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Prediction of Soil Cation Exchange Capacity Based on Some Soil Physical and Chemical Properties

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Abstract: There are many cases in which it is desirable to determine relationships among some soil physical and chemical properties. For instance, soil Cation Exchange Capacity (CEC) are often determined using laborious and time consuming laboratory tests, but it may be more suitable and economical to develop a method which uses some soil physical and chemical properties. Therefore, a relationship between soil CEC and some soil physical and chemical properties is needed. In this study, thirty-one linear multiple regression models for predicting soil CEC from some physical and chemical properties such as Sand (SA), Silt (SI), Clay (CL) and Organic Carbon (OC) content (% by weight) and pH (PH) of soil were suggested. Models were divided into five main classifications and the soil CEC was estimated as a function of one, two, three, four or five independent variables. The statistical results of the study indicated that in order to predict soil CEC based on the soil physical and chemical properties the three variables linear regression model CEC = 23.56 + 0.09 SA + 7.35 OC – 2.36 PH with R^2 = 0.80 and the four variables linear regression model CEC = 20.50 + 0.17 SA + 0.11 CL + 7.67 OC – 2.67 PH with R^2 = 0.82 can be recommended.

Key words: Cation exchange capacity · organic carbon · clay · prediction

INTRODUCTION

Soil Cation Exchange Capacity (CEC) is the total of the exchangeable cations that a soil can hold at a specified pH. Soil components known to contribute to soil CEC are clay and organic matter and to a lesser extent, silt [1, 2].

The exchange sites can be either permanent or pH-dependent. Mineral soils have an exchange capacity that is a combination of permanent and pH-dependent exchange sites, while that of organic soils is predominantly pH-dependent. In any given soil, the number of exchange sites is dependent on the soil pH; type, size and amount of clay and amount and source of the organic material [3-6].

The relationship between clay content (% by weight) and CEC can be highly variable because different clay minerals have very different CEC values. In addition, the relative proportion of pH-dependant and permanent CEC varies among clay minerals [6]. Several researchers have attempted to predict CEC from clay and organic carbon contents alone, using multiple regression. Results show that greater than 50% of the variation in CEC could be explained by the variation in clay and organic carbon content for several New Jersey soils [7], for sandy soils in Florida [8], for some Philippine soils [9] and for four soils in Mexico [10]. Only a small improvement was obtained by adding pH to the model for four Mexican soils [10]. In B horizons of a toposequence, the amount of fine clay (particle size < 0.2 μm) was shown to explain a larger percent of the variation in CEC than the total clay content [11]. In gleyed subsoil horizons of lowland soils in Quebec, surface area (of the soil) gave a better prediction of CEC than did total clay [1]. Martel *et al.* [1] also showed that the variations in mineralogical composition, although small, were sufficient to explain nearly 50% of the variation in CEC. Similarly, Miller [6] found that the type of clay alone could explain up to 50% of the variation in CEC.

Many of the above predictive models are specific to a region or area and confined to only a few soil types. Many attempts have been made to predict CEC indirectly

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from some easily available soil physical and chemical properties. MacDonald [12] developed two equations CEC = 2.0 (organic carbon) + 0.5 (clay) and CEC = 3.8 (organic carbon) + 0.5 (clay) for Quebec and Alberta soil state in Canada, respectively. Bell and Keulen [10] studied Mexico soils and proposed an equation to predict soil CEC by some independent variables such as clay, organic carbon and pH. In their equation, 96% of soil CEC variations were explained by clay, organic carbon and pH. Also, Krogh *et al.* [13] suggested an equation based on silt, clay, organic carbon and pH which explained 90% of soil CEC variation. Asadu and Akamigbo [14] predicted soil CEC from organic matter and clay content grouped by taxonomic order (Inceptisols, Alfisols, Ultisols and Oxisols).

Despite the considerable amount of research done, which shows the relationship between soil CEC and soil physical and chemical properties, very limited work has been conducted to predict soil CEC based on soil physical and chemical properties. Therefore, the main objectives of this research were: (a) to determine optimum soil CEC model(s) based on some physical and chemical properties and (b) to verify the soil CEC model(s) by comparing their results with those of the laboratory tests.

MATERIALS AND METHODS

Experimental procedure: Seventy-five soil samples were taken at random from different fields of experimental site of Varamin, Iran. The site is situated at latitude of 35°-19'N and longitude of 51°-39'E and is 1000 m above mean sea level, in arid climate in the center of Iran. The soil of the experimental site was a fine, mixed, thermic, Typic Haplacambids clay-loam soil.

In order to obtain required parameters for determining soil CEC linear regression models, some soil physical and chemical properties i.e. sand, silt, clay and organic carbon content (% by weight) and pH of the soil samples were measured using laboratory tests as described by the Soil Survey Staff [15]. Table 1 shows physical and chemical properties of the soil samples used to determine soil CEC linear regression models.

Also, in order to verify soil CEC linear regression models, fifteen soil samples were taken at random from different fields of the experimental site. Again, mentioned soil physical and chemical properties of these soil samples were measured using laboratory tests as described by the Soil Survey Staff [15]. Table 2 shows physical and chemical properties of the soil samples used to verify soil CEC linear regression models.

Table 1: The mean values, Standard Deviation (S.D.) and Coefficient of Variation (C.V.) of soil physical and chemical properties of the seventy-five soil samples used to determine soil CEC models

Parameter	Minimum	Maximum	Mean	S.D.	C.V. (%)
Sand (%)	14.0	44.0	33.1	6.31	19.1
Silt (%)	30.0	56.0	45.3	4.13	9.12
Clay (%)	9.00	50.0	22.0	6.65	30.2
Organic carbon (%)	0.15	1.90	0.68	0.32	47.1
pH	7.00	8.10	7.50	0.27	3.60
CEC (cmol (+) kg^{-1})	7.00	23.0	13.9	3.25	23.4

Table 2: The mean values, Standard Deviation (S.D.) and Coefficient of Variation (C.V.) of soil physical and chemical properties of the fifteen soil samples used to verify soil CEC models

Parameter	Minimum	Maximum	Mean	S.D.	C.V. (%)
Sand (%)	10.0	34.0	24.1	5.87	24.4
Silt (%)	40.0	56.0	48.2	4.40	9.13
Clay (%)	18.0	50.0	28.2	7.90	28.0
Organic carbon (%)	0.36	2.00	0.83	0.39	47.0
pH	7.00	8.00	7.31	0.33	4.51
CEC (cmol (+) kg^{-1})	8.00	25.0	15.2	3.72	24.5

Table 3: One, two, three, four and five variables linear regression models in five classifications

Model classification	Model No.	Model
First	1	$CEC = k_0 + k_1$ SA
	2	$CEC = k_0 + k_2$ SI
	3	$CEC = k_0 + k_3$ CL
	4	$CEC = k_0 + k_4$ OC
	5	$CEC = k_0 + k_5$ PH
Second	6	$CEC = k_0 + k_1$ SA $+ k_2$ SI
	7	$CEC = k_0 + k_1$ SA $+ k_3$ CL
	8	$CEC = k_0 + k_1$ SA $+ k_4$ OC
	9	$CEC = k_0 + k_1$ SA $+ k_5$ PH
	10	$CEC = k_0 + k_2$ SI $+ k_3$ CL
	11	$CEC = k_0 + k_2$ SI $+ k_4$ OC
	12	$CEC = k_0 + k_2$ SI $+ k_5$ PH
	13	$CEC = k_0 + k_3$ CL $+ k_4$ OC
	14	$CEC = k_0 + k_3$ CL $+ k_5$ PH
	15	$CEC = k_0 + k_4$ OC $+ k_5$ PH
Third	16	$CEC = k_0 + k_1$ SA $+ k_2$ SI $+ k_3$ CL
	17	$CEC = k_0 + k_1$ SA $+ k_2$ SI $+ k_4$ OC
	18	$CEC = k_0 + k_1$ SA $+ k_2$ SI $+ k_5$ PH
	19	$CEC = k_0 + k_1$ SA $+ k_3$ CL $+ k_4$ OC
	20	$CEC = k_0 + k_1$ SA $+ k_3$ CL $+ k_5$ PH
	21	$CEC = k_0 + k_1$ SA $+ k_4$ OC $+ k_5$ PH
	22	$CEC = k_0 + k_2$ SI $+ k_3$ CL $+ k_4$ OC
	23	$CEC = k_0 + k_2$ SI $+ k_3$ CL $+ k_5$ PH
	24	$CEC = k_0 + k_2$ SI $+ k_4$ OC $+ k_5$ PH
	25	$CEC = k_0 + k_3$ CL $+ k_4$ OC $+ k_5$ PH
Forth	26	$CEC = k_0 + k_1$ SA $+ k_2$ SI $+ k_3$ CL $+ k_4$ OC
	27	$CEC = k_0 + k_1$ SA $+ k_2$ SI $+ k_3$ CL $+ k_5$ PH
	28	$CEC = k_0 + k_1$ SA $+ k_2$ SI $+ k_4$ OC $+ k_5$ PH
	29	$CEC = k_0 + k_1$ SA $+ k_3$ CL $+ k_4$ OC $+ k_5$ PH
	30	$CEC = k_0 + k_2$ SI $+ k_3$ CL $+ k_4$ OC $+ k_5$ PH
Fifth	31	$CEC = k_0 + k_1$ SA $+ k_2$ SI $+ k_3$ CL $+ k_4$ OC $+ k_5$ PH

Regression models: A typical linear multiple regression model is shown in Eq. 1:

$$Y = k_0 + k_1X_1 + k_2X_2 + k_3X_3 + \ldots + k_nX_n \qquad (1)$$

Where:
Y = Dependent variable, for example soil CEC
$X_1, X_2, X_3, \ldots, X_n$ = Independent variables, for example sand, silt, clay and organic carbon content (% by weight) and pH of soil
$k_0, k_1, k_2, k_3, \ldots, k_n$ = Regression coefficients

In order to predict soil CEC from the soil physical and chemical properties i.e. Sand (SA), Silt (SI), Clay (CL) and Organic Carbon (OC) content (% by weight) and pH (PH), thirty-one linear regression models were suggested (Table 3).

Statistical analysis: A paired samples t-test and the mean difference confidence interval approach were used to compare the soil CEC values predicted using models with the soil CEC values measured by laboratory tests. The Bland-Altman approach [16] was also used to plot the agreement between the soil CEC values measured by laboratory tests with the soil CEC values predicted using models. The statistical analyses were performed using Microsoft Excel (Version 2003).

RESULTS

A total of thirty-one linear regression models have been categorized in five different classifications based on the number of independent variables (Table 3). The p-value of the independent variables, Coefficient of Determination (R^2) and Coefficient of Variation (C.V.) of all the linear regression models are shown in Table 4.

First classification models: In this classification soil CEC can be predicted as a function of one independent variable. As indicated in Table 4, among the first classification models (models No. 1-5), model No. 2 where silt was considered as independent variable had the lowest R^2 value (0.01) and the highest C.V. (23.5%). However, model No. 4 where organic carbon was considered as independent variable had the highest R^2 value (0.74) and the lowest C.V. (12.1%). Model No. 4 is given in Eq. 2.

$$CEC = 7.93 + 8.72\ OC \qquad (2)$$

Table 4: Linear regression models, p-value of model variables, coefficient of determination (R^2) and Coefficient of Variation (C.V.)

Model	p-value						C.V.
No.	SA	SI	CL	OC	PH	R^2	(%)
1	3.41E-06	-	-	-	-	0.26	20.3
2	-	0.559616	-	-	-	0.01	23.5
3	-	-	1.20E-04	-	-	0.19	21.2
4	-	-	-	7.04E-23	-	0.74	12.1
5	-	-	-	-	3.82E-05	0.21	20.9
6	4.20E-06	0.628322	-	-	-	0.26	20.4
7	7.63E-03	-	0.508363	-	-	0.26	20.3
8	4.04E-03	-	-	9.99E-20	-	0.77	11.5
9	9.20E-06	-	-	-	1.01E-04	0.40	18.4
10	-	0.031511	1.39E-05	-	-	0.24	20.7
11	-	0.011746	-	6.61E-24	-	0.76	11.6
12	-	0.945443	-	-	5.15E-05	0.21	21.1
13	-	-	0.491333	1.75E-19	-	0.74	12.1
14	-	-	1.82E-03	-	5.73E-04	0.31	19.7
15	-	-	-	2.75E-21	1.01E-03	0.77	11.3
16	0.114894	0.871137	0.634083	-	-	0.26	20.5
17	5.15E-03	0.014849	-	9.97E-21	-	0.79	11.1
18	1.06E-05	0.899986	-	-	1.26E-04	0.40	18.5
19	7.17E-04	-	0.052447	3.32E-20	-	0.78	11.2
20	1.71E-03	-	0.849531	-	1.39E-04	0.40	18.5
21	3.34E-03	-	-	1.22E-18	8.53E-04	0.80	10.7
22	-	4.07E-04	9.61E-03	5.60E-21	-	0.78	11.1
23	-	0.018458	9.98E-05	-	3.68E-04	0.36	19.1
24	-	0.002136	-	4.40E-23	2.00E-04	0.80	10.6
25	-	-	0.816982	6.49E-19	1.37E-03	0.77	11.3
26	0.283181	0.138841	0.825056	2.03E-20	-	0.79	11.1
27	0.039725	0.944113	0.874804	-	1.57E-04	0.40	18.6
28	4.11E-03	2.64E-03	-	2.20E-20	1.68E-04	0.82	10.1
29	6.44E-05	-	6.06E-03	4.77E-20	1.20E-04	0.82	10.2
30	-	1.14E-04	0.017470	9.68E-21	3.71E-04	0.82	10.2
31	0.099741	0.199248	0.689037	3.82E-20	1.76E-04	0.83	10.1

Second classification models: In this classification soil CEC can be predicted as a function of two independent variables. Among the second classification models (models No. 6-15), models No. 6, 10, 11 and 12 where silt was considered as one of the two independent variables in the models were considered unacceptable based on the statistical results of the first and second classification models (Table 4). Among the remaining models of this classification, model No. 15 where organic carbon and pH were considered as two independent variables had the highest R^2 value (0.77) and the lowest C.V. (11.3%). Model No. 15 is given in Eq. 3.

$$CEC = 26.76 + 8.06\ OC - 2.45\ PH \qquad (3)$$

Third classification models: In this classification soil CEC can be predicted as a function of three independent variables. Among the third classification models (models No. 16-25), models No. 16, 17, 18, 22, 23 and 24 where silt was considered as one of the three independent variables in the models were considered unacceptable based on the statistical results of the first and third classification models (Table 4). Among the remaining models of this classification, model No. 21 where sand, organic carbon and pH were considered as three independent variables had the highest R^2 value (0.80) and lowest C.V. (10.7%). Model No. 21 is given in Eq. 4.

$$CEC = 23.56 + 0.09\ SA + 7.35\ OC - 2.36\ PH \quad (4)$$

Forth and fifth classification models: In these classifications soil CEC can be predicted as a function of four and five independent variables, respectively. Among the forth and fifth classification models (models No. 26-31), models No. 26, 27, 28, 30 and 31 where silt was considered as one of the independent variables in these models were judged unacceptable based on the statistical results of the first, forth and fifth classification models (Table 4). Based on the statistical results, only model No. 29 where sand, clay, organic carbon and pH were considered as four independent variables was considered acceptable. The R^2 value and C.V. of model No. 29 were 0.82 and 10.2%, respectively. Model No. 29 is given in Eq. 5.

$$CEC = 20.50 + 0.17\ SA + 0.11\ CL + 7.67\ OC - 2.67\ PH \quad (5)$$

DISSCUSSION

Among the acceptable models (models No. 4, 15, 21 and 29), models No. 21 and 29 were chosen due to higher R^2 value and lower C.V. and a paired samples t-test and the mean difference confidence interval approach were used to compare the soil CEC values predicted using models No. 21 and 29 with the soil CEC values measured by laboratory tests. The Bland-Altman approach [16] was also used to plot the agreement between the soil CEC values measured by laboratory tests with the soil CEC values predicted using models No. 21 and 29.

Comparison of model No. 21 with laboratory test: The soil CEC values predicted by model No. 21 were compared with the soil CEC values determined by laboratory tests and are shown in Table 5. A plot of the soil CEC values determined by model No. 21 and laboratory tests with the line of equality (1.0: 1.0) is shown in Fig. 1. The mean soil CEC difference between two methods was 0.67 cmol (+) kg^{-1} (95% confidence interval: -0.84 and 2.18 cmol (+) kg^{-1}; P = 0.358). The standard deviation of the soil CEC differences was 2.72 cmol (+) kg^{-1}. The paired samples t-test results showed that the soil CEC values predicted with model No. 21 were not significantly different than the soil CEC measured with laboratory tests (Table 6). The soil CEC differences between these two methods were normally distributed and 95% of the soil CEC differences were expected to lie between μ+1.96σ and μ–1.96σ, known as 95% limits of agreement [16]. The 95% limits of agreement for comparison of soil CEC determined with laboratory test and model No. 21 were calculated

Table 5: Physical and chemical properties of soil samples used in evaluating soil CEC models No. 21 and No. 29

	Soil physical and chemical properties					CEC (cmol (+) kg^{-1})		
Sample No.	Sand (%)	Silt (%)	Clay (%)	OC (%)	pH	Laboratory test	Model No. 21	Model No. 29
1	18	45	37	0.65	7.8	12.0	11.5	11.8
2	21	53	26	0.98	7.9	11.0	14.0	13.4
3	28	48	24	1.26	7.0	17.0	18.8	18.9
4	34	48	18	0.86	7.3	14.5	15.7	15.4
5	22	48	30	0.76	7.2	15.0	14.1	14.1
6	10	40	50	0.36	7.4	16.0	9.60	10.7
7	17	47	36	0.71	7.0	18.0	13.8	14.1
8	27	43	30	0.46	7.1	16.0	12.6	13.0
9	24	55	21	0.73	8.0	8.00	12.2	11.1
10	24	52	24	2.00	7.0	25.0	23.9	23.9
11	26	48	26	0.93	7.3	16.0	15.5	15.4
12	29	49	22	0.56	7.2	13.5	14.0	13.6
13	27	47	26	0.65	7.1	15.0	14.0	14.0
14	28	44	28	0.72	7.3	16.5	14.1	14.4
15	27	48	25	0.68	7.0	15.0	14.5	14.4

Table 6: Paired samples t-test analyses on comparing soil CEC determination methods

Determination methods	Average difference (cmol(+)kg^{-1})	Standard deviation of difference (cmol(+)kg^{-1})	p-value	95% confidence intervals for the difference in means (cmol (+) kg^{-1})
Model No. 21 & laboratory test	0.67	2.72	0.358	-0.84, 2.18
Model No. 29 & laboratory test	0.70	2.29	0.257	-0.57, 1.96

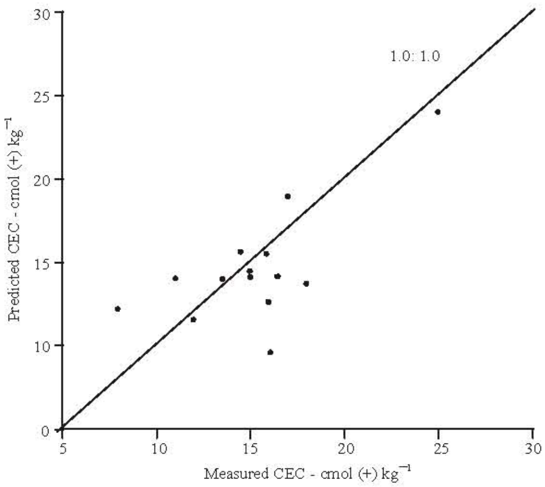

Fig. 1: Soil CEC values measured using laboratory tests (Measured CEC) and soil CEC values predicted using model No. 21 (Predicted CEC) with the line of equality (1.0: 1.0)

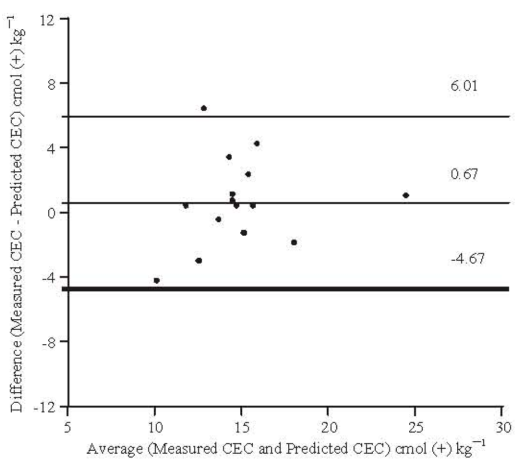

Fig. 2: Bland-Altman plot for the comparison of soil CEC values measured using laboratory tests (Measured CEC) and soil CEC values predicted using model No. 21 (Predicted CEC); the outer lines indicate the 95% limits of agreement (-4.67, 6.01) and the center line shows the average difference (0.67)

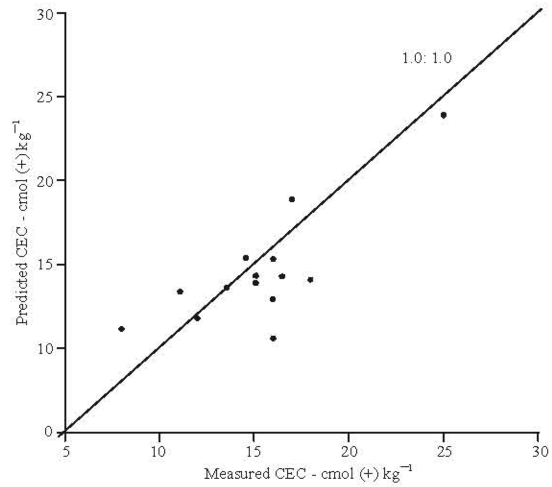

Fig. 3: Soil CEC values measured using laboratory tests (Measured CEC) and soil CEC values predicted using model No. 29 (Predicted CEC) with the line of equality (1.0: 1.0)

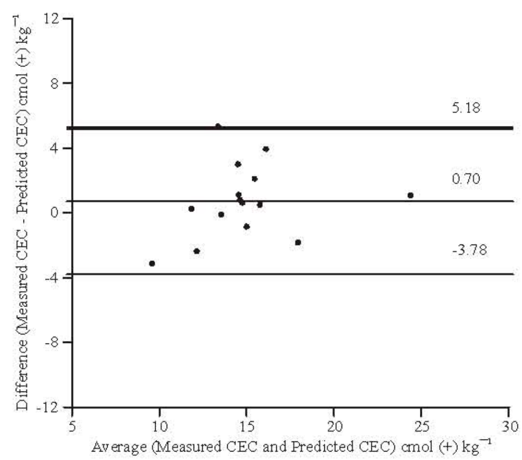

Fig. 4: Bland-Altman plot for the comparison of soil CEC values measured using laboratory tests (Measured CEC) and soil CEC values predicted using model No. 29 (Predicted CEC); the outer lines indicate the 95% limits of agreement (-3.78, 5.18) and the center line shows the average difference (0.70)

at -4.67 and 6.01 cmol (+) kg^{-1} (Fig. 2). Thus, soil CEC predicted by model No. 21 may be 4.67 cmol (+) kg^{-1} lower or 6.01 cmol (+) kg^{-1} higher than soil CEC measured by laboratory test. The average percentage differences for soil CEC prediction using model No. 21 and laboratory test was 15.2%.

Comparison of model No. 29 with laboratory test: The soil CEC values predicted by model No. 29 were also compared with the soil CEC values measured by laboratory tests and are shown in Table 5. A plot of the soil CEC values determined by model No. 29 and laboratory tests with the line of equality (1.0: 1.0) is shown in Fig. 3. The mean soil CEC difference between two methods was 0.70 cmol (+) kg^{-1} (95% confidence interval: -0.57 and 1.96 cmol (+) kg^{-1}; P = 0.257). The standard deviation of the soil CEC differences was 2.29 cmol (+) kg^{-1}. Again, the paired samples t-test results showed that the soil CEC values predicted with model No. 29 were not significantly different than the soil CEC values measured with laboratory tests (Table 6). The soil CEC differences between these two methods were also normally distributed and the 95% limits of agreement in comparing these two methods were calculated to be -3.78 and 5.18 cmol (+) kg^{-1} (Fig. 4). Thus, soil CEC predicted by model No. 29 may be 3.78 cmol (+) kg^{-1} lower or 5.18 cmol (+) kg^{-1} higher than soil CEC measured with laboratory test. The average percentage differences for soil CEC prediction using model No. 29 and laboratory test was 12.8%.

CONCLUSIONS

Multiple linear regression models were used to estimate the soil CEC. The soil CEC values predicted using these models were compared to the soil CEC values measured by laboratory tests. The difference between the soil CEC values predicted by multiple linear regression models and measured by laboratory tests were not statistically significant ($P>0.05$). Therefore, multiple linear regression soil CEC models provide an easy, economic and brief methodology to estimate soil CEC. Results of the study also indicate that organic carbon is the most important factor which affects soil CEC.

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