Effect of Applying Cattle Manure as a Potassium-containing Material for the Reclamation of Saline-sodic Soils: A Model Experiment

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Authors' contributions

This work was carried out in collaboration between both authors. Both authors read and approved the final manuscript.

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ABSTRACT

Sodification has developed into severe, world-wide soil problem, especially in arid region. Although the most common method for treating such sodic soils is to replace sodium (Na) with calcium (Ca) using gypsum, replacing Na with potassium (K) is also a possible solution. The present study was aimed at confirming the effectiveness of applying cattle manure as a local material in rangelands that are rich in K for remediating sodic soils in model experiments. Two saline-sodic soil samples collected from Tongliao, Inner Mongolia, China, were used. Cattle manure was applied to soils at mass ratios of 0, 1, 2, 5, 10%, and the soils were leached with water three times. The pH and electrical conductivity of the leachates and soils, cation concentrations in the leachates, and exchangeable cation contents in the soils were then measured after completion of the leaching. In both soils, Na release was increased with increasing amount of cattle manure used. The decrease in exchangeable Na and the simultaneous increase in exchangeable K indicated that the soil Na was replaced by manure K. The soil pH decreased with increasing rate of manure application, and soil infiltration was also improved, as indicated by hydraulic conductivity tests.

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1. INTRODUCTION

Arid and semi-arid regions cover 41% of Earth's land surface [1], and 43 million ha of irrigated land in those regions are affected by soil degradation, mainly waterlogging, salinization, and sodication [2]. Sodic soils are a subset of salt-affected soils that contain a high percentage of sodium ions (Na^+), which can destabilize the soil structure and decrease hydraulic conductivity (HC) [3,4].

The most common method for dealing with such sodic soils is to replace the Na with calcium (Ca) using materials that contain Ca, such as gypsum and Ca chloride [5–8]. It is generally recognized that the ease of replacement among major exchangeable cations is in the order Na > K > Mg > Ca. Thus, Ca would be expected to easily force Na out of cation exchange sites. However, another order, Na ≥ Mg > Ca > K, indicating that K would replace Na more readily than Ca and Mg, has also been reported [9]. Furthermore, a new theory referred to as 'nanopore inner-sphere enhancement (NISE)' counters the traditional viewpoint of cation exchange reactions. In this theory, a weakly hydrated ion is dehydrated and adsorbed to a mineral surface via a strong inner-sphere mechanism when the nanopore diameters are larger than the ionic diameter of the ion but much smaller than the hydrated diameter of the ion [10]. According to NISE theory, Ca cannot break the bonds with its hydrating water molecules as easy as Na or K because of the higher hydration energy, resulting in stronger adsorption of Na and K than Ca in nanopores [11]. This theory suggests that K would outperform Ca in terms of Na desorption. As such, K-containing materials are expected to remove Na more effectively than Ca materials in the remediation of sodic soils [10].

Water permeability frequently deteriorates in sodic soils. HC is affected by both the electric conductivity (EC) and sodium adsorption ratio (SAR). HC decreases with decreasing EC and increasing SAR, because low-electrolytic water can flow into the spaces in platelets easier than high-electrolytic water [12]. The effect of a given SAR on the soil infiltration rate decreases with increasing salinity. McNeal and Coleman [13] contended that the permeability level of a soil is generally fixed by the EC of the solution that is initially applied, and that the process is basically irreversible. Pluym et al. [14] suggested that a high saline solution should be used to maintain a high permeability in the reclamation of saline-sodic soils, because the elimination of salts in a saline-sodic soil by water with a low salt concentration can cause an irreversible loss of soil structure [15].

Although organic amendments are commonly applied to agricultural lands to enhance soil fertility and improve productivity, it is also used for the reclamation of salt-affected soils. Tejada et al. [16] indicated that an application of organic waste, a cotton gin crushed compost or poultry manure, increased the stability of a soil structure and decreased EC and the exchangeable sodium percentage (ESP) as a result of accelerated Na^+ leaching. Jalali and Ranjbar [17] reported that the use of poultry and sheep manure at a rate of 5% increased the adsorption of Ca^{2+}, Mg^{2+}, and K^+ in a sandy loam soil relative to Na^+, These results suggest that organic amendments might be useful for reducing soil sodification induced by the use of sodic groundwater for irrigation in areas where there is a shortage of fresh water.

Currently, the use of gypsum is the most economic method for reclaiming salt-affected soils. Nevertheless, it is not easy for people living in arid areas, most of which are located in developing countries, to purchase sufficient amounts of gypsum to allow salt-affected soil areas to be reclaimed. To accomplish this, an alternative low cost method is required. The use of a cheap and readily acquirable K containing material is a potential solution, and cattle manure, a local material in rangelands, is the most suitable. The present study is aimed at proving the availability of cattle manure as a K-containing material for improving plant growth environment in saline-sodic soils, and the objective of this paper was to confirm the abilities of cattle manure for replacing soil exchangeable Na and improving soil physical and chemical properties using Inner Mongolian saline-sodic soils in model experiments.

2. MATERIALS AND METHODS

2.1 Soil and Manure Samples

Two soil samples were collected from Hou Chaganhua, located east of Tongliao City, Inner Mongolia, China. Tongliao City has a 6.2×10^3 km^2 of salt-affected soil area, which accounts for

14% of the total agriculture lands, and 97% of the salt-affected soils are classified as sodic or saline-sodic soils [18]. Salt-affected soils in Tongliao were formed naturally under specific conditions of hydrology, meteorology, and geology. Human activities including the destruction of vegetation, excessive cultivation, inappropriate irrigation, and the construction of reservoirs, accelerated the formation of these salt-affected soils. According to Fan et al. [19], the mean annual rainfall in this area between 1978–2008 was 384 mm, of which 85% occurred May to October, and the mean annual evaporation was 1890 mm or almost 5 times the mean annual precipitation. Soil sampling was discriminated by different vegetation coverage. One sample was collected from a spot of salt-tolerant windmill grass (*Chloris virgata*) (TL1; N 44°01′50″, E 122°40′07″), and another (TL2; N 44°01′41″, E 122°42′08″) was collected from a spot of common seepweed (*Suaeda Forsk*). *Suaeda Forsk* is a halophyte. Both samples were collected from a 0–15 cm depth and air-dried.

The air-dried soil samples could be passed through a 2-mm mesh sieve without the need for grinding. Soil pH and EC were measured using suspensions with water at a ratio of 1:2.5 and 1:5, respectively (pH meter M-12 or pH/COND D-24, Horiba, Kyoto, Japan). Soil texture was measured by the pipet method. Cation exchange capacity (CEC) was determined by the Schollenberger method. Soil saturated EC (EC_e) was calculated using the following equation [20]:

$$EC_e = (14.0 - 0.13 \times clay\%) \times EC_{1:5} \qquad (1)$$

Where clay% is soil clay content, and $EC_{1:5}$ is soil EC under measurement with water at a ratio of 1:5. Based on soil pH and EC_e values, both of two soil samples were classified into saline-sodic soils in Salt-effected Soils Classification [21].

Cattle manure was collected from the Nagoya University Farm, Aichi, Japan air-dried, and sieved for collecting particles with < 2 mm. The pH, EC, and CEC of the cattle manure were measured by the same procedures that were used for the soil samples. Soluble cations were extracted from 1 g of cattle manure with 20 mL of ultrapure water by shaking for 1 h at room temperature. Basic cations in leachates were determined using inductively coupled plasma atomic emission spectrometry (ICP-AES), IRIS, Nippon Jarrel Ash, Tokyo, Japan.

2.2 Batch Experiment

A 8 g sample of the TL1 or TL2 soil was mixed with 0, 0.08, 0.16, 0.4, and 0.8 g of manure (mass ratios of 0, 1, 2, 5, and 10%, respectively) (3 replicates). These treatments were designated using a combination of soil name (TL1 or TL2) and the manure application rate (m0, m1, m2, m5, and m10), such as TL1+m0 and TL2+m5. Then, 20 mL of distilled water was added to the soil samples and they were allowed to stand overnight. The cations that were eluted were collected by centrifugation (8900 g, 10 min) (L1). The same volume of distilled water was added to the residue, and the suspension was shaken for 30 min and centrifuged to give the eluted cations (L2). The same procedures were repeated again (L3) and the pH, EC, and concentrations of Ca^{2+}, Mg^{2+}, K^+, and Na^+ (ICP-AES), of the leachates were measured.

The soil residues were freeze-dried, and the pH, EC, and exchangeable cation contents were measured. A portion of the TL1 soils was fractionated into cattle manure and soil by wet sieving using a 0.5-mm mesh sieve. Soil particles dispersed were passed through the sieve completely while most of cattle manure was retained on the sieve. Manure was further washed until the EC of the washing reached < 0.1 ms m^{-1}, when soil attached to the manure was also washed away. Then the cattle manure remaining on the sieve was freeze-dried and used for the measurement of exchangeable cations. Exchangeable cations were extracted with 1 M ammonium acetate (pH 7.0) added at a rate of 15 mL g^{-1} with shaking for 30 min at room temperature, followed by allowing them to stand overnight and centrifuging. The concentration of Ca^{2+}, Mg^{2+}, K^+, and Na^+ in the extract was measured using ICP-AES.

2.3 Hydraulic Conductivity (HC)

Soil HC was measured using the falling head permeability test. Soil samples mixed with cattle manure at ratios of 0, 1, 2, 5, and 10 %, respectively, were packed in a stainless soil core sampler (19.6 cm^2) and saturated with distilled water overnight. Core samples were settled in a stainless sink and sealed with a graduated tube fitted lid (Daiki, Tokyo, Japan). Distilled water was then allowed to percolate and the time that water head declined from the highest scale to the lowest scale of the graduated tube (9.9 cm) was recorded. The EC of the leachates was also measured. The same procedures were repeated

3–7 times. Soil saturated HC was calculated using the following equation:

$$Ks = (2.3aL)/At \log_{10}(H_1/H_2) \qquad (2)$$

Where a and A are section area of graduated tube and core sampler, respectively, and L is the height of sample. H_1 and H_2 are water head at the beginning and end of the measurement, respectively, and t is the duration of measurement. Bulk density of soils after leaching was determined weighing soil cores that had been heated at 105°C for 24 h.

3. RESULTS

3.1 Effect of Manure Application on the Leaching of Basic Cations from Soil

Physico-chemical properties of the soil and cattle manure samples are presented in Table 1. Tables 2 and 3 show the amounts of basic cations leached during 3 periods of leaching. In TL1 (Table 2), the cattle manure treatment leached a greater quantity of Na^+, 27.5–56.7 $mmol_c$ kg^{-1}, than the control (TL1+m0), 20.9 $mmol_c$ kg^{-1}, during the first leaching (L1), and the amount of Na^+ leached increased with increasing rate of application of cattle manure increased ($P < 0.01$). A similar trend was also observed for TL2 (Table 3), where 20.1 $mmol_c$ kg^{-1} and 25.3–64.9

$mmol_c$ kg^{-1} of Na^+ had leached from the control and 4 cattle manure treatments, respectively. The amount of Na^+ leached decreased in the second leaching (L2; 13.6–15.9 $mmol_c$ kg^{-1} in TL1 and 17.5–20.1 $mmol_c$ kg^{-1} in TL2) and the effect of cattle manure was significant only in the TL2+m10 sample ($P < 0.05$). At the third leaching (L3), the amount of Na^+ leached was further decreased to 6.7–7.9 (TL1) or 10.0–13.0 (TL2) $mmol_c$ kg^{-1}. No significant difference from the control treatment was observed for the remaining manure treatments.

The difference in the sum of the amount of Na^+ leached during 3 leachings between the cattle manure treatments and the control, 6.7–38.2 $mmol_c$ kg^{-1} in TL1 and 4.5–43.9 $mmol_c$ kg^{-1} in TL2, was proportional to the rate of manure application ($r = 0.99$). The increment of Na^+ leaching due to cattle manure application was much larger than the amount of water-soluble Na^+ in the cattle manure (Table 1) in each manure treatment (2.0–20 $mmol_c$ kg^{-1}), and it was estimated that 48–56% of the increased Na^+ was derived from the soil sample.

The leaching of K^+ was also increased as the result of the cattle manure application at rates of >1%, except for TL1+m2 in the second leaching (L2). The amount of K^+ leached was greater when the cattle manure was applied at a higher rate, which was more drastic at application rates

Table 1. Physico-chemical properties of soils and cattle manure used

Sample	TL1	TL2	Manure
pH[*]	10.1	10.3	8.5
EC[**] (ds m^{-1})	0.51	0.59	3.3
CEC ($mmol_c$ kg^{-1})	77.8	88.0	103
Exchangeable cation[***] ($cmol_c$ kg^{-1})			
Na	5.98	7.02	23.7
K	0.36	0.26	125
Ca	16.1	14.6	47.0
Mg	1.92	3.17	38.5
Sand (%)	80.0	81.3	—
Silt (%)	6.9	3.7	—
Clay (%)	13.2	15.1	—
Texture	Sandy loam	Sandy clay loam	—
Dominant clay minerals	Kaolinite, Mica	Kaolinite, Mica	—
Soluble cation ($cmol_c$ kg^{-1})			
Na	n.d.	n.d.	20.5
K	n.d.	n.d.	69.6
Ca	n.d.	n.d.	3.15
Mg	n.d.	n.d.	4.75
Total Carbon (g kg^{-1})	n.d.	n.d.	387

n.d., Not determined
[*]*Material: Water = 1:2.5,* [**]*Material: Water = 1:5,* [***] *including water-extractable cations*

of 5% and 10%. A similar trend was observed for all 3 periods of leaching. The increase in K^+ leaching can be attributed to being derived from cattle manure K^+. The difference in the sum of the amount of K^+ leached between the cattle manure treatments and the control ranged from 1.5–61.3 $mmol_c$ kg^{-1} in TL1 and 1.3–66.2 $mmol_c$ kg^{-1} in TL2.

Table 2. Amounts of basic cations leached from TL1 soil during each time of leaching (mmol$_c$ kg^{-1})

No. of leaching	Treatment	Na	K	Ca	Mg
L1	TL1+m0	20.9±0.8a	2.6±0.4a	4.0±1.1a	10.3±1.4d
	TL1+m1	27.5±1.8b	3.3±0.8ab	5.0±0.9a	7.9±1.0c
	TL1+m2	32.3±1.8c	4.2±0.4b	5.0±1.4a	5.1±1.5b
	TL1+m5	41.5±2.0d	16.7±0.8c	4.5±0.2a	2.8±0.1a
	TL1+m10	56.7±1.7e	48.9±1.2d	6.9±0.5b	5.6±0.1b
L2	TL1+m0	13.9±0.9a	3.4±1.0a	3.4±0.8d	10.4±1.7b
	TL1+m1	14.0±0.9a	3.8±0.2a	3.3±0.2cd	10.5±0.4b
	TL1+m2	13.6±0.7a	4.1±0.5a	2.8±0.6bc	8.3±2.4b
	TL1+m5	13.8±0.8a	5.9±0.5b	2.0±0.2b	4.1±1.0a
	TL1+m10	15.9±0.5b	13.7±0.8c	2.8±0.2ab	2.5±0.2a
L3	TL1+m0	7.5±0.1a	1.6±0.1a	2.3±0.2c	6.2±0.4c
	TL1+m1	7.5±0.2a	2.0±0.3ab	2.0±0.2b	5.8±0.7c
	TL1+m2	7.0±0.0a	2.8±0.1b	1.9±0.0b	6.1±0.2c
	TL1+m5	6.7±0.1a	4.1±0.1c	1.4±0.1a	3.8±0.4b
	TL1+m10	7.9±2.5a	6.4±0.9d	1.4±0.0a	2.3±0.2a
Total	TL1+m0	42.3±0.2a	7.6±0.7a	9.6±0.5b	27.0±1.4d
	TL1+m1	49.1±2.6b	9.1±1.1ab	10.3±1.3bc	24.2±1.4c
	TL1+m2	52.9±2.0c	11.1±0.1b	9.7±0.8bc	19.5±1.4b
	TL1+m5	62.0±1.3d	26.7±0.9c	7.9±0.2a	10.8±0.5a
	TL1+m10	80.5±2.8e	69.0±2.3d	11.0±0.6c	10.5±0.5a

Average±standard deviation (n = 3). Values followed by different letter differ among five treatments of each soil at the same leaching time significantly (P < 0.05)

Table 3. Amounts of basic cations leached from TL2 soil during each time of leaching (mmol$_c$ kg^{-1})

No. of leaching	Treatment	Na	K	Ca	Mg
L1	TL2+m0	20.1±0.5a	2.8±0.0a	2.1±0.1a	12.7±0.9d
	TL2+m1	25.3±0.7 b	2.3±0.3ab	2.1±0.1a	6.9±0.4c
	TL2+m2	32.0±0.3c	3.1±0.1b	2.4±0.2a	4.4±0.4b
	TL2+m5	49.3±0.6d	14.4±0.2c	3.3±0.1b	3.2±0.0a
	TL2+m10	64.9±0.6e	49.2±0.5d	5.2±0.4c	5.2±0.1bc
L2	TL2+m0	18.3±0.2a	4.2±0.2a	3.5±0.2b	18.2±0.3c
	TL2+m1	18.2±0.9a	5.0±0.8ab	3.1±0.6ab	17.1±2.4c
	TL2+m2	18.3±0.9a	6.9±0.4b	3.4±0.2b	19.4±1.4c
	TL2+m5	17.5±1.0a	9.7±2.7c	2.5±0.7a	8.0±0.4b
	TL2+m10	20.1±0.8b	17.4±0.4d	2.3±0.1a	5.4±0.3a
L3	TL2+m0	13.0±0.7c	3.4±0.4a	3.3±0.3c	14.6±1.1c
	TL2+m1	12.3±0.3c	4.4±0.3b	3.2±0.2bc	15.6±1.0c
	TL2+m2	11.3±0.4b	5.2±0.3c	2.8±0.2b	14.6±1.0c
	TL2+m5	10.0±0.4a	6.3±0.2d	1.7±0.2a	8.5±0.5b
	TL2+m10	10.3±0.3a	9.9±0.4e	1.5±0.1a	4.4±0.8a
Total	TL2+m0	51.3±1.1a	10.4±0.2a	8.9±0.2b	45.5±0.3d
	TL2+m1	55.8±1.3b	11.7±1.1a	8.3±0.8b	39.6±3.2c
	TL2+m2	61.6±1.6c	15.3±0.6b	8.6±0.6b	38.4±2.7c
	TL2+m5	76.8±0.6d	30.4±2.4c	7.6±0.8a	19.7±0.9b
	TL2+m10	95.2±0.6e	76.5±1.1d	9.0±0.3bc	15.0±1.2a

Average±standard deviation (n = 3). Values followed by different letter differ among five treatments of each soil at the same leaching time significantly (P < 0.05)

The amount of Mg^{2+} leached during the first leaching was smaller in the cattle manure treatments, 2.8–7.9 mmol$_c$ kg^{-1}, than the control, 10.3–12.7 mmol$_c$ kg^{-1}, in both soils. The difference from the control tended to be greater when the cattle manure was applied at a higher rate. At the second and third leaching, a 5% and 10% manure application still leached a greater amount of Mg^{2+} compared to the control. In total, the difference in Mg^{2+} leaching between the cattle manure treatments and the control ranged from 2.8–16.6 mmol$_c$ kg^{-1} in TL1 and 6.0–30.6 mmol$_c$ kg^{-1} in TL2. The amount of Ca^{2+} leached was less different among the treatments, 2.1–6.9, 2.0–3.5, and 1.4–3.3 mmol$_c$ kg^{-1} during the first, second, and third leaching, respectively, for both soils.

3.2 Effect of Manure Application on the amount of Exchangeable Cations in Soil after Leaching

Yields of basic cations from the TL1 and TL2 soil samples after 3 periods of leaching by ammonium acetate extraction are shown in Table 4. When cattle manure was applied at rates of 2–10%, the yield of Na decreased to 4.0–8.0 and 3.5–9.2 mmol$_c$ kg^{-1} for the TL1 and TL2 soils, respectively The decrease due to the manure application was greater for Ca, 49.0–135.5 (TL1) or 16.0–24.5 (TL2) mmol$_c$ kg^{-1}, while the yield of

K was larger in the cattle manure treatments than in the control, except for TL2+m1. The maximum difference in the yield of K from the control, 42.8 and 66.4 mmol$_c$ kg^{-1}, was recorded for TL1+m10 and TL2+m10, respectively. Exchangeable Mg^{2+} also increased as the result of a manure application.

The exchangeable Mg^{2+} content in the cattle manure that separated from the TL1 soils after leaching (Table 5) was larger than that in the initial manure sample (Table 1). This indicates that some of the soil Mg^{2+} that had eluted into the soil solution had become adsorbed to the cattle manure.

3.3 Effect of Manure Application on Soil EC and pH after Leaching

The EC of the leachates from the 4 manure treatments was higher than that from the control at the first leaching, but then decreased drastically (Table 6). At the second and third leaching, the EC of the leachates from the treatments in which the manure was applied at 1% and 2% were essentially the same as the control. The EC of leachates from the treatments in which the manure was applied at 5% and 10% at the third leaching was also decreased to a level similar to or lower than that for the control at the first leaching. After 3 leachings, soil EC of

Table 4. Contents of ammonium acetate extracted cations in Tongliao soils after leaching

Treatment	Na (mmol$_c$ kg^{-1})	K (mmol$_c$ kg^{-1})	Ca (mmol$_c$ kg^{-1})	Mg (mmol$_c$ kg^{-1})
TL1+m0	27.2±1.1 c	5.8±0.6 a	306.4±4.0 e	25.6±0.9 a
TL1+m1	24.5±1.0 bc	11.5±1.0 b	275.0±1.5 d	26.8±1.4 a
TL1+m2	23.2±3.4 ab	17.9±1.4 c	257.6±5.8 c	30.3±2.2 b
TL1+m5	19.9±1.1 a	31.5±1.2 d	209.2±3.6 b	38.6±0.5 c
TL1+m10	19.2±0.6 a	48.7±1.3 e	171.1±3.3 a	47.5±1.3 d
TL2+m0	42.1±0.4 c	11.6±3.1 a	250.1±1.8 c	37.8±0.7 a
TL2+m1	40.9±4.3 bc	16.7±1.4 a	247.0±3.0 c	41.4±1.4 b
TL2+m2	38.6±0.3 ab	25.9±1.9 b	234.9±1.5 b	42.2±0.9 b
TL2+m5	34.3±5.0 a	52.5±3.1 c	233.6±4.4 b	54.5±1.8 c
TL2+m10	33.6±1.2 a	81.9±5.2 d	225.7±1.2 a	66.9±1.3 c

Average±standard deviation (n = 3). Values followed by different letter differ among five treatments of each soil significantly (P < 0.05)

Table 5. Contents of exchangeable cations in cattle manure separated from TL1 soil after leaching

Treatment	Na (mmol$_c$ kg^{-1})	K (mmol$_c$ kg^{-1})	Ca (mmol$_c$ kg^{-1})	Mg (mmol$_c$ kg^{-1})
TL1+m1	0.8±0.0 a	0.4±0.0 a	13.8±0.7 a	2.6±0.2 a
TL1+m2	0.8±0.1 a	0.7±0.1 a	24.4±1.6 b	5.6±0.3 b
TL1+m5	0.8±0.0 a	1.4±0.1 b	53.2±2.0 c	16.4±0.5 c
TL1+m10	1.0±0.0 b	3.0±0.3 c	87.2±2.5 d	36.6±1.3 d

Average±standard deviation (n = 3). Values followed by different letter differ among five treatments significantly (P < 0.05)

TL2+m1, TL2+m2, and TL2+m5 was similar to that of TL2+m0. The soil EC of TL1+m5, TL1+m10, and TL2+m10 was also lower than that of the control before leaching (Table 1).

Fig. 1 indicates that the manure application decreased the pH of the leachates for both the TL1 and TL2 soil samples. The lowest pH, 7.9 or 8.1, was recorded for TL1+m10 and TL2+m10 at the first leaching. However, the pH of the leachate increased as the frequency of leaching increased in all of the cattle manure treatments, which probably was the result of the loss of bicarbonate during the leaching process. Soil pH of the manure treatments after 3 leachings (Fig. 2) was 9.3–9.8 for TL1 and 9.8–10.2 for TL2. Because the pH of TL1+m0 was 9.8 and that of TL2+m0 was 10.4, cattle manure application was more effective in decreasing the soil pH than water washing.

3.4 Effect of Manure Application on HC

Variations in HC as a function of EC are illustrated in Fig. 3. The HC of TL1+m0 and TL2+m0 was very low, 4.7×10^{-5} and 7.6×10^{-6} cm s^{-1}, respectively. Dilution of soil solution with leaching water resulted in a further decrease in HC to 7.9×10^{-6} and 7.0×10^{-7} cm s^{-1}. The cattle manure application enhanced HC, although the effect was slight when the rate of application was 1% or 2%. In each treatment, the HC declined with decreasing EC during repeated leachings, and a positive correlation ($P < 0.05$) was observed between them. These results indicate that the improvement in soil HC caused by the application of cattle manure was not only due to the physical effect, which has generally been assumed [22], but also due to its high electrolyte concentration. Although both soils showed a similar tendency, the HC value declined more rapidly in TL2 than in TL1.

Table 6. EC of leachates and soils after leaching

Treatment	L1 (ds m^{-1})	L2 (ds m^{-1})	L3 (ds m^{-1})	Soil (ds m^{-1})
TL1+m0	0.67±0.01 a	0.53±0.13 a	0.29±0.03 a	0.18±0.01 a
TL1+m1	0.92±0.02 b	0.50±0.03 a	0.28±0.01 a	0.19±0.01 a
TL1+m2	1.24±0.06 c	0.57±0.04 a	0.29±0.01 a	0.19±0.01 a
TL1+m5	2.15±0.04 d	0.75±0.03 b	0.36±0.01 b	0.25±0.00 b
TL1+m10	3.78±0.02 e	1.21±0.02 c	0.52±0.01 c	0.34±0.01 c
TL2+m0	0.69±0.01 a	0.53±0.01 a	0.40±0.01 a	0.27±0.02 a
TL2+m1	0.91±0.01 b	0.55±0.00 a	0.40±0.00 a	0.27±0.00 a
TL2+m2	1.21±0.02 c	0.58±0.13 a	0.39±0.01 a	0.27±0.01 a
TL2+m5	2.14±0.01 d	0.81±0.13 b	0.47±0.01 b	0.30±0.01 a
TL2+m10	3.66±0.04 e	1.25±0.03 c	0.62±0.01 c	0.37±0.01 b

Average±standard deviation (n = 3). Values followed by different letter differ among five treatments of each soil significantly (P < 0.05)
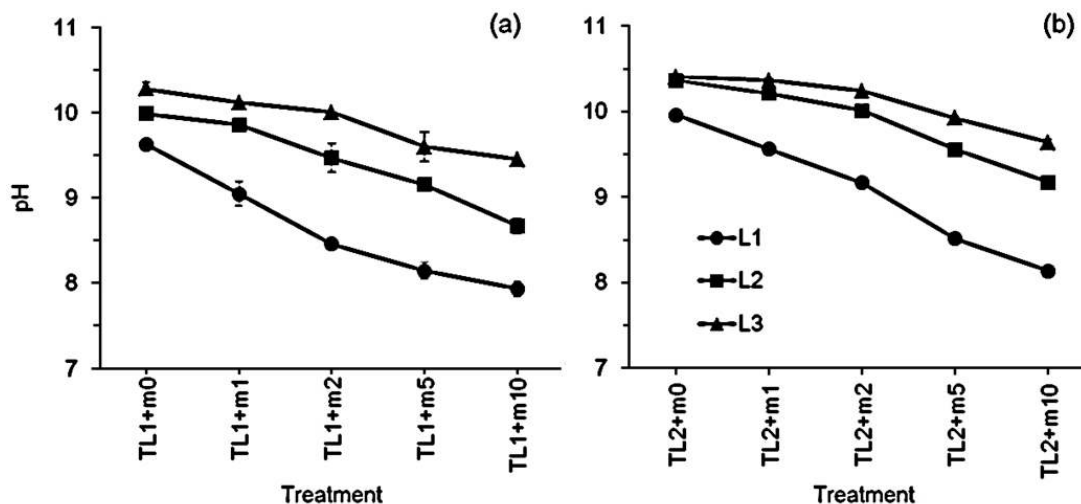

Fig. 1. pH of leachates from the TL1 (a) and TL2 (b) soil samples with cattle manure applied at different rates
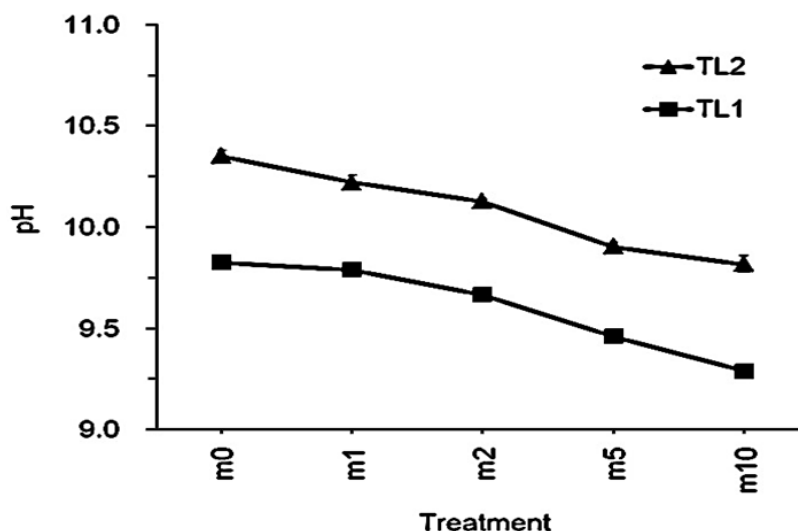
Fig. 2. pH values of the TL1 and TL2 soil samples with cattle manure applied at different rates after leaching
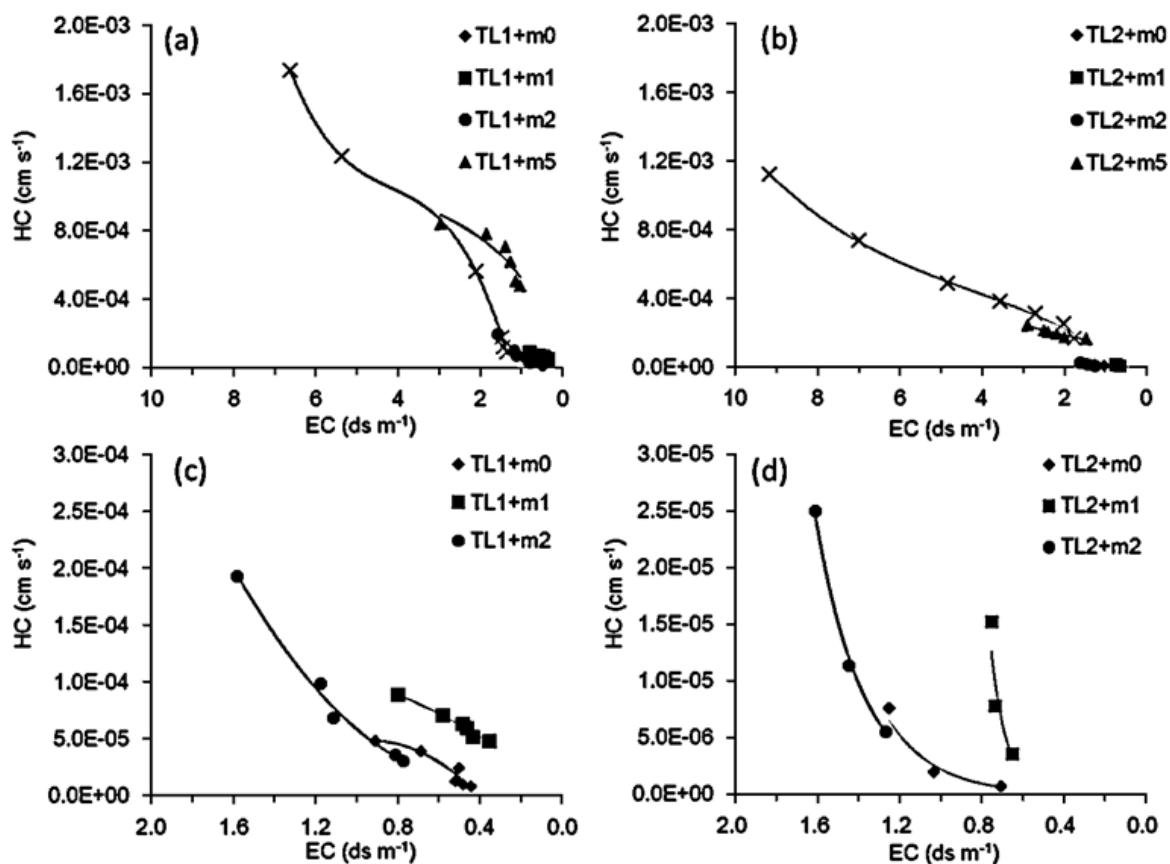

Fig. 3. Relationship between hydraulic conductivity (HC) and electrical conductivity (EC) of TL1 (a) and TL2 (b) soils with cattle manure applied at different rates. Results from 0–2% applications are expanded in (c) and (d)

Table 7. Bulk density before and after water infiltration (g cm^{-3})

Treatment	TL1+m0	TL1+m1	TL1+m2	TL1+m5	TL1+m10
Before infiltration	1.50±0.01 de	1.28±0.02 c	1.10±0.25 a	1.28±0.11 bc	1.14±0.09 a
After infiltration	1.59±0.02 e	1.45±0.08 d	1.38±0.02 cd	1.16±0.09 ab	1.12±0.05 a
Treatment	TL2+m0	TL2+m1	TL2+m2	TL2+m5	TL2+m10
Before infiltration	1.50±0.01 d	1.28±0.02 c	1.10±0.25 a	1.28±0.11 c	1.14±0.09 ab
After infiltration	1.94±0.09 e	1.83±0.08 e	1.57±0.02 d	1.36±0.03 c	1.26±0.02 bc

Average±standard deviation (n = 3). Values followed by different letter differ among five treatments of each soil significantly (P < 0.05)

Table 7 above shows the change in soil bulk density during infiltration. The bulk density of TL1 and TL2 increased from 1.50 g cm^{-3} before infiltration (Table 1) to 1.59 (TL1) or 1.94 (TL2) g cm^{-3} afterward. This can be attributed to the plugging of the soil pores by dispersed clay particles [23]. An increase in bulk density was also observed when the cattle manure was applied at a lower rate. However, there was no significant change in the TL1+m10, TL2+m5, and TL2+m10, suggesting that the deterioration in the soil structure during the leaching process was prevented when high mixing ratios of cattle manure were used.

4. DISCUSSION

In the present study, both exchangeable K$^+$ and water soluble K$^+$ (sum of the amount of K leached during 3 periods of leaching) increased with increasing rate of cattle manure application (Table 4). This result is consistent findings reported by Feigenbaum et al. [24], which suggested that soil exchangeable potassium percent (EPP) correlates positively with the potassium adsorption ratio (PAR). The SAR in soil solutions was also larger when the manure was applied at a higher rate, because the leaching of Na$^+$ was increased and Mg^{2+} leaching was decreased without any significant change in Ca^{2+} leaching. As such, this confirms that the relation of EPP-PAR was not affected by the SAR level of the leachate [25].

Wada and Seki [26] showed that coexisting K reduced the exchange of Na for Ca, and Ferreira and Schulthess [11] showed that K outperformd Ca in the desorption of Na that was entrapped in the nanopore by soil minerals because of the stronger dehydration ability. Our findings also suggest the preferential adsorption of K over Ca and Mg, based on the decreases in exchangeable Ca^{2+} and Mg^{2+} after the cattle manure application. The superiority of using sheep or poultry manure to gypsum at the same rate (5%) in terms of CEC and exchangeable K$^+$

was suggested, based on studies using a sandy loam soil [17]. An application of K-fertilizer to saline-sodic soils that was irrigated with saline-sodic water reduced the Na: K ratio of plant tissues, resulting in the improvement of plant growth [27,28]. Similar effect would be expected of cattle manure application. Although we showed a rapid effect of manure application on Na desorption, manure may supply more K over a longer period of time with the progression of decomposition [29]. The rate of manure application 1% could not replace soil exchangeable Na, while the 2–10% applications decreased soil exchangeable Na without significant differences between the treatments (Table 4). Therefore, a rate of 2% or more is recommendable for the manure application to the field practically. However, we should be aware that K selectivity differs among soils with different clay minerals dominated [30]. Our results are based on the kaolinite dominated soils. Confirmation of an effective level may be required if manure is applied to soils having the other types of clay minerals as dominance.

The cattle manure application had no detectable adverse effects on the soil EC (Table 6) and decreased soil pH when the application rate was high (Fig. 1). Hussain et al. [28] reported that an application of K sulfate (50 or 100 kg K ha^{-1}) did not change the EC$_e$ of saline-sodic soils. Jalali and Ranjbar [17] showed that the increased soil EC due to the application of sheep or poultry manure could be easily returned to the initial level by a leaching treatment, while that due to a gypsum application was maintained during the leaching treatment. Such difference in the reactivity of components between manure and gypsum is one advantage of the manure application to sodic soils. The soil pH of TL1+m10 after leaching was close to the soil pH near the soil sampling points where *Chinese* Wild Rye (*Aneurolepidium pseudogrogropyrum*), a high quality herbage, was grown (9.0, data not shown). In the case of calcareous saline-sodic soils, it is difficult to decrease the soil pH

because of the buffering effect of $CaCO_3$ [31]. We did not determine the $CaCO_3$ content in the soil samples. However, since the area including the sampling spot of TL2 is recognized as being rich in $CaCO_3$ [19], $CaCO_3$ might have contributed to the lower decrease in soil pH after the manure application in the TL2 soil compared to the TL1 soil.

In our study, no adverse effects of added K on soil saturated HC was observed (Table 7), suggesting that the use of cattle manure is completely safe for soils in the sampling area. Overall, the effect of exchangeable K on soil HC is intermediate between Ca and Na [32]. The advantage of K in comparison with Na is its smaller hydration energy that contributes to the development of repulsive forces between clay particles, which is equivalent to 72% of the Na [33]. Laurenson et al. [34] showed that clay dispersion occurred in soil with an EPP larger than 11 when it was irrigated with low EC (<0.2 ds m^{-1}) water. However, the EC of the leachates did not decrease below 0.2 ds m^{-1} even in the third leaching of the cattle manure applied soils (Table 6). Shainberg et al. [35] showed that the effect of EPP on the deterioration of soil structure and the decrease in HC in smectitic soils was smaller in soils with a higher charge density, in which strong attractive forces between clay particles are in force. The effect of irrigation with high K water on the HC also differed between a montmorillite-dominated and a vermiculite-dominated soil [36]. The major clay minerals in the TL1 and TL2 soils were Kaolinite and Mica (Table 1), and it has been recognized that the dispersibility of Kaolinitic soils is low [13,37]. Thus, soil mineralogy should be taken into consideration when of a K-containing material is used for removing Na from a sodic soil.

Many studies showed the positive effect of organic matter application on soil properties, soil structure and aggregate stability [38–40]. Since our experiments were conducted in a short period (1–2 days), the contribution of the aggregate formation effect by manure organic matter on the maintenance of HC was not definitive. However, such function is very important to evaluate the long-term effect of manure application on saline-sodic soil. Due to the multiple functions derived from high K content, high EC, and high organic matter content, manure is considered to be more effective and more generic in remediation of sodic or saline-sodic soils than inorganic K materials.

5. CONCLUSIONS

The findings of the present study indicate that K$^+$ from cattle manure applied to soil can replace Na$^+$ and can decrease the exchangeable Na content, pH, and EC in the two saline-sodic soils examined. Soil physical properties, HC and bulk density, were also improved. Thus, cattle manure has potential as a functional K material for remediating sodic and saline-sodic soils alternative to Ca materials. Further research to confirm these effects of cattle manure applied at practical levels in the field scale and the effect of repetitive cattle manure applications will be required.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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