e., 22 July, 19 August, 10 September and 2 October) and one day before next irrigation or harvest (15 August, 7 September, 29 September and 20 October). Using a soil auger with diameter of 1.2 cm, soil samples were collected at depths of 0–20, 20–40, 40–60 and 60–80 cm at three random locations in each lysimeter; all samples were oven dried at 105 °C to a constant weight to calculate their gravimetric water content (%).

The soil samples for salinity test were taken with the soil auger (40 mm diameter, 90 cm long) at the same layers as the soil moisture tests. The sampling was scheduled for five main growth stages, i.e., seeding stage (19 July), jointing stage (10 August), tasseling stage (31 August), filling stage (12 September) and full ripe stage (29 September). Soil samples were air dried and sieved through 0.5 mm screen; they were then wetted with fresh water (EC of 5~7 μs/cm) before measuring the electrical conductivity of 1:5 soil–water leachate ($EC_{1:5}$) using the DDBJ-350 EC meter (Shanghai INESA Scientific Instrument Co., Ltd., Shanghai, China). All sampling holes in the lysimeters were filled with the surrounding soil after each sample collection.

The groundwater table depth (m) was recorded on an hourly basis during each irrigation event, and the drainage rate (mm/h) was measured one hour after flow started. Water samples were collected with plastic measuring bucket from each treatment during the drainage process, and the drainage water salinity was measured with the DDBJ-350 EC meter.

Upon harvest, three maize plants were harvested randomly for measuring the aboveground biomass and the grain yield in each lysimeter. Plant materials were oven dried at 75 °C to the constant weight. Plant height, stem diameter, dry shoot weight, 100-grain weight and grain yield were measured accordingly. For root length and dry weight measurement, undisturbed soil samples were collected by carefully digging cubic blocks (20 cm × 20 cm × 20 cm) centering a maize plant roots; four soil cubic samples were extracted from one plant at 20 cm depth interval down to 80 cm. After sampling the attached soil was washed out and roots were sieved through a 1 mm screen filter. The clean roots were stored in refrigerator before measurement for root length. A high definition scanner (Epson Perfection V700) was used to generate image files of roots, and WinRHIZO (Regent Instruments Inc., Quebec City, QC, Canada) was used to measure total root length we obtained from each soil cubic core. Roots were then recovered and dried at 75 °C until showing constant weight. The root length density (RLD) (cm/cm^3) was calculated by dividing the total root length (cm) with the volume (cm^3) of the sampling core, and the root weight density (RWD) (mg/cm^3) was calculated by dividing the total root dry weight (g) with the volume (cm^3) of the sampling core.

2.3. Evaluation Methods

The soil moisture variation rate (MSV) during each irrigation interval was calculated by the following equation:

$$\mathrm{MSV} = \frac{\theta_0 - \theta_1}{\theta_0} \quad (1)$$

where θ_0 is the soil gravimetric water content measured 2–3 days after irrigation events, and θ_1 is the soil water content measured one day before next irrigation event or harvest.

The soil desalination rate was calculated with the following equation:

$$S_d = \frac{C_0 - C}{C_0} \times 100\% \quad (2)$$

where C_0 is the initial electrical conductivity ($EC_{1:5}$) in ms/m, and c is the electrical conductivity ($EC_{1:5}$) after crop harvest in ms/m.

The efficiency of subsurface drainage in leaching salt from the soil profile is evaluated with the leaching fraction (LF) calculated with the following equation:

$$\mathrm{LF} = \frac{V_d}{V_i} \times 100\% \quad (3)$$

where V_d is the subsurface drainage discharge collected in the plastic bucket after each irrigation event of certain volume, V_i.

2.4. Statistical Analysis

Significant differences in different soil moisture and soil desalination rate were analyzed using one-way ANOVA, and the differences were considered statistically significant at $p < 0.05$. Duncan's multiple-range test was used for comparisons of means at the 0.05 level of significance ($n = 3$) in terms of plant height, stem diameter, dry shoot weight, 100-grain weight and grain yield. SPSS 20.0 was used for statistical analyses with the collected data (SPSS, Chicago, IL, USA).

3. Results and Discussion

3.1. Variability of Soil Moisture Content

As shown in Figure 3, the soil moisture distribution of the straw drainage treatments generally had a similar trend as that in the plastic pipe drainage treatments under same irrigation management; the average soil moisture along the profile decreased slightly in the following sequence: CK > MSD > RSD > HPD. The soil moisture level in the top 30 cm in the drained plots dropped more quickly than the control plots. Soil water contents all increased with the depth of soil layers or the increased irrigation amount. The soil moisture profiles varied less obviously in the third and the fourth irrigation intervals due to the reduced water requirement of maize in the late growth stages and lower daily evaporation in September and October. Similar results of drainage effects on soil water conservation distribution have been reported by Feng et al. [37] and Chang et al. [38].

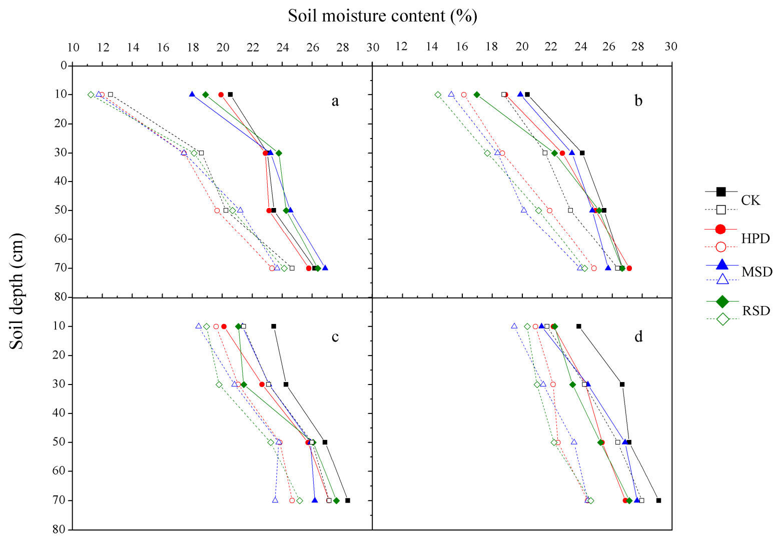

Figure 3. Measured soil water content along depth in different treatment plots during the: (**a**) first irrigation interval; (**b**) second irrigation interval; (**c**) third irrigation interval; and (**d**) fourth irrigation interval. Solid lines represent the water content 2–3 days after irrigation and dash lines represent the water content tested one day before next irrigation event or harvest. (CK is the control plot without subsurface drainage, HPD is the treatment plot with perforated plastic pipes, MSD is the treatment plot with maize stalks, and RSD is the plot with rice straw.)

The variations in soil water content were analyzed for each treatment based on the index of soil moisture variation rate (MSV) for four evaporation periods, during which there were no irrigation or drainage, soil moisture changes were due to evapotranspiration process only. Table 1 lists MSV in different evaporation period and the ANOVA results for the drainage treatments. Considering the low water demand of maize in the seedling stage, the first irrigation application was designed as 40 mm only, which produced no drainage flow in all treatments, so there was no significant ($p > 0.05$) difference among the four treatments. The MSVs for MSD and RSD at the soil layers of 0–20 cm and 20–40 cm were generally higher than that for HPD, and the differences were significant ($p < 0.05$) in the later three periods. However, in the deeper soil layers (40–80 cm), the only significant difference was found at the 40–60 cm layer in the second evaporation period. This showed that subsurface drainage via crop straws removed more soil water than plastic drainage pipes, displaying better soil drainage performance under the irrigation application, especially in the root zone layer (0–40 cm).

Table 1. The average soil moisture variation rate (%) of treatments in four evaporation stages.

Soil Layer (cm)	Treatments	First Evaporation Period (23 July–15 August)	Second Evaporation Period (18 August–7 September)	Third Evaporation Period (10–29 September)	Fourth Evaporation Period (2–20 October)
0–20 cm	CK	38.91% a	7.76% c	6.61% b	7.92% b
	HPD	39.86% a	14.72% b	8.20% b	8.55% ab
	MSD	34.63% a	23.20% a	9.45% a	10.33% a
	RED	40.55% a	15.32% b	10.10% a	9.26% a
20–40 cm	CK	19.07% a	10.33% b	4.74% b	7.11% b
	HPD	23.73% a	17.64% ab	7.65% a	10.15% ab
	MSD	24.86% a	21.28% a	8.12% a	12.23% a
	RED	23.77% a	20.27% a	8.87% a	11.16% a
40–60 cm	CK	13.65% a	8.76% b	3.28% b	2.80% b
	HPD	14.97% a	12.29% ab	7.27% a	9.65% a
	MSD	13.65% a	18.48% a	8.19% a	12.66% a
	RED	14.76% a	16.12% a	10.89% a	12.33% a
60–80 cm	CK	7.60% b	1.16% b	4.37% b	3.91% b
	HPD	9.51% ab	8.70% a	9.03% a	9.34% a
	MSD	11.95% a	7.23% a	10.09% a	11.86% a
	RED	8.49% ab	9.38% a	10.91% a	9.51% a

Note: Values followed by different letters within a column are significantly different at the significance level of 0.05.

3.2. Drainage Performance

Before each irrigation the depth to water table was maintained at constant depth of 1.2 m in all lysimeters, thus the groundwater control system was operated to keep that level by supply water during each evaporation period (Table 2). The first irrigation of 40 mm produced no subsurface drainage, so our analysis focused on the later three irrigation events.

Table 2. Measured irrigation and drainage volume in all treatments.

Treatment	Irrigation Volume (mm)				Groundwater Supply (mm)				Subsurface Drainage (mm)			
	20 July	16 August	8 September	30 September	23 July–15 August	18 August–7 September	10–29 September	2–20 October	20–21 July	16–18 August	8–9 September	30 September–1 October
CK	40	80	120	160	100.66	12.42	7.86	5.96	0	0	0	0
HPD	40	80	120	160	96.19	52.91	33.32	25.83	0	26.69	45.79	74.83
MSD	40	80	120	160	105.28	57.47	36.17	28.04	0	29.42	57.14	93.86
RSD	40	80	120	160	103.11	56.85	35.78	27.73	0	28.21	51.89	84.03

3.2.1. Variation of Water Table Depth and Drainage Rate

Figure 4 shows that the water table rose quickly after irrigation and lowered gradually due to subsurface drainage effect; however, the drainage flow hydrographs showed a relatively symmetrical shape from rise to fall, even though the irrigation amounts were larger in the third and fourth irrigation event. The drainage rate and water table rise among treatments were in sequence of MSD > RSD > HPD for the three different drainage pipes. Regardless of irrigation amount, treatments with HPD, RSD and MSD started to drain when the water table was up to 1.01, 1.11 and 1.06 m, respectively. The crop straw treatment plots started drainage earlier than that of plastic pipes, but the difference in the starting time among different treatments were narrowed by the increasing irrigation amount. Drainage duration (from the beginning to the end of the drainage process) of treatments with MSD and RSD were shorter than those with HPD. Under all treatments, the highest groundwater level was observed at the time when the drainage rate reached the peak value. Liu et al. [39] reported that lowering groundwater level can temporarily increase the rate of infiltration. However, in Figure 4, the peak of water table rise for HPD was delayed comparing with MSD and RSD; the peak values were in the order of HPD > RSD > MSD. The drainage rate in the MSD and RSD plots increased faster than that in the HPD plot before reaching the maximum. This is mainly due to the higher permeability of crop straws, which allowed more soil water flow into the drainage module.

Shallow water table or prolonged periods of waterlogging may cause decreased crop production [40]. Figure 4 shows that subsurface drainage in the MSD and RSD plots occurred more rapidly, in approximately one-third to one-fourth of time of that in HPD. Thus, we can conclude that the higher drainage rate in crop straw treatments may lower water table more quickly after heavy rainfall or large leaching irrigation.

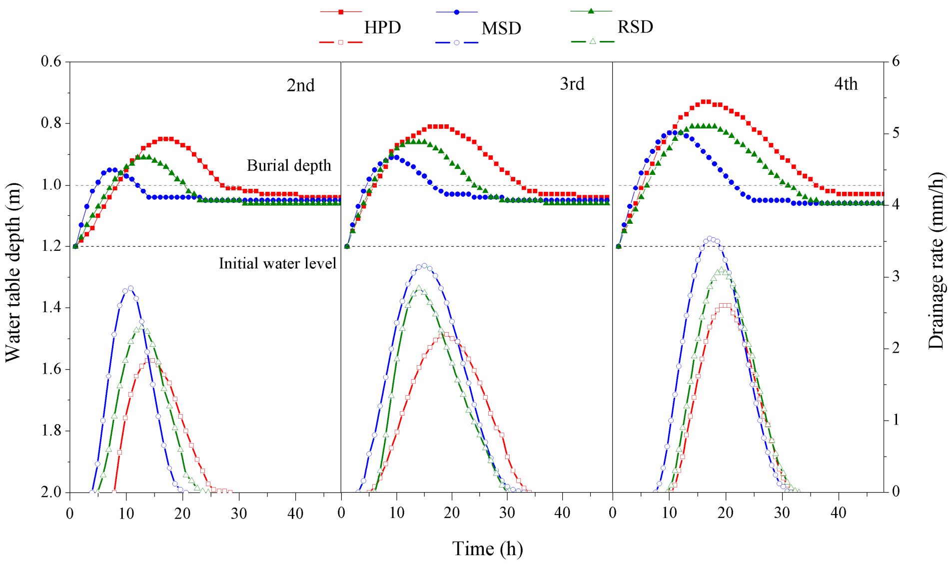

Figure 4. Measured water table fluctuation and subsurface drainage hydrograph from different treatments after three irrigation events (lines with solid markers represent the water table depth, and lines with hollow markers represent the subsurface drainage rate).

3.2.2. Drainage Effect

Figure 5 lists the average drainage rate (ADR), leaching fraction (LF), drainage water salinity (DWS) of different treatments, and the ANOVA results. The ADR and LF were positively correlated with the increasing amount of irrigation water, while the DWS was inversely correlated with the amount of irrigation. The ADR and LF of HPD were significantly lower than that of MSD and RSD in terms of the magnitude of drainage events regardless of the irrigation volume (Figure 5a,b). Higher ADR and LF indicate that the drainage system can discharge more water through the subsurface drains, and consequently leach more salts from the soil profile [41,42]. The higher value in ADR and LF with straw drainage may due to the beneficial effects of the multiple flow paths along the bundled maize stalks or rice straws, resulting in improved soil water transmission along the straw drainage line [43,44]. Although HPD had higher value of DWS than that from MSD and RSD after the second irrigation and the fourth irrigation (Figure 5c), the measured average DWS were 9.21 ds/m for HPD, 9.11 ds/m for MSD and 9.06 ds/m for RSD, showing insignificant ($p > 0.05$) difference among the three drainage treatments.

The above results proved that rice straws and maize stalks can be considered as potential subsurface drainage materials for targeting water table control. They presented similar or better performances to the traditional plastic pipes in salt leaching.

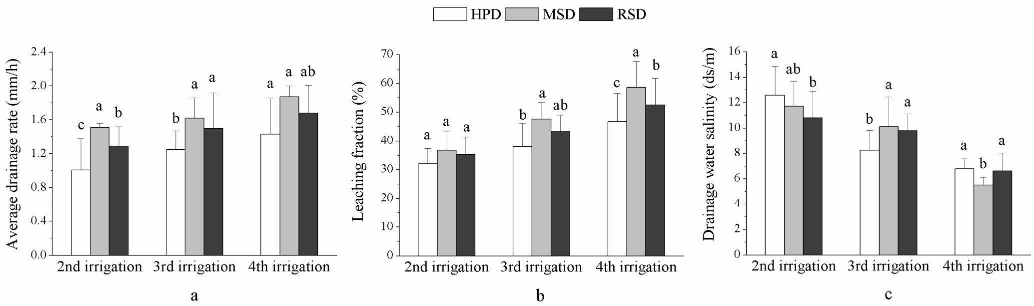

Figure 5. Drainage indices of all treatments during the different irrigation events: (**a**) average drainage rate; (**b**) leaching fraction; and (**c**) drainage water salinity. Different lowercase letters indicate significant ($p < 0.05$) differences among the treatments of the same irrigation event.

3.3. Variations of Soil Salinity

Table 3 lists the ANOVA results for the measured soil salinity ($EC_{1:5}$) from different lysimeters during the five main growth stages of maize during the experiment. The experimental lysimeters were close to each other and they all had similar soil salinity. The measured average soil salinity from all soil samples taken on 19 July 2016 was used as the initial soil salinity. High salinity of soil may lead to salt accumulations on the soil surface if no proper drainage is available for timely discharge of the excess water in the soil profile [45], which is why the soil salinity increased on 10 August, especially at the upper layer (0–40 cm), in all treatment plots. With subsurface drainage, large amounts of salt were removed from the soil profile through the subsurface drainage system in HPD, MSD and RSD treatments. Based on the observations, soil layers at 0–20 cm and 20–40 cm showed significantly lower S_d in MSD and RSD than HPD (Table 3). The low level soil water transfer in MSD limited upward flux and reduced salt movement to the upper layer of soil [46]. The S_d in the treatments of MSD and RSD were 37.04% and 38.90% in the 40–60 cm layer, and 31.86% and 33.21% in the 60–80 cm layer, respectively. These values were not significantly higher ($p > 0.05$) than those with the HPD treatment in the same soil layers (i.e., 39.16% in the 40–60 cm layer and 34.32% in the 60–80 cm layer). These results suggest that the crop straw drainage modules had better desalination performances in the root zone (0–40 cm), and similar desalinization rate (S_d) was observed in the deeper soil layer (40–80 cm) as compared with the HPD.

In general, the soil salinity significantly decreased with the increasing amount of irrigation water, especially in the last two irrigation events (120 mm on 8 September and 160 mm on 25 September) for HPD and the last three irrigations (80 mm on 16 August, 120 mm on 8 September and 160 mm on 25 September) for MSD and RSD. These results indicate that crop straw drainage may produce a relatively higher soil desalination rate with less irrigation water as compared to the traditional plastic drainage pipes. This may attribute to the reason of greater water penetration through the full range of the crop stalks, while the plastic pipes allowed only partial infiltration [47]. In addition, decreasing soil salinity was observed in MSD as the soil depth increased from 0 to 80 cm. This trend was also observed in RSD but less evident to that in MSD, indicating that the maize stalk drainage modules were the most effective in salt leaching due to their improved drainage through the porous stalks that facilitated faster water movement in all directions, leading to faster soil salinity reduction following the infiltration or evaporation process [48].

Table 3. Measured soil $EC_{1:5}$ (ms/m) and salt accumulation with time and soil depth as influenced by the drainage material.

Soil Depth (cm)	Drainage Type	Soil $EC_{1:5}$ (ms/m)									Soil Desalination Rate
		Seeding Stage		Jointing Stage		Tasseling Stage		Filling Stage		Full Ripe Stage	
0–20	CK	193.23(11.23)	First irrigation (40 mm 20 July)	204.67(15.26)	Second irrigation (80 mm 16 August)	199.26(11.85)	Third irrigation (120 mm 8 September)	186.09(8.91)	Fourth irrigation (160 mm 25 September)	175.39(12.43)	9.12 c
	HPD	180.32(12.11)		188.71(17.98)		173.29(9.21)		160.82(10.33)		137.22(7.09)	23.90 b
	MSD	188.05(14.32)		201.69(12.13)		165.52(11.92)		141.65(7.38)		125.34(11.45)	33.35 a
	RSD	194.2(9.90)		211.32(14.71)		176.42(14.23)		154.83(12.58)		138.68(13.87)	28.59 ab
20–40	CK	146.77(12.19)		152.52(8.76)		131.34(12.31)		122.85(14.50)		119.93(10.54)	18.29 c
	HPD	140.21(11.36)		135.52(12.24)		121.62(10.69)		108.26(10.03)		93.97(5.66)	32.98 b
	MSD	132.08(15.92)		129.46(13.01)		113.79(5.78)		99.78(9.72)		82.11(8.72)	37.83 a
	RSD	138.76(12.36)		133.34(8.98)		121.62(13.26)		100.74(7.15)		85.46(10.20)	38.41 a
40–60	CK	137.6(11.56)		134.9(13.87)		129.4(12.14)		119.02(7.99)		108.26(8.53)	21.32 b
	HPD	128.88(7.63)		120.11(8.92)		111.69(10.15)		103.13(6.89)		78.41(6.34)	39.16 a
	MSD	126.59(11.33)		118.98(11.64)		109.75(12.40)		98.21(9.41)		79.7(7.56)	37.04 a
	RSD	134.9(10.49)		139.23(8.56)		121.2(10.67)		105.6(8.88)		82.43(6.67)	38.90 a
60–80	CK	129.56(7.81)		119.43(12.59)		125.64(13.41)		119.62(13.44)		107.35(14.10)	17.14 b
	HPD	117.79(9.68)		109.06(10.98)		103.46(12.57)		89.63(7.90)		77.36(10.34)	34.32 a
	MSD	111.95(8.18)		110.89(9.26)		101.3(11.14)		91.44(13.90)		76.28(6.22)	31.86 a
	RSD	121.86(10.79)		114.45(13.12)		107.89(7.63)		100.3(9.59)		81.5(10.59)	33.12 a

Note: Values in parentheses are the standard deviations. Different letters in the row indicate significant differences at a certain soil layer ($p \leq 0.05$).

3.4. Responses of Maize Growth

As displayed in Figure 6, maize grown in the lysimeters with subsurface drainage had greater root growth as compared to that in CK. This is consistent with the research findings that subsurface drainage affected root length density (RLD) along the soil depth [49,50]. In Figure 6a, RLD reached the maximum in the top 20 cm and the minimum in 40–60 cm in all treatments. Close values ($p > 0.05$) of RLD in HPD, MSD and RSD were found in the 0–40 cm soil layer; significant differences were observed in the 60–80 cm soil layer; the RLD values decreased in the sequence of MSD > RSD > HPD. Owing to the less distribution of root in the 40–80 cm layer, no significant ($p < 0.05$) differences were observed in the average root length density among the three treatments.

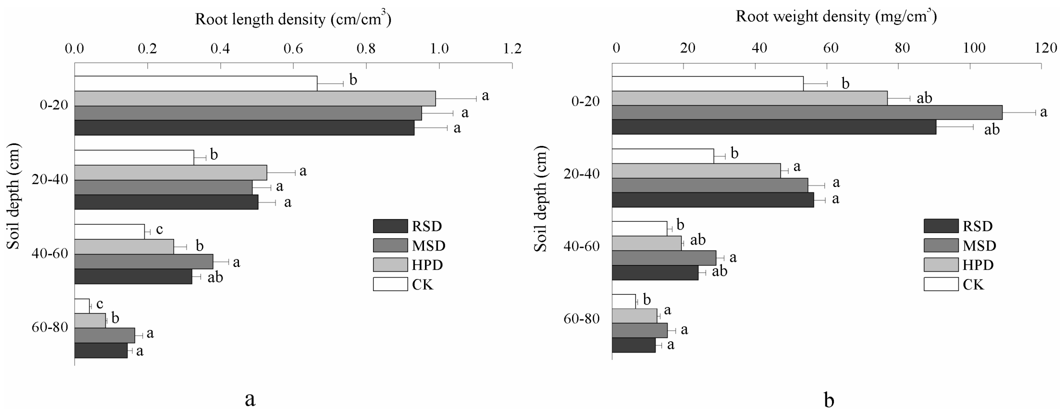

Figure 6. The average individual root length density (**a**); and dry root weight density (**b**) of different treatments in soil cores sampled in different depth. Different lowercase letters indicate significant ($p < 0.05$) differences among the treatments of the same sampling depth.

Corresponding to the variation of RLD, the value of root weight density (RWD) present higher under the MSD and RSD than that with the HPD, particularly in the upper layer. However, under the same planting condition, significantly heavier weight ($p < 0.05$) was found in the average value of RWD among three treatments and they were ranked as MSD (52.12 mg/cm^3) > RSD (45.81 mg/cm^3) > HPD (39.03 mg/cm^3), indicating that crop straws had a positive effect on root matter growth. The better root development of the growing maize inevitably led to improved soil water holding capacity [51], and the improved soil condition encourages more root growth. This may be attributed to the good subsurface drainage that significantly improved the soil properties such as the drainable porosity [52] and the hydraulic conductivity [53] in the soil layers where roots were more concentrated.

In the present study, salt stress from the saline soil affected the maize growth (Table 4). Reduction in plant growth as result of the salt stress has been reported in many studies [54,55]. Plant height, stem diameter, shoot dry weight, 100-grain weight and grain yield were found significantly higher ($p < 0.05$) in HPD (24.60%, 146.16%, 27.14%, 44.35%, and 30.93%, respectively), MSD (39.68%, 230.77%, 41.64%, and 41.32%, respectively) and RSD (43.65%, 261.54%, 39.70%, and 38.64%, respectively) as compared to the control plot without drainage. The utilization of crop straws as drainage materials produced significant ($p < 0.05$) increase in the above ground biomass, including the plant height, stem diameter and shoot dry matter as compared to the plastic pipes. Among the treatments of HPD, MSD and RSD, however, no significant ($p > 0.05$) difference was observed in the values of 100-grain weight and grain yield. Overall, the growth and yield of maize excelled in the lysimeters with the subsurface drainage system; some observed beneficial effect in above ground biomass may be the result of the crop straws that provided more favorable condition for root growth.

Table 4. The Effect of drainage type and salinity of irrigation water on above ground biomass and the grain of maize.

Treatments	Plant Height (cm)	Stem Diameter (cm)	Shoot Dry Weight (g)	100-Grain Weight (g)	Grain Yield (g/plant)
CK	126 (5.3) c	1.3(0.2) b	86.22(4.63) c	13.53(2.96) b	78.77(12.66) b
HPD	157 (4.2) b	3.2(0.3) b	109.62(8.26) b	19.43(3.04) ab	103.13(5.44) b
MSD	176(7.2) ab	4.3(0.5) a	122.12(7.58) ab	20.31(1.86) ab	111.32(11.73) ab
RSD	181(9.4) a	4.7(0.3) a	129.38(13.09) a	18.90(2.56) a	109.21(11.29) a

Note: Different letters after the data in the same column indicate significant differences among treatments at $p < 0.05$.

4. Conclusions

Through parallel experiment in lysimeters, this study examined the potential of using crop straws as subsurface drainage material in the initial land reclamation of the saline coastal soils. Observations through the maize growing period concluded that:

(1) Subsurface drainage with crop straws had positive effect on the salt and water distribution in the soil profile; less soil moisture variation and higher desalination rate were observed in the root zone drained with the bundled crop straw than that drained with the conventional plastic pipes.
(2) The crop straws drainage modules displayed faster soil water transmission properties, as reflected in the quick water table drawdown, greater average drainage rate and leaching fraction.
(3) The crop straw treatments produced better crop growth in terms of the root distribution, plant length, stem diameter and shoot dry weight of the maize, showing potential benefit of the organic drainage material.

The experimental results suggest that using the crop straws as subsurface drainage material may be a good option in the initial land reclamation of the saline soils. Considering the renewable and biodegradable nature of crop straw resources, the application of crop straw as subsurface drainage materials may achieve a good balance between crop production and drainage system construction. The long-term impact of crop straw as subsurface drainage material on drainage water quality and soil properties under different irrigation schedules will be studied in the future.

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