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Influences of Exogenic Organic Materials Application on Soil Fertility Status and Paddy Growth under a Coastal Saline Soil Condition

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Abstract: Paddy cultivation in saline soil can rapidly reduce soil salinity, which is an important approach for managing, utilizing, and improving such soils. However, the high salinity of saline soil severely limits the sustainability of paddy production. Adding exogenic organic material to improve soil fertility in saline soil is a key measure for obtaining high-yield, efficient and sustainable cultivation of paddy. This study used a field experiment to explore the influences of different organic materials application on soil desalination and fertility improvement in saline paddy soil. The results showed that the application of dairy manure (DM), sludge vermicompost (SV), and vinegar residue (VR) reduced soil barrier factors, including electrical conductivity (EC) and pH, increased soil fertility, including soil organic carbon (SOC), nitrogen (N), and phosphorus (P), and promoted paddy growth in saline soil. Specifically, soil EC decreased by 29.0%, 32.9% and 49.4% and paddy biomass increased by 27.7%, 63.7% and 107.6% in DM, SV, and VR-treated soils with the highest application rates, respectively, compared to the control. At an equal carbon application rate, VR was more conducive to decreasing soil EC and pH and increasing paddy biomass. Compared to DM and SV, VR addition resulted in an average decrease of 20.7% and 19.1% in soil EC, respectively, and an average increase of 57.3% and 29.5% in paddy biomass. In addition, soil water-stable aggregates (WSA), SOC, N, and P contents in VR-treated soil were lower than those in DM and SV-treated soils. Correlation and path analysis revealed that there was a significant negative correlation between paddy biomass and soil barrier factors. However, EC in VR-treated soil had a direct negative effect on paddy biomass, while EC in DM and SV-treated soils had an indirect negative effect on paddy biomass. Additionally, the direct contribution of soil pH to paddy biomass was higher with VR (−1.49) than that with DM (−0.21) and SV (0.89). In contrast to DM and SV, the effect of soil WSA on paddy biomass in VR-treated soil was mainly an indirect positive effect, and the direct effect was negative. The corresponding results provided new options and ideas for the efficient utilization of saline soils and high-yield cultivation of paddy.

Keywords: saline paddy soil; soil barrier factor; soil fertility; vinegar residue; paddy

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1. Introduction

China is facing a shortage of arable land resources, so the comprehensive utilization of saline soil plays an important strategic role in ensuring national food security. Paddy cultivation in saline soils can rapidly reduce soil salinity, which is an important approach to manage, utilize, and improve such soils [1,2]. However, the high soil salinity, which is the primary barrier factor in saline paddy soil, results in weak seedlings, limited tillering, low biomass, and difficulties in achieving high and stable yields. In addition, the low nutrient content and poor fertility retention and supply capacity of saline paddy soils weaken the ability of paddy plants to grow, thus limiting the sustainability of paddy production in such soils [3,4]. Therefore, rapid soil desalination and fertility improvement to improve soil conditions conductive to paddy growth are essential measures for cultivating high-yielding paddy in saline soils.

The process of salinity reduction in saline soils can be accelerated by freshwater irrigation, concentrated rainfall, and paddy cultivation [5–7]. The key point of soil fertility improvement is to increase soil organic carbon (SOC) content [8]. SOC is an important indicator of soil fertility, especially in coastal saline soils. Because of its high negative charge, increasing SOC greatly improves the fertility retention and supply performance of saline soils [9,10]. At the same time, the acidic substances released during the decomposition of SOC effectively adjust the pH of saline soils [11]. In addition, an increase in SOC promotes the formation of soil aggregate, thus improving the physical structure of the soil, further facilitating soil desalination, and preventing soil resalination in saline soils [12]. However, the coastal saline soils have very low SOC content, and the natural accumulation process of SOC in saline soil is extremely slow under high salinity and pH conditions. Artificial input of exogenic organic materials to increase the SOC content may be a key measure to enhance soil fertility retention and supply capacity, reduce soil salinity, and improve the fertility of saline paddy soils [13].

Sufficient exogenic organic material input is necessary for the substantial accumulation of SOC [6]. In general, SOC content increases with increasing organic material input. Our previous research has shown that exogenic organic material input promoted the rapid accumulation of SOC in saline soil [13]. However, SOC content was not linearly related to exogenic organic material input [14], and there were differences in the ability of different organic material to promote SOC accumulation [15]. The reason may be the differences in the mineralization and decomposition processes of SOC formed by different types of organic material [16]. In addition, the soil environmental conditions, carbon–nitrogen ratio, and composition of organic material also directly affect the mineralization and accumulation rates of SOC [17,18]. Therefore, dairy manure (DM), sludge vermicompost (SV), and vinegar residue (VR) were used as exogenic organic materials to investigate their effects on reducing soil barrier factors and improving soil fertility in coastal saline paddy soils. The corresponding results not only enriched the theoretical basis for soil fertility improvement, but also provided practical guidance for the efficient utilization of coastal saline soil and high-yield cultivation of salt-tolerant paddy.

2. Materials and Methods

2.1. Experimental Site and Materials

The field experiment was conducted in 2022 at Jianfeng farm (120°56′03′′ E, 32°36′30′′ N), Dafeng district, Yancheng city, Jiangsu province, China. During the experiment, the average annual temperature and rainfall of the experimental area were 18.5 °C and 1012 mm, respectively, and the soil was sandy loam and typical coastal saline soil. The tested DM, SV, and VR were obtained from Nantong Ruihua Bioengineering Co., Ltd. (Nantong, China), Ecological Agriculture Development Co., Ltd. (Nantong, China), and Zhenjiang Hengshun Vinegar Co., Ltd. (Zhenjiang, China), respectively. In addition, the SV was produced by digesting the sewage sludge with earthworms, and the sludge was complied with the Control Standards of pollutants in sludge for agricultural use (GB 4284-2018) [19]. The detailed digestion steps can be found in our previous study [20]. The general physical and chemical properties of the tested soil, DM, SV, and VR are listed in Table 1.

Table 1. Basic properties of saline soil and exogenic organic materials used in this study.

Items	Saline Soil	Vinegar Residue	Dairy Manure	Sludge Vermicompost
pH	9.02 ± 0.13	4.94 ± 0.08	7.32 ± 0.11	6.28 ± 0.12
EC (mS cm^{-1})	1.34 ± 0.14	0.65 ± 0.06	2.74 ± 0.19	9.49 ± 0.34
SOC (g kg^{-1})	5.46 ± 0.36	541.4 ± 27.35	431.2 ± 18.72	242.9 ± 10.80
Total N (g kg^{-1})	0.37 ± 0.03	15.4 ± 1.02	31.22 ± 4.09	35.38 ± 2.73
Total P (g kg^{-1})	0.62 ± 0.11	4.02 ± 0.87	7.82 ± 1.01	15.02 ± 1.07
Alkaline N (mg kg^{-1})	32.34 ± 3.24	824 ± 29.48	1103 ± 54.92	2583 ± 60.82
Available P (mg kg^{-1})	27.51 ± 4.71	206.2 ± 21.03	296.3 ± 30.19	849 ± 48.28

Values are mean ± standard deviation of three replicates. EC, electrical conductivity. SOC, soil organic carbon. N, nitrogen. P, phosphorus.

2.2. Experimental Design

A field randomized block experiment was performed, and each plot had an area of 16 m^2 (4.0 m × 4.0 m). In the experiment, the different exogenic organic materials (DM, SV, and VR) were applied at equal carbon application rates to achieve SOC contents of 5‰, 7.5‰ and 10‰ in the corresponding saline soil (0–20 cm), respectively, and the treatments were repeated three times. The DM-treated soils (5‰, 7.5‰ and 10‰) were named DM_L, DM_M, and DM_H; The SV-treated soils (5‰, 7.5‰ and 10‰) were named SV_L, SV_M, and SV_H; The VR-treated soils (5‰, 7.5‰ and 10‰) were named VR_L, VR_M, and VR_H. Meanwhile, the soil without exogenic organic material application was used as a control, named CK. Experimental plots were separated by ridges and irrigated individually in single rows, and the ridges were covered with an impermeable membrane buried at a depth of 50 cm between plots. The plots were treated with DM, SV, and VR in a one-time application in early May 2022 according to the target rate, then they were mixed uniformly with the soil to a depth of 0–20 cm through manual plowing, and allowed to mature naturally until mid-June. Subsequently, the plots were irrigated and soaked with water. The paddy variety used in the experiment was Huaidao 5, which was transplanted in late June. Fertilization and field management measures in the plots were consistent with the paddy production in local farms.

2.3. Sample Processing and Analysis

In early October 2022, a sample (2 m^2) of aboveground paddy plants was cut from each plot, and soil samples (0–20 cm), soil bulk density (BD) samples, and soil water-stable aggregate (WSA) samples were collected. The aboveground paddy plants were killed in a ventilated drying oven at 105 °C for 15 min, then dried at 80 °C until they reached a constant weight, and then they were weighed to obtain the aboveground paddy biomass. Soil samples were naturally air-dried, crushed, and then passed through 2 mm and 0.149 mm sieves for the determination of soil electrical conductivity (EC), pH, SOC, nitrogen (N), and phosphorus (P) nutrient contents. Soil EC and pH were determined using a conductivity meter and a pH meter at a soil–water ratio of 1:5; SOC was determined by external heating with potassium dichromate; soil total N, total P, alkaline N, and available P were determined by the semimicro-Kjeldahl method, sulfuric acid–perchloric acid digestion method, alkaline hydrolysis diffusion method, and sodium bicarbonate extraction (molybdenum-antimony anticolorimetric method), respectively [21]. Soil BD was determined by the ring knife method [21]. Soil aggregate samples were crushed into small clumps along the natural structural surface of the soil and passed through an 8-mm sieve, coarse roots and small stones were removed, and then the samples were naturally air-dried [12]. Soil WSA was determined using a wet sieve apparatus.

2.4. Statistical Analysis

Data were analyzed using the mean of each treatment replicate. Data were statistically analyzed using Microsoft Excel 2019 and SPSS 19.0 software, and the significance of the main indicators was tested using the least significant difference (LSD) method at the 0.05 level, and graphing was performed using Origin 2022 software. The influences of related soil barrier factors and fertility indicators in organic material-treated saline soil on paddy biomass were evaluated using Pearson correlation analysis and path analysis, and the significance was set at $p < 0.05$.

3. Results and Discussion

3.1. Adding Exogenic Organic Materials Accelerated the Reduction of Soil Barrier Factors

The application of organic materials significantly reduced soil EC in saline soils (Figure 1). Compared to the control (without organic material application), the highest application rates of DM, SV, and VR (DM_H, SV_H, and VR_H) reduced soil EC by 29.0%, 32.9% and 49.4%, respectively. Under equal carbon application rates, soil EC in VR-treated soil (VR_L, VR_M, and VR_H) was lower than that in DM-treated soil by 19.6%, 13.6% and 28.8%, respectively, and lower than that of SV-treated soil by 20.3%, 12.4% and 24.6%, respectively, and the differences were all significant. The high salinity of saline soil was mainly attributed to the accumulation of underground salt in the surface soil under capillary action due to the dense capillary pores in the soil [22]. In this study, the desalination effect of VR was better than that of DM and SV, which may be due to the loose structure of VR, which was more conducive to increasing the noncapillary pores in soil and thus promoting the downward leaching of salt in the surface soil. Xiao et al. [23] similarly found that VR addition was more beneficial in reducing soil salinity than gypsum and straw. In addition, the application of organic materials significantly lowered the pH of saline soil (Figure 1). Compared to the control, the highest application rates of DM, SV, and VR (DM_H, SV_H, and VR_H) decreased the pH by 0.30, 0.33 and 0.42 units, respectively, and this result was mainly attributed to the neutralizing effect of humic acid substances released during the decomposition of exogenic organic materials on the pH of saline soil [24]. Under an equal carbon application rate, VR addition was more effective in reducing soil pH. Specifically, the highest application rate of VR resulted in a pH that was 0.12 and 0.09 units lower than DM and SV, respectively, mainly due to the inherently lower pH of VR.

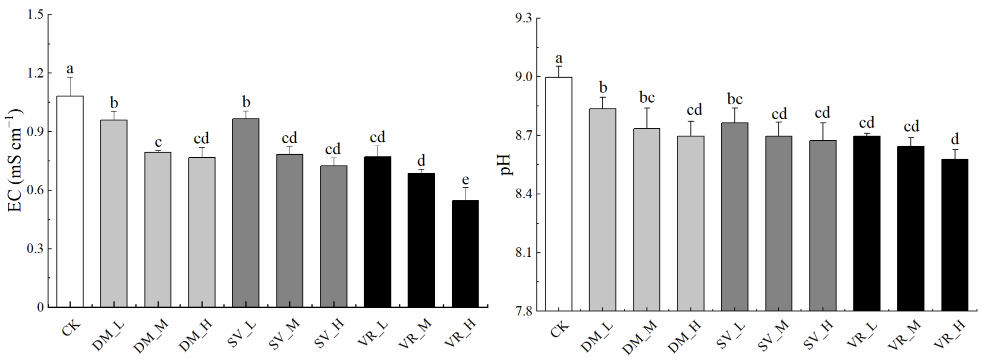

Figure 1. Soil EC and pH in response to the application of different exogenic organic materials in saline soil. EC, electrical conductivity. The vertical bars denote standard errors. Different small letters denote significant difference at $p < 0.05$.

3.2. Adding Exogenic Organic Materials Improved Soil Physical Properties

High salinity in saline soils is closely related to the poor soil physical properties, especially low soil aggregate content and high bulk density. Promoting the formation of saline soil aggregates and increasing bulk density is an effective way to accelerate soil salinity reduction. The application of exogenic organic materials promoted the formation of soil aggregate in saline soil (Figure 2). Compared to the control treatment, the highest application rates of DM, SV, and VR (DM_H, SV_H and VR_H) increased the percentages of >0.25 mm WSA by 89.8%, 151.0% and 41.6%, respectively, and increased the percentages of 0.106–0.25 mm WSA by 47.1%, 65.5% and 33.5%, respectively. The formation and stability of soil aggregates are related to binder and dispersant [25]. SOC is an important base material for promoting the formation of aggregate and is generally considered a binder during the formation and stability of soil aggregate [26,27]. The application of organic materials promoted the increase in SOC in saline soil, improved the aggregation of soil particles, and effectively promoted the formation of soil aggregates [28,29]. The high soil salinity (especially exchangeable Na^+) is recognized as a dispersant that disrupts the formation and stability of aggregate [27,30]. The application of organic materials decreased soil EC and increased the stability and number of soil aggregate. Under equal carbon application rates, the promoting effect of different organic materials on the formation of WSA in saline soil was ranked in descending order as follows: SV > DM > VR. The percentages of >0.25 mm WSA in VR-treated soil (VR_L, VR_M, and VR_H) were lower than those in DM-treated soil by 10.9%, 22.1% and 25.4%, and lower than those in SV-treated soil by 24.5%, 31.5% and 43.6%, respectively. Previous studies have also found that different organic materials can result in a five-fold difference in the number of soil aggregates formed, which may be due to the differences in the ability of different organic materials to bind to soil minerals [31,32]. In this study, DM and SV were rich in organic cementing agents required for aggregate formation, while VR was mainly composed of cellulose and contained fewer organic cementing agents, which was not conducive to aggregate formation in saline soil. The formation of soil aggregates after exogenic organic materials application increased soil noncapillary porosity and reduced the soil compaction tendency, thereby reducing soil BD (Figure 2). Compared to the control, the highest application rates of DM, SV, and VR (DM_H, SV_H, and VR_H) reduced soil BD by 13.6%, 16.5% and 17.3%, respectively. Under equal carbon application rates, the outcome of lower soil BD in VR-treated soil than in DM- and SV-treated soils was mainly attributed to the loose structure of VR, which was more conducive to increasing soil porosity.

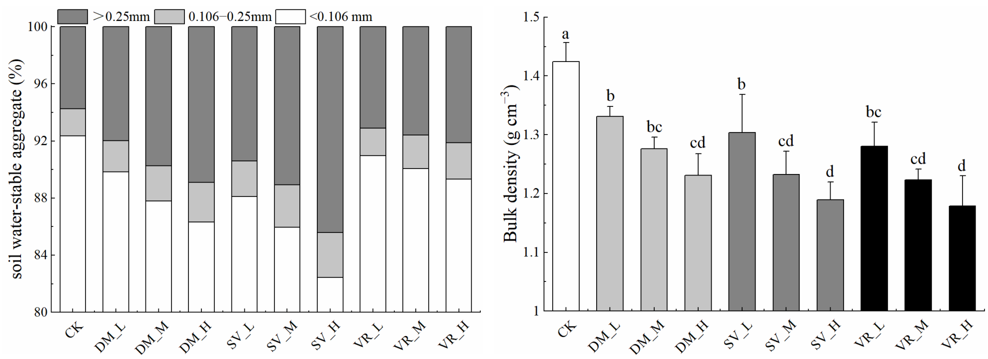

Figure 2. Soil water-stable aggregate and bulk density in response to the application of different exogenic organic materials in saline soil. The vertical bars denote standard errors. Different small letters denote significant difference at $p < 0.05$.

3.3. Adding Exogenic Organic Materials Promoted SOC Accumulation and Soil Fertility Improvement

SOC accumulation is an important prerequisite for soil fertility improvement in coastal saline soil. In this study, the application of exogenic organic materials significantly increased SOC content (Figure 3). The SOC content of DM_H, SV_H, and VR_H treatments reached 16.63 g kg^{-1}, 17.01 g kg^{-1} and 12.68 g kg^{-1}, respectively, which increased 112.4%, 117.3% and 62.0%, respectively, compared with the control. Under equal carbon application rates, the SOC contents in VR-treated soils (VR_L, VR_M, and VR_H) were 11.4%, 17.0%, 23.8% and 19.8%, 25.7%, 25.5% lower than those in DM- and SV-treated soils, respectively, and the treatments were all at significant levels. The difference in SOC accumulation after the application of different organic materials may be mainly attributed to the differences in the inherent properties (e.g., carbon–nitrogen ratio and component composition) of the organic materials. The carbon–nitrogen ratio of VR is significantly higher than that of DM and SV. Therefore, a high nitrogen fertilizer application during paddy cultivation in saline soil may be more favorable for the mineralization and decomposition of VR [33–35].

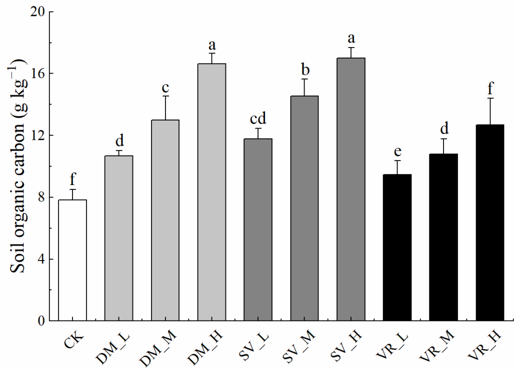

Figure 3. Effects of different organic material application on soil organic carbon content in saline soil. The vertical bars denote standard errors. Different small letters denote significant difference at $p < 0.05$.

The application of DM, SV, and VR significantly increased soil N and P contents, and soil total N, alkaline N, total P, and available P increased with increasing organic material application rates (Figure 4). Under an equal carbon application rate, the lower N and P contents of VR resulted in significantly lower N and P contents in VR-treated soil than in DM- and SV-treated soils. Specifically, the contents of total N, alkaline N, total P, and available P in VR-treated soil were on average 13.5%, 5.0%, 29.5% and 9.5% lower than those in DM-treated soil, respectively, and 43.9%, 43.7%, 48.0% and 58.4% lower than those in SV-treated soil, respectively.

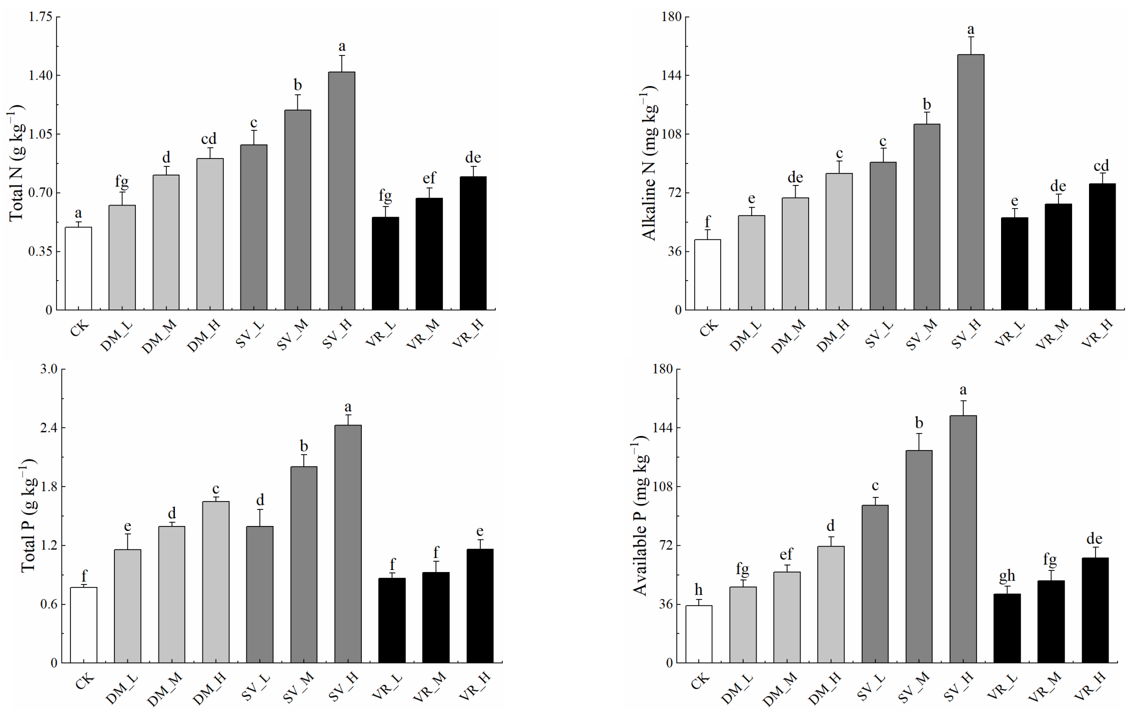

Figure 4. Soil nitrogen and phosphorus contents in response to the application of different exogenic organic materials in saline soil. N, nitrogen. P, phosphorus. The vertical bars denote standard errors. Different small letters denote significant difference at $p < 0.05$.

3.4. Adding Exogenic Organic Materials Promoted Paddy Growth

The application of exogenic organic materials promoted paddy growth, and the aboveground biomass of paddy showed an increasing trend with the increasing organic material application rates (Figure 5). In this study, the paddy biomass in the control treatment was only 17.15 t ha^{-1}, and the paddy biomass under the highest application rates of DM, SV, and VR (DM_H, SV_H, and VR_H) was 21.89, 28.07 and 35.61 t ha^{-1}, respectively, representing an increase of 27.7%, 63.7% and 107.6% over the control. Numerous studies have also found that organic material addition such as vermicompost and vinegar residue increased the biomass and yield of various crops such as rice, corn, and wheat [13,36,37]. In this study, the increase in paddy biomass was attributed to the reduction in soil barrier factors (e.g., salinity and pH) in the saline soil, the enhancement of soil physical properties (e.g., the formation of aggregate), and the improvement of soil fertility (e.g., an increase in SOC as well as N and P nutrients) due to the application of exogenic organic materials, which provided a favorable root growth environment for paddy. Bowden et al. [38] reported that the application of different organic materials can result in a 2.3-fold difference in soil fertility (soybean yield). The present study similarly found that under an equal carbon application rate, the growth-promoting effect of VR on paddy growth was significantly higher than that of DM and SV. Specifically, the paddy biomass in VR-treated soil (VR_L, VR_M, and VR_H) was 56.0%, 53.3%, 62.6% and 5.5%, 16.1%, 26.8% higher than that in DM- and SV-treated soils, respectively. The reason for this may be that the application of VR was more favorable for the reduction of salinity and pH in saline soil.

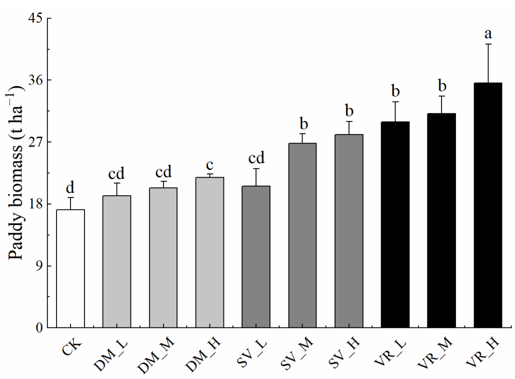

Figure 5. The aboveground biomass of paddy in response to the application of different exogenic organic materials in saline soil. The vertical bars denote standard errors. Different small letters denote significant difference at $p < 0.05$.

The correlation and path analysis showed that paddy biomass was negatively correlated with soil barrier factors (EC and pH), while EC in VR-treated soil had a direct negative effect (−1.10) on paddy biomass, and EC in DM- and SV-treated soils had indirect negative effects on paddy biomass (Table 2). In addition, the direct effect of soil pH on paddy biomass in VR-treated soil (−1.49) was greater than that in DM-treated soil (−0.21) and SV-treated soil (0.89), indicating that the reducing effect of VR addition on soil pH was more favorable to the increase of paddy biomass. WSA in DM-treated soil primarily had a direct positive effect (2.30) on paddy biomass, and the direct and indirect effects of WSA in SV-treated soil were both positive, while WSA in VR-treated soil primarily had an indirect positive effect on paddy biomass, and the direct effect of WSA on paddy biomass in VR-treated soil was negative. The reason may be that DM and SV additions were more favorable to soil WSA formation, compared with VR, thereby promoting an increase in paddy biomass. SOC in DM, SV, and VR treatments primarily had direct positive effects on paddy biomass, suggesting that exogenic organic carbon addition tends to affect other physical and chemical indicators of saline soil and thus affect paddy biomass.

Table 2. Correlation and path analysis of paddy biomass and related soil fertility indicators in saline soil amended by different organic materials.

OM	Item	Paddy Biomass		IPC									
		CC	**DPC**	**EC**	**pH**	**WSA**	**BD**	**SOC**	**TN**	**AN**	**TP**	**AP**
DM	EC	−0.77 **	1.06	\	−0.17	−2.09	2.05	−0.21	−1.29	0.40	−0.49	−0.02
	pH	−0.66 *	−0.21	0.89	\	−1.93	2.00	−0.20	−1.07	0.33	−0.46	−0.02
	WSA	0.82 **	2.30	−0.97	0.17	\	−2.40	0.23	1.35	−0.42	0.53	0.03
	BD	−0.73 **	2.47	0.88	−0.17	−2.23	\	−0.22	−1.32	0.39	−0.52	−0.02
	SOC	0.84 **	0.24	−0.94	0.17	2.20	−2.30	\	1.32	−0.41	0.52	0.03
	TN	0.84 **	1.42	−0.97	0.15	2.18	−2.30	0.22	\	−0.43	0.53	0.02
	AN	0.86 **	−0.45	−0.94	0.15	2.13	−2.15	0.22	1.35	\	0.52	0.02
	TP	0.87 **	0.55	−0.96	0.17	2.23	−2.32	0.23	1.38	−0.43	\	0.03
	AP	0.83 **	0.03	−0.87	0.17	2.04	−2.13	0.23	1.24	−0.38	0.50	\
SV	EC	−0.88 **	−1.10	\	0.74	−0.19	−0.55	0.91	−1.08	0.09	1.75	−1.46
	pH	−0.85 **	0.89	−0.92	\	−0.18	−0.58	0.84	−1.10	0.08	1.53	−1.41
	WSA	0.90 **	0.21	1.02	−0.75	\	0.58	−0.95	1.15	−0.10	−1.81	1.56
	BD	−0.88 **	−0.66	−0.92	0.79	−0.18	\	0.89	−1.10	0.09	1.77	−1.56
	SOC	0.90 **	−0.98	1.03	−0.76	0.20	0.60	\	1.15	−0.10	−1.83	1.59
	TN	0.91 **	1.18	1.00	−0.83	0.20	0.61	−0.95	\	−0.09	−1.79	1.57
	AN	0.87 **	−0.10	1.02	−0.70	0.21	0.57	−0.96	1.11	\	−1.83	1.56
	TP	0.92 **	−1.88	1.03	−0.72	0.20	0.62	−0.95	1.13	−0.10	\	1.61
	AP	0.92 **	1.64	0.98	−0.77	0.20	0.62	−0.95	1.14	−0.09	−1.85	\
VR	EC	−0.93 **	0.90	\	−1.38	0.53	−0.60	0.41	−0.49	−0.32	−0.81	0.83
	pH	−0.88 **	−1.49	0.83	\	0.52	−0.54	0.37	−0.47	−0.28	−0.66	0.84
	WSA	0.90 **	−0.56	−0.84	1.37	\	0.60	−0.40	0.46	0.30	0.84	−0.86
	BD	−0.89 **	−0.65	0.83	−1.25	0.52	\	0.41	−0.47	−0.31	−0.82	0.85
	SOC	0.84 **	−0.45	−0.82	1.22	−0.50	0.59	\	0.53	0.33	0.86	−0.91
	TN	0.80 **	0.57	−0.77	1.22	−0.46	0.53	−0.42	\	0.29	0.83	−0.99
	AN	0.74 **	0.36	−0.78	1.16	−0.47	0.55	−0.41	0.45	\	0.72	−0.85
	TP	0.80 **	1.01	−0.72	0.97	−0.47	0.52	−0.39	0.47	0.26	\	−0.86
	AP	0.77 **	−1.04	−0.71	1.19	−0.46	0.52	−0.39	0.54	0.29	0.83	\

OM, organic material. DM, dairy manure. SV, sludge vermicompost. VR, vinegar residue. EC, electrical conductivity. WSA, water-stable aggregate. BD, bulk density. SOC, soil organic carbon. TN, total nitrogen. AN, alkaline nitrogen. TP, total phosphorus. AP, available phosphorus. CC, correlation coefficient. DPC, direct path coefficient. IPC, indirect path coefficient. * $p < 0.05$, ** $p < 0.01$.

4. Conclusions

This study confirmed that adding exogenic organic material is a key measure for the efficient and sustainable utilization of coastal saline paddy soils. After the application of dairy manure (DM), sludge vermicompost (SV), and vinegar residue (VR) in saline soil, the increase in SOC provided a material basis for soil aggregate formation and promoted the formation and stabilization of soil aggregates, which in turn accelerated the reduction of soil barrier factors (EC and pH). In addition, DM, SV, and VR contained large amounts of N and P nutrients, which promoted soil fertility in saline soils. The reduction of soil barrier factors and the improvement of soil fertility created a good growing environment for paddy cultivation, and thus paddy biomass increased in saline soils. Under an equal carbon application rate, VR addition was more favorable for reducing soil barrier factors due to the loose structure, resulting in a better growth-promoting effect on paddy than that of DM and SV. Correlation analysis revealed that paddy biomass was significantly negatively correlated with soil barrier factors and significantly positively correlated with soil fertility indicators. Path analysis further indicated EC in VR-treated soil had a direct negative effect on paddy biomass, while EC in DM- and SV-treated soils had indirect negative effects on paddy biomass. Moreover, the direct effect of soil pH on paddy biomass in VR-treated soil was greater than that of DM-treated soil and SV-treated soil. Furthermore, in contrast to DM- and SV-treated soils, water-stable aggregates (WSA) in VR-treated soil mainly had an indirect positive effect on paddy biomass, and the direct effect of WSA on paddy biomass was negative. Therefore, VR was more advantageous in terms of reducing the soil barrier and promoting paddy growth in coastal saline paddy soil.

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