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Research Article

Effects of Biochar, Lime, and Compost Applications on Soil Physicochemical Properties and Yield of Pomelo (*Citrus grandis* Osbeck) in Alluvial Soil of the Mekong Delta

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Soil acidity is an important factor affecting crop productivity in the tropics. The soil of the Vietnamese Mekong Delta has high acidity, deficient levels of exchangeable bases, and low fertility. This study aimed to evaluate soil amendments' role in improving soil fertility, soil acidity, and pomelo yield cultivated in raised beds. The field trial was carried out in Hau Giang Province consecutively over 3 years from 2018 to 2020. Four treatments were used, namely control, biochar (5 ton·ha^{-1}·year^{-1}), lime (2 ton·ha^{-1}·year^{-1}), and compost (5 ton·ha^{-1}·year^{-1}). All treatments applied the same amount of NPK fertilizers at rates of 400 kg·N, 300 kg·P_2O_5, and 400 kg·K_2O·ha^{-1}·year^{-1}. Physicochemical properties of the topsoil (0–20 cm) and subsoil (20–40 cm) and fruit yield were investigated. The results showed that biochar or compost application increased soil pH, soil organic matter (SOM), and exchangeable cations and decreased soil bulk density (BD), improving soil fertility and fruit yield in the raised beds. Applications of biochar or compost resulted in about 1.5-fold higher fruit yield than that of chemical fertilizer alone. The average profit increased to USD 1,672 ha^{-1} after applying biochar and compost in the three-year experiments. Biochar and compost amendments have a positive effect on reducing soil acidity and soil BD, elevating SOM, supplying available Ca^{2+} and Mg^{2+}, improving soil fertility, enhancing fruit yield, and increasing profit.

1. Introduction

Fruit is one of the most crucial agricultural commodities in the Vietnamese Mekong Delta (VMD). The fruit production area in the VMD is estimated to be about 30% of the country's total agricultural production area [1]. Pomelo is considered a high-value fruit in the area for both domestic markets and export [2]. In 2017, the pomelo cultivation area in the VMD was about 4,000 ha, with an estimated production of 82,000 tones, occupying about 17% of the total area and 40% of the total production in Vietnam [3].

In recent years, pomelo production has been unstable because farmers have used excessive chemical fertilizers, which in the long term cause soil acidity, reduced soil fertility, serious soil degradation, and decreased fruit yield [4]. According to Dung et al. [5], soil pH, soil organic matter (SOM), and exchangeable cations declined severely in the pomelo soil. Our previous study revealed that pomelo orchards have high occurrence of soil compaction [6]. The production of pomelo in this area decreased drastically to 60,000 tons in 2020 [7].

Alluvial soil in the VMD was formed and developed during the Holocene period. Based on field measurements, a new elevation model discovered that the VMD is just 0.8 m above the local sea level [8]. Therefore, to avoid waterlogging during the rainy season, the VMD farmers had to construct raised beds to cultivate pomelo [9]. Raised bed systems are constructed by digging parallel ditches and using the soil to establish alternate beds, on which orchards will be planted. However, exchangeable base ions (potassium, magnesium, and calcium) leach out in tropical conditions through irrigation water and rainwater [10].

Limestone decreases soil acidity, neutralizes toxins, and supplies calcium and magnesium to the soil, promoting the development of root systems and improving nutrient use efficiency and water uptake by the crop [11, 12]. The application of lime increases soil pH, removes soil contaminants, amends soil cation exchange capacity and percentage of soil base saturation [13], promotes SOM decomposition, increases available nutrients of soil, increases dehydrogenase activity, and enhances crop production [14].

Biochar has high carbon content, produced from the pyrolysis of agricultural residues, such as rice straw, rice husk, and maize stems and cobs [15]. Adding biochar to soil increases its water-holding and cation exchange capacity, pH, SOM, and available soil nutrients, reduces soil nutrient losses, and improves soil microorganism diversity. Biochar addition improves crop productivity and reduces soil erosion [16].

Compost is used to increase crop productivity and for sustainable agriculture because of its high available nutrient content and low harmful microorganisms [17]. Besides, using compost significantly improves soil physical properties, such as increased porosity, hydraulic conductivity, and water retention capacity [18]. Furthermore, using compost resulted in macroaggregate stability, increased available P and N in soil, decreased nutrient losses due to leaching, reduced food-borne pathogens, and increased crop yield [19].

Although the roles of biochar, lime, and compost have been widely studied in the agricultural system, their research information in fruit orchards in the VMD area remains limited. Therefore, this study aimed to evaluate amendments used to improve soil pH, SOM, available nutrients, and soil porosity in the soil of pomelo orchards. We hypothesized that the raised bed soil in the VMD tends to be acidic and compacted, with low fertility, owing to overexploitation. Thus, the use of lime, biochar, and compost aimed to enhance soil fertility and raise fruit yield.

2. Materials and Methods

2.1. Compost, Lime, and Biochar. The compost and biochar used in the trial were commercial products (PPE Co., Ltd., Can Tho, Vietnam, and Mai Anh Co., Dong Thap, Vietnam, respectively). Their nutrient composition and chemical characteristics were presented by Phuong et al. [20]. The initial biochar physicochemical properties were pH, 7.70; total porosity, 92.3%; exchangeable Na, $0.24\,cmol_c{\cdot}kg^{-1}$; exchangeable K, $12.9\,cmol_c{\cdot}kg^{-1}$; exchangeable Ca, $0.16\,cmol_c{\cdot}kg^{-1}$; total C, $471\,g{\cdot}kg^{-1}$; soluble Na, $0.24\,cmol_c{\cdot}kg^{-1}$; soluble K, $3.35\,cmol_c{\cdot}kg^{-1}$; and soluble Ca, $0.15\,cmol_c{\cdot}kg^{-1}$. Those of the compost were pH, 8.70; total porosity, 76.2%; exchangeable Na, $0.60\,cmol_c{\cdot}kg^{-1}$; exchangeable K, $15.0\,cmol_c{\cdot}kg^{-1}$; exchangeable Ca, $61.6\,cmol_c{\cdot}kg^{-1}$; total C, $154\,g{\cdot}kg^{-1}$; soluble Na, $1.59\,cmol_c kg^{-1}$; soluble K, $20.0\,cmol_c{\cdot}kg^{-1}$; and soluble Ca, $7.29\,cmol_c{\cdot}kg^{-1}$. The lime used in this research was a commercial product made from limestone (Voi bot, Son Nam Mineral Co., Ltd., Ho Chi Minh, Vietnam), with CaO and MgO content of about 85% and 10%, respectively.

2.2. Experimental Design and Site. The experiment used a pomelo orchard with a raised bed that had existed for 8 years (9°51′48.8″ N, 105°47′21.8″ E), located in Chau Thanh District, Hau Giang Province, Vietnam. The study areas were in a location with a tropical monsoon climate, with an average annual temperature of about 25.9°C–29.5°C. There are two main seasons: the sunny season from December to April and the rainy season between May and November. The average annual rainfall from 2018 to 2020 at the experimental location was 2,113 mm (Hau Giang Hydrometeorological Station).

The experimental orchard has a long history of rice cultivation, after which raised beds were constructed for the King mandarin (*Citrus reticulata* × *sinensis*) plantation (about 4 years) and then pomelo. The pomelo trees in this study were aged 4 years and had given fruits one year. The research was conducted from January 2018 to December 2020 (approximately 3 years). The experimental layout was according to the randomized complete block design, with four replications (three trees in each replicate) in all treatments, including control (NPK fertilizer), compost (NPK fertilizer + $5\,ton{\cdot}ha^{-1}{\cdot}yr^{-1}$ of compost), biochar (NPK fertilizer + $5\,ton{\cdot}ha^{-1}{\cdot}yr^{-1}$ of biochar), and lime (NPK fertilizer + $2\,ton{\cdot}ha^{-1}{\cdot}yr^{-1}$ of lime).

In this study, the dose of compost applied was based on the recommendation of Binh et al. [21], who reported that the application rate of compost at $5\,ton\ ha^{-1}$ significantly improved the soil fertility and fruit yield of rambutan cultivated in the VMD. Meanwhile, the application rate of biochar ($5\,ton{\cdot}ha^{-1}$) was in accordance with the recommendation of Thu et al. [22] and the lime dose ($2\,ton{\cdot}ha^{-1}$) used was based on the result of Dang et al. [23]. Biochar, compost, and lime were applied by topdressing around the canopy. After application, plowing was done. They were applied twice per year in the wet and dry seasons.

The application rates of N, P_2O_5, and K_2O (400 kg, 300 kg, and 400 kg per ha per year, respectively) and timing of fertilizer application were in accordance with the recommendation of the Southern Horticultural Research Institute [24]. According to Ve and Trieu [25], the rate of NPK fertilizers used in the study was the optimal range for the growth of pomelo. Reducing the amount of NPK fertilizers may negatively affect the development of pomelo trees, thereby impacting the results of the study. Therefore, NPK fertilizers were applied as basal plus topdressing at the same amount for all treatments. N, P, and K were used as urea (46% N), superphosphate (16% P_2O_5), and potassium chloride (60% K_2O). NPK fertilizers were applied on surface in a 1.5 m radius around the tree trunk. After application, using the grass and dead pomelo leaves mulched.

In this research, the size of a raised bed was 5 m wide × 20 m long, and the total pomelo orchard area was approximately $800\,m^2$. The "Nam Roi" pomelo variety was used in this experiment. The pomelo plant density was $625\,trees\ ha^{-1}$, with 4 × 4 m spacing.

Soil samples were collected according to the standard procedures described by the Department of Soil Science, College of Agriculture, Can Tho University, Vietnam. Soil samples were collected at the same time with pomelo fruit harvest (December 2018, 2019, and 2020). The soil samples were taken from two layers: surface (0–20 cm depth) and subsurface (20–40 cm depth), at five different positions for each replicate and then mixed evenly to obtain a soil sample.

At the same time, soil samples were taken using 100 cm^3 cores at two layers to survey the soil bulk density. The cores had a height of 5 cm; hence, the topsoil layer (0–20 cm) included four samples (at 0–5, 5–10, 10–15, and 15–20 cm). Similarly, the subsoil layer (20–40 cm) was also sampled at four depths (20–25, 25–30, 30–35, and 35–40 cm).

The fruit yield per tree, that is, the number of fruits per tree, was collected at the ripe phase. The yield of pomelo ($ton \cdot ha^{-1}$) was calculated as fruit productivity per tree multiplied by plant density.

2.3. Soil Sampling Analyses. Soil samples were air-dried at 25°C–28°C for ten days, crushed and sieved through 0.5 and 2.0 mm sieves, and stored in plastic boxes to analyze the soil physicochemical parameters. For pH tests, soil was mixed with water at a 1 : 2.5 soil: water ratio. SOM was determined by the Walkley–Black method [26]. Exchangeable cations (Ca^{2+}, Mg^{2+}, and K^+) were extracted using $BaCl_2$ 0.1 M solution and measured with flame photometry [27]. Soil bulk density (BD) was determined using the core method [28].

2.4. Economic Analyses. For economic analyses of soil amendments, several parameters were measured, such as the costs of soil amendments (biochar, compost, and lime), NPK fertilizers, fruit yield, fuel input (petrol), and fruit price. Besides, the costs of pesticides, weedicides, and disease control, as well as labor costs, were recorded. The profit was calculated as the revenue minus the total costs.

2.5. Linear Regression Models. Multiple regression models were used to evaluate the influence of different soil covariables on fruit yield. The multiple regression model is shown in the following equation:

$$Y = a_0 + a_1X_1 + a_2X_2 + a_3X_3 + \cdots + a_nX_n, \quad (1)$$

where Y = the dependent variable, X_1, X_2, X_3, … X_n = independent variables, and a_0, a_1, a_2, a_3, … a_n = regression coefficients. In this study, Y = pomelo fruit yield; X_1 = pH; X_2 = SOM; $X_3 = Ca^{2+}$; $X_4 = K^+$; $X_5 = Mg^{2+}$; and X_6 = soil BD.

2.6. Data Analyses. SPSS Software (version 16.0) was used for statistical analyses in this study. Analyses of variance were used to calculate mean values, and the comparison of differences between treatments was evaluated using Duncan's multiple range test, at $p < 0.05$. Microsoft Excel (version 2013) was used to determine the relationship between soil properties based on Pearson's correlation coefficient.

3. Results

3.1. Initial Soil Physicochemical Properties. Table 1 presents the initial physicochemical properties of the soil before the experiments were conducted. At 0–20 cm depth, the pH was 4.95; EC, 0.65 $mS \cdot cm^{-1}$; available P (AP), 28.2 $mg \cdot kg^{-1}$; total nitrogen (TN), 0.38%; SOM, 3.05%; soil exchangeable cations (K, Ca, and Mg), 0.48, 3.77, and 4.23 $cmol_c \cdot kg^{-1}$, respectively; and BD, 1.13 $g \cdot cm^{-3}$. The soil texture of silty clay was as follows: 0.60% sand, 44.8% silt, and 54.6% clay. The physicochemical properties at the depth of 20–40 cm were pH, 5.00; EC, 0.72 $mS \cdot cm^{-1}$; AP, 22.9 $mg \cdot kg^{-1}$; TN, 0.31%; SOM, 3.15%; and soil exchangeable cations (K, Ca, and Mg), 0.64, 3.82, and 4.01 $cmol_c \cdot kg^{-1}$, respectively. The soil texture of silty clay was as follows: 1.50% sand, 48.5% silt, and 51.0% clay.

3.2. Influence of Soil Amendments on Soil Properties in Surface (0–20 cm). Soil amendments in the experimental years changed the soil pH value (Table 2). In particular, using biochar, compost, and lime increased the soil pH in the study orchard. Treatment with only inorganic fertilizer reduced pH significantly compared with other treatments. Compost, lime, and biochar treatments raised the pH values by about 0.5 units compared with the control treatment. Besides, pH tended to increase in the year 2020. Biochar and compost enhanced SOM compared with the control treatment. There was no difference in SOM during the three years of the experiment. Applications of compost and lime in three years increased SOM compared with that using only chemical fertilizer.

The exchangeable Ca^{2+} and Mg^{2+} cations were significantly higher in biochar, lime, and compost than in the control treatment over the three years and between soil amendment treatments. In particular, the Ca concentration increased from 3.79 to 4.13 $cmol_c \cdot kg^{-1}$ between 2018 and 2020, respectively. Likewise, the Mg^{2+} concentration increased to 4.82 $cmol_c \cdot kg^{-1}$ in 2020. Using lime and compost significantly increased the exchangeable Ca^{2+} and Mg^{2+}. The exchangeable K^+ concentration was not affected by soil amendment application; the K^+ concentration increased from 0.61 to 0.66 $cmol_c \cdot kg^{-1}$ in all treatments (Table 2). The application of compost or biochar decreased soil BD compared with the control treatment. Over the three years, soil BD in the 0–20 cm depth declined from 1.07 to 1.01 $g \cdot cm^{-3}$.

The correlation analysis of soil parameters (Figure 1) indicated positive correlations between pH and SOM ($r = 0.50$), pH and Ca^{2+} ($r = 0.81$), and pH and Mg^{2+} ($r = 0.80$). The exchangeable Ca^{2+} showed a great positive correlation with exchangeable Mg^{2+} ($r = 0.85$) and a negative correlation with BD ($r = -0.81$). There was a negative correlation between soil pH, SOM, Mg^{2+}, and soil BD ($r = -0.72$, -0.66, and -0.75, respectively).

3.3. Impact of Soil Amendments on Soil Properties in Subsurface (20–40 cm). Table 3 shows that applications of lime, biochar, and compost improved soil pH, soil BD, and

Table 1: Physicochemical characteristics of the soil before the experiments.

Parameters	Unit	Depth (cm) 0–20	Depth (cm) 20–40
pH_{H2O}		4.95	5.00
EC	$mS{\cdot}cm^{-1}$	0.65	0.72
Available phosphorus	$mg{\cdot}kg^{-1}$	28.2	22.9
Total nitrogen	%	0.38	0.31
Soil organic matter	%	3.05	3.15
Exchangeable cations			
K^+		0.48	0.64
Ca^{2+}	$cmol_c{\cdot}kg^{-1}$	3.77	3.82
Mg^{2+}		4.23	4.01
Bulk density	$g\ cm^{-3}$	1.13	1.10
Soil texture			
Sand		0.60	1.50
Silt	%	44.8	48.5
Clay		54.6	51.0
Soil textural class		Silty clay	Silty clay

Table 2: Effects of soil amendments and years on soil properties in topsoil (0–20 cm).

Factors		pH	SOM (%)	Ca^{2+}	K^+ $cmol_c\ kg^{-1}$	Mg^{2+}	BD ($g\ cm^{-3}$)
(A) Soil amendments	Control	4.91^c	2.87^c	2.84^c	0.64	3.95^c	1.18^c
	Biochar	5.36^b	3.82^a	4.01^b	0.61	4.71^b	0.99^a
	Lime	5.34^b	3.04^b	4.41^a	0.61	4.91^a	1.05^b
	Compost	5.54^a	3.92^a	4.54^a	0.66	4.92^a	0.96^a
(B) Years	2018	5.19^b	3.39	3.79^b	0.57^b	4.39^c	1.07^b
	2019	5.25^b	3.39	3.92^{ab}	0.65^a	4.66^b	1.04^a
	2020	5.41^a	3.45	4.13^a	0.67^a	4.82^a	1.01^a
F (A)		***	***	***	ns	***	***
F (B)		**	ns	**	***	***	**
F (A × B)		**	***	***	ns	*	**

Different letters in the same column indicate significant differences at $p < 0.001$ (***), $p < 0.01$ (**), and $p < 0.05$ (*); ns indicates no significant difference at $p > 0.05$. Control, NPK fertilizer; biochar, NPK fertilizer + 5 $ton{\cdot}ha^{-1}{\cdot}yr^{-1}$ of biochar; lime, NPK fertilizer + 2 $ton{\cdot}ha^{-1}{\cdot}yr^{-1}$ of lime; compost, NPK fertilizer + 5 $ton{\cdot}ha^{-1}{\cdot}yr^{-1}$ of compost.

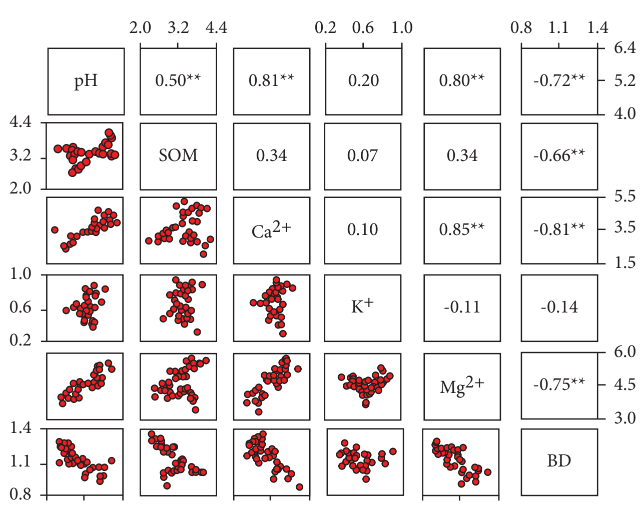

Figure 1: Correlation plots of the soil physicochemical characteristics in the surface layer (0–20 cm)**indicates a significant difference at $p < 0.01$.

exchangeable Ca^{2+} and Mg^{2+}. The biochar, lime, and compost applications increased soil pH by about 1.3-fold compared with that in the control treatment. SOM content was increased using compost compared with biochar, lime, and control treatments. The SOM content was 3.43% in 2018, and it increased to 3.70% in 2020. Except for exchangeable K^+, the exchangeable cations increased significantly by applying lime, biochar, and compost. There was a gradual increase in the Ca^{2+} and Mg^{2+} bases over the three years of the experiment. Soil amendment treatments yielded a Ca^{2+} concentration 1.5-fold higher than the control treatment in 2020. The control treatment decreased Mg^{2+} and Ca^{2+} bases significantly. For K^+ concentrations, there was no significant difference in all treatments. The K^+ concentration was 0.89–0.93 $cmol_c{\cdot}kg^{-1}$ from 2018 to 2020. The addition of biochar, lime, and compost decreased soil BD. The application of chemical fertilizers increased soil BD from 1.10 $g{\cdot}cm^{-3}$ (Table 1) to 1.19 $g{\cdot}cm^{-3}$ (Table 3).

Figure 2 shows a positive correlation between SOM content, Ca^{2+}, Mg^{2+}, and soil pH ($r = 0.65$, 0.92, and 0.83, respectively). The concentrations of exchangeable Mg^{2+} and

Table 3: Effects of soil amendments and years on subsoil properties (20–40 cm).

Factors		pH	SOM (%)	Ca^{2+}	K^+	Mg^{2+}	BD (g cm^{-3})
					$cmol_c\ kg^{-1}$		
(A) Soil amendments	Control	4.45^b	3.04^d	3.37^b	0.94	4.05^b	1.19^b
	Biochar	5.56^a	3.89^b	4.72^a	0.88	5.02^a	1.01^a
	Lime	5.52^a	3.22^c	4.82^a	0.89	5.00^a	1.03^a
	Compost	5.62^a	4.12^a	4.71^a	0.93	5.10^a	1.01^a
(B) Years	2018	4.93^c	3.43^b	4.09^c	0.89	4.64^b	1.06
	2019	5.26^b	3.57^a	4.47^b	0.92	4.79^{ab}	1.07
	2020	5.68^a	3.70^a	4.72^a	0.93	4.94^a	1.04
F (A)		***	***	***	ns	***	***
F (B)		**	***	***	ns	**	ns
F (A × B)		**	**	***	ns	*	ns

Different letters in the same column indicate significant differences at $p < 0.001$ (***), $p < 0.01$ (**), and $p < 0.05$ (*); ns indicates no significant difference at $p > 0.05$. Control, NPK fertilizer; biochar, NPK fertilizer +5 ton·ha^{-1}·yr^{-1} of biochar; lime, NPK fertilizer +2 ton·ha^{-1}·yr^{-1} of lime; compost, NPK fertilizer +5 ton·ha^{-1}·yr^{-1} of compost.

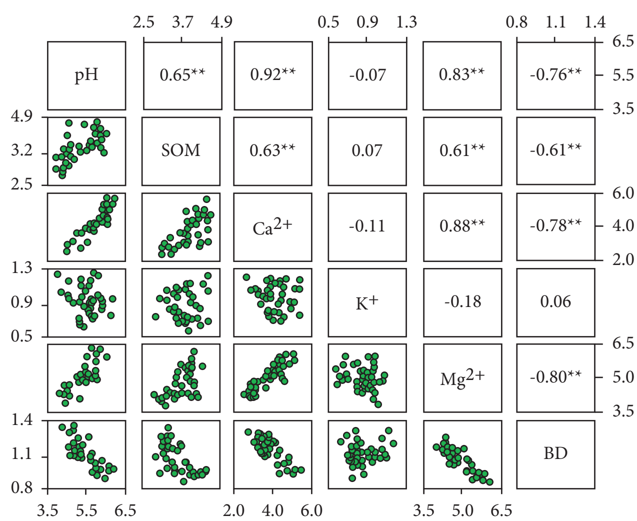

Figure 2: Pearson's correlation coefficient (*r* value, $n = 48$) of the soil physicochemical characteristics in the subsurface layer. **indicates significant difference at $p < 0.01$.

Ca^{2+} also correlated positively with SOM content. There was a negative correlation between exchangeable Mg^{2+} and Ca^{2+}, SOM, soil pH, and BD ($r = -0.80$, -0.78, -0.61, and -0.76, respectively). A strong positive correlation was demonstrated by the relationship between Mg^{2+} and Ca^{2+} ($r = 0.88$) and Mg^{2+} and SOM ($r = 0.61$).

3.4. Fruit Yield as Affected by Soil Amendments. Compost and biochar applications increased the fruit per tree and raised the pomelo yield (Table 4). Applying lime also improved the amount of fruit per tree and the pomelo yield compared with the control. However, liming treatment was significantly lower than compost and biochar treatments. The fruit numbers per tree were 29.3, 41.1, 34.0, and 41.2 fruits with the control, biochar, lime, and compost treatments, respectively. There was a significant difference in fruit yield per tree between adding biochar or compost and the control treatment. Fruit yields (kg $tree^{-1}$) with biochar and compost applications were the highest. The pomelo yield (ton·ha^{-1}) after biochar and compost applications was about 1.5-fold higher than that of the control. The pomelo fruit yield increased from 15.5 to 22.5 ton·ha^{-1} between 2018 and 2020.

3.5. Multiple Regression Models between Fruit Yield and Soil Properties. Multiple regression models were used to evaluate the relationship between fruit yield and soil properties, such as soil pH, SOM, exchangeable cations (Ca, K, Mg), and soil BD. The results of the models are presented in Table 5. Correlations between the yield of fruit and soil physicochemical characteristics at 0–20 and 20–40 cm were high, with $R^2 = 0.71$ and 0.74, respectively.

3.6. Profits after Applying Biochar, Lime, and Compost. The profits after treatments (biochar, lime, and compost) were higher than that after the control treatment (Table 6). In this study, differences in profit varied between years and treatments. In 2018, compared with the control, the average profits after biochar, lime, and compost treatments were USD 590, USD 385, and USD 521 ha^{-1}, respectively. Meanwhile, in 2019, the average profit after soil amendments increased to about USD 1,300 ha^{-1} compared with the profit without applying soil amendments. In 2020, the biochar, lime, and compost treatments provided USD 3,146, USD 2,936, and USD 3,096 additional income, respectively.

4. Discussion

Many global studies have reported that soil pH substantially increased by liming [14], biochar [29], and compost applications [30]. Our study indicated that soil pH in the 0–20 cm layer increased by about 0.45, 0.43, and 0.63 units after biochar, lime, and compost treatments, compared with the control. Likewise, the soil pH of the subsurface (20–40 cm) increased significantly, with averages of 1.11, 1.07, and 1.17 units after biochar, lime, and compost treatments, respectively. There was a slight increase in the pH value in the control treatment over the three years. The soil pH increase after the applications of biochar and compost is due to the high pH of biochar and compost. Biochar and compost applications can cause decreased soil

Table 4: Effects of soil amendments and years on pomelo fruit number and fruit yield.

Factors		Number of fruit per tree	Fruit yield per tree (kg $tree^{-1}$)	Yield (ton ha^{-1})
(A) Soil amendments	Control	29.3^c	24.5^c	15.3^c
	Biochar	41.1^a	33.8^a	21.1^a
	Lime	34.0^b	29.6^b	18.5^b
	Compost	41.2^a	33.3^a	20.8^a
(B) Years	2018	28.8^c	24.8^c	15.5^c
	2019	35.9^b	30.1^b	18.8^b
	2020	44.6^a	36.0^a	22.5^a
F (A)		***	***	***
F (B)		***	**	***
F (A × B)		*	**	***

Different letters in the same column indicate significant differences at $p < 0.001$ (***), $p < 0.01$ (**), and $p < 0.05$ (*). Control, NPK fertilizer; biochar, NPK fertilizer + 5 ton·ha^{-1}·yr^{-1} of biochar; lime, NPK fertilizer + 2 ton·ha^{-1}·yr^{-1} of lime; compost, NPK fertilizer + 5 ton·ha^{-1}·yr^{-1} of compost.

Table 5: Multiple regression models between fruit yield and soil properties ($n = 48$).

Equations	R^2	p
Surface layer (0–20 cm)		
$FY = 0.33 + 3.79 \times pH + 0.21 \times SOM - 1.98 \times Ca + 10.8 \times K + 3.59 \times Mg - 17.1 \times BD$	0.71	<0.01
Subsurface layer (20–40 cm)		
$FY = -29.2 + 4.64 \times pH + 1.90 \times SOM - 0.21 \times Ca + 2.09 \times K + 1.11 \times Mg + 9.90 \times BD$	0.74	<0.01

FY, fruit yield; SOM, soil organic matter; BD, bulk density.

Table 6: Economic aspects of soil amendment addition.

Year	Treatment	Revenue	Total cost USD ha^{-1}	Profit	Profit compared with control (USD ha^{-1})
2018	Control	7,219	3,500	3,719	—
	Biochar	9,309	5,000	4,309	590
	Lime	8,264	4,160	4,104	385
	Compost	9,240	5,000	4,240	521
2019	Control	9,585	5,000	4,585	—
	Biochar	12,270	7,250	5,020	1,301
	Lime	11,175	6,160	5,015	1,296
	Compost	12,195	7,100	5,095	1,376
2020	Control	10,230	5,500	4,730	—
	Biochar	15,465	8,600	6,865	3,146
	Lime	13,155	6,500	6,655	2,936
	Compost	15,165	8,350	6,815	3,096

acidity, resulting in the proton consumption capacity of humic material in biochar and compost, as reported by Naramabuye and Haynes [31]. Biochar contains many Ca^{2+} and K^+ cations, which cause the replacement of hydrogen in soil colloids and greatly reduce soil acidity [32]. This suggests that the pH of biochar and compost is not the sole factor in decreasing soil acidity. Compounds produced in biochar and compost may affect the biochar and compost characteristics [33]. For instance, biochar produced from wood feedstock can have a higher liming potential than that from non-wood feedstocks [29]. This investigation used rice husk biochar and sugarcane cake compost to increase exchangeable Ca^{2+}, which increased soil pH. Plant growth involves N uptake, increases H^+ ions, and induces soil acidification. As organic fertilizers contain rich nutrients for crops, they reduce the impact of soil acidification related to the formation of soil parent materials. This process of acidification is complex. Lime added to soil reacts with the available soil moisture and releases OH^- groups that neutralize H^+ in the soil solution, thus increasing the soil pH [34].

The addition of biochar and compost increased SOM at both depths (Tables 2 and 3). According to Cox et al. [35], who reported that application of biochar on soil surface improved SOM in not only 0–10 cm depth but also 10–20 cm depth. They also concluded that biochar and compost application increased SOM at 10–20 cm soil layer due to movement and leaching of soil amendments. In this study, biochar and compost were applied at 15 cm depth. Hence, SOM was possible leaching to the subsurface layer (20–40 cm). Biochar is a product rich in carbon content, which contributes to the production of humus and improves soil fertility [36, 37]. Many studies reported that soil microbes might use the decomposable carbon contained in biochar as a carbon source [38], pushing the humification process in organic matter and increasing the SOM content. Organic fertilizers increase SOM quantity and quality

[39, 40] because of increased soil microbial activities. Moreover, compost addition increases beneficial enzymes and bacterial activities in soil, improving the total organic carbon and soil fertility, compared with adding inorganic fertilizers alone.

This study showed that biochar and compost are more efficient in improving soil BD (Tables 2 and 3). Soil BD is a vital indicator of increased soil compaction with decreased SOM content and reduced soil porosity [41]. Plant root growth is negatively affected by soil compaction, which reduces the soil's water-holding capacity and nutrient uptake by plant roots [42]. Furthermore, soil compaction causes a decrease in soil microbiological activities [43]. Organic fertilizers have high porosity and more mineral nutrition that effectively improves and maintains the available nutrient content in the soil [40, 44]. Elevating SOM by adding organic fertilizers plays an important role in forming soil aggregates and increasing stabilization as well as soil microbe communities [45]. Compost fertilizer improved the soil structure and stability by enhancing soil organic carbon and available nutrient content, resulting in decreased soil BD and increased total porosity [46]. According to Blanco-Canqui [47], biochar addition decreased BD from 3% to 31% in 19 soils. On average, soil BD decreased by 12%. Biochar decreased soil compaction by interacting with soil particles and elevating wet aggregate stability (3–226%) and soil porosity [47]. Increasing soil porosity reduced soil BD because of the negative correlation between BD and total porosity [48].

In this study, the exchangeable cations (Ca^{2+} and Mg^{2+}) increased remarkably after adding organic fertilizer. In addition, the use of lime increased Mg^{2+} concentration compared with the control treatment because lime had higher Mg^{2+} content than the initial soil. As a result, the lime application improved the concentration of Mg^{2+} in soil. Many studies indicated that the mineralization of compost or biochar released more available nutrients into the soil solution, including calcium, potassium, and magnesium. However, this study showed that adding biochar and compost did not raise the concentration of K^+ but increased the content of Ca^{2+} and Mg^{2+} in the 20–40 cm layer. This result might be due to the low application rate of biochar (5 $Mg{\cdot}ha^{-1}$). Our results are not in agreement with the results of Phuong et al. [20] who found that biochar application rates at 10 $Mg{\cdot}ha^{-1}$ had a greater effect on enhancing soluble and exchangeable K^+ in salt-affected soils. Increased Ca^{2+} and Mg^{2+} content may affect the organic carbon content that increases soil respiration, enzyme activity, available water capacity, and porosity, thus elevating nutrient use efficiency [49]. Moreover, changes in the exchangeable cation concentration are more effective in improving nutrient uptake and crop yield [50]. According to Abreru et al. [51], the exchangeable contents of Ca^{2+} and Mg^{2+} were greatly increased by applying compost (on average, 200% and 86%, respectively). Jien and Wang [52] indicated that applying biochar increased the base cation percentage from 6.40% to 26.0%.

The addition of biochar or compost achieved optimal soil conditions (soil pH, SOM, and BD) for the growth and production of pomelo trees in the VMD soil. According to Ve and Trieu [25], the optimum content of SOM for the growth and productivity of "5 Roi" pomelo varied in the range of 3.50–4.50%. The pomelo developed better in soil pH conditions above 5.0 and soil BD under 1.05 $g{\cdot}cm^{-3}$ [25].

Many studies have indicated a positive correlation between Ca, Mg, and soil pH [53, 54]. The study found that soil pH significantly correlated with exchangeable Ca and Mg. The correlation coefficients (r) were 0.81 and 0.80 in the surface layer and 0.92 and 0.83 in the subsurface layer, respectively. According to Khadka et al. [53], there was a strong positive correlation between soil pH and Ca ($r = 0.79^{**}$) and Mg ($r = 0.69^{**}$). Similarly, Panhwar et al. [54] reported that the pH of soil had a linear regression with Ca ($R^2 = 0.75$) and Mg ($R^2 = 0.76$).

The amount of fruit per tree was increased by about ten fruits after biochar and compost treatments compared with that after chemical fertilizer treatment (Table 4). Similarly, the pomelo yield was the highest after the rice husk biochar and compost treatments. The pomelo yield effect of the liming treatment was less pronounced but still higher than that of the inorganic fertilizer treatment. Biochar and compost additions produced fruit yields of 21.1 and 20.8 $ton{\cdot}ha^{-1}$ compared with those of lime addition and the control, which were 18.5 and 15.3 $ton{\cdot}ha^{-1}$, respectively. In this research, biochar and compost enhanced nutrients available for crop development and mitigated the soil H^+ concentration (increased pH) for better plant health. The reason for the increased amount of fruit and pomelo yield might be decreased soil BD and improved porosity, which increase root penetration and respiration and elevate nutrient uptake from the solution of soil, thus improving fruit yield. Besides, an increase in SOM could enhance crop yield by increasing the available water capacity and nutrients [55]. Furthermore, biochar and compost are considered significant for improving soil fertility; promoting the soil microbial population; and increasing macronutrients, such as nitrogen, phosphorus, calcium, magnesium, and potassium, and trace elements, such as zinc, manganese, copper, and iron [55, 56]. Oldfield et al. [57] concluded that the potential yield of maize would increase by 10% and 23% for wheat by increased SOM content. Studies have shown that a combination of manure and chemical fertilizer (NPK) increased crop productivity [58, 59], and biochar combined with inorganic fertilizer elevated crop yield [60, 61].

Multiple regression is an effective tool to predict the crop yield based on soil properties that affect the direction of growth and yield of plants [62, 63]. In this study, the mean productivity of pomelo had a relationship with soil physicochemical characteristics in both layers studied. This research indicated that to estimate fruit yield based on the soil physicochemical properties of the six variables of linear regression model (Table 5), there was a negative effect on fruit yield by soil BD in the topsoil layer. Root growth and development were affected by soil compaction because of restricted oxygen, water, and nutrient supply. High BD leads to decreased root length, concentrating roots in the surface layer and decreasing rooting depth [64].

The results revealed that the economic gains over the three years were increased considerably by amending soil with biochar, lime, and compost compared with those without soil improvement practices (Table 6). The greater net profit gains by soil amendments (biochar, lime, and compost) were due to their positive impact on pomelo fruit yield, which increased net revenues. The benefits of soils amended with biochar, compost, and lime demonstrate that farmers can improve their livelihoods and increase soil pH, soil fertility, and available nutrients in their soil for a longer time [65, 66]. In this study, the use of compost or biochar is considered to be a beneficial measure for improving soil quality and fruit of pomelo, as well as enhanced income of farmers.

5. Conclusion

The use of biochar, lime, or compost is beneficial and crucial for reducing the negative impacts of soil acidity and soil compaction, improving SOM, and maintaining fruit yield. This type of management enhances soil fertility, improves soil health, and reduces land degradation for a sustainable land use strategy. Using soil amendments will help farmers to achieve a higher fruit yield. Moreover, applying soil amendments significantly improved the farmer's livelihood because of enhancing profit compared with using chemical fertilizers alone. From the results of the present work, we suggest the use of biochar or compost as the best choice for improving pomelo productivity and farmer's income. Further research on the age of raised beds, crop types, and resources of biochar and compost are needed because the responses and effects of soil amendments might be different.

Data Availability

All data supporting the conclusions of this study are included in this article.

Conflicts of Interest

The authors declare no conflicts of interest, financial or otherwise.

Authors' Contributions

L.V.D. and N.N.H. conceptualized the experiment, analyzed the data, and wrote the original draft of this study; L.V.D. and N.P.N. designed and conducted the experiments and collected and performed sample analyses; and L.V.D., N.P.N., and N.N.H. reviewed, edited, and approved the final manuscript. All authors have read and agreed to the published version of the manuscript.

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