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Effects of Balancing Exchangeable Cations Ca, Mg, and K on the Growth of Tomato Seedlings (*Solanum lycopersicum* L.) Based on Increased Soil Cation Exchange Capacity

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Abstract: (1) Background: Previous research has demonstrated that the cation exchange capacity (CEC) of soil and the balance of exchangeable cations Ca, Mg, and K are key factors affecting plant growth and development. We hypothesized that balancing exchangeable cations based on increased CEC would improve plant growth and development. (2) Methods: This study conducted a two-phase experiment to evaluate methods for increasing soil CEC and the effects of increasing CEC and balancing Ca, Mg, and K on plant growth. Therefore, we first conducted a soil culture experiment using organic fertilizer, montmorillonite, and humic acid to investigate fertilizers that can effectively increase CEC in the short term. Then, a tomato seedling pot experiment was conducted using the control (CK) and OMHA fertilizer-treated soils collected from soil culture experiments. The CK and OMHA treatment soils were constructed with balanced exchangeable cations and an unbalanced control, respectively. (3) Results: The soil culture experiments revealed that the combination of organic fertilizer, montmorillonite, and humic acid (OMHA treatment) had the most significant effect on increasing CEC. The CEC of the OMHA treatment increased by 41.07%, reaching 27.10 $cmol \cdot kg^{-1}$. The tomato pot experiments demonstrated that balancing the exchangeable cations in OMHA soil improved the Mg and K nutrition of tomato seedlings and significantly increased SPAD, leaf nitrogen content, and dry weight, while balancing the exchangeable cations in CK soil improved only the K nutrition of tomato seedlings. (4) Conclusions: Overall, balancing exchangeable cations based on increasing CEC can improve soil nutrient availability and alleviate the competition effects of Ca, Mg, and K cations. Low CEC and imbalanced exchangeable cations can be detrimental to tomato seedling growth.

Keywords: soil cation exchange capacity; base cation saturation ratio; percentage base saturation; balance exchangeable cations; tomato

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1. Introduction

Unbalanced application of mineral fertilizers can cause competition between Mg^{2+} and other cations, such as Ca^{2+} and K^+. This competition can result in magnesium deficiency. Zalewska et al. [1] demonstrated that potassium saturation above 5% leads to an imbalance in the Mg/K ratio. Excess K^+ affects the movement of Mg^{2+} to the root surface, leading to lower silage yields in sunflowers. In nutrient solution, an increase in the concentration of potassium nutrients creates a strong antagonistic relationship between Mg^{2+} and K^+ ions, which reduces the uptake of magnesium nutrients by the plant [2]. In Japan, dolomite ($CaMg(CO_3)_2$) is widely used in soybean production to improve soil pH. Recent evidence has indicated that the soil Ca/Mg ratio is the most important positive factor affecting soybean plants [3]. Dolomite has a theoretical equivalent ratio of Ca and Mg of 1:1 based on cmol·kg^{-1}. Its application reduces the soil Ca/Mg ratio [3,4]. Brady et al. [5] noted that Ca, Mg, and K compete with each other in the soil, and their ratios affect plant uptake of these elements. However, the University of Missouri soil scientist William Albrecht, in his book series "The Albrecht Papers", proposes that maintaining soil Ca, Mg, and K cations at 65–85%, 6–20%, and 2–10% of total cation exchange capacity (CEC), respectively, can mitigate ionic nutrient antagonism between them [4,6]. This recommendation is widely supported by organic farmers in the United States [6,7]. Many soil testing laboratories also provide soil diagnostic reports that include base cation saturation percentages and Ca/Mg, Mg/K, and Ca/K ratios [6,7]. Zalewska et al. [8] found that ryegrass yield and mineral nutrient uptake increased when the total cation exchange in the soil was 50–60% for Ca, 8–20% for Mg, and 4–10% for K.

To balance the exchangeable cations of Ca, Mg, and K in the soil, it is necessary to determine appropriate fertilizer application rates based on CEC. CEC is a soil property that measures the total negative charge in the soil. This negative charge holds adsorbed plant nutrient cations such as calcium (Ca^{2+}), magnesium (Mg^{2+}), and potassium (K^{+}). CEC describes the soil's ability to supply nutrient cations to the soil solution for uptake by plants and is, therefore, a key determinant of soil fertility [9,10]. The soil diagnostic analysis report provides a value for CEC, which indicates the conditions or possible limitations that must be considered when treating a particular soil [10,11]. Usually, a high CEC allows the soil to hold more cations, making it rich in calcium, magnesium, and other cations. Conversely, soil with a low CEC limits the availability of mineral nutrients to plants. Low soil nutrient retention forces plants to expend considerable energy searching for nutrients in the soil. Applying high doses of soluble mineral salts to low-CEC soils is ineffective because the cation store or reservoir is too small [10]. Therefore, increasing CEC has a critical role to play in improving soil quality.

Previous research has mainly focused on changes in soil CEC and the factors that influence it. However, there has been limited research on methods to increase CEC. Soil CEC is determined by the content of clay minerals and/or organic matter [12]. Studies have indicated that the presence of negatively charged groups (e.g., carboxyl and phenolic groups) in soil organic matter provides about 30–60% of the adsorption sites for cations [13–15]. To enhance the organic matter content of the soil, it is generally suggested to utilize fertilizers. Organic fertilizers with high organic matter content or humic acid fertilizers are preferred. These fertilizers contain active groups, such as carboxyl and phenolic hydroxyl groups, which are acidic, hydrophilic, and adsorptive. This allows them to generate chelates with certain metal ions [13,16,17]. In addition to organic matter and clay content, CEC is greatly influenced by the parent mineralogy. According to Astera's "Ideal Soil" handbook [4], adding montmorillonite to soil can increase CEC and improve soil water and nutrient retention. Minerals with a 1:1 ratio have been reported to have a lower CEC than those with a 2:1 ratio. Among 2:1 minerals, montmorillonite (59–100 cmol·kg^{-1}) contributes more to the CEC than illite (15–40 cmol·kg^{-1}) [4,18–20]. Further study is required in order to investigate the short-term effects of applying organic and mineral fertilizers on increasing soil CEC.

Tomatoes (*Solanum lycopersicum* L.) are the most widely cultivated and consumed vegetable crop globally, with China ranking among the largest producers and consumers of tomatoes [21]. Compared to other crops, tomato biomass accumulation is significantly affected by soil Ca, Mg, and K saturation ratios [22]. However, studies on exchangeable cation interactions have mainly focused on forests, grasses, and arable crops, with less attention paid to vegetable crops [22,23]. Severe soil degradation in China has led to substantial losses of essential base cations, especially the exchangeable cations Ca, Mg, and K [20]. Such depletion contributes to soil nutrient deficiencies, especially in areas with light texture and low CEC, exacerbating the challenges of providing essential elements. Research on fertilizers enhancing CEC is scarce, and the effects of simultaneously considering increased soil CEC and balanced Ca, Mg, and K nutrients on healthy tomato growth have not been verified separately.

In this study, it was hypothesized that the balance of exchangeable cations Ca, Mg, and K based on increased CEC would promote a balanced uptake of mineral nutrients by tomato seedlings. Therefore, the specific purposes of this study were to screen for fertilizers that increase CEC and to determine the relevant factors affecting soil CEC. Additionally, this study investigated the effect of balancing the exchangeable cations Ca, Mg, and K on the growth and development of tomato seedlings based on increasing soil CEC. Enhancing soil quality is crucial, as is mitigating the adverse effects of soil cation imbalances on tomato growth. This study also provides a novel management approach to soil nutrient management.

2. Materials and Methods

2.1. Collection and Preparation of Soil, Fertilizers, and Tomato Seeds

The experiment used yellow-brown soil collected from Xiashu Town, Jurong City, Jiangsu Province. The soil was air-dried and sieved through a 20-mesh sieve after removing stones and plant debris. Table 1 shows the basic physical and chemical parameters of the soil. The montmorillonite powder used in the soil culture experiment was provided by Dehang Mineral Products Co., Ltd. (Lingshou County, Shijiazhuang City, Hebei Province, China), and its main components are Fe_2O_3, Al_2O_3, and silicate [4]. The commercial organic fertilizer, with an organic matter content of at least 45%, was provided by Qingdao Steven Agricultural Science and Technology Co., Ltd. (Huangdao District, Qingdao City, Shandong Province, China) [4]. The humic acid was supplied by Qingdao Steven Agricultural Science and Technology Co., Ltd. Its main components include organic matter (≥62.8%), K_2O (≥10%), humic acid (≥60%), xanthohumic acid (≥18%), and South African macroalgae extract (≥18%).

Table 1. Basic physical and chemical properties of test soil.

Soil	pH	EC [1] ($mS \cdot cm^{-1}$)	SOM [2] (%)	CEC [3] ($cmol \cdot kg^{-1}$)	Ex. Ca^{2+} [4] ($cmol \cdot kg^{-1}$)	Ex. Mg^{2+} [5] ($cmol \cdot kg^{-1}$)	Ex. K^{+} [6] ($cmol \cdot kg^{-1}$)	PBS [7] (%)	Ca/M [8]	Mg/K [9]	Ca/K [10]
Yellow-brown soil	6.96	0.24	0.69	19.88	6.42	1.74	0.19	42.00	3.69	9.16	33.79

[1] EC: soil conductivity; [2] SOM: soil organic matter; [3] CEC: cation exchange capacity; [4] Ex. Ca^{2+}: exchangeable calcium ions; [5] Ex. Mg^{2+}: exchangeable magnesium ions; [6] Ex. K^+: exchangeable potassium ions; [7] PBS: percentage base saturation; [8] Ca/Mg: Ex. Ca^{2+}/Ex. Mg^{2+}; [9] Mg/K: Ex. Mg^{2+}/Ex. K^+; [10] Ca/K: Ex. Ca^{2+}/Ex. K^+.

The potting tomato seedling experiments used dolomite (CaO ≥ 30.8%, MgO ≥ 21.0%, provided by Dehang Mineral Products Co., Ltd. of Shijiazhuang City, China), calcium sulfate dihydrate ($CaSO_4 \cdot 2H_2O$ ≥ 99.0%), and potassium sulfate (K_2SO_4 ≥ 99.0%) to balance soil exchangeable cations Ca, Mg, and K. The test crop was a dwarf tomato variety (Geranium Kiss) purchased at the Marseed flagship store.

2.2. Experimental Design

The soil culture experiment was conducted in the daylight greenhouse of the College of Resource and Environmental Sciences at Nanjing Agricultural University from April to May 2023. The average indoor temperature was controlled to an average of 20 °C at night and 30 °C during the day, with a relative humidity of 60% and a daily light duration of 12 h.

The soil culture experiment employed three types of fertilizers: montmorillonite, commercial organic fertilizer, and humic acid. A total of eight treatments were established, each of which was replicated three times. The treatments are listed below: (1) CK, the control (without fertilizer); (2) O treatment, commercial organic fertilizer; (3) M treatment, montmorillonite; (4) HA treatment, humic acid; (5) OM treatment, commercial organic fertilizer and montmorillonite; (6) OHA treatment, commercial organic fertilizer and humic acid; (7) MHA treatment, montmorillonite, and humic acid; and (8) OMHA treatment, commercial organic fertilizer, montmorillonite, and humic acid. Fertilizer application rates were as follows [4]: commercial organic fertilizer, 3 $t \cdot ha^{-1}$, 2.22 $g \cdot pot^{-1}$; montmorillonite, 0.3 $t \cdot ha^{-1}$, 0.22 $g \cdot pot^{-1}$; humic acid, 0.045 $t \cdot ha^{-1}$, 0.01 $g \cdot pot^{-1}$.

The air-dried soil was mixed with the fertilizers and placed into pots. Each pot was filled with 300 g of soil. To maintain the water-holding capacity of the field at 60–80%, 50 mL of deionized water was added every two days. On the 30th day of soil culture, soil samples were collected to determine the basic physicochemical properties. The soil properties measured in this study were soil pH; electrical conductivity (EC); soil organic matter content (SOM); cation exchange capacity (CEC); and the content of exchangeable cations Ca, Mg, and K.

The pot experiment was conducted on tomato seedlings from 15 July to 2 September 2023 in the daylight greenhouse of the College of Resource and Environmental Sciences at Nanjing Agricultural University.

The pot experiment used the control (CK) and OMHA treatment soils collected from the soil culture experiment. Both the control and OMHA treatment soils were constructed with balanced exchangeable cations and unbalanced control, respectively, for a total of four treatments: (1) CK-Unbalanced, (2) CK-Balanced, (3) OMHA-Unbalanced, and (4) OMHA-Balanced, with six replicates for each treatment. Refer to Section 2.3 for instructions on calculating the fertilizer application rates needed to balance exchangeable cations in the control and OMHA treatment soils.

The fertilizers were mixed with air-dried soil that had been sieved through a 20-mesh sieve. Each pot was filled with 500 g of soil. Three tomato seeds of the 'Geranium Kiss' variety were sown in each pot at a depth of 1 cm. The surface was then covered with a thin layer of soil. To maintain a water-holding capacity of 60–80% in the field, 100 mL of deionized water was added to the tomato seedlings every two days during their growth. Seedlings were randomly planted at the three-leaf stage (the 25th day of tomato seedlings growth, 10 August 2023), selecting seedlings with uniform growth.

2.3. Balancing Soil Exchangeable Cations Ca, Mg, and K

Before conducting the tomato seedling pot experiment, we analyzed the exchangeable cations content of Ca, Mg, and K in the soils from both the CK and OMHA treatments, as shown in Table 2. The results of the CEC analysis (Table 2) indicated that the CK soils had exchangeable Ca/Mg, Mg/K, and Ca/K ratios of 3.69, 9.16, and 33.79, respectively. The OMHA treatment soils had Ca/Mg, Mg/K, and Ca/K ratios of 3.61, 9.35, and 33.80. The results indicated that the OMHA fertilizer treatment effectively increased the CEC of the soil; however, it did not effectively replenish the content of exchangeable cations Ca, Mg, and K in the soil. In addition, the soil Ca/Mg, Mg/K, and Ca/K ratios were all higher than the optimal BCSR (base cation saturation ratio). Therefore, to achieve the optimal BCSR (exchangeable cations Ca:Mg:K = 5:2:1), exchangeable cations need to be balanced to reduce the Ca/Mg, Mg/K, and Ca/K ratios. CEC was determined for the CK and OMHA treatment soils from the soil culture experiment. The application rates of fertilizers required to balance the exchangeable cations in the CK and OMHA treatment soils were then calculated using the following formulas, as shown in Table 3.

$$\text{Formulae: Need to supplement Ca } (\text{mg}\cdot\text{kg}^{-1}) = \frac{\left(\text{CEC} \times 50\% - \text{Ex.Ca}^{2+}\text{in soil}\right)\text{coml/kg}}{\frac{1}{2}\text{Ca}^{2+}\text{cmol}\cdot\text{mg}^{-1}} \quad (1)$$

$$\text{Need to supplement Mg } (\text{mg}\cdot\text{kg}^{-1}) = \frac{\left(\text{CEC} \times 20\% - \text{Ex.Mg}^{2+}\text{in soil}\right)\text{coml/kg}}{\frac{1}{2}\text{Mg}^{2+}\text{cmol}\cdot\text{mg}^{-1}} \quad (2)$$

$$\text{Need to supplement K } (\text{mg}\cdot\text{kg}^{-1}) = \frac{\left(\text{CEC} \times 10\% - \text{Ex.K}^{+}\text{in soil}\right)\text{coml/kg}}{\text{K}^{+}\text{cmol}\cdot\text{mg}^{-1}} \quad (3)$$

Table 2. Soil physical and chemical properties of CK and OMHA soils in the pot experiment.

Treatments	CEC ($cmol \cdot kg^{-1}$)	PBS (%)	Ex. Ca^{2+} ($cmol \cdot kg^{-1}$)	Ex. Mg^{2+} ($cmol \cdot kg^{-1}$)	Ex. K^{+} ($cmol \cdot kg^{-1}$)	Ca/Mg	Mg/K	Ca/K
CK	19.21	43.46	6.42	1.74	0.19	3.69	9.16	33.79
OMHA	27.10	31.61	6.76	1.87	0.20	3.61	9.35	33.80

Table 3. Fertilizer application of CK and OMHA soils in the pot experiment.

Treatments	CEC ($cmol \cdot kg^{-1}$)	Measured Value ($cmol \cdot kg^{-1}$)			Target Value ($cmol \cdot kg^{-1}$)			Supplemental Value ($cmol \cdot kg^{-1}$)			Fertilizer Application ($mg \cdot kg^{-1}$)		
		Ex. Ca^{2+}	Ex. Mg^{2+}	Ex. K^{+}	Ex. Ca^{2+}	Ex. Mg^{2+}	Ex. K^{+}	Ex. Ca^{2+}	Ex. Mg^{2+}	Ex. K^{+}	Ex. Ca^{2+}	Ex. Mg^{2+}	Ex. K^{+}
CK	19.21	6.42	1.74	0.19	9.61	3.84	1.92	3.19	2.10	1.73	638.0	253.0	665.4
OMHA	27.10	6.76	1.87	0.20	13.55	5.42	2.71	6.79	3.55	2.51	1358.0	427.7	965.4

The optimal BCSR was determined using the following values: optimal Ca^{2+} saturation: 50%, optimal Mg^{2+} saturation: 20%, optimal K^{+} saturation: 10%, $\frac{1}{2}Ca^{2+}$ $cmol \cdot mg^{-1}$ = 0.005 $cmol \cdot mg^{-1}$, $\frac{1}{2}Mg^{2+}$ $cmol \cdot mg^{-1}$ = 0.0083 $cmol \cdot mg^{-1}$, K^{+} $cmol \cdot mg^{-1}$ = 0.0026 $cmol \cdot mg^{-1}$. These values were then converted to $mg \cdot kg^{-1}$ (Table 3).

Dolomite was chosen as the source of Mg and Ca, while $CaSO_4 \cdot 2H_2O$ was selected as the source of Ca for supplementation. K_2SO_4 was used as the source of K to balance the soil exchangeable cations. It was calculated that CK soils required 1.00 g of dolomite, 0.43 g $CaSO_4 \cdot 2H_2O$, and 0.74 g K_2SO_4 per 500 g of soil, while the OMHA soils required 1.70 g dolomite, 1.32 g $CaSO_4 \cdot 2H_2O$, and 1.08 g K_2SO_4 per 500 g of soil.

2.4. Statistical Analysis

The impacts of different fertilizer treatments on basic soil physicochemical properties in the soil culture experiment was analyzed by one-way analysis of variance (ANOVA) and tested with Duncan's test of significant difference using SPSS 22.0. In the tomato pot experiment, the physiological and biochemical indices of the tomato plants were analyzed using a two-way ANOVA in SPSS 22.0. The experimental data were averaged over three replicates, and the means were compared using Tukey's multiple comparison test. A two-factor ANOVA was used to evaluate the effects of amendments on the soil properties. The balanced exchangeable cations (B) and applied fertilizers (S) were used as two fixed factors.

3. Results

3.1. Short-Term Effects of Different Combinations of Organic Fertilizer, Montmorillonite, and Humic Acid on Soil CEC

After 30 days of soil incubation, the results confirmed that different combinations of organic fertilizers, montmorillonite, and humic acid all significantly increased the CEC (Table 4). As expected, the addition of the OMHA fertilizer treatment resulted in a significant increase in CEC, with a relative increase of 41.07% to 27.10 $cmol \cdot kg^{-1}$ compared to the control treatment (CK). The O, M, and OM treatments showed a similar situation, where CEC increased by 40.69, 39.56, and 34.29% to 27.03 $cmol \cdot kg^{-1}$, 26.81 $cmol \cdot kg^{-1}$, and 25.80 $cmol \cdot kg^{-1}$, respectively, compared to CK. The HA, OHA, and MHA fertilizer treatments also had positive effects on CEC, although not as significant as the treatments mentioned above. The relative increases were 30.14%, 28.25%, and 22.59% to 25.00 $cmol \cdot kg^{-1}$, 24.64 $cmol \cdot kg^{-1}$, and 23.55 $cmol \cdot kg^{-1}$, respectively. Furthermore, it was observed that soil pH and PBS showed significant decreases in all treatments compared to CK, while EC and SOM tended to increase. Notably, there was no significant difference in the exchangeable cation contents of Ca, Mg, or K. To further investigate the relationships between CEC and soil pH, EC, SOM, and PBS, as well as exchangeable cations Ca, Mg, and K, after the application of amendments, a Pearson correlation analysis was conducted on the above physicochemical properties.

Table 4. Physicochemical properties of soils under different fertilizer treatments.

Treatments	pH	EC [1] (mS·cm^{-1})	SOM [2] (%)	CEC [3] (cmol·kg^{-1})	Ex. Ca^{2+} [4] (cmol·kg^{-1})	Ex. Mg^{2+} [5] (cmol·kg^{-1})	Ex. K^{+} [6] (cmol·kg^{-1})	PBS [7] (%)
CK	7.33 ± 0.01 a	0.22 ± 0.01 e	1.07 ± 0.00 c	19.21 ± 0.26 e	6.42 ± 0.15 c	1.74 ± 0.06 bc	0.19 ± 0.03 abc	43.67 ± 1.33 a
O	6.97 ± 0.04 cd	0.40 ± 0.00 b	1.21 ± 0.00 ab	27.03 ± 0.14 a	6.48 ± 0.11 c	1.76 ± 0.02 bc	0.21 ± 0.02 ab	31.33 ± 0.88 c
M	6.99 ± 0.01 cd	0.24 ± 0.00 de	1.10 ± 0.00 c	26.81 ± 0.19 ab	7.22 ± 0.24 ab	1.93 ± 0.06 ab	0.18 ± 0.01 abc	34.67 ± 0.67 c
HA	7.05 ± 0.04 bc	0.25 ± 0.01 d	1.10 ± 0.01 c	25.00 ± 0.13 bcd	6.37 ± 0.15 c	1.75 ± 0.03 bc	0.16 ± 0.00 bc	33.00 ± 0.58 c
OM	6.96 ± 0.02 cd	0.34 ± 0.01 c	1.18 ± 0.01 b	25.80 ± 0.19 abc	7.21 ± 0.16 ab	1.94 ± 0.06 ab	0.21 ± 0.01 ab	35.67 ± 1.20 bc
OHA	6.93 ± 0.02 d	0.43 ± 0.01 a	1.25 ± 0.01 a	24.64 ± 1.17 cd	7.36 ± 0.28 a	2.02 ± 0.09 a	0.22 ± 0.01 a	39.67 ± 2.67 ab
MHA	7.14 ± 0.06 b	0.26 ± 0.01 d	1.11 ± 0.01 c	23.55 ± 0.77 d	6.53 ± 0.13 bc	1.60 ± 0.05 c	0.16 ± 0.01 c	35.00 ± 0.58 c
OMHA	6.88 ± 0.01 d	0.45 ± 0.00 a	1.25 ± 0.03 a	27.10 ± 0.86 a	6.76 ± 0.64 abc	1.87 ± 0.18 ab	0.20 ± 0.03 abc	32.00 ± 2.08 c

One-way analysis of variance (ANOVA) was used to analyze the data. Duncan's test was used to determine the mean ± standard error of the mean (n = 3). If the same letter appeared after a particular column of data, it indicated that the differences between soil physicochemical indices were not significant within the same period of sample collection ($p < 0.05$). [1] EC: soil conductivity; [2] SOM: soil organic matter; [3] CEC: cation exchange capacity; [4] Ex. Ca^{2+}: exchangeable calcium ions; [5] Ex. Mg^{2+}: exchangeable magnesium ions; [6] Ex. K^{+}: exchangeable potassium ions; [7] PBS: percentage base saturation.

Pearson correlation analysis results showed that there exists a relationship between CEC and the indicators which we measured, in which CEC had a significant positive correlation with SOM and EC, with correlation coefficients of 0.51 and 0.50, respectively (Figure 1). However, it had a significant negative correlation with PBS and pH, with correlation coefficients of −0.81 and −0.83, respectively, and the exchangeable Ca, Mg, and K contents in the soil were not significantly correlated with CEC. When the soil CEC increases, the inorganic environment of the soil will automatically be buffered, SOM will become more abundant, and pH will gradually decrease. However, changes in CEC will not cause significant changes in exchangeable base cations, resulting in a decrease in PBS along with the increase in CEC.

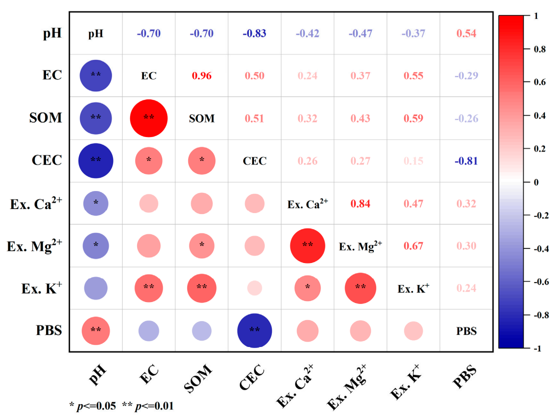

Figure 1. Pearson correlation analysis. CK, the control; O, organic fertilizer; M, montmorillonite; HA, humic acids; OM, organic fertilizer and montmorillonite; OHA, organic fertilizer and humic acid; MHA, montmorillonite and humic acid; OMHA, organic fertilizer, montmorillonite, and humic acid. Significance levels are denoted as follows: *: $p < 0.05$, **: $p < 0.01$. EC: soil conductivity; SOM: soil organic matter; CEC: cation exchange capacity; Ex. Ca^{2+}: exchangeable calcium ions; Ex. Mg^{2+}: exchangeable magnesium ions; Ex. K^{+}: exchangeable potassium ions; PBS: percentage base saturation.

3.2. Effects of Balancing Soil Exchangeable Cations on the Tomato Plants' Height, Biomass, Leaf SPAD Values, and N Content

Balancing exchangeable cations did not have a significant effect on the height or dry weight of the tomato seedlings in CK soils (Table 5, Figure 2). Similarly, in OMHA soils, there was no significant change in the height of the tomato seedlings, but a significant increase in biomass was observed. Balancing exchangeable cations increased the dry weight of seedlings by 125.0% to 0.09 g·plant^{-1} compared with the unbalanced control.

Table 5. Effect of balancing exchangeable cations on tomato plant height and dry weight in CK and OMHA soils.

Soil	Balance	Plant Height (cm)	Dry Weight (g·plant^{-1})
CK	Unbalanced	3.57	0.02
	Balanced	3.09	0.04
	ANOVA (*p* Values)	ns	ns
OMHA	Unbalanced	3.71	0.04
	Balanced	4.22	0.09
	ANOVA (*p* Values)	ns	***
Source of variation			
Soil(S)		*	***
Balance(B)		ns	***
S × B		ns	*

The data presented in this study are the means of three replications. A two-factor ANOVA was conducted, and Tukey's test was used to determine significant differences between data points. Significance levels were set at $p < 0.05$ (*), $p < 0.001$ (***), ns: not significant.

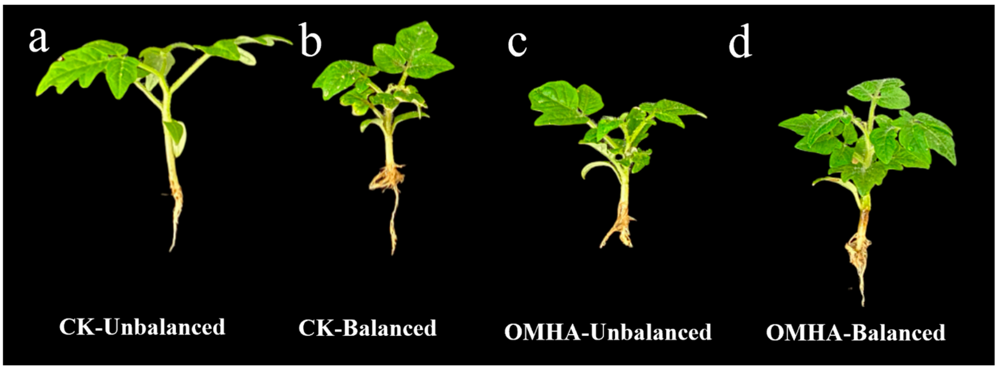

Figure 2. Growth traits of tomato seedlings under different balance treatments of the CK and OMHA soils. Note: (**a**) Tomato seedlings grown in CK-Unbalanced soils; (**b**) Tomato seedlings grown in CK-Balanced soils; (**c**) Tomato seedlings grown in OMHA-Unbalanced soils; (**d**) Tomato seedlings grown in OMHA-Balanced soils. CK-Unbalanced: unbalanced exchangeable cations in CK soils; CK-Balanced: balanced exchangeable cations in CK soils; OMHA-Unbalanced: unbalanced exchangeable cations in OMHA soils; OMHA-Balanced: balanced exchangeable cations in OMHA soils.

The analysis of variance (ANOVA) results indicated that the application of fertilizer (S) and balancing exchangeable cations (B) had an effect on the dry weight of the tomato seedlings, and the interaction was significant. Balancing exchangeable cations in soils (B) based on the application of fertilizers (S) promoted effective biomass accumulation in tomato seedlings.

The effects of balancing exchangeable cations (B) and the application of soil fertilizers (S) to the soil on the leaf chlorophyll SPAD values and leaf N content of tomato seedlings were significant (Figure 3). In CK soils, balancing exchangeable cations increased the leaf chlorophyll SPAD value of tomato seedling plants by 7.38% to 49.31 (SPAD) compared with the unbalanced control. Additionally, leaf N content also showed a positive response to the balancing of exchangeable cations. The leaf N content of tomato seedlings balanced for soil exchangeable cations increased by 13.64%, from 14.42 mg·g^{-1} to 16.39 mg·g^{-1}, compared to the unbalanced control.

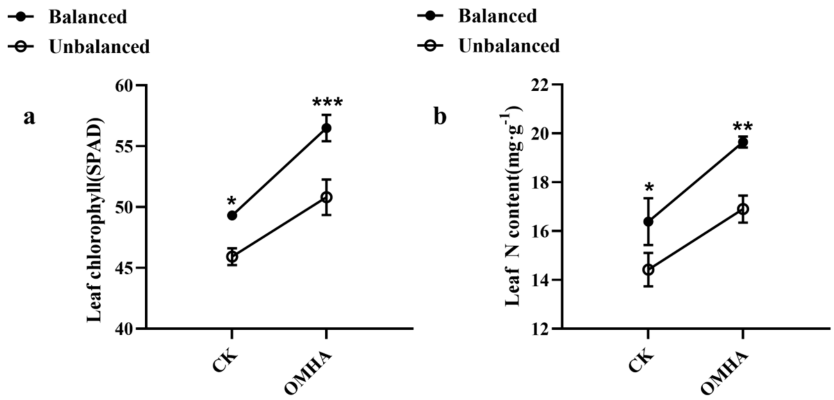

Figure 3. Leaf chlorophyll SPAD values and N content of tomato plants under different balance treatments in CK and OMHA treatment soils. (**a**) Chlorophyll SPAD values of tomato seedling leaves in CK and OMHA soils; (**b**) N content of tomato seedling leaves in CK and OMHA soils. Note: The data represent the mean of three replications, with the standard error represented by the error line ($n = 3$). A two-way ANOVA was used, and the means of different treatments were found to be significantly different at $p < 0.05$ according to Tukey's test. If both the different balance treatments (B) and the different treated soils (S) had significant effects according to the ANOVA, the groups were compared according to the different equilibrium treatments (B). Significance levels were denoted as follows: *: $p < 0.05$, **: $p < 0.01$, ***: $p < 0.001$.

However, these results were consistently observed in OMHA soils with more significant improvements. In particular, balancing soil exchangeable cations significantly increased the leaf chlorophyll SPAD by 11.20% to 56.49 (SPAD) in tomato seedlings as compared with the unbalanced control. Leaf N content increased by 16.24% to 19.64 mg·g^{-1}. Overall, balancing soil exchangeable cations positively affected the biomass, leaf chlorophyll SPAD values, and N content of tomato seedlings, with the positive effect being more pronounced in the soils treated with the OMHA fertilizer than in CK soils.

3.3. Effect of Balancing Soil Exchangeable Cations on the Concentration and Uptake of Ca, Mg, and K in Tomato Seedlings

The effects of balancing soil exchangeable cations on plant nutrient concentrations and uptake of Ca, Mg, and K are shown in Figure 4. In CK soils, balancing soil exchangeable cations significantly improved K nutrition, as evidenced by significantly higher K concentrations and uptake by the tomato seedlings balanced for exchangeable cations than by the unbalanced control. Specifically, balancing soil exchangeable cations resulted in a significant increase in K nutrition in tomato seedlings to 6.25 mg·g^{-1}, a 97.12% increase compared to the unbalanced control. The same was found for K nutrient uptake by tomato seedlings when balanced for exchangeable cations: it was 5 times that of the unbalanced control, increasing to 0.25 mg·plant^{-1}. However, balancing exchangeable cations did not significantly affect the concentration or uptake of the Ca nutrient or the uptake of the Mg nutrient, but it did have a positive effect on the concentration of the Mg nutrient.

In OMHA soils, balancing exchangeable cations resulted in a 91.69% relative increase in the Mg nutrient concentration in tomato seedlings to 8.11 mg·g^{-1} compared to the unbalanced control, while the uptake of the Mg nutrient in tomatoes with balanced exchangeable cations was three times higher than that of the unbalanced control, increasing to 0.75 mg·plant^{-1} (Figure 4). The concentration of the K nutrient in tomato seedlings for balanced exchangeable cations was approximately three times higher than that of the unbalanced control, reaching 8.89 mg·g^{-1}. Additionally, the K uptake was approximately two times higher than that of the unbalanced control, reaching 0.80 mg·plant^{-1}. These results indicate that balancing exchangeable cations significantly improved the Mg and K nutrition of tomato seedlings in OMHA soils. However, the concentration of Ca nutrients did not increase in response to balancing exchangeable cations, but positively influenced Ca nutrient uptake.

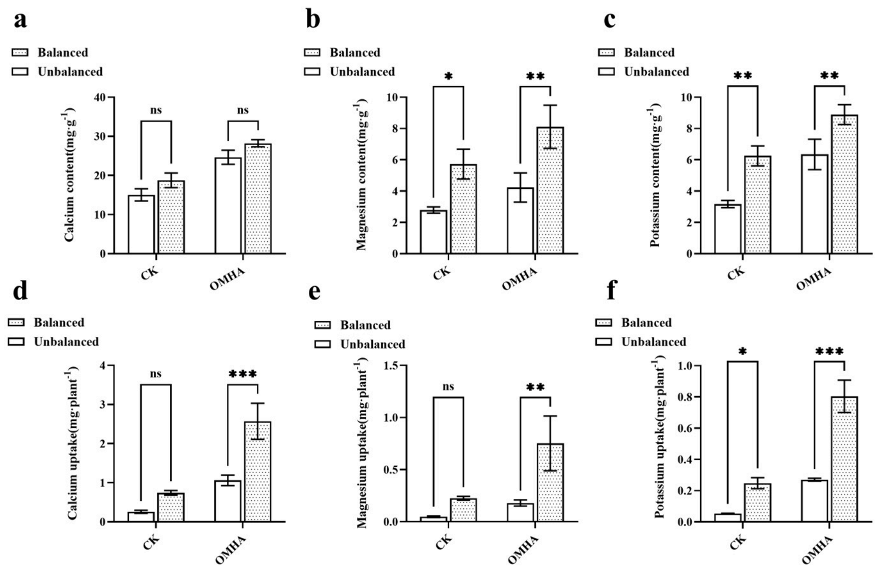

Figure 4. Concentration and uptake of Ca, Mg, and K in tomato plants under different balance treatments in CK and OMHA soils. (**a**) Calcium content in tomato seedlings in CK and OMHA soils; (**b**) Magnesium content in tomato seedlings in CK and OMHA soils; (**c**) Potassium content in tomato seedlings in CK and OMHA soils; (**d**) Calcium uptake in tomato seedlings in CK and OMHA soils; (**e**) Magnesium uptake in tomato seedlings in CK and OMHA soils; (**f**) Potassium uptake in tomato seedlings in CK and OMHA soils. Note: The data presented in this study are the means of three replications. A two-factor ANOVA was conducted, and Tukey's test was used to determine significant differences between data points. Significance levels were set at $p < 0.05$ (*), $p < 0.01$ (**), $p < 0.001$ (***), ns: not significant.

Overall, the analysis of variance (ANOVA) showed that the application of fertilizers (S) had an effect on the concentration and uptake of Ca, Mg, and K nutrients, and the results indicate that balancing exchangeable cations based on the application of fertilizers improved Mg and K nutrients in tomato seedlings. However, directly balancing the exchangeable cations without the application of fertilizers improved only K nutrients in tomato seedlings. There was also a significant interaction between balancing exchangeable cations (B) and the application of fertilizers (S), with an effect on the nutrient uptake of Ca, Mg, and K in tomato seedlings.

4. Discussion

4.1. Interrelationships between Soil CEC and SOM, Exchangeable Cations, and pH

We found a positive correlation (0.51) between CEC and SOM, indicating that an increase in organic matter has a positive effect on soil nutrient adsorption capacity (Table 4, Figure 1). Previous studies by Yang et al. [24–26] have also demonstrated that the addition of SOM is an effective method for improving CEC. The increase in the CEC of organic fertilizer and humic-acid-treated soils may be due to the increase in SOM. Organic matter contains a large number of functional groups, such as -COOH, -OH, etc. When these functional groups dissociate from H^+, the colloid becomes negatively charged, allowing for the adsorption of more positive charges. Microorganisms transform organic matter into a complex, stable molecular organic compound known as humic acid. Humic acid has a larger adsorption surface [27]. Additionally, the use of montmorillonite mineral fertilizers can increase CEC. Southern soils in China generally have lower cation exchange capacity (CEC) compared to northern soils. This is due to the predominance of illite (15–40 $cmol \cdot kg^{-1}$) and montmorillonite (60–120 $cmol \cdot kg^{-1}$) as soil-forming minerals in the north, while kaolinite (2–6 cmol·kg^{-1}) is the main soil-forming mineral in the south [12]. Meanwhile, the interlayer charge of montmorillonite is distributed in aluminum–oxygen octahedron and silicon–oxygen tetrahedron. Such a structure results in a weak electric coulomb force of interlayer cations, favoring the exchange of interlayer cations. In this study, OMHA treatment reached the highest level of CEC, which demonstrated that the combined application of organic and mineral fertilizers can be used to increase CEC in the short term. However, further research is necessary to explore more types of fertilizers that can increase CEC, to promote the development of fertilizers featuring increased CEC.

There was no significant correlation between CEC and exchangeable cations, which contradicts the findings of Bouajila et al. [28]. They reported that the application of organic fertilizers significantly increased the content of soil exchangeable cations. Astera [4] also emphasized the importance of montmorillonite as a source of exchangeable cations. However, this study found that the application of organic fertilizers, montmorillonite, and humic acid fertilizers significantly increased CEC, but did not replenish exchangeable Ca, Mg, or K cations (Table 4, Figure 1). Previous studies have confirmed that the application of organic fertilizer reduces the activities of K^+, Na^+, Ca^{2+}, and Mg^{2+} in the soil while leading to a decrease in pH [29]. Montmorillonite relies on interlayer adsorption and coordination to adsorb exchangeable cations present in the interlayer position. In a high-pH soil environment, interlayer minerals are not easily released. There was a negative correlation between soil pH and exchangeable cations in this study (Figure 1). Organic fertilizers can supply nutrients to soil microorganisms. Organic acids generated by microorganisms during the decomposition of organic matter can regulate or buffer soil pH [30]. Montmorillonite fertilizers containing Fe and Al acid cations also reduce the soil pH. Overall, the results above indicate that the application of organic fertilizers, montmorillonite, and humic acid fertilizers can increase soil CEC, but not exchangeable Ca, Mg, or K ions. This result may be related to changes in soil pH. Therefore, it is necessary to further investigate the relationship between soil CEC; exchangeable Ca, Mg, and K; and pH.

4.2. Effect of Balancing Soil Exchangeable Cations Ca, Mg, and K Based on Increased CEC on the Growth of Tomato Seedlings

The ratios of exchangeable cations Mg/K (9.16) and Ca/K (33.79) in CK soils were much higher than the ideal ratios of 2 and 5, respectively. The same situation occurred in OMHA soils, where Mg/K was 9.35 and Ca/K was 33.80 (Table 2). Previous studies have demonstrated that nutrient imbalances are often associated with unscientific fertilization, long-term continuous monoculture, and soil nutrient depletion [31,32]. We further conducted soil diagnostic tests on CK and OMHA soils to calculate the fertilizer doses that would balance soil Ca, Mg, and K nutrients. The results indicated that tomato seedlings grown in soils treated with CK and OMHA after cation balancing had significantly increased K nutrient concentration and uptake in tomato seedlings compared to the unbalanced control, and the SPAD value and N content of tomato leaves were also significantly increased (Figures 3 and 4). Therefore, regular soil testing to determine soil exchangeable Ca, Mg, and K levels provides an effective way to resolve soil nutrient imbalances and calculate appropriate fertilizer doses.

Balancing exchangeable cations leads to effective improvement in the K nutrition of tomato seedlings. Compared to the unbalanced control, the concentration and uptake of K nutrients in tomato seedlings increased significantly under the balanced exchangeable cations in the CK and OMHA soils (Figure 4). Balancing Ca, Mg, and K cations leads to an improvement in K nutrition, which can be attributed to an increase in soil K saturation so that tomato seedlings can obtain sufficient quantities of the K nutrient. The Ca/K and Mg/K ratios of soils with CK and OMHA unbalanced exchangeable cations exceeded the ideal range (Table 2). It has been reported that the content of Ca and Mg in soils is higher than K, which would cause an ionic competition effect between them. Ca and Mg would replace K on the soil colloid, resulting in a K nutrient deficiency in soils [33,34]. As observed in our study, the imbalance of exchangeable cations in soils requires fertilizer dosage calculation based on ideal Ca, Mg, and K saturation ratios, which are in turn based on soil diagnostic results and precise supplementation of Ca, Mg, and K nutrients to successfully mitigate the cation competition effect. This result is consistent with other studies showing that balancing exchangeable cations can increase K nutrient availability, thereby promoting plant growth and yield. It is advisable to maintain a soil K saturation level of approximately 10% to ensure the efficacy of K nutrients [4].

A significant increase in dry weight and improvement in Mg nutrition were observed only in tomato seedlings in OMHA soils with balanced exchangeable cations (Figure 4). The positive effects of OMHA soils through cation balance were more pronounced compared to CK soils. This difference may be related to the increase in the CEC of OMHA soils through fertilization and the improvement of its inorganic environment. This hypothesis was supported by the improvement in Mg and K nutrition and the increase in the dry weight of the tomato seedlings in OMHA soils that had balanced exchangeable cations (Figures 3 and 4). Fertilization significantly increased the CEC of OMHA soils (Table 4), indicating that the ability of OMHA soils to adsorb cations increased, thereby providing more effective nutrients to plants [4,14]. To improve soil quality management practices for nutrient-poor soils, it is recommended to first increase CEC and then conduct the necessary soil diagnostics to balance Ca, Mg, and K nutrients. However, this approach is limited to providing specific and feasible nutrient management practices for soils that are deficient in exchangeable cations, and does not include soils that are saturated with excess exchangeable cations.

Li et al. [22] discovered that Mg deficiency inhibited tomato growth. Similarly, during wheat growth, Mengutay et al. [35] observed a 21% decrease in dry weight due to Mg deficiency. The dry weight of tomato seedlings grown in OMHA soils balanced with exchangeable cations significantly increased, which may be related to the improvement in Mg nutrition (Figure 3). As is well known, Mg is the most abundant divalent cation in the cytosol of plant cells and plays a crucial role in various physiological processes. It regulates the activity of enzymes such as Rubisco and is involved in protein synthesis, lipid metabolism, and carbohydrate partitioning in plants [36,37]. In addition, Mg is the central atom of the chlorophyll molecule [38]. A deficiency in Mg can significantly reduce the photosynthetic rates of plants [22]. The Mg saturation of unbalanced control OMHA soils did not reach the level of the balanced exchangeable cations (Mg saturation: 20%). This was confirmed by the significant decrease in leaf chlorophyll SPAD value (Figure 3). Therefore, soil magnesium saturation should be maintained at about 20%.

5. Conclusions

The results of the study indicate that the combination of organic and mineral fertilizers can significantly increase CEC in the short term. To achieve the ideal saturation levels, Ca, Mg, and K fertilizers should be applied in appropriate amounts based on the results of the soil analysis. Specifically, Ca saturation should be at 50%, Mg saturation at 20%, and K saturation at 10%. The Ca/K and Mg/K ratios were significantly reduced to 5 and 2, alleviating the problem of ion competition between Ca, Mg, and K and resulting in improved K nutrition in tomatoes. Our research also revealed that balancing exchangeable cations based on increasing CEC not only improved the K nutrition of tomato seedlings, but also improved soil nutrient utilization while improving Mg nutrition and increasing the chlorophyll SPAD value, the nitrogen content of tomato seedlings leaves, and the dry weight. The results of the research can inform agricultural management practices that promote sustainable soil use and management to improve soil quality and ensure plant health. Future research should focus on determining the general applicability of the practical approach of balancing exchangeable cations based on increasing soil CEC under field conditions. This can help to mitigate the adverse effects of Ca, Mg, and K imbalances on plant growth.

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