




Article

Improvement of Photosynthesis by Biochar and Vermicompost to Enhance Tomato (*Solanum lycopersicum* L.) Yield under Greenhouse Conditions

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Abstract: Chlorophyll fluorescence is an important tool in the study of photosynthesis and its effect on the physiological indicators of crop growth is worth exploring. The trial was conducted to investigate the effect of biochar (CK, 0%; BA₃, 3%; BA₅, 5%; by mass of soil) and vermicompost (VA₃, 3%; VA₅, 5%) on photosynthesis, chlorophyll fluorescence, and tomato yield under greenhouse condition. Results revealed that photosynthetic parameters and chlorophyll fluorescence traits of BA₃, VA₃, BA₅, and VA₅ were significantly higher than those of CK, and the improvement of vermicompost was more effective than biochar at the same application rate. VA₃ treatment had the highest net photosynthetic rate (P_n), intercellular CO₂ concentration (C_i), variable fluorescence (F_v), maximum fluorescence (F_m), PSII maximum photochemical efficiency (F_v/F_m), PSII potential photochemical activity (F_v/F_0), absorption flux per cross section (CS; ABC/CSm), trapped energy flux per CS (TRo/CSm), and electron transport flux per CS (ETo/CSm), which increased by 49%, 65%, 17%, 12%, 4%, 25%, 10%, 15%, and 30%, respectively, compared with CK. The study also found that BA and VA rates could effectively improve tomato yield and water use efficiency (WUE). The yield under BA₃, VA₃, BA₅, and VA₅ treatments was 21%, 33%, 23%, and 25% higher than that under CK, and the WUE increased from 31.2 kg·m⁻³ under CK to 41.4 kg·m⁻³ under VA₃. Pearson correlation analysis indicated that the increment of photosynthesis showed a highly significant correlation with F_v/F_0 , ABC/CSm , TRo/CSm , and ETo/CSm and enhanced the light energy absorbed, trapped, and transported per CS of plant leaves, thereby contributing to the increase in tomato yield. Therefore, for one-season tomato production, the application of 3% vermicompost was considered economical with regard to improving photosynthesis, enhancing WUE , and increasing tomato yield.

Keywords: biochar; vermicompost; net photosynthetic rate; intercellular CO₂ concentration; photosystem II; maximum photochemical efficiency; active reaction center density



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1. Introduction

As an effective way to improve vegetable production, facility cultivation plays an important role in anti-seasonal and inter-regional vegetable cultivation in China [1]. Tomato is a temperature-loving, light-loving, and semi-drought-tolerant facility cultivation crop with high promotion potential and economic value [2]. However, unreasonable fertilizer application and cultivation management have resulted in facility soils showing a susceptibility to pests and diseases, which seriously affected the growth and development of tomatoes and reduced tomato yield [3,4]. Therefore, optimizing the fertilizer application pattern and improving the photosynthesis and chlorophyll fluorescence characteristics of plants are important for the high yield and quality of tomatoes.

Photosynthesis is the basic physiological activity for crop yield formation, and the strength of photosynthesis is closely related to the level of yield [5–7]. Photosynthesis is influenced by various environmental factors, including water, nutrients, light, and CO₂

concentration [8–10]. Biochar is beneficial to plant growth and physiological characteristic indicators, and it can improve the growth performance and yield of different crops [11]. Appropriate application of biochar can improve the apparent quantum efficiency, P_n , photosynthetic capacity, and stomatal conductance (G_s) of plants [12], which can play a role in improving crop quality and yield [13]. Zhu [14] showed that biochar increased P_n and seedling emergence and promoted plant height and dry matter mass of tomatoes. Cao et al. [15] found that biochar improved the nutritional quality of cherry tomato fruits and increased the yield. Lu et al. [16] concluded that biochar could increase the chlorophyll content of plant leaves and positively affect crop yield. The special physical and chemical properties and biological structure of vermicompost improve the transpiration rate (T_r), G_s , P_n , and intercellular CO_2 concentration (C_i) of tomato leaves, thereby promoting photosynthesis in plants [17]. Hosseinzadeh et al. [18] showed that the application of vermicompost could improve the photosynthesis of the crop primarily because it increased the CO_2 content of the crop roots and improved the soil water-holding capacity. In addition, numerous studies have demonstrated that the application of vermicompost in soil had a positive effect on crop growth and yield [19]. Zhou et al. [20] showed that the application of 80% vermicompost in soil significantly increased the growth of height and stem diameter of tomato plants. Joshi et al. [21] revealed that the application of 45% vermicompost also promoted the growth and development of tomato plants.

Geng et al. [22] concluded that chlorophyll fluorescence parameters could reflect the absorption and conversion of light energy, energy transfer, distribution, and photosynthesis in plants, which were important indicators used to study plant stress resistance physiology and increase crop yield. Chlorophyll fluorescence can be used to study the effect of environmental changes on the photosynthetic structure of plant photosystem II ($PSII$) and yield responses to the efficiency of light energy conversion in plants [23,24]. Li et al. [25] revealed that biochar treatment could significantly affect the chlorophyll fluorescence parameters of cucumber, but the application of 0.5–2.0% biochar had no significant effect on the maximum photochemical efficiency (F_v/F_m). Meanwhile, Cheng et al. [26] also revealed that F_v/F_m and the actual quantum yield of $PSII$ ($Y(II)$) of plant leaves significantly increased when the vermicompost content was higher than 50%. Gong et al. [27] found that F_v/F_m of $PSII$ and the actual photochemical efficiency (Φ_{PSII}) of plants were elevated by water–nitrogen content, and a moderate increase in nitrogen fertilization could improve F_v/F_m and Φ_{PSII} of crop leaves, enhance crop growth traits, and increase yield.

Numerous studies have shown that the application of biochar and vermicompost changed the physicochemical properties of soil and microbial communities. It also affected the physiological and biochemical properties of plants. Furthermore, photosynthesis has become an important indicator of tomato production, which is essential for promoting plant growth and development and improving yield. Therefore, the tomato water use efficiency (WUE) together with plant physiology must be improved through the use of accurate soil management methods, with emphasis on the methods that improve soil quality by the application of biochar and vermicompost with a considerable enhancement in plant physiological responses and yield. To date, there has been little knowledge on the interactive effects of biochar and vermicompost application on photosynthesis rate, especially using the chlorophyll fluorescence of tomato as a probe. Additionally, the effects of biochar and vermicompost on synergistic response of plant growth are not well understood. Moreover, data on the synergistic response of tomato yield with WUE are largely scarce [28]. Thus, this study hypothesized that increasing biochar and vermicompost addition could improve the soil properties; regulating the plant photosynthesis by improving chlorophyll fluorescence parameters would, thus, improve the tomatoes' productivity. The study also assumed that the biochar and vermicompost application to the plant can increase plant growth, contributing to an increasing yield of tomato. To test the hypothesis mentioned above, the study investigated the effects of increasing biochar and vermicompost amendment application rates under greenhouse conditions on soil properties related to plant growth. The study also measured the photosynthesis and chlorophyll fluorescence of tomato by measuring the

P_n , Tr , G_s , C_i , including F_o , F_v , F_m , F_v/F_m , F_v/F_o , ABC/CSm , RC/CSm , ETo/CSm , DIo/CSm , and TRo/CSm and, thus, regulated tomato yield in a greenhouse experiment to provide proper regulation for the high quality and yield of tomatoes under greenhouse conditions.

2. Materials and Methods

2.1. Experimental Site

Greenhouse experiments were carried out from 25 July 2020 to 11 January 2021 in a non-temperature-controlled greenhouse under natural light conditions, at the water-saving Park of Hohai University located at latitude $31^{\circ}57'$ N and longitude $118^{\circ}50'$ E, at 144 m above sea level in Jiangning District, Nanjing City, Jiangsu Province, China. The climate of the region is humid subtropical, and it is influenced by the East Asian monsoon. The average annual temperature in the region was 15.7°C ; the absolute maximum temperature reached 40.4°C in August 2020, and the absolute minimum temperature dropped to -13.3°C in January 2021. The rainy season spanned from July to September, and the average annual rainfall in the area was nearly 1025.12 mm, which was concentrated in the rainy–summer season. The annual sunshine time was 2200 h, and the annual average evaporation was approximately 900 mm. The average monthly rainfall and temperature in the greenhouse during the years of the experiment (2020–2021) are shown in Table 1.

Table 1. Mean monthly climate records during the years of the experiment (2020–2021).

Season	2020						2021
Month	Jul	Aug	Sept	Oct	Nov	Dec	Jan
Max. temp $^{\circ}\text{C}$	33.8	40.1	30.3	29.3	16.4	9.8	8.3
Min. temp $^{\circ}\text{C}$	23.4	29.2	17.7	14.8	8.3	2.1	1.2
Max. Relative humidity %	98.6	85.0	89.5	76.0	82.3	82.6	80.2
Min. Relative humidity %	69.5	62.4	68.7	68.9	70.1	70.8	69.1
Sunshine (h)	10.2	11.4	9.1	8.3	6.5	6.1	5.8
Solar Rad. $\text{MJ m}^{-2} \text{day}^{-1}$	97.8	113.7	78.2	73.8	58.7	56.0	55.4

Note: Meteorological data were monitored using HOBO mini weather stations.

2.2. Soil, Biochar, and Vermicompost Preparation

The experimental soil was collected from the top 10–20 cm of the farmland soil of the water-saving Park of Hohai University ($31^{\circ}57'$ N, $118^{\circ}50'$ E) and classified as a typical yellow–brown loam based on the Chinese classification [29]. The tested biochar was classified as maize straw biochar (purchased from Henan Lize Environmental Protection Technology Co., Ltd., Zhengzhou, China), and the experimental vermicompost was obtained by fermenting pure cow dung through the digestive system of earthworms. The physicochemical properties of the soil before the experiment, biochar, and vermicompost are shown in Table 2.

The physicochemical properties of the abovementioned soil samples, biochar, and vermicompost were measured by the following methods: Available potassium was determined using flame photometry [30]. Available nitrogen was determined by using a UV–Vis spectrophotometer (L007, 7522112059A; Essence Technology Instruments, Shanghai, China) [31,32]. Available phosphorus was measured using UV–Vis spectrophotometry [33]. Organic matter content was determined using high-temperature oxidation [34]. pH value was determined by using the Remag pH meter in 1:5 samples and water extracts [35].

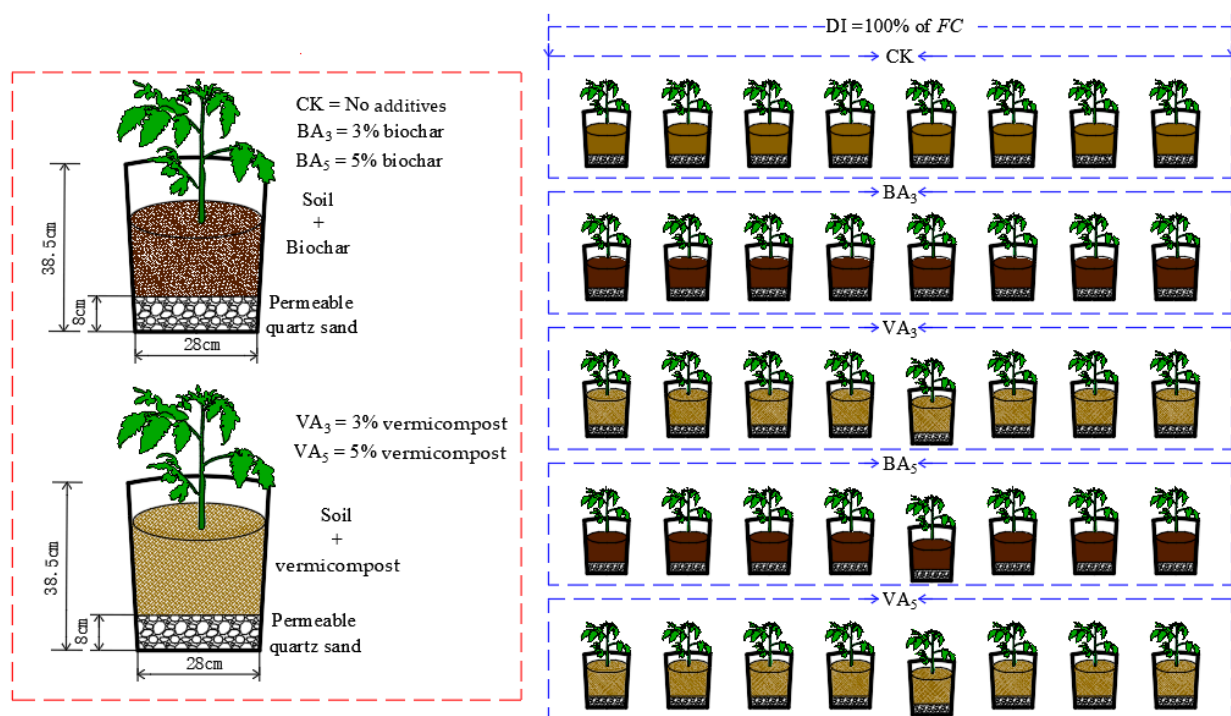
Table 2. Specific physicochemical properties of soil, biochar, and vermicompost.

Property	Soil	Biochar	Vermicompost
<i>BD</i>	1.41 g·cm ⁻³	0.42 g·cm ⁻³	-
<i>TP</i>	46.3%	55.3%	-
<i>FC</i>	28.7%	-	-
<i>K</i>	101 mg·kg ⁻¹	58,513 mg·kg ⁻¹	1892 mg·kg ⁻¹
<i>N</i>	11.1 mg·kg ⁻¹	390 mg·kg ⁻¹	564 mg·kg ⁻¹
<i>P</i>	5.81 mg·kg ⁻¹	56.4 mg·kg ⁻¹	461 mg·kg ⁻¹
<i>OMC</i>	1.04%	41.1%	44.9%
<i>pH</i>	7.07 value	9.40 value	8.17 value

Note: Values are the average of three replicates of each property; *BD*, *TP*, *FC*, *K*, *N*, *P*, and *OMC* indicate bulk density, total porosity, field capacity, available potassium, available nitrogen, available phosphorus, and organic matter content, respectively.

2.3. Greenhouse Experimental Setup

The main treatments used biochar and vermicompost. This experiment included the following five treatments: CK (0% rate, 12 kg soil + no addition), BA₃ (3% rate, 12 kg soil + 360 g biochar), VA₃ (3% rate, 12 kg soil + 360 g vermicompost), BA₅ (5% rate, 12 kg soil + 600 g biochar), and VA₅ (5% rate, 12 kg soil + 600 g vermicompost) on a mass basis. Each pot (cylindrical, top diameter: 32.5 cm, bottom diameter: 28 cm, height: 38.5 cm) was filled with quartz sand to a height of 8 cm, considering the water permeability and air permeability of the roots. The soil was air-dried and passed through a 6.3 mm sieve, and then biochar and vermicompost were weighed and mixed with soil thoroughly in proportion, respectively, and added to the pot with a natural bulk density based on each treatment. The pots were placed in a non-temperature-controlled greenhouse under natural light conditions and arranged in a completely randomized block design. Each treatment was replicated eight times (Figure 1).

**Figure 1.** Layout of tomato pots in the greenhouse.

The experimental tomato variety was “Cooperative 903,” which is a widely cultivated vegetable planted in Jiangsu Province, China. Tomato seeds were sown at a density of 2–3 seeds per hole in a 72-hole plate of cultivation seedlings and diluted to one plant per well after 2 weeks of seed germination. When seedlings developed five leaves and a heart, seedlings of similar growth were selected and transplanted into pots on 25 August 2020. The tomatoes were managed uniformly based on the experience of local agronomic practices. That is, each pot was applied with 20 g of compound fertilizer (N:P:K = 15:15:15) as a base fertilizer. Each pot was irrigated with tap water to maintain the soil water content at *FC*. The irrigation of each pot was carried out in accordance with the difference in daily weight to compensate for the water loss caused by evaporation [36], and the soil moisture content of all pots was maintained at *FC* throughout the experimental period. Each pot was frequently weeded by hand, and four fruits were left on each inflorescence in each treatment, leaving three leaves pinched at the top after the second inflorescence had set fruit. In addition, field management was carried out in the greenhouse to control pests and diseases and avoid yield losses. The final harvest was completed in January 2021.

2.4. Measurement Items and Methods

2.4.1. Determination of Photosynthetic Parameters

During flowering and fruit setting of the experiment, four plants were randomly selected for each treatment. Healthy fully expanded leaves with sufficient light exposure and consistent leaf position and without visible symptoms of damage at the first inflorescence were selected from each plant. The net photosynthetic rate (P_n), stomatal conductance (G_s), transpiration rate (Tr), and intercellular CO_2 concentration (C_i) were determined using a portable photosynthesis system (Li-6800, LI-COR, Lincoln, NE, USA) under an artificial light source with a radiation flux density of $1000 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ from 9:00 a.m. to 11:00 a.m. on a sunny day. The limitation of stomatal conductance (L_s) was calculated using the following equation [37]:

$$L_s = 1 - \frac{C_i}{C_a} \quad (1)$$

where L_s is the limitation of stomatal conductance; C_i is the intercellular CO_2 concentration; C_a is the ambient CO_2 concentration.

2.4.2. Determination of Chlorophyll Fluorescence Traits

Chlorophyll fluorescence parameters of plant leaves were measured using a portable chlorophyll fluorometer (Pocket PEA, Hansatech, King’s Lynn, UK), and the measurement time and plant site were the same as the photosynthetic parameters. After the leaves were subjected to dark-adapted treatment for 20 min, the rapid chlorophyll fluorescence induction kinetic curve (O-J-I-P curve) was measured using Pocket PEA, which was induced by $5000 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ of pulsed light, and the fluorescence signal was recorded from 10 μs to 2 s. The initial rate of recording was 105 datapoints per second, and the initial fluorescence (F_o), maximum fluorescence (F_m), and fluorescence intensity at 2 ms of the O-J-I-P curve (F_j) were obtained. Fluorescence parameters were calculated as follows [38,39]: variable fluorescence ($F_v = (F_m - F_o)/F_m$), *PSII* maximum photochemical efficiency (F_v/F_m), and *PSII* potential photochemical activity (F_v/F_o). In addition, the tomato leaf energy partitioning ratio and *PSII* reaction center activity parameters were measured as follows: absorption flux per cross section ($ABC/CSm \approx F_m$), trapped energy flux per CS ($TRo/CSm = (1 - F_o/F_m) \cdot (ABC/CSm)$), electron transport flux per CS ($ETo/CSm = (1 - F_o/F_m) \cdot (1 - (F_j - F_o)/(F_m - F_o)) \cdot (ABC/CSm)$), non-photochemical quenching per CS ($DIo/CSm = (ABC/CSm) - (TRo/CSm)$), and the number of active reaction centers per CS (RC/CSm) [40].

2.4.3. Determination of Tomato Yield and WUE

At the mature stage of tomato, the yield of four plants selected for each treatment was measured. Fruits of two inflorescences were collected sequentially on the basis of their ripeness and weighed on an electronic scale with an accuracy of 0.01 g. Then, the total fresh

weight of fruits of these two inflorescences was calculated as the total yield of each plant. The yield was converted on the basis of planting density ($45,000 \text{ plants} \cdot \text{hm}^{-2}$). The WUE was determined using the following equation [41]:

$$WUE = \frac{Y}{TWU} \quad (2)$$

where WUE is the water use efficiency, $\text{kg} \cdot \text{m}^{-3}$; Y is the tomato yield, $\text{kg} \cdot \text{hm}^{-2}$; and TWU is the total water use, $\text{m}^3 \cdot \text{hm}^{-2}$.

2.5. Data Processing and Analysis

Experimentally measured data were recorded and analyzed by Excel 2010 and one-way analysis of variance (ANOVA) and plotted by GraphPad Prism 8.0. ANOVA was performed using SPSS 26.0, where Duncan's multiple range test was used to compare data means at the 0.05 level of significance, and statistical significance was considered when $p \leq 0.05$. Pearson correlation analysis was also conducted to obtain the degree of relationship among photosynthetic parameters, chlorophyll fluorescence traits, and tomato yield.

3. Results and Analysis

3.1. Net Photosynthetic Rate and Photosynthetic Parameters

The measured plant photosynthetic parameters during flowering and fruit setting of the experiment were significantly ($p < 0.05$) affected by biochar and vermicompost application (Figure 2). P_n increased significantly with the increase in BA and VA rates (Figure 2a), in which VA_3 treatment had the highest P_n , with an increase of 49% compared with CK. In addition, VA_3 was significantly different from BA_3 and BA_5 ($p < 0.05$), and no significant difference was observed between BA_3 and BA_5 treatments.

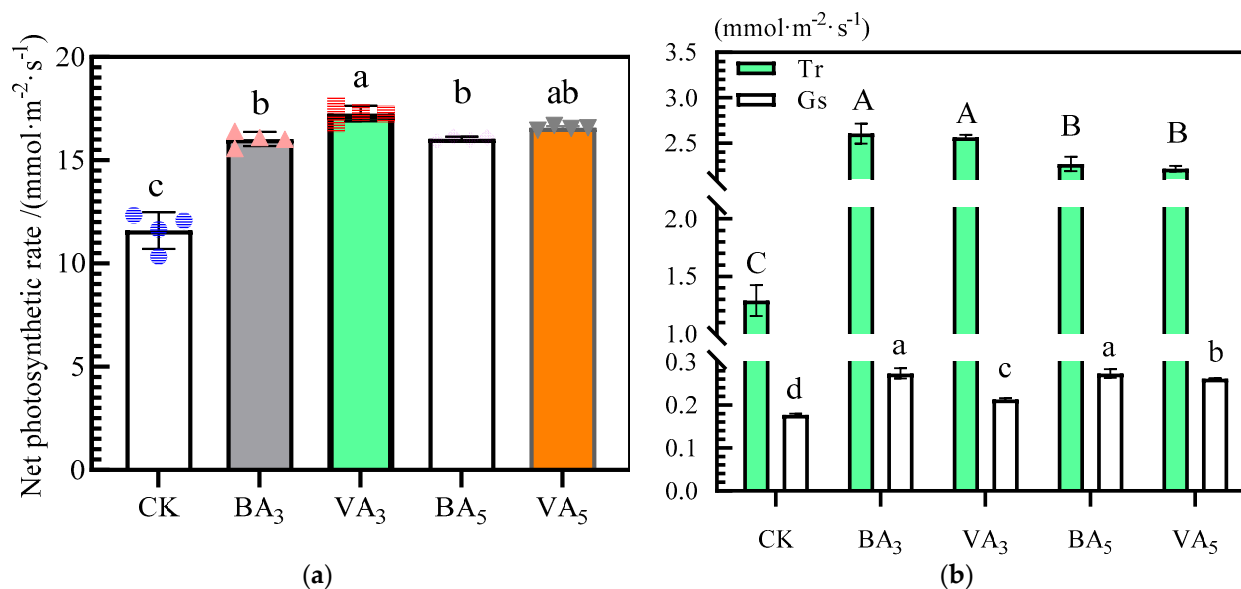


Figure 2. Cont.

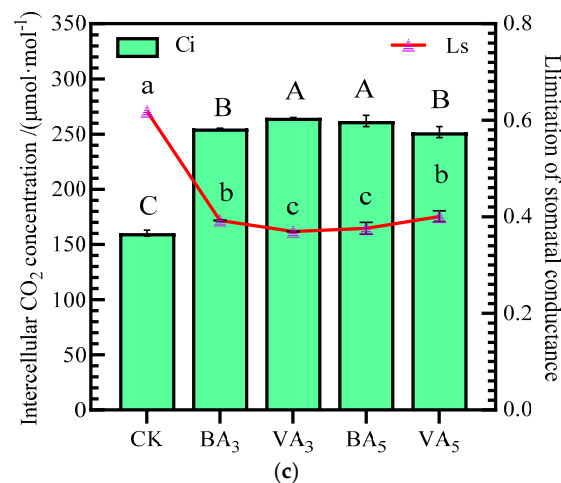


Figure 2. Effects of BA and VA rates on photosynthetic parameters of tomato leaves: (a) Effects of BA and VA rates on the P_n . (b) Effects of BA and VA rates on the T_r and G_s . (c) Effects of BA and VA rates on the C_i and L_s . Note: BA represents biochar application and VA vermicompost application. The meanings of the circles, triangles, and rectangles on the bars in (a) are indicated as duplicate data points for the different treatments. Means of P_n , G_s , and L_s are significantly different between BA and VA rates ($p \leq 0.05$) when followed by different lowercase letters. Means of T_r and C_i are significantly different between BA and VA rates ($p \leq 0.05$) when followed by different uppercase letters. Meanwhile, the increase in P_n in BA₃, VA₃, BA₅, and VA₅ was accompanied by a decrease in L_s and an increase in C_i , T_r , and G_s . As shown in (b), the highest and lowest T_r rates were observed for BA₃ and CK treatments, respectively, and BA₃ and VA₃ showed no statistically significant difference. G_s under BA₃ treatment was the highest, whereas that under CK treatment was the lowest. For C_i (c), the highest C_i was observed for treatments under VA₃, followed by plants under BA₅, BA₃, and VA₅, whereas the lowest values were observed under CK. L_s under BA₃, VA₃, BA₅, and VA₅ treatments decreased by 37%, 40%, 39%, and 35%, respectively, compared with that under CK treatment.

3.2. Chlorophyll Fluorescence Traits

The important chlorophyll fluorescence parameters of F_o , F_v , F_m , F_v/F_m , and F_v/F_o for different biochar and vermicompost addition rates during flowering and fruit setting are shown in Table 3. F_v , F_m , F_v/F_m , and F_v/F_o under BA₃, VA₃, BA₅, and VA₅ treatments, respectively, were significantly increased compared with those under CK treatment ($p < 0.05$). The highest F_v , F_m , F_v/F_m , and F_v/F_o were observed after VA₃ treatment, which increased by 17%, 12%, 4%, and 25%, respectively, compared with CK, where F_v and F_v/F_o of VA₃ were significantly higher than other treatments. On the contrary, BA₃ and BA₅ showed no statistically significant difference.

Table 3. Effect of BA and VA rates on chlorophyll fluorescence parameters.

Fluorescence Parameters	F_o	F_v	F_m	F_v/F_m	F_v/F_o
CK	3490 ± 45 ^a	13,253 ± 132 ^c	16,766 ± 416 ^b	0.791 ± 0.013 ^b	3.80 ± 0.03 ^d
BA ₃	3300 ± 86 ^{bc}	15,061 ± 316 ^b	18,390 ± 358 ^a	0.819 ± 0.008 ^a	4.56 ± 0.09 ^b
VA ₃	3278 ± 55 ^c	15,523 ± 203 ^a	18,816 ± 268 ^a	0.825 ± 0.002 ^a	4.74 ± 0.04 ^a
BA ₅	3266 ± 42 ^c	15,095 ± 214 ^b	18,365 ± 301 ^a	0.822 ± 0.002 ^a	4.62 ± 0.03 ^b
VA ₅	3380 ± 63 ^b	15,080 ± 185 ^b	18,496 ± 240 ^a	0.815 ± 0.001 ^a	4.46 ± 0.03 ^c

Note: BA for Biochar application and VA for Vermicompost application. ± indicates standard deviation. Means are not significantly different between different BA and VA rates when followed by the same lowercase letter; means are significantly different between BA and VA rates ($p \leq 0.05$) when followed by different lowercase letters. The same below.

As shown in Figure 3a, RC/CSm , ABC/CSm , TRo/CSm , and ETo/CSm were increased, and DIo/CSm was decreased by biochar and vermicompost application. BA₃ treatment

had the highest RC/CSm , which was significantly higher than CK by 22%, and VA_3 and VA_5 showed no statistically significant difference. ABC/CSm , TRo/CSm , and ETo/CSm of VA_3 were significantly ($p < 0.05$) higher than other treatments (Figure 3b,c). The highest ABC/CSm , TRo/CSm , and ETo/CSm were observed in VA_3 treatment, which increased by 10%, 15%, and 30%, respectively, compared with CK treatment. Meanwhile, the increase in ABC/CSm , TRo/CSm , and ETo/CSm in BA_3 , VA_3 , BA_5 , and VA_5 treatments were accompanied by a decrease in DIo/CSm , in which VA_3 treatment had the lowest DIo/CSm , with a decrease of 6% compared with CK, indicating that the application of biochar and vermicompost was effective in reducing the heat dissipation energy per cross section.

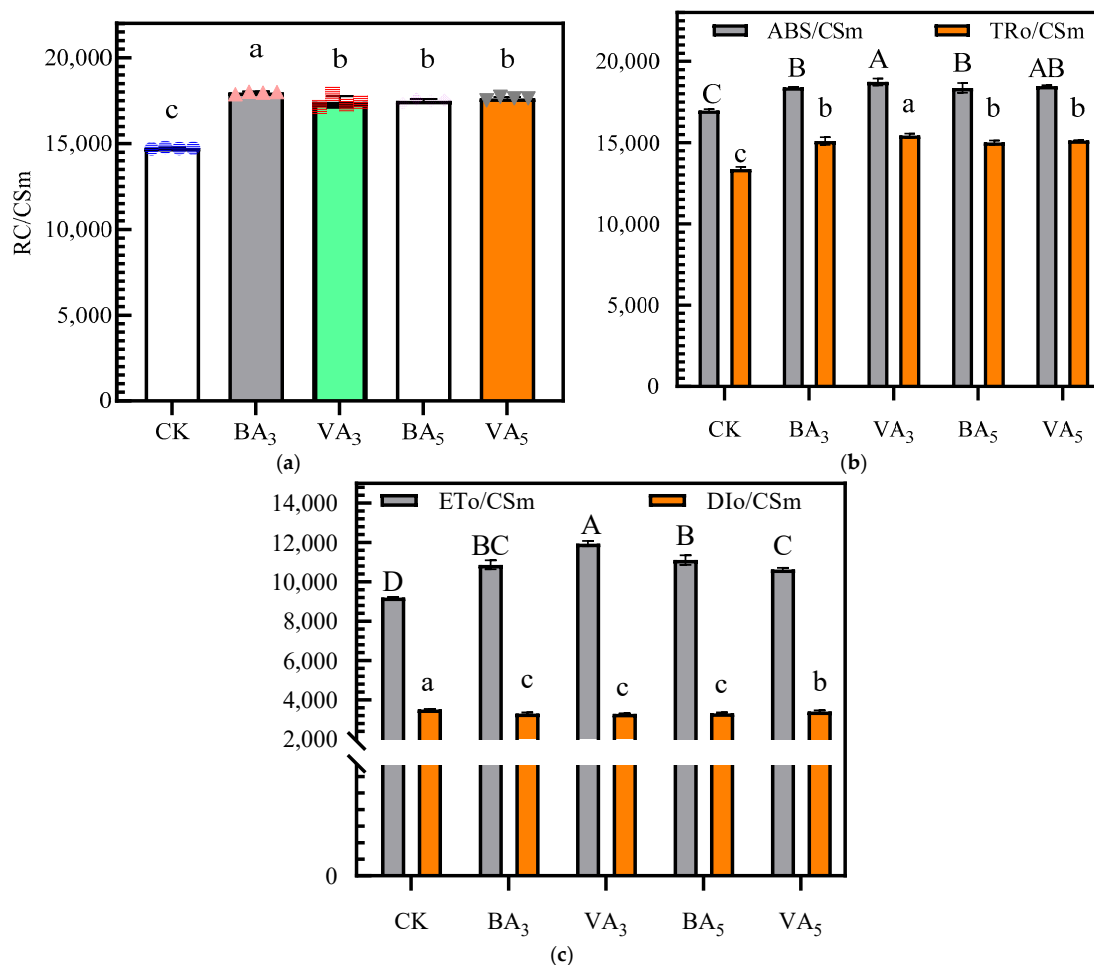


Figure 3. Effect of BA and VA rates on light energy absorption, capture, and transfer: (a) Effect of BA and VA rates on the RC/CSm . (b) Effect of BA and VA rates on the ABC/CSm and TRo/CSm . (c) Effect of BA and VA rates on the ETo/CSm and DIo/CSm . Note: BA represents biochar application and VA vermicompost application. Data are presented as mean \pm standard error ($n = 4$). The meanings of the circles, triangles, and rectangles on the bars in (a) are indicated as duplicate data points for the different treatments. Means of RC/CSm , TRo/CSm , and DIo/CSm are significantly different between BA and VA rates ($p \leq 0.05$) when followed by different lowercase letters. Means of ABC/CSm and ETo/CSm are significantly different between BA and VA rates ($p \leq 0.05$) when followed by different uppercase letters. RC/CSm indicates the number of active reaction centers per CS; ABS/CSm indicates the absorption flux per CS; TRo/CSm indicates the trapped energy flux per CS; ETo/CSm indicates the electron transport flux per CS; DIo/CSm indicates the non-photochemical quenching per CS.

3.3. Yield and WUE of Tomato

Biochar and vermicompost application rates significantly ($p < 0.05$) influenced the tomatoes' average yield and WUE (Table 4). The yield parameters significantly increased

with the application of BA and VA rates, whereas the average single-fruit weight of the first inflorescence and second inflorescence in BA₃, VA₃, BA₅, and VA₅ was not statistically significant. In addition, the first inflorescence of each treatment was higher than that of the second inflorescence. When the TWU of each treatment was 1425 m³·hm⁻², the WUE was linearly correlated with yield; the highest yield and WUE (59.0 t·hm⁻² and 41.4 kg·m⁻³, respectively) were observed in the VA₃ treatment, and Y and WUE under BA₃, VA₃, BA₅, and VA₅ treatments were 21%, 33%, 23%, and 25% higher, respectively, than those under CK treatment. The results indicated that the vermicompost had a better effect on increasing yield and WUE than biochar with the same application rates.

Table 4. Effects of BA and VA rates on tomato yield and water use efficiency.

Treatments	Average Fruit Weight Per Fruit (g)		Yield Per Plant (g)	Yield (t·hm ⁻²)	WUE (kg·m ⁻³)
	First Inflorescence	Second Inflorescence			
CK	135 ± 17 ^b	112 ± 4 ^b	990 ± 76 ^c	44.5 ± 3.4 ^c	31.2 ± 2.4 ^c
BA ₃	150 ± 14 ^{ab}	149 ± 4 ^a	1196 ± 68 ^b	53.8 ± 3.1 ^b	37.8 ± 2.1 ^b
VA ₃	173 ± 12 ^a	155 ± 18 ^a	1312 ± 63 ^a	59.0 ± 2.8 ^a	41.4 ± 2.0 ^a
BA ₅	157 ± 23 ^{ab}	148 ± 8 ^a	1220 ± 77 ^{ab}	54.9 ± 3.5 ^{ab}	38.5 ± 2.4 ^{ab}
VA ₅	169 ± 14 ^a	141 ± 7 ^a	1240 ± 48 ^{ab}	55.8 ± 2.2 ^{ab}	39.2 ± 1.5 ^{ab}

Note: BA for Biochar application and VA for Vermicompost application. ± indicates standard deviation. Means are not significantly different between different BA and VA rates when followed by the same lowercase letter; means are significantly different between BA and VA rates ($p \leq 0.05$) when followed by different lowercase letters. The same below.

3.4. Correlation Analysis of Plant Physiological Indicators and Tomato Yield

Pearson correlation analysis results among photosynthetic parameters (P_n , C_i , T_r , and G_s), chlorophyll fluorescence traits (F_v/F_m , F_v/F_o , ABS/CSm , TRo/CSm , ETo/CSm , and DIo/CSm), and yield are displayed in Table 5. P_n , C_i , T_r , F_v/F_m , F_v/F_o , ABS/CSm , TRo/CSm , ETo/CSm , and yield had a strong positive correlation ($R > 0.6$), apart from G_s , with ETo/CSm and yield. These factors showed a strong negative correlation with DIo/CSm . In addition, photosynthetic parameters (P_n , C_i , and T_r) showed a strongly significant correlation with chlorophyll fluorescence traits (F_v/F_m , F_v/F_o , ABS/CSm , TRo/CSm , ETo/CSm , and DIo/CSm). Moreover, P_n , C_i , F_v/F_o , ABS/CSm , TRo/CSm , and ETo/CSm showed a highly significant correlation ($R > 0.8$) with yield, indicating that the increment in net photosynthesis and light energy absorbed, trapped, and transported per cross section of plant leaves could increase tomato yield.

Table 5. Correlation analysis between plant physiological indicators and tomato yield.

Indices	P_n	C_i	T_r	G_s	F_v/F_m	F_v/F_o	ABS/CSm	TRo/CSm	ETo/CSm	DIo/CSm	Yield
P_n	1										
C_i	0.960	1									
T_r	0.918	0.936	1								
G_s	0.660	0.759	0.696	1							
F_v/F_m	0.899	0.895	0.869	0.626	1						
F_v/F_o	0.939	0.975	0.932	0.663	0.911	1					
ABS/CSm	0.950	0.947	0.903	0.635	0.829	0.949	1				
TRo/CSm	0.962	0.964	0.925	0.661	0.857	0.961	0.969	1			
ETo/CSm	0.904	0.905	0.886	0.463	0.854	0.943	0.883	0.900	1		
DIo/CSm	-0.775	-0.816	-0.871	-0.608	-0.795	-0.860	-0.729	-0.774	-0.859	1	
Yield	0.876	0.826	0.775	0.485	0.725	0.821	0.843	0.817	0.800	-0.686	1

Note: Pearson correlation coefficient ranging from 0.8 to 1.0 indicates very strong correlation, from 0.6 to 0.8 indicates strong correlation, from 0.4 to 0.6 indicates medium correlation, from 0.2 to 0.4 indicates weak correlation, and from 0.0 to 0.2 indicates very weak correlation or no correlation. "-" represents a negative correlation.

4. Discussion

4.1. BA and VA Rates Improved Photosynthesis and Chlorophyll Fluorescence Traits

Biochar and vermicompost rates had a positive effect on photosynthetic parameters and chlorophyll fluorescence traits of treated plants. VA₃ treatment had the highest P_n , C_i , F_v , F_m , F_v/F_m , F_v/F_o , ABC/CSm , TRo/CSm , and ETo/CSm , which increased by 49%, 65%, 17%, 12%, 4%, 25%, 10%, 15%, and 30%, respectively, compared with CK. Photosynthesis is the basis for crop yield and quality formation, and 95% of organic matter in crops is derived from photosynthesis [42]. Previous studies illustrated the improvement of water- and fertilizer-holding capacity of soil, enhanced photosynthesis of plant leaves, and increased P_n , Tr , and G_s by biochar [43,44]. Our results are supported by Cui et al. [45], who revealed that biochar significantly improved the photosynthesis of plants, and P_n , Tr , and G_s of 3% biochar-treated plants increased by 94%, 35%, and 35%, respectively, compared with the control. As described by Shi et al. [46], the application of vermicompost increased Tr , G_s , P_n , and C_i of tomato plant leaves by 84%, 52%, 21%, and 43%, respectively. Chlorophyll fluorescence parameters are closely related to various reaction processes in photosynthesis [47]. The energy changes in photosynthesis can be reflected by chlorophyll fluorescence-induced kinetic curves. Chlorophyll fluorescence can sensitively reflect changes in leaf photosynthesis and is a probe for studying photosynthesis [48–50]. Zhang et al. [51] reported that biochar reduced the shutdown of active reaction centers in alfalfa leaves, increased F_v/F_m of PSII, and enhanced photosynthesis. Fan et al. [52] showed that biochar increased F_o and F_v/F_m of plants, enhanced photosynthetic performance, and promoted plant growth and development. Yang et al. [53] found that the relative chlorophyll content of winter wheat was highly significantly and positively correlated with RC/CSm and ETo/CSm , and that RC/CSm and ETo/CSm were all related to the photosynthetic efficiency of plants, while the level of chlorophyll content reflected the strength of photosynthetic efficiency of plants and changes in fluorescence parameters [54]. Our results are also consistent with the results of Wang et al. [55], who reported that spraying exogenous phytohormones alleviated the impairment of light energy use and overall photosystem II performance in sweet potato leaves by drought stress, with good linear relationships for P_n , G_s , F_v/F_m , ETo/CSm and ABS/CSm . In our study, the effect of vermicompost in improving photosynthesis and chlorophyll fluorescence was more effective than that of biochar at the same application rate, as indicated by the N and P contents of the experimental vermicompost, which were 1.45 and 8.17 times higher than those of biochar (Table 1), thereby enhancing soil fertility and promoting the growth and development of tomato plants. This finding was consistent with the conclusion of previous studies, that is, vermicompost was richer in nutrients than biochar, which could remarkably enhance soil fertility [56,57].

4.2. Yield and WUE in Response to BA and VA Rates

The experimental results revealed significant enhancements in the yield parameters under BA- and VA-amended treatments. The application of biochar and vermicompost significantly increased the average single-fruit weight of tomatoes compared with CK (Table 4). Consequently, the total yield of each treatment was also significantly increased. Under the present experimental conditions, irrigation levels were consistent among the treatments; therefore, the BA and VA rates significantly improved WUE . The results are consistent with those of Blouin et al. [58], who revealed that the application of VA rates significantly increased the yield and biomass of crops. Wang et al. [59] also showed that the VA-amended treatment significantly increased tomato yield. These results were consistent with those of Zhang et al. [60] and Akhtar et al. [61], who reported that the application of biochar promoted the ability of tomato plants to absorb nutrients and increased tomato yield and WUE . This study also found that the application of vermicompost was more effective in improving tomato yield than biochar at the same application rate probably because the application of vermicompost under the experimental conditions increased the effectiveness of the nutrients required by the crop and promoted the photosynthesis and growth of the plant, thereby significantly increasing yield and WUE [62]. Our results are also

supported by Ding et al. [63], who revealed that vermicompost and biochar significantly increased the yield of tomatoes every year compared with the control, and the biomass accumulation showed that vermicompost was better than biochar. Moreover, in our study, the application of 3% vermicompost (equivalent to 16,200 kg·hm⁻²) increased tomato yield by up to 32.56%, which was better than the 5% vermicompost treatment, probably because the excessive accumulation of humic acid in the high content (5%) of vermicompost inhibited plant growth and development, resulting in lower yield [64,65]. As described by Wu et al. [66], among the treatments applying different rates of vermicompost (7500, 15,000, and 22,500 kg·hm⁻²), the highest tomato yield was obtained in the 15,000 kg·hm⁻² treatment, which was consistent with the results of our study.

5. Conclusions

The results showed that BA- and VA-amended treatments had a positive effect on improving photosynthetic parameters and chlorophyll fluorescence traits, particularly at the 3% application rate of vermicompost. The application of biochar and vermicompost effectively increased photosynthetic parameters (*Pn*, *Ci*, and *Tr*) as shown by studying the improvement of chlorophyll fluorescence traits (*Fv/Fm*, *Fv/Fo*, *ABC/CSm*, *TRo/CSm*, *ETo/CSm*, and *Dlo/CSm*), producing organic substances needed by the crop, thereby increasing yield. Moreover, vermicompost with the same rate was significantly more effective in enhancing *Pn*, *Ci*, *Fv*, *Fm*, *Fv/Fm*, *Fv/Fo*, *ABC/CSm*, *TRo/CSm*, and *ETo/CSm* of plants than biochar, resulting in significantly higher yield in VA₃ and VA₅ than in BA₃ and BA₅. The WUE of plants under CK, BA₃, VA₃, BA₅, and VA₅ treatments increased from 31.2 to 37.8, 41.4, 38.5, and 39.2 kg·m⁻³, respectively. The results of Pearson correlation analysis revealed that biochar and vermicompost rates improved the net photosynthesis and light energy absorbed, trapped, and transported per cross section of plant leaves, which could increase tomato yield. These results indicated that vermicompost was more effective than biochar at the same rate in improving photosynthesis as shown by studying chlorophyll fluorescence and increasing tomato yield, particularly at 3% application rate.

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