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# Boosting Soil Health and Pak Choy Growth: Synergistic Effects of Biochar, Lime, and Manure on Saline Acid Sulfate Soils

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## ABSTRACT

Saline acid sulfate soils limit crop production due to acidity, salinity, toxicity, and nutrient deficiencies. Although biochar, lime, and cow manure are individually known to enhance soil physiochemical quality, their combined effects on these constraints and vegetable growth remain insufficiently understood. This study evaluates the combined effects of biochar, lime, and cow manure on saline acid sulfate soil constraints and identifies key factors affecting Pak Choy (*Brassica rapa* L.) growth. A field randomized complete block design with four replicates was conducted over two seasons with six treatments: control (no amendment), lime, cow manure, biochar, biochar–lime, and biochar–cow manure, applied at standard rates. The treatment with five amendments improved soil constraints such as acidity, toxicity, and nutrient deficiencies by 32%–128%, while decreasing salinity by 25%–26% compared to the control. The biochar–cow manure combination most effectively improved the soil nutrient status, increasing Pak Choy biomass by more than 200% compared with the sole amendments and the biochar–lime treatment. In contrast, the biochar–lime combination was most effective in alleviating soil acidity and metal toxicity, resulting in a higher soil quality index (0.67–0.69), relative to the control (0.33–0.35). Overall, biochar and cow manure synergistically enhanced the nutrient availability and vegetable growth, whereas biochar and lime were more effective in correcting acidity and toxicity but produced comparatively smaller yield gains due to limited nutrient enhancement. These results underscore the potential of tailored amendments, especially biochar and cow manure, to enhance vegetable production in saline acid sulfate soils, supporting sustainable agriculture in challenging environments.

## 1 | Introduction

Saline acid sulfate soils originate from acid sulfate soils found in coastal areas, containing high levels of sulfides, which oxidize to form sulfuric acid, raising acidity and elevating concentrations of potentially phytotoxic elements such as aluminum (Al) and iron (Fe) [1, 2]. Acid sulfate soils are present globally, with an estimated 12–14 million hectares worldwide, approximately 7.5 million hectares of which are located in the tropics, primarily in Southeast Asia [1]. Proximity to the sea often leads to these soils becoming salinized due to seawater intrusion, which introduces salts, resulting in the formation of saline acid sulfate soil. Consequently, these soils are well known to exhibit four primary constraints restricting crop growth and production: high acidity; high salinity; toxicity from Al, Fe, and Mn; and nutritional limitations [1–5]. Mitigating these constraints is essential for

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improving the quality and productivity of saline acid sulfate soils for sustainable agriculture.

Recent work by Nguyen et al. [6] has demonstrated that combining biochar, lime, and cow manure produces synergistic improvements in key physiochemical properties, thereby enhancing the overall soil quality of saline acid sulfate soils. As saline acid sulfate soils face four major constraints, a key question is whether these synergistic effects address all four constraints uniformly or vary across functions. Due to its high alkalinity, lime in clay loam acid soils increases pH and exchangeable bases while reducing exchangeable $Al^{3+}$ [7]. Calcium (Ca) and magnesium (Mg) in lime can displace $H^+$, $Fe^{3+}$, $Al^{3+}$, and $Mn^{4+}$ from soil adsorption sites, reducing phytotoxicity [8]. However, lime also has several drawbacks, including soil hardening, nutrient loss through leaching, and micronutrient deficiencies [9]. In addition, lime can reduce the nutrient use efficiency [10] and decrease available phosphorus (P) in a 17%-clay-content Typic Stagnic Anthrosol [11]. Thus, while lime can efficiently address acidity and toxicity, it does not resolve nutrient limitations or salinity, two constraints that strongly influence plant performance in saline acid sulfate soils.

Saline acid sulfate soil can be deficient in essential nutrients such as P, Ca, K, and N [2, 12]. This constraint of nutrient deficiency can be efficiently remediated using animal or organic manure, which contains high levels of various nutrients. Animal manure is commonly applied to improve the physical, chemical, and biological properties of low-fertile soil [13, 14]. The manure was also reported to contain high levels of total N, P, and K, as well as micronutrients [13, 15]. Although animal manure improves the nutrient content, it also has some limitations in addressing other constraints of the saline acid sulfate soil, such as acidity and toxicity. The successive use of animal manure for a few seasons was reported to even lower the pH value and increase salinity of an alluvial sandy loam soil [16]. Another important constraint of saline acid sulfate soil is generally characterized by high salt levels, leading to increased levels of electrical conductivity (EC), sodium (Na), and chloride (Cl). Biochar, a carbon-rich material made from agricultural by-products, was reported as a potential amendment for remediating salt-affected soils through improving the physical, chemical, and biological properties of the soils [17]. However, due to the high C : N ratio, biochar is more effective in increasing soil quality and crop productivity when applied in combination with N fertilizer or organic manure, although the effectiveness may vary with soil texture and biochar type [18, 19]. Additionally, the application of biochar produced from mixed hardwood chips by gasification at 700°C was found to reduce mineral N levels in a silt loam soil [20], which may lead to N deficiency for some crops.

Various soil amendments have been studied to remediate the four primary constraints of saline acid sulfate soils, each demonstrating specific advantages and limitations in addressing particular soil issues. Several studies suggest that combining different soil amendments can be a promising strategy, as their complementary functions may enhance the overall effectiveness in alleviating multiple soil constraints [6, 21]. This leads to our first hypothesis that the acidity, salinity, and toxicity of saline acid sulfate soil can be effectively mitigated through the combination of biochar and lime. To leverage the advantages of animal manure and biochar, we propose combining these two amendments with the hypothesis that the four primary constraints, especially the nutritional constraints, of saline acid sulfate soil can be effectively remediated. The combination of these amendments is expected to generate synergistic impacts from their characteristics, leading to greater improvement in soil quality compared to single applications.

Moreover, a recent study also demonstrated that the overall soil quality index (SQI) of saline acid sulfate soils amended with rice husk biochar, lime, and cow manure showed a significant exponential relationship with rice productivity (both yield and biomass) [6]. Building on this foundation, the present study introduces three key advancements. First, while the previous work focused on rice grown under submerged conditions, this study examines Pak Choy (*Brassica rapa* L.), a shallow-rooted leafy vegetable cultivated under moist but nonflooded conditions, to explore how soil improvement strategies function across contrasting crop and water management systems. Second, to clarify soil–plant mechanisms, we fractionated the overall SQI into four componential indices representing acidity, salinity, metal toxicity, and nutrient limitation, allowing precise identification of the constraints most strongly influencing crop performance. Third, given that leafy vegetables generally demand higher nitrogen (N) and phosphorus (P) for optimal growth [22], the study investigates whether amendments enhancing nutrient availability exert stronger effects on productivity than those alleviating acidity or salinity alone.

Accordingly, our third research hypothesis posits that Pak Choy growth and yield can be effectively enhanced by mitigating the primary constraints of saline acid sulfate soils, with particular emphasis on improving nutritional availability. Pak Choy is widely cultivated across Asia and Europe [23, 24], and its high nutrient demand suggests that simply correcting soil acidity or salinity may not ensure better productivity. Therefore, this study aims (1) to assess the synergistic effects of combined rice husk biochar, lime, and cow manure on alleviating the four major constraints of saline acid sulfate soils and (2) to identify the primary soil factors determining Pak Choy growth and yield under moist conditions.

## 2 | Materials and Methods

### 2.1 | Study Site and Experimental Materials

The study was conducted over two growing seasons in a 268-$m^2$ vegetable cultivation area located in Kieng Phuoc commune, Go Cong Dong district, Tien Giang province, Vietnam (10.380791°N, 106.773088°E). Go Cong Dong district covers an area of 267 $km^2$, borders the East Sea with a 21.5-km coastline, and is characterized by coastal aquaculture and mangrove ecosystems near the Soai Rap and Cua Tieu river mouths. The soil at the study site was saline and potential acid sulfate soil with relatively high pH, similar to those reported in Thailand [25]. The study area has an average annual temperature of about 27°C with two distinct seasons: the dry season from December to April and the rainy season from May to November. The average annual rainfall is around 1100 mm to 1400 mm and remains relatively stable across the years. The experimental soil was classified as Salic Thionic Fluvisols [26] with a silty clay loam texture, containing 14.2% sand, 30.8% clay, and 55.0% silt. The biochar used in this study was produced from rice husks through slow pyrolysis at 400°C. Cow manure, burnt lime (pH = 13), and vegetable seeds (Pak Choy) were purchased from local agricultural stores. The chemical properties of biochar, cow manure, and soil before the experiment are given in Supporting Table 1.

## 2.2 | Experimental Setup

The experiment was implemented as a two-factor factorial randomized complete block design (RCBD) with four replicates, in which responses were measured at all combinations of factor levels [27]. Two experimental factors were defined. Factor 1 (biochar application) consisted of two levels: no biochar and biochar applied at 10 $t{\cdot}ha^{-1}$ [28]. Factor 2 (traditional amendment type) consisted of three levels: no amendment (control, CT), lime applied at 1 $t{\cdot}ha^{-1}$, and cow manure applied at 10 $t{\cdot}ha^{-1}$ [29]. The full combination of these factor levels generated six treatment combinations: CT (no biochar × no amendment), LI (no biochar × lime), CM (no biochar × cow manure), BC (biochar × no amendment), BL (biochar × lime), and BM (biochar × cow manure). The CT treatment represents the zero–zero combination of both factors, which is an integral component of factorial designs. This experimental structure allows the main effects of biochar and traditional amendments, as well as their interaction effects, to be explicitly evaluated under the same blocking structure. The experiment included 24 plots (6 treatments × 4 replicates), each plot measuring 9 $m^2$ (5 m × 1.8 m). The experimental plots were situated on raised beds, with each plot separated by a small trench 0.5 m wide for irrigation and management. Biochar, lime, and cow manure were weighed and evenly applied to the soil surface using the broadcasting method, followed by manual incorporation into the top 15 cm of soil. The amendments were applied once at the beginning of the first season. Germinated seeds of Pak Choy were directly sown into the plots. No inorganic fertilizers were applied throughout the experiment. Crop management followed local farmers' practices for Pak Choy cultivation in the Mekong Delta. Before planting, the soil was plowed to ensure good drainage. Seedlings were raised in nursery beds and transplanted after 10–12 days when they had three true leaves. During cultivation, manual weeding and pest control using neem extract were carried out as needed. Irrigation was done every 2 days, maintaining moist but nonflooded conditions. The Pak Choy was maintained on the field plots over two seasons from June 2023 to September 2023.

## 2.3 | Measurements and Chemical Analysis

At the end of each growing season, the aboveground biomass and roots from the 24 plots were harvested. Aboveground biomass and roots were sampled from five 1-$m^2$ frames (1 m × 1 m), randomly placed in each of the 24 plots. The aboveground biomass from these frames was collected, washed, air-dried, and weighed for assessment. In each field plot, root biomass was sampled using 10 square subsampling frames, each measuring 0.2 m × 0.2 m (0.04 $m^2$). From each $1 - m^2$ frame, two of these subsamples were collected. The harvested roots were then carefully washed with clean water, air-dried, and weighed for evaluation. For each experimental plot, a composite soil sample was collected from 10 points randomly distributed over one plot from the top layer (0–15 cm) [30] using a stainless steel sampler, making 24 soil samples per growing season. These soil samples were air-dried, sieved through a 2-mm sieve, and stored in the Soil Laboratory at Industrial University of Ho Chi Minh City for subsequent chemical analyses. Before the experiment, four soil samples were taken from the experimental field for the 15-cm topsoil layer for chemical analyses.

A total of 52 sieved soil samples (24 samples per season × 2 seasons + 4 samples before the experiment) were subjected to chemical analyses following standard procedures, as described below. pH and electrical conductivity ($EC_{1:5}$) values were determined using sieved soil added with distilled water at a 1 : 5 (w/w) ratio, and the extract was measured using a pH meter (Thermo Scientific ™ Orion™ 3-Star Benchtop pH meter) and an EC meter (SevenExcellence S700-Kit, cond. benchtop meter) after 1 hour of shaking, respectively. The concentrations of exchangeable cations including exchangeable aluminum (Al), calcium (Ca), iron (Fe), potassium (K), magnesium (Mg), manganese (Mn), and sodium (Na) were determined using the barium chloride method [31], and the extract was measured using inductively coupled plasma optical emission spectrometry (ICP-OES). The sulfate ($SO_4^{2-}$) concentration in soil was determined using the turbidimetric method [32], and the chloride ($Cl^-$) concentrations were quantified using the titration method [33]. Other soil properties such as Mehlich-1 phosphorus (Mehlich-1 P), organic carbon (OC), ammonium ($NH_4^+$), exchangeable acidity, exchangeable hydrogen ($H^+$), and cation exchange capacity (CEC) were determined using relevant methods described in Ref. [31].

## 2.4 | Statistical Analysis

The SQI was calculated using the principal component/factor analysis (PCA/FA) method [34] according to

$$\mathrm{SQI} = \sum_{i=1}^{n} w_i s_i, \tag{1}$$

where $n$ is the number of soil parameters (17 parameters), $w_i$ is the weightage of the $i$th parameter, and $s_i$ is the score of the $i$th parameter. $w_i$ was determined using PCA/FA (Supporting Table 2), and $s_i$ is the standardized values, calculated through equations (2) and (3). The 17 analyzed soil parameters were divided into three groups: "higher is better," "optimal is better," and "lower is better." The parameters in the "higher is better" group included Ca, K, Mg, Mehlich-1 P, CEC, OC, and $NH_4^+$, and parameters in the "optimal is better" group included pH, while the parameters in the "lower is better" group included EC, Cl, $SO_4^{2-}$, exchangeable acidity, exchangeable $H^+$, Na, Al, Fe, and Mn. For the first two groups, $s_i$ was calculated using

$$S_i = \frac{x_i - x_{\min}}{x_{\max} - x_{\min}}. \tag{2}$$

For the parameters in the "lower is better" group, $s_i$ was calculated using

$$S_i = \frac{x_{\max} - x_i}{x_{\max} - x_{\min}}, \tag{3}$$

where $x_i$, $x_{\min}$, and $x_{\max}$ are the analyzed value, the minimum value, and the maximum value of the $i$th parameter, respectively.

The 17 soil properties measured in this study were categorized into four distinct groups reflecting the four primary constraints of saline acid sulfate soil, including those reflecting soil acidity (pH,

$SO_4^{2-}$ content, exchangeable acidity, and exchangeable $H^+$), salinity (EC, Na, and $Cl^-$), toxicity (Al, Fe, and Mn), and nutrition (CEC, OC, $NH_4^+$, P, K, Ca, and Mg). Consequently, the overall SQI was further fractionated into four component SQIs corresponding to these four constraints, including acidity SQI (SQI (aci)), salinity SQI (SQI (sal)), toxicity SQI (SQI (tox)), and nutritional SQI (SQI (nut)). The componential SQIs were calculated based on

$$\text{Componential SQI} = \sum_{j,i=1}^{z} w_i s_i, \tag{4}$$

where $z$ was the total number of soil parameters belonging to constraint $j$th ($j$ varying from 1 to 4, corresponding to four constraints of saline acid sulfate soil). $i$, $w_i$, and $s_i$ were the same as those in equation (1). Since these componential SQIs were calculated based on standardized data, their higher values indicated better soil quality, reflecting the associated constraints.

Moreover, for comparison purposes, $EC_e$ (electrical conductivity of the saturated paste extract) was estimated from the directly measured $EC_{1:5}$ values using the conversion equation (5) proposed by Kargas et al. [35].

$$EC_e = \left(1.054 + \frac{283.4}{49.699 + 0.524 * \text{Clay}\ \% - 0.339 * \text{sand}\ \%}\right) * EC_{1:5}. \tag{5}$$

A simple linear regression was first used to examine the relationship between individual SQIs and the yield of Pak Choy. Subsequently, multiple regression analysis was performed using yield as the dependent variable and selected soil parameters and componential SQIs as independent variables to identify the most influential soil factors determining yield. Variables were selected based on their statistical significance ($p \leq 0.05$) and contribution to model fit. The percentage contribution of componential SQIs reflecting the four constraints to the total variance of the total biomass of Pak Choy was determined based on the multiple regression analysis (Table 1). In addition, all experimental data, including SQI and componential SQIs, were statistically analyzed using two-way analysis of variance (ANOVA). The ANOVA model is expressed as follows:

$$\gamma_{ije} = \mu + \gamma_i + \alpha_j + (\gamma\alpha)_{ij} + \beta_e + \varepsilon_{ije}, \tag{6}$$

where $\gamma_{ije}$ represents the response for the $e$th replicate of the $i$th biochar level and the $j$th traditional amendment treatment, $\mu$ is the overall mean, $\gamma_i$ denotes the main effect of biochar, $\alpha_j$ denotes the main effect of the traditional amendment, $(\gamma\alpha)_{ij}$ represents the interaction effect between the biochar and traditional amendment, $\beta_e$ denotes the effect of block, and $\varepsilon_{ije}$ is the random error term, assumed to be independently and normally distributed with a mean of zero [27]. If the ANOVA results were statistically significant, the LSMeans Differences Student's test was employed to rank the means of the six treatments.

## 3 | Results

### 3.1 | Initial Chemical Properties of the Soil and Amendments

The basic properties of materials used for the current study, including biochar, cow manure, and soil are given in Supporting Table 1. Before the experiment, the soil had an $EC_{1:5}$ value of 1.8 $dS \cdot m^{-1}$, which corresponds to an estimated $EC_e$ of approximately 10.3 $dS \cdot m^{-1}$. The soil also contained high levels of exchangeable $Na^+$ (1107.34 $mg \cdot kg^{-1}$) and measurable exchangeable acidity (1.14 cmol(+) $kg^{-1}$). The soil exhibited low pH (5.59), low OC content (1.11%), and relatively low Mehlich-1 P and $NH_4^+$ concentrations, reflecting its degraded fertility status. In contrast, the amendment materials had more favorable chemical characteristics: biochar and cow manure showed higher pH and OC contents, while cow manure also contained greater levels of available nutrients such as Mehlich-1 P and $NH_4^+$. Other characteristics of biochar, cow manure, and soil such as $SO_4^{2-}$, exchangeable acidity, Mehlich-1 P, CEC, and exchangeable metal contents are also presented in Supporting Table 1.

### 3.2 | Soil Acidity Indicators as Affected by Experimental Treatments

Four acidity-related properties of the saline acid sulfate soil, pH, $SO_4^{2-}$, exchangeable acidity, and exchangeable $H^+$, showed significant differences among the six treatments in both vegetable-growing seasons, except for exchangeable $H^+$ in the second season (Table 2). Soil pH increased markedly with biochar application, reaching the highest levels of 7.69 and 7.62 in BL (biochar combined with lime) in the first and second vegetable crops, respectively. In contrast, CT had the lowest pH values in both crop seasons. A similar pattern was observed for the exchangeable acidity, which was highest in CT (7.7 and 5.4 cmol(+)$\cdot kg^{-1}$ in the first and second crops, respectively) and lowest in BL (5.5 and 4.1 cmol(+)$\cdot kg^{-1}$, respectively). Biochar, with its high pH and alkaline nature, helps increase the soil pH and lower acidity. The highest $SO_4^{2-}$ content was found in BM, with values of 0.95 $g \cdot kg^{-1}$ in the first growing season and 2.01 $g \cdot kg^{-1}$ in the second growing season.

### 3.3 | Soil Salinity Indicators as Affected by Experimental Treatments

Soil quality parameters reflecting salinity (EC, $Cl^-$, and exchangeable Na) showed statistically significant differences between the experimental treatments in both vegetable seasons, except for the $EC_{1:5}$ value in the first vegetable crop (Table 3). BL, which used biochar combined with lime, had the highest $EC_{1:5}$ value (1.03 $dS \cdot m^{-1}$ equivalent to 5.87 $dS \cdot m^{-1}$ for $EC_e$) in the second season. In the first season, $EC_{1:5}$ values among the six treatments were not significantly different, ranging from 0.70 to 0.88 $dS \cdot m^{-1}$. The combination of biochar with lime (BL) or cow manure (BM) significantly reduced the exchangeable Na content compared to the CT in both Pak Choy seasons. BL recorded exchangeable Na contents of 942.97 $mg \cdot kg^{-1}$ in the first vegetable season and 801.46 $mg \cdot kg^{-1}$ in the second season. In contrast, treatments containing cow manure (CM and BM) showed the highest $Cl^-$ concentrations among all treatments.

### 3.4 | Soil Phytotoxicity Indicators as Affected by Experimental Treatments

Overall, the application of amendments, including biochar, lime, or their combination statistically reduced the concentration of exchangeable Al, Fe, and Mn in the soil (Table 3) after two vegetable seasons. In the first season, CT without amendments had the highest exchangeable Al and Fe contents, with values of 51.21 and 9.49 $mg \cdot kg^{-1}$, respectively. BL exhibited the lowest

**TABLE 1** | Contributive percentage of componential SQI (CSQI) to determine the total biomass of Pak Choy.

| Componential SQIs | Season 1 | | | Season 2 | | |
|---|---|---|---|---|---|---|
| | *F*-ratio[**] | Contributive percentage | The best treatment | *F*-ratio | Contributive percentage | The best treatment |
| CSQI (aci) | 1.12 | 1.86 | BL | 1.06 | 3.68 | BL |
| CSQI (sal) | 0.11 | 0.18 | BM | 0.66 | 2.28 | LI |
| CSQI (tox) | 7.77 | 12.94 | BL | 0.02 | 0.06 | BL |
| CSQI (nut) | 32.05[*] | 53.38 | BM | 7.97 | 27.77[*] | BM |
| Error | | 31.64 | | | 66.21 | |
| C. total | | 100.00 | | | 100.00 | |

Abbreviations: BL, biochar + lime; BM, biochar + cow manure; LI, lime.

[*] Indicates that the relationship between the total biomass of Pak Choy with the associated componential SQIs is statistically significant.

[**] *F*-ratio: the *F*-statistic value from ANOVA indicating differences among treatments.

exchangeable Al and Fe levels, with values of 38.49 and 7.24 mg·kg$^{-1}$, respectively. Similarly, in the second Pak Choy season, BL resulted in the lowest exchangeable Al, Fe, and Mn contents, while CT showed the highest values among all experimental treatments.

### 3.5 | Soil Nutrition Indicators as Affected by Experimental Treatments

Seven soil parameters related to plant nutrition were analyzed in this study, and their values showed statistically significant differences across the six experimental treatments in both Pak Choy seasons (Table 4). Biochar application (BC, BL, and BM) increased CEC, Mehlich-1 P, OC, and exchangeable K compared to no biochar treatments (CT, LI, and CM), with the magnitude of the increase varying depending on the traditional amendments used. BM (biochar and cow manure) resulted in the highest levels of soil properties such as CEC (15.00 and 14.84 cmol(+)·kg$^{-1}$), $NH_4^+$ (33.62 and 38.45 mg·kg$^{-1}$), Mehlich-1 P (503.11 and 590.84 mg·kg$^{-1}$), and OC (3.81% and 4.00% for the first and second Pak Choy seasons, respectively). The CT without amendments exhibited the lowest values of CEC, exchangeable K, Ca, and Mg among the six experimental treatments in both seasons. The lowest $NH_4^+$ content was found in BC with sole biochar addition (20.28 mg·kg$^{-1}$) in the first season, but it was lowest in LI with sole lime addition (31.86 mg·kg$^{-1}$) in the second Pak Choy season. Sole lime addition (LI) also led to the lowest levels of Mehlich-1 P in both seasons (416.10 and 432.93 mg·kg$^{-1}$ in the first and second seasons, respectively). In contrast, lime applications in LI and BL resulted in the highest levels of exchangeable Ca (647.04 mg·kg$^{-1}$ in LI in Season 1 and 612.41 mg·kg$^{-1}$ in BL in Season 2) and exchangeable Mg (334.50 mg·kg$^{-1}$ in LI in Season 1 and 411.21 mg·kg$^{-1}$ in BL in Season 2).

### 3.6 | The SQI and Componential Indices (CSQI)

PCA identified three main factors ($F_1$, $F_2$, and $F_3$) that together explained 68.6% of the total variance among the 17 soil parameters (Supporting Table 2). Factor 1 accounted for 34.4% of the variance and was strongly associated with exchangeable Na, Mn, Fe, Al, Mg, Ca, exchangeable acidity, EC, and pH. Factor 2 explained 23.0% of the variance and was mainly associated with

**TABLE 2** | The levels of acidity-related parameters (pH, $SO_4^{2-}$, exchangeable acidity, and exchangeable $H^+$) in the tested soil after the two vegetable seasons of six treatments.

| Treatment | Biochar (BC) | Traditional amendment | pH | $SO_4^{2-}$ (g·kg$^{-1}$) | Exchangeable acidity (cmole$_+$·kg$^{-1}$) | Exchangeable $H^+$ (cmole$_+$·kg$^{-1}$) |
|---|---|---|---|---|---|---|
| *Season 1* | | | | | | |
| CT | Without BC | No amendment | 6.5$^{e}$ (0.10) | 0.68$^{b}$ (0.05) | 7.69$^{a}$ (0.18) | 2.85$^{a}$ (0.12) |
| LI | | Lime | 7.36$^{b}$ (0.06) | 0.47$^{c}$ (0.05) | 5.88$^{c}$ (0.32) | 2.47$^{b}$ (0.17) |
| CM | | Cow manure | 6.8$^{d}$ (0.11) | 0.91$^{a}$ (0.05) | 5.68$^{c}$ (0.17) | 2.26$^{bc}$ (0.16) |
| BC | With BC | No amendment | 7.12$^{c}$ (0.02) | 0.67$^{b}$ (0.04) | 6.81$^{b}$ (0.1) | 2.15$^{c}$ (0.01) |
| BL | | Lime | 7.69$^{a}$ (0.10) | 0.78$^{b}$ (0.06) | 5.5$^{c}$ (0.44) | 2.22$^{bc}$ (0.05) |
| BM | | Cow manure | 6.99$^{cd}$ (0.1) | 0.95$^{a}$ (0.05) | 5.6$^{c}$ (0.23) | 2.45$^{b}$ (0.1) |
| *Season 2* | | | | | | |
| CT | Without BC | No amendment | 6.39$^{c}$ (0.12) | 1.05$^{cd}$ (0.05) | 5.36$^{a}$ (0.14) | 3.26$^{a}$ (0.05) |
| LI | | Lime | 7.16$^{b}$ (0.06) | 0.83$^{d}$ (0.06) | 4.33$^{c}$ (0.1) | 3.17$^{a}$ (0.08) |
| CM | | Cow manure | 6.43$^{c}$ (0.20) | 1.30$^{b}$ (0.07) | 4.97$^{ab}$ (0.15) | 3.3$^{a}$ (0.11) |
| BC | With BC | No amendment | 6.90$^{b}$ (0.06) | 1.02$^{cd}$ (0.06) | 4.55$^{bc}$ (0.22) | 2.97$^{a}$ (0.34) |
| BL | | Lime | 7.62$^{a}$ (0.11) | 1.06$^{c}$ (0.06) | 4.13$^{c}$ (0.24) | 2.85$^{a}$ (0.21) |
| BM | | Cow manure | 6.97$^{b}$ (0.04) | 2.01$^{a}$ (0.16) | 4.65$^{bc}$ (0.07) | 3.17$^{a}$ (0.13) |

*Note:* The numbers in parentheses are the standard error of the mean. Within a season and a parameter, data attached with the same letters are not statistically significantly different from each other at $p \leq 0.05$.

**TABLE 3** | The levels of salinity-related parameters (EC, $Cl^-$, and exchangeable $Na^+$) and toxicity-related parameters (exchangeable Al, Fe, and Mn) in the tested soil after the two vegetable seasons in six treatments.

| Treatment | Biochar (BC) | Traditional amendment | EC ($dS \cdot m^{-1}$) | $Cl^-$ ($g \cdot kg^{-1}$) | Na ($mg \cdot kg^{-1}$) | Al ($mg \cdot kg^{-1}$) | Fe ($mg \cdot kg^{-1}$) | Mn ($mg \cdot kg^{-1}$) |
|---|---|---|---|---|---|---|---|---|
| *Season 1* | | | | | | | | |
| CT | Without BC | No amendment | $0.75^{a}$ (0.09) | $0.67^{b}$ (0.02) | $1282.81^{a}$ (46.79) | $51.21^{a}$ (2.81) | $9.49^{a}$ (0.39) | $34.15^{a}$ (1.56) |
| LI | | Lime | $0.83^{a}$ (0.08) | $0.61^{b}$ (0.03) | $993.15^{cd}$ (32.90) | $47.91^{a}$ (2.55) | $7.98^{bc}$ (0.4) | $23.79^{c}$ (0.82) |
| CM | | Cow manure | $0.70^{a}$ (0.03) | $0.86^{a}$ (0.07) | $1113.71^{b}$ (31.78) | $50.13^{a}$ (0.53) | $8.4^{ab}$ (0.26) | $34.31^{a}$ (1.37) |
| BC | With BC | No amendment | $0.72^{a}$ (0.05) | $0.61^{b}$ (0.04) | $1051.61^{bc}$ (17.06) | $41.63^{bc}$ (0.41) | $8.14^{bc}$ (0.45) | $27.97^{bc}$ (1.34) |
| BL | | Lime | $0.88^{a}$ (0.05) | $0.61^{b}$ (0.03) | $942.97^{d}$ (33.62) | $38.49^{c}$ (0.54) | $7.24^{c}$ (0.41) | $24.84^{c}$ (1.53) |
| BM | | Cow manure | $0.74^{a}$ (0.05) | $0.65^{b}$ (0.03) | $1012.26^{cd}$ (37.96) | $46.39^{ab}$ (0.92) | $8.66^{ab}$ (0.49) | $31.64^{ab}$ (0.98) |
| *Season 2* | | | | | | | | |
| CT | Without BC | No amendment | $0.82^{b}$ (0.05) | $1.95^{ab}$ (0.15) | $1209.17^{a}$ (16.46) | $51.98^{a}$ (1.55) | $9.86^{a}$ (0.37) | $30.79^{a}$ (1.53) |
| LI | | Lime | $0.81^{b}$ (0.05) | $1.96^{ab}$ (0.1) | $934.33^{c}$ (65.50) | $43.94^{cd}$ (0.73) | $8.45^{b}$ (0.23) | $24.41^{bc}$ (0.89) |
| CM | | Cow manure | $0.89^{ab}$ (0.04) | $1.94^{ab}$ (0.11) | $1110.77^{ab}$ (26.96) | $48.00^{b}$ (0.57) | $8.61^{b}$ (0.36) | $26.55^{b}$ (1.73) |
| BC | With BC | No amendment | $0.86^{ab}$ (0.07) | $1.84^{ab}$ (0.06) | $1061.29^{bc}$ (35.63) | $41.75^{d}$ (0.68) | $7.18^{c}$ (0.18) | $25.23^{bc}$ (1.52) |
| BL | | Lime | $1.03^{a}$ (0.09) | $1.75^{b}$ (0.09) | $801.46^{d}$ (21.07) | $41.17^{d}$ (1.03) | $6.59^{c}$ (0.22) | $21.74^{c}$ (1.22) |
| BM | | Cow manure | $0.87^{ab}$ (0.06) | $2.13^{a}$ (0.06) | $1035.91^{bc}$ (57.01) | $46.01^{bc}$ (1.02) | $8.33^{b}$ (0.24) | $23.60^{bc}$ (1.08) |

*Note:* The numbers in parentheses are the standard error of the mean. Within a season and a parameter, data attached with the same letters are not statistically significantly different from each other at $p \leq 0.05$.

**TABLE 4** | The levels of nutrition-related parameters (CEC, $NH_4^+$, Mehlich-1 P, OC, exchangeable K, Ca, and Mg) in the tested soil after the two vegetable seasons in six treatments.

| Treatment | Biochar (BC) | Traditional amendment | CEC ($cmole_+ \cdot kg^{-1}$) | $NH_4^+$ ($mg \cdot kg^{-1}$) | Mehlich-1 P ($mg \cdot kg^{-1}$) | OC (%) | K ($mg \cdot kg^{-1}$) | Ca ($mg \cdot kg^{-1}$) | Mg ($mg \cdot kg^{-1}$) |
|---|---|---|---|---|---|---|---|---|---|
| *Season 1* | | | | | | | | | |
| CT | | No amendment | $12.05^b$ (0.64) | $24.69^c$ (0.8) | $462.28^{ab}$ (24.92) | $3.24^b$ (0.07) | $448.79^d$ (11.83) | $416.31^c$ (21.75) | $293.67^c$ (10.21) |
| LI | Without BC | Lime | $12.06^b$ (0.41) | $23.25^c$ (0.9) | $416.10^b$ (15.82) | $3.20^b$ (0.05) | $573.66^c$ (4.63) | $647.04^a$ (30.66) | $334.50^a$ (7.08) |
| CM | | Cow manure | $13.45^{ab}$ (0.59) | $28.69^b$ (0.95) | $480.35^{ab}$ (35.71) | $3.31^b$ (0.07) | $604.27^{bc}$ (16.48) | $411.82^c$ (12.59) | $283.08^c$ (8.80) |
| BC | | No amendment | $14.59^a$ (0.41) | $20.28^d$ (0.46) | $480.16^{ab}$ (39.23) | $3.69^a$ (0.09) | $627^{bc}$ (38.76) | $437.7^{bc}$ (21.32) | $302.93^{bc}$ (1.94) |
| BL | With BC | Lime | $14.03^a$ (0.63) | $24.81^c$ (0.47) | $426.89^b$ (33.33) | $3.64^a$ (0.07) | $654.45^{ab}$ (16.07) | $622.69^a$ (26.18) | $320.94^{ab}$ (7.00) |
| BM | | Cow manure | $15.00^a$ (0.44) | $33.62^a$ (1.11) | $503.11^a$ (47.78) | $3.81^a$ (0.11) | $709.25^a$ (24.89) | $505.48^b$ (27.87) | $319.02^{ab}$ (9.12) |
| *Season 2* | | | | | | | | | |
| CT | | No amendment | $10.96^c$ (0.42) | $34.41^b$ (0.58) | $489.14^b$ (25.24) | $3.38^c$ (0.13) | $518.67^c$ (17.51) | $481.73^b$ (29.41) | $294.21^c$ (9.82) |
| LI | Without BC | Lime | $12.93^b$ (0.37) | $31.86^c$ (0.87) | $432.93^b$ (25.09) | $3.54^{bc}$ (0.03) | $607.5^b$ (3.86) | $591.09^a$ (12.92) | $319.73^{bc}$ (11.2) |
| CM | | Cow manure | $12.62^b$ (0.55) | $35.83^b$ (0.71) | $480.09^b$ (22.77) | $3.63^b$ (0.10) | $631.55^{ab}$ (27.41) | $513.81^{ab}$ (39.42) | $386.71^a$ (42.9) |
| BC | | No amendment | $13.58^{ab}$ (0.35) | $32.1^c$ (0.20) | $510.9^{ab}$ (36.43) | $3.60^a$ (0.06) | $680.04^a$ (12.93) | $586.29^{ab}$ (25.65) | $386.22^a$ (8.97) |
| BL | With BC | Lime | $13.09^b$ (0.16) | $32.20^c$ (0.74) | $476.59^b$ (15.35) | $3.91^a$ (0.05) | $650.66^{ab}$ (26.85) | $612.41^a$ (50.79) | $411.21^a$ (13.04) |
| BM | | Cow manure | $14.84^a$ (0.70) | $38.45^a$ (0.46) | $590.84^a$ (33.14) | $4.00^a$ (0.08) | $634.66^{ab}$ (23.53) | $602.46^a$ (41.04) | $365.00^{ab}$ (8.18) |

*Note:* The numbers in parentheses are the standard error of the mean. Within a season and a parameter, data attached with the same letters are not statistically significantly different from each other at $p \leq 0.05$.

$NH_4^+$, $Cl^-$, $SO_4^{2-}$, and exchangeable $H^+$. Factor 3, contributing 11.3% of the total variance, was associated with CEC, exchangeable K, organic carbon (OC), and Mehlich-1 P. These weighted parameters from $F_1$–$F_3$ were subsequently used to calculate the SQI.

The overall SQI, calculated from 17 chemical soil parameters after two vegetable seasons, showed significant differences among the six treatments (Figure 1). Across both seasons, the SQI followed a consistent order: BL (biochar + lime) > BM (biochar + cow manure) ≈ BC (biochar) ≈ LI (lime) > CM (cow manure) > CT (control). Treatments containing biochar (BC, BL, and BM) generally had higher SQI values than those without biochar (CT, LI, and CM), indicating the beneficial effects of biochar-based amendments on improving overall soil quality.

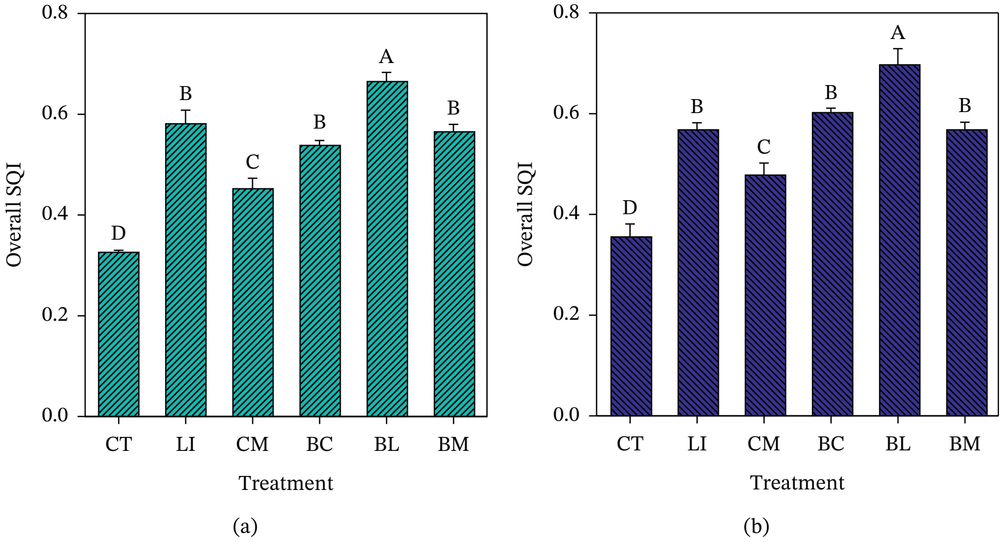
The overall SQI was fractionated into four components, each reflecting one of the four primary constraints of saline acid sulfate soil: acidity, salinity, toxicity, and nutrition (Figure 2). The componential SQI for soil acidity (CSQI (aci)) was highest in BL, followed by LI, and lowest in CT. The componential SQI for soil salinity (CSQI (sal)) was higher in treatments added with amendments (LI, CM, BC, BC, and BM) than in CT during the first season. In the second season, CSQI (sal) was highest in LI and lowest in CT. The componential SQI for soil toxicity (CSQI (tox)) was highest in BL, followed by BC, LI, BM, CM, and CT in both seasons, indicating that biochar and lime were the most effective in mitigating soil toxicity. The second season exhibited higher CSQI (tox) values across all treatments compared to the first season. The componential SQI for soil nutrition (CSQI (nut)) reached its highest value in BM (biochar + cow manure) and its lowest value in CT. The three biochar-added treatments (BC, BL, and BM) exhibited higher levels of CSQI (aci), CSQI (tox), and CSQI (nut) compared to the three treatments without biochar (CT, LI, and CM). While the combination of biochar with lime yielded the highest levels of CSQI (aci) and CSQI (tox), the combination of biochar and cow manure resulted in the highest values of CSQI (nut).

## 3.7 | Growth and Yield of Pak Choy

In both seasons, two treatments added with cow manure (CM and BM) produced significantly higher total biomass of Pak Choy, 29.91 and 65.27 $g \cdot m^{-2}$ for CM and BM in Season 1 and 23.46 and 53.81 $g \cdot m^{-2}$ for CM and BM in Season 2, respectively, compared to CT (13.57 and 7.74 $g \cdot m^{-2}$ for Seasons 1 and 2, respectively) (Figure 3). These corresponded to increases in total biomass of approximately 120%–380% in Season 1 and 203%–594% in Season 2, respectively. Similarly, the root weight of CM and BM was significantly higher compared to the CT treatment. Notably, BM had aboveground biomass 4 to 6 times higher after Seasons 1 and 2 compared to CT. These results indicate that treatments with cow manure, especially the combination of biochar and cow manure, led to the greatest vegetable growth and yield compared to the CT treatment.

## 3.8 | The Relationships Between the Total Biomass of Pak Choy and SQI

Since the data were standardized before calculating the SQIs, higher SQI and its components indicate better soil quality. Figure 4 shows that the total biomass of Pak Choy did not have a statistically significant correlation with the overall SQI and the componential SQIs reflecting acidity, salinity, and toxicity. In



(a)

(b)

**FIGURE 1** | Overall soil quality index (SQI) in six treatments (CT, control; LI, lime; CM, cow manure; BC, biochar; BL, biochar + lime; BM, biochar + cow manure) across two vegetable seasons. Error bars indicate the standard error of the mean. Within a panel, bars labeled with the same letters are not statistically significantly different from each other at $p \leq 0.05$. The interaction effects between biochar and traditional amendment on SQI were significant in both seasons. (a) Season 1. (b) Season 2.

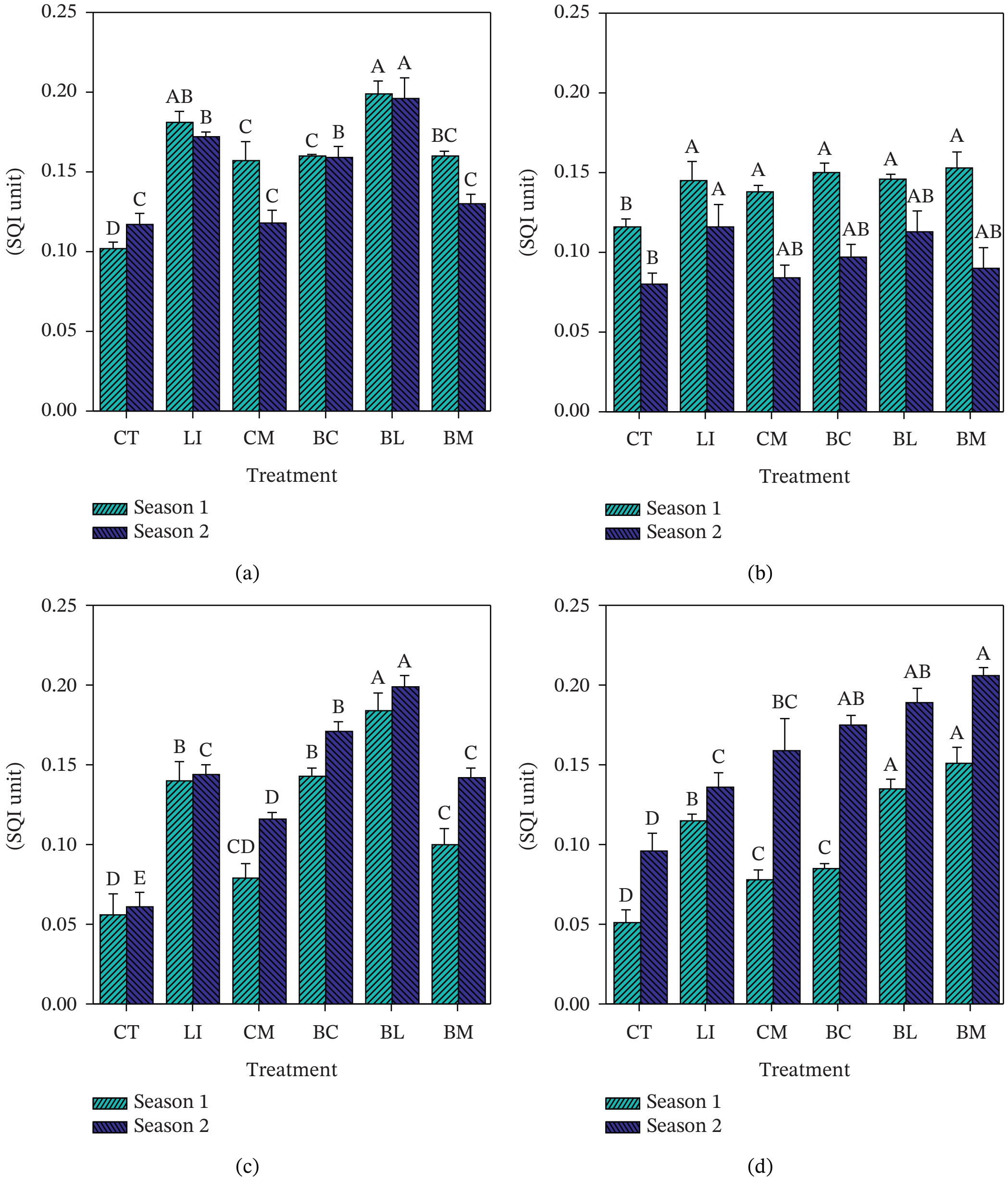
contrast, the total biomass had a strong correlation with CSQI (nut) in both seasons, following an exponential function. In the first season, biomass showed only a slight rise to around 25 $g{\cdot}m^{-2}$ at CSQI (nut) values below 0.12, but once CSQI (nut) reached approximately 0.18, biomass responded strongly and increased to nearly 75 $g{\cdot}m^{-2}$. Likewise, in the second season, the total biomass quickly increased from 15 to 50 $g\,m^{-2}$ when CSQI (nut) exceeded 0.17 units. The relationship between the total biomass and CSQI (nut) had the determination coefficients ($r^2$) of 0.43 and 0.40 for the first and second seasons, respectively. Multivariate regression analysis also showed a statistically significant relationship between the total biomass of Pak Choy and CSQI (nut), accounting for 53.38% and 27.77% of the total variance in the first and second seasons, respectively (Table 1). Overall, the results demonstrate clear improvements in soil quality and Pak Choy biomass under amendments containing biochar, particularly when combined with cow manure or lime.

## 4 | Discussion

### 4.1 | Single Impacts of the Amendments

As identified in the Introduction section, saline acid sulfate soil had four primary constraints, including acidity, salinity, toxicity, and nutrition, which need mitigation for better quality and productivity [1–5]. The CSQI (tox) was computed using three soil properties, including exchangeable Al, Fe, and Mn, which can potentially cause phytotoxicity to various crops [36, 37]. The exchangeable levels of these elements strongly depended on soil pH [38]. At lower pH, the solubility of Al and Fe increases due to protonation and dissolution of their hydroxides, whereas at higher pH, they tend to precipitate as insoluble oxides and hydroxides, thereby reducing their exchangeable concentrations [39, 40]. The application of biochar produced from various feedstocks, such as hardwood, cacao shell, oil palm, and rice husk, was well-documented to induce “liming effects” on various soil types [41, 42], which can reduce acidity and levels of exchangeable phytotoxic elements such as Al and Fe. Moreover, the surface of biochar is rich in negatively charged functional groups (such as -COOH and -OH) [38, 43], which can bind and immobilize positively charged metal ions in the soil, such as $Al^{3+}$. Similar findings were observed in other studies using rice-straw biochar on an Oxisol soil [44]. According to a review by Dai et al. [45], biochar can effectively lower soil acidity and reduce Al toxicity to plants due to its alkaline properties.

Both cow manure and biochar greatly improved the CSQI, reflecting the nutritional quality (CSQI (nut)) of the soil. Numerous studies have reported that rice husk-derived biochar can enhance nutritional parameters such as CEC [46], available P [47], exchangeable [48], and base cations such as Ca and Mg [6] in salt-affected soils. The consistent improvements observed across these studies indicate that biochar positively affects soil nutrient status, as observed in this study (Table 3), leading to enhanced overall SQI, as reported from various studies in salt-affected soils using the rice husk biochar [49, 50]. Additionally, cow manure was also effective in improving nutrient status, similar to biochar. This is likely due to the nature of cow manure, which contained high levels of nutrients, especially $NH_4^+$ and Mehlich-1 P (Supporting Table 1). Other studies have also found that organic manure substantially improved nutrient concentrations of saline soils [51, 52]. However, biochar reduced the $NH_4^+$ concentration in the soil, while cow manure largely increased plant-available N in the soil (Table 3), compared to the CT treatment. Previous studies have suggested that the associated mechanisms could be related to the great $NH_4^+$ adsorption capacity and a high C : N ratio of biochar, leading to the immobilization of plant-available N [53–55]. In contrast, the N contained in cow manure serves as a direct nutrient source, thereby increasing soil N availability after its incorporation. These findings highlight both the similarities and differences in the effects of biochar and cow manure on soil quality in the current study.



(a)

(b)

(c)

(d)

**FIGURE 2** | Componential soil quality index (CSQI) in the tested soil after two vegetable seasons of six treatments (CT, control; LI, lime; CM, cow manure; BC, biochar; BL, biochar + lime; BM, biochar + cow manure). (a) CSQI (aci) reflecting soil acidity, (b) CSQI (sal) reflecting salinity, (c) CSQI (tox) reflecting toxicity, and (d) CSQI (nut) reflecting nutrient status. Error bars indicate the standard error of the mean. Within a panel and for each season, bars labeled with the same letters are not statistically significantly different from each other at $p \leq 0.05$.

Lime is a common agricultural amendment used to neutralize soil acidity [56]. In this study, lime sustainably increased pH and reduced exchangeable acidity in the soil more effectively than single applications of biochar and cow manure. Lime, which contains high amounts of Ca and Mg, has been reported to increase soil pH and enhance the availability of these base cations, which in turn lowered the available concentration of Al and Fe [57]. The primary mechanism of lime application involves dissolving nutrients that were previously immobilized in the soil, thereby increasing their availability [58, 59]. However, the low nutrient content of lime, particularly nitrogen and phosphorus, led to relatively weak impacts on the nutrient status of the experimental soil. This is a great concern when using lime to amend saline acid sulfate soils for better productivity.

## 4.2 | Synergistic Interaction of the Amendments

The three soil amendments exhibited distinct characteristics and varying effectiveness in ameliorating the constraints of saline acid sulfate soil. Although lime alone most effectively increased CSQI (aci) and biochar alone enhanced CSQI (tox), their combined application produced the highest overall SQI and componential SQIs

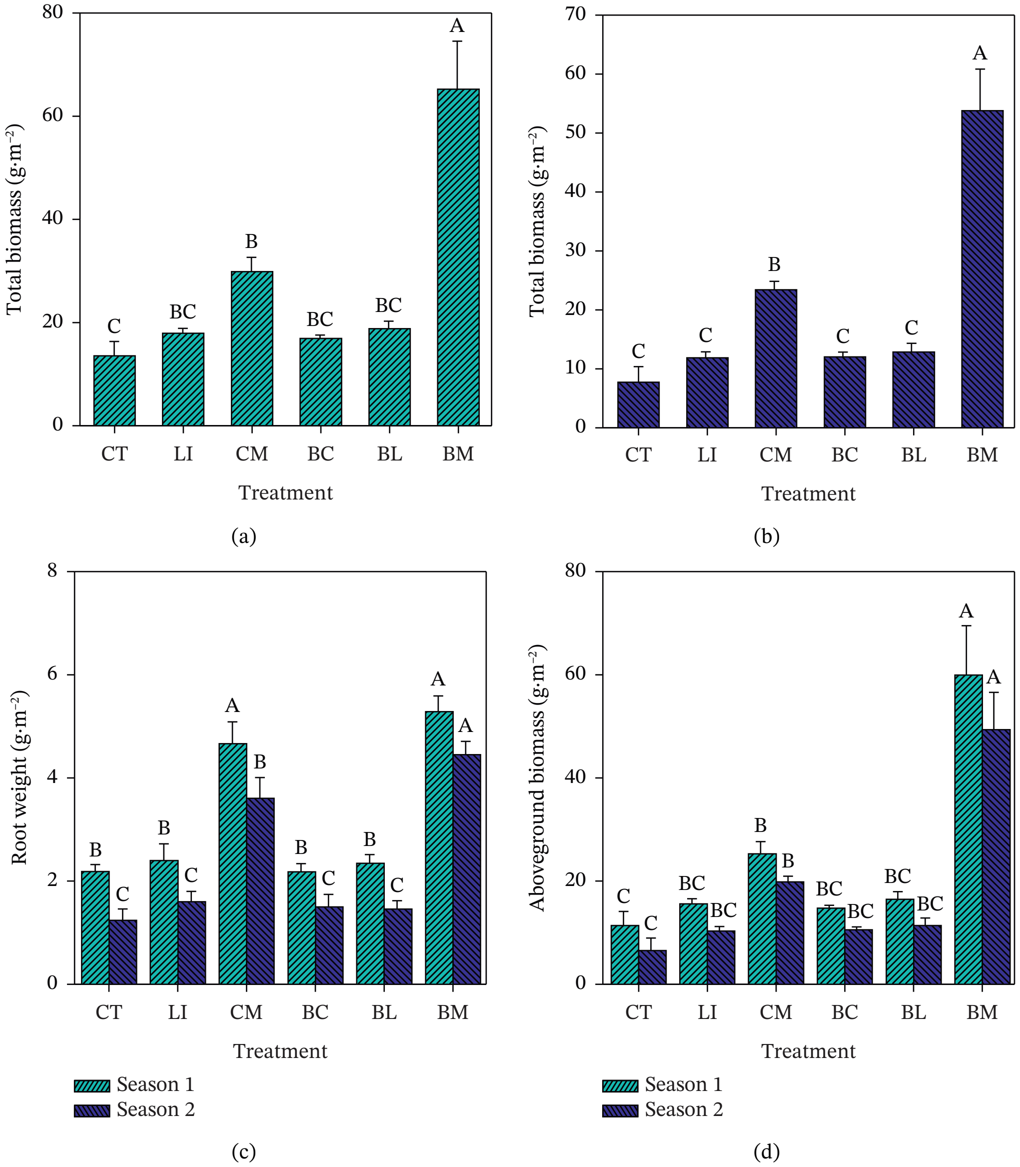


**FIGURE 3** | Total biomass in Season 1 (a), Season 2 (b), root weight (c), and aboveground biomass (d) of Pak Choy after the two vegetable seasons in six treatments (CT, control; LI, lime; CM, cow manure; BC, biochar; BL, biochar + lime; BM, biochar + cow manure). Error bars indicate the standard error of the mean. Within a panel (for a and b) and for each season (for c and d), bars labeled with the same letters are not statistically significantly different from each other at $p \leq 0.05$. For total biomass and aboveground biomass, the interaction effects of biochar and traditional amendment were significant in two seasons. For root weight, only the effects of traditional amendment were statistically significant in two seasons.

related to soil acidity and toxicity, thereby confirming the first research hypothesis. This synergy likely resulted from the complementary effects of lime in neutralizing soil acidity and biochar in adsorbing toxic elements. Previous studies have also reported that the combination of rice husk biochar and lime can improve soil properties related to acidity, such as pH, and reduce properties related to toxicity, such as Al and Fe in acidic soils (isohyperthermic, Typic Paleudult) [9]. Similarly, the combination of coffee husk biochar and lime was effective in ameliorating strongly acidic to very strongly acidic loam soils in Western Ethiopia [60]. However, it led to an improvement in componential SQI reflecting only soil salinity in the first season, not in the second, as observed in the current study. All five amendment treatments exhibited a greater CSQI (sal) than the CT in the first season, while only the sole lime treatment showed substantial impacts on the soil constraint of salinity in the second season. The combination of biochar and lime or cow manure did not exhibit statistically significant impacts on the salinity of the soil. These findings suggest that the salinity of the soil was less improved by the amendments, compared to the other constraints.

The combination of biochar and cow manure exhibited greater improvement in the four primary constraints, especially nutrient quality, of saline acid sulfate soil, compared to the CT treatment, confirming our second hypothesis. Nevertheless, this combination did not improve CSQI (acid) and CSQI (tox) as effectively as the combination of biochar and lime. This indicates that lime is an effective amendment in mitigating the acidity and toxicity of the soil [56]. The advantages of the biochar and cow manure combination were primarily derived from the great improvement in the soil nutrient status. Cow manure supplied abundant N and

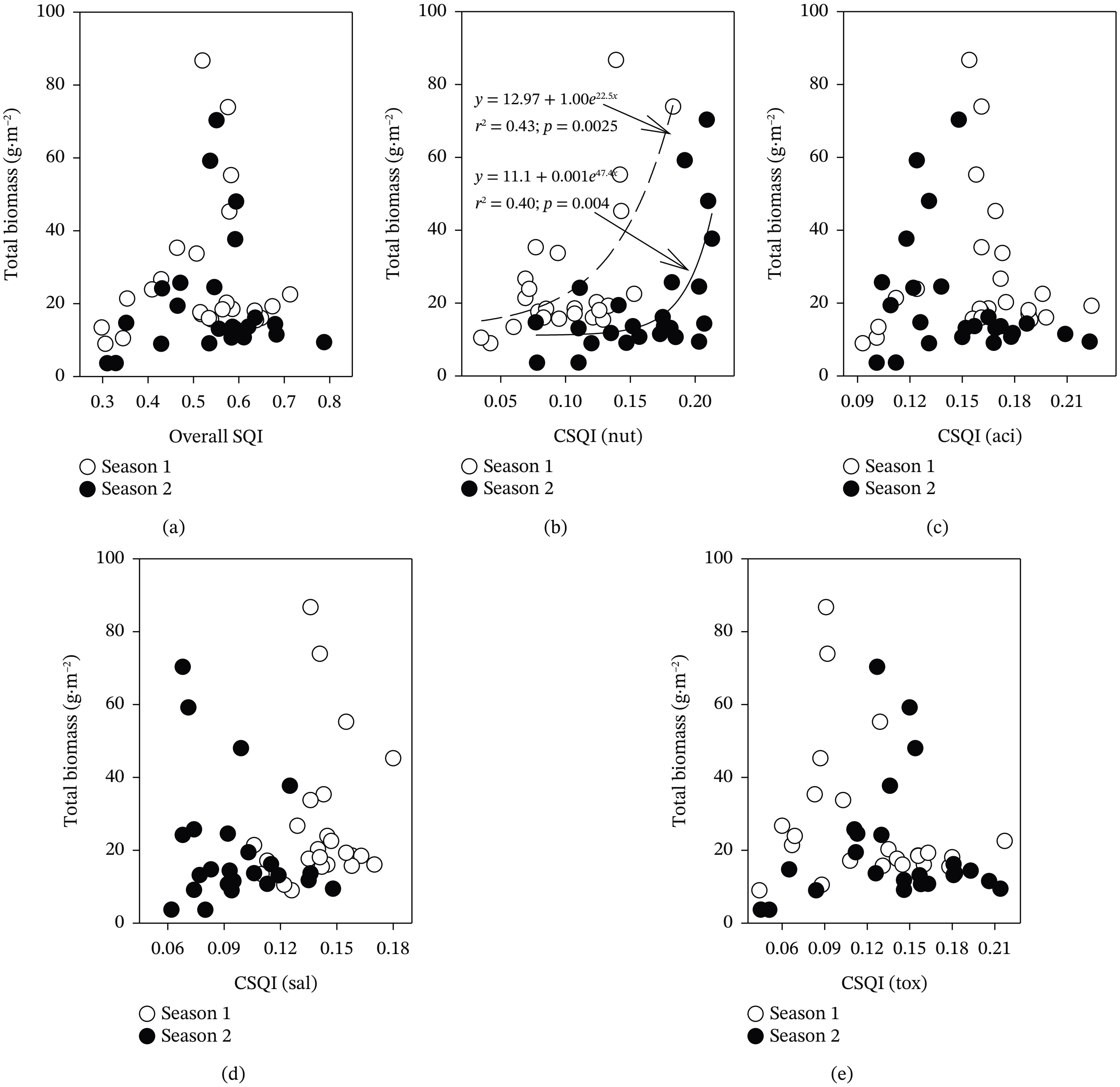


**FIGURE 4** | The relationship between the total biomass of Pak Choy with overall SQI and with each of the four componential SQIs after two vegetable seasons. CSQI (aci), CSQI (sal), CSQI (tox), and CSQI (nut) are the componential soil quality indices reflecting the acidity, salinity, toxicity, and nutrition, respectively. Only (b) shows a statistically significant relationship, while the others are nonsignificant. (a) Total biomass–overall SQI. (b) Total biomass–CSQI (nut). (c) Total biomass–CSQI (aci). (d) Total biomass–CSQI (sal). (e) Total biomass–CSQI (tox).

P, while biochar contributed high levels of exchangeable P and Ca. Additionally, biochar was reported to increase available P through various mechanisms, such as priming effects [61], pH enhancement [62], and reduced phosphorous fixation by soil components [14]. According to a meta-analysis by Gao et al. [62], sole biochar addition reduced the concentration of $NH_4^+$ in soil, but the combination of biochar with organic fertilizers enhanced the levels of this parameter in agricultural soils. The combination of rice husk biochar or bamboo biochar with organic manure was also reported to have synergistic impacts on enhanced soil nutrients [63, 64]. Therefore, the combination of biochar and cow manure represents a promising strategy for improving the nutrient status and mitigating other constraints, leading to enhanced overall quality of saline acid sulfate soils. Nonetheless, the biochar–lime combination remains crucial for addressing specific issues related to soil acidity and toxicity.

Although biochar alone (BC) or in combination with lime (BL) did not markedly improve the growth or yield of Pak Choy, its combination with cow manure (BM) led to more than a 200% increase in total biomass compared to the sole applications of either amendment. This outcome highlights a strong synergistic interaction between biochar and cow manure, likely resulting from the complementary effects of nutrient supply from manure and the enhanced nutrient retention and reduced toxicity provided by biochar, thereby confirming our third hypothesis. Similarly, other studies also reported the combined impacts of biochar and organic manure on cotton root systems in loess-like

Diluvial–Alluvial [18], tomato growth in a silty clay loam agricultural soil [65], and cucumber yield in an Ultisol [66], which were attributed to the enhanced soil nutrient status. The key characteristic of this combination was its ability to highly improve soil nutrient quality, as reflected through the componential SQI related to soil nutrition in both vegetable seasons (Figure 2). The CSQI (nut) had a strong correlation with the total biomass of Pak Choy, a leafy vegetable that requires high levels of nutrients, particularly nitrogen and phosphorus for its growth [67, 68]. Moreover, the combination of biochar and cow manure leverages each other's strengths: biochar effectively addresses constraints related to acidity and toxicity, while cow manure enhances soil nutrient content. Thus, this combination has a synergistic impact, significantly increasing the growth and yield of Pak Choy.

Multivariate correlation analysis also showed that only CSQI (nut) had a statistically significant correlation with the total biomass of the vegetables in both cropping seasons. In contrast, other componential SQIs reflecting acidity, toxicity, and salinity showed weak relationships with the total biomass. This indicates that soil nutrition plays a decisive role in the growth of Pak Choy. Additionally, stepwise multivariate analysis revealed that $NH_4^+$ content and CEC values were key determinants of the total biomass of the vegetables (data not shown). Because biochar most effectively enhanced CEC, and cow manure supplied the highest $NH_4^+$ levels, their combination likely created complementary benefits, improving both nutrient retention and nutrient supply. This synergistic effect explains why the biochar–cow manure treatment produced the highest vegetable yield observed in this study.

Although the combination of biochar and lime markedly improved soil quality in terms of acidity and toxicity, it did not result in a corresponding increase in Pak Choy growth and yield compared to the CT, likely due to several underlying factors. First, acidity and metal toxicity were unlikely the primary growth-limiting constraints for Pak Choy in this study. As a fast-growing leafy vegetable, Pak Choy has high demands for readily available N, P, K, and micronutrients [68, 69]; therefore, alleviating acidity alone is insufficient when nutrient availability remains suboptimal. This suggests that nutrition is likely the limiting factor in determining the growth of Pak Choy. Second, the combined application of biochar and lime substantially increased soil pH, potentially surpassing the optimal range for Pak Choy (5.5–6.5; Maludin et al. [70]). The excessive pH values can potentially reduce the availability of some essential nutrients [42] through reduced solubility, thereby limiting the nutrient uptake despite improved chemical conditions. Similarly, high rates of this combination were found to even lower the grain yield of cowpeas, attributed to overimprovement of some soil properties, typically high pH levels in an Oxic Haplustalf using biochar produced from hardwood (*Prosopis africana*) [42]. Third, the biochar–lime combination could not supply labile organic matter or mineralizable nutrients capable of stimulating microbial activity, nutrient cycling, and enzymatic processes [71]. In contrast, cow manure provides readily decomposable organic substrates and nutrient inputs that enhance both biological functioning and nutrient availability, explaining why biochar + cow manure produced a markedly stronger growth response. In brief, these factors demonstrate that while biochar + lime effectively corrected chemical constraints, it did not sufficiently address the nutritional and biological requirements needed to support vigorous Pak Choy growth in saline acid sulfate soils.

## 4.3 | Implications and Limitations of the Current Study

Technically, the combination of biochar and lime is most effective in ameliorating constraints related to acidity and toxicity, while the combination of biochar and cow manure is best in improving soil nutrition, thereby promoting greater growth and yield of Pak Choy. This result is noteworthy and can be applied on a larger scale for growing Pak Choy or similar crops. From an environmental perspective, the use of biochar produced from agricultural organic by-products offers various benefits, such as utilizing waste for soil improvement, enhancing agricultural productivity, and increasing carbon sequestration in the soil due to the stability of biochar [72, 73]. Economically, both biochar–lime and biochar–cow manure combinations provide measurable improvements in soil quality, but their application at large scales may involve considerable costs related to material production, transport, and labor. A comprehensive evaluation of their long-term economic efficiency is therefore needed to determine whether the benefits justify the investment under real farming conditions. Nevertheless, both biochar and cow manure can be produced on-farm using locally available biomass and livestock waste, which substantially reduces input costs and enhances the practicality and economic feasibility of the amendment strategies assessed in this study.

While this study provides useful insights into soil improvement for Pak Choy cultivation, several limitations must be recognized. First, the experiment was conducted under controlled pot conditions, which may not fully capture field-scale variability in soil hydrology, salinity dynamics, and crop–soil–microbe interactions. Second, the short study duration limits the understanding of long-term effects on soil properties, nutrient cycling, crop responses, and the longevity of improvements in acidity, toxicity, and nutrient status. These benefits may decline under field conditions due to leaching, seasonal hydrological changes, and depletion of amendment-derived inputs. Longer-term field trials are therefore needed to evaluate the persistence and practical durability of these improvements. Third, the study focused on a single vegetable species, Pak Choy, which may respond differently to soil amendments compared with other crops. Finally, potential interactions with microbial processes were not assessed. The study did not measure microbial indicators relevant to sulfate transformation dynamics. Although postharvest $SO_4^{2-}$ concentrations were quantified, key metrics such as microbial respiration and enzymatic activities [74] were not included, limiting interpretation of sulfate processes to chemical endpoints rather than biological mechanisms.

## 5 | Conclusions

Among the four primary constraints of saline acid sulfate soil, acidity, metal toxicity, nutrient deficiency, and salinity, the first three were improved most effectively by the amendments and their combinations, while salinity showed less clear improvement. The combination of biochar and lime was most effective in ameliorating constraints of acidity and toxicity, while the combination of biochar and cow manure was best for improving nutritional status, reflecting the nature of the amendments. Single and multivariate correlation analyses showed that the componential SQI reflecting soil nutrition was the key factor determining the growth of Pak Choy. The combination of biochar and cow manure led to a total biomass increase of over 200% compared to any single application, or the biochar and lime combination, highlighting their strong synergistic effect on Pak Choy growth. Although the combination of biochar and lime effectively alleviated soil acidity and toxicity and produced the highest overall SQI, it did not result in a corresponding increase in vegetable yield. This suggests that the soil quality improvements due to this combination did not meet the specific needs of Pak Choy. Findings suggest that soil improvement strategies should align plant nutritional needs with amendment effectiveness in alleviating the key constraints of saline acid sulfate soils.

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## Author Contributions

All authors contributed to the study's conception and design. Material preparation, data collection, and analysis were performed by Binh Vu Thai and Tung Xuan Tan Nguyen. Binh Thanh Nguyen and Tung Xuan Tan Nguyen wrote the first draft of the manuscript, and Binh Thanh Nguyen wrote the final version. All authors commented on both versions of the manuscript.

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## Disclosure

All authors read and approved the final manuscript.

## Conflicts of Interest

The authors declare no conflicts of interest.

## Data Availability Statement

The data that support this study will be shared upon reasonable request to the corresponding author.

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## Supporting Information

Additional supporting information can be found online in the Supporting Information section. *(Supporting Information)*

This includes two Supporting Tables that support the findings of the current study. Supporting Table 1 presents the basic properties of the experimental materials (soil, biochar, and cow manure), while Supporting Table 2 provides the loading values and weights of the measured parameters, derived from principal component analysis (PCA)/factor analysis.