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Fenlong-Ridging Deep Tillage Integrated with Biochar and Fertilization to Improve Sugarcane Growth and Yield

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Abstract: Sugarcane yield in China is low because of the shallow A-horizon soil layer, or as it is commonly called by farmers, the "plow soil layer", as well as low soil organic matter and fertilizer utilization efficiency. Fenlong-ridging deep tillage (FT), also called vertical rotary tillage, and amendment with biochar have been shown to improve soil quality and crop yield. In this study, field trials were conducted with newly planted and ratoon sugarcane to evaluate the effectiveness of FT, together with amendment with biochar and nitrogen fertilization, to improve sugarcane yield. The treatments were conventional tillage with chemical fertilizer without biochar (CT-CF, which was the control of this experiment), FT with chemical fertilizer without biochar (FT-CF), conventional tillage with chemical fertilizer mixed with biochar (CT-CFB), and FT with chemical fertilizer mixed with biochar (FT-CFB). FT-CFB treatment presented higher soil porosity, as well as higher contents of available N, P, K, total N, and organic matter, and lower soil bulk density. Similarly, results showed that FT-CFB presented higher sugarcane root fresh and dry weights, higher germination percentage, higher tiller number, and higher yield with statistically significant differences among treatments for both newly planted and ratoon sugarcane plants. Significant interactions between biochar and FT were observed for these crop traits. The interactions of FT and amendment with biochar improved the soil's physical and chemical properties and increased the available nutrients, resulting in improved root growth and sugarcane yield. The statistical results of the present study imply that Fenlong-ridging deep tillage combined with chemical fertilizer mixed with biochar (FT-CFB) application is a new promising farm management practice for improving the soil's physical and chemical properties and root growth, increasing total yield in China's sugarcane belt area.

Keywords: fenlong-ridging deep tillage; agronomic traits; yield; soil nutrient; root system

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1. Introduction

Sugarcane (*Saccharum* spp. hybrids) is a crop of global importance for the production of sugar and biofuel (ethanol and alcohol) [1]. China is one of the world's leading sugarcane-producing countries (128.2 million tons in the 2018 harvest), with a harvested area of 1.37 million hectares [2], following Brazil and India [3]. In China, sugarcane planting areas are mainly distributed in Guangxi, Guangdong, and Yunnan [4]; the distribution of major sugarcane-producing areas in China is shown in Figure 1a. The main soil type in these areas is red soil. The main cultivars are Liucheng 05136 and Guitang 42. The overall level of sugarcane mechanization is low. At present, the main types of fertilization in the process of sugarcane production in China are mainly chemical fertilizers, and the amount of fertilization is large [5]. In recent years, sugarcane yield has achieved a certain level, and the economic efficiency of production has decreased [6,7]. This may be owing to the shallow plow layer, low fertilizer utilization rate [8], and degradation in physical, chemical, and biological soil properties [9–12].

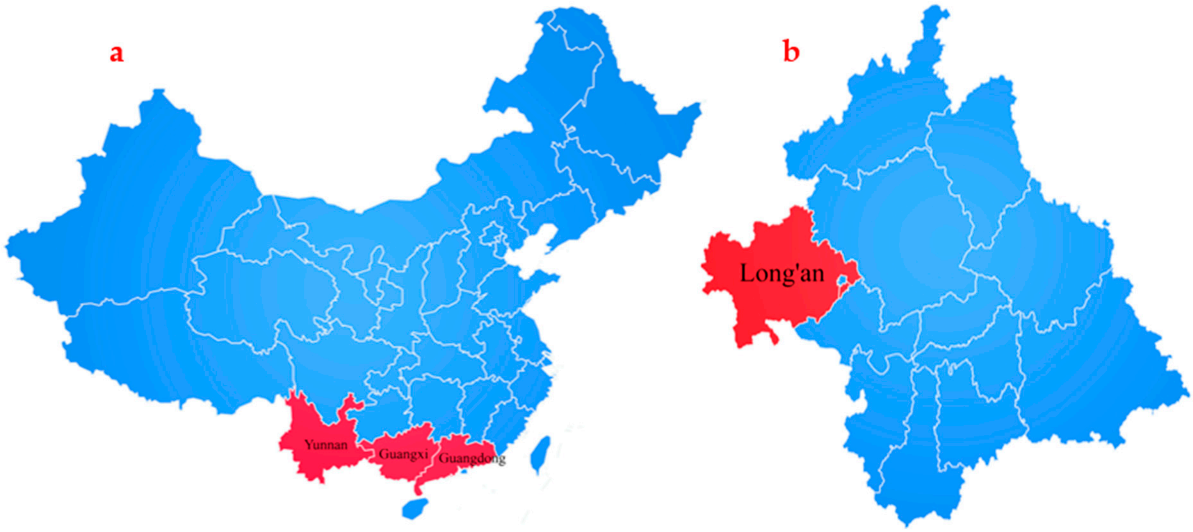

Figure 1. (**a**) Map of the main sugarcane-producing area in China, marked with red color. (**b**) Map of the study area (Long'an County, Nanning City, Guangxi Province, China), marked with red color.

Tillage is a major agricultural practice that can affect soil physicochemical characteristics and modify soil microbial activity and community structure [13,14]. It is a fundamental factor influencing the soil quality, crop performance, and sustainability of cropping systems [13,15]. Associated with intensive land use, currently, most of the areas where sugarcane is grown are cultivated under traditional tillage and monoculture systems [15]. The shallow plow layer of traditional tillage affects only the physical and chemical properties of the 0–20 cm surface soil. Repeated plowing with traditional tillage often results in the formation of dense plow pans, which may negatively affect root growth [16]. Deep tillage up to the subsoil can alleviate this problem by increasing infiltration and water storage, thus increasing rooting depth, water and nutrient uptake, and subsequent crop yield [17]. In this context, Fenlong-ridging deep tillage (FT) was developed in China to break plow pans using a 'spiral drill' (vertical deep tillage subsoiler), which can reach a soil depth of 40–50 cm. This deep tillage reduces bulk density and increases total porosity, thus increasing the available water for plants, root growth, and yield of maize, peanut, soybean, sugarcane, and mulberry by 26%, 14%, 10%, 22%, and 55%, respectively, as compared with conventional tillage [18–20]. However, the soil of the original plow pans after FT did not form an aggregate structure, which is unfavorable for crop growth. Therefore, it is important to study how to rapidly improve soil aggregate structure by increasing the organic matter content in the plow layer after FT.

Biochar is a highly aromatic and carbon-rich solid material produced by pyrolysis of biomass under anaerobic or oxygen-limited conditions. The inherent structure and physicochemical properties of biochar have a direct or indirect impact on the soil microecological environment by affecting the soil bulk density, water content, porosity, cation exchange capacity, and nutrient availability [21]. A meta-analysis showed that amendment with biochar improves almost all of the soil's physical properties. The role of biochar in ameliorating soil physical properties (particularly the soil water-holding capacity) has been extensively reported [22]. Biochar enhances soil aggregation, improves aggregate stability, and decreases penetration resistance and soil strength [23]. However, according to different raw materials, temperatures, and soil types, the application effect of biochar is also inconsistent. Some negative effects have also been reported, such as volatile substances, bio-oil, and salts contained in biochar will pollute the environment. Therefore, the effect of biochar needs to be further verified in subsequent studies [24]. High sugarcane yield is accompanied by applying a large amount of fertilizer N, which has adverse environmental impacts. The loss of applied N fertilizer was estimated to range from 22 to 53%, which increases the overall costs of the sugarcane production system [25].

The high temperatures in the subtropical region of China contribute to high N losses [26]. Coarse-textured soils using traditional tillage poorly fix the released N, thus predisposing the soil to high N losses [27]. Reducing this loss requires improvement in fertilizer utilization in sugarcane planting systems [28]. Biochar has a large specific surface area and numerous pores that can adsorb nutrients from the soil solutions [29]. It can be used as a carrier for slow/controlled-release fertilizers and microbial inoculants that can be applied to produce biochar-based compound fertilizers, biochar-based organic fertilizers, and biochar-based bio-fertilizers owing to their ability to delay the release of nutrients in the soil, reduce leaching and fixing losses, and consequently improve the efficiency of nutrient utilization [30]. In China, researchers have mixed biochar with fertilizers that significantly increase crop yields [30]. The organic matter content in the soil increased following the application of biochar due to its sorption to biochar and occlusion within aggregates [31]. The fertilization with biochar was reported to significantly increase soil organic matter content and the height and weight of sugarcane stems compared with the fertilized controls [32]. Butphu et al. [33] found that biochar addition significantly increased nutrient uptake and sugarcane yield, thereby increasing fertilizer-use efficiency. Thus, the use of biochar-based biofertilizer amendments to build soil organic matter can improve soil properties, sugarcane yield, and long-term management costs [34]. However, the current application of biochar in sugarcane is mostly based on traditional tillage, and there are few studies on its application in FT and its effect on the aggregate structure of the soil in the plow layer.

Recently, the interactions between biochar and tillage have been reported in maize [35], wheat [36], and tobacco [37]. Deep tillage with biochar significantly improved the content and stability of large aggregates and promoted humus formation and accumulation, thereby increasing soil organic carbon content [38]. Xiao et al. [39] also demonstrated that deep tillage combined with biochar can improve soil physical properties, which is beneficial to soil aeration, water filtration, and salt leaching. However, there are few studies on the interactions between biochar and deep tillage since the effects of tillage combined with biochar differ depending on the crop, and there is a lack of research on sugarcane.

Researchers have shown that FT promoted seedling growth, root growth, tillering, and sugarcane yield by improving the physical and chemical properties of the soil [40]. In addition, biochar application has been reported to enhance sugarcane growth. Therefore, maximizing the potential benefits of biochar and FT for soil improvement and high crop yield should be studied by analyzing the interactions between them. However, this type of study has not yet been reported for sugarcane.

The objectives of this study were to determine the changes in soil physicochemical properties, particularly available N, P, and K; root growth; and yield of sugarcane in response to the interactions between FT and biochar amendment in the newly planted and ratoon sugarcane. These results are expected to shed light on the mechanisms of FT and biochar amendment for improving soil quality and sugarcane yield.

2. Materials and Methods

2.1. Study Area

The experiments were conducted in Xin'an village (22°99′28′′ N, 107°88′52′′ E), Nantong Town, Long'an County, and Nanning City, Guangxi Zhuang Autonomous Region, in the 2018 and 2019 cropping seasons (Figure 1b). Xin'an village is in the hilly region of south China with subtropical humid monsoon climate. The average annual temperature, rainfall, and relative humidity are 21.6 °C, 1304 mm, and 79%, respectively. The average monthly temperatures and rainfall in the region during the test period are shown in Figure 2.

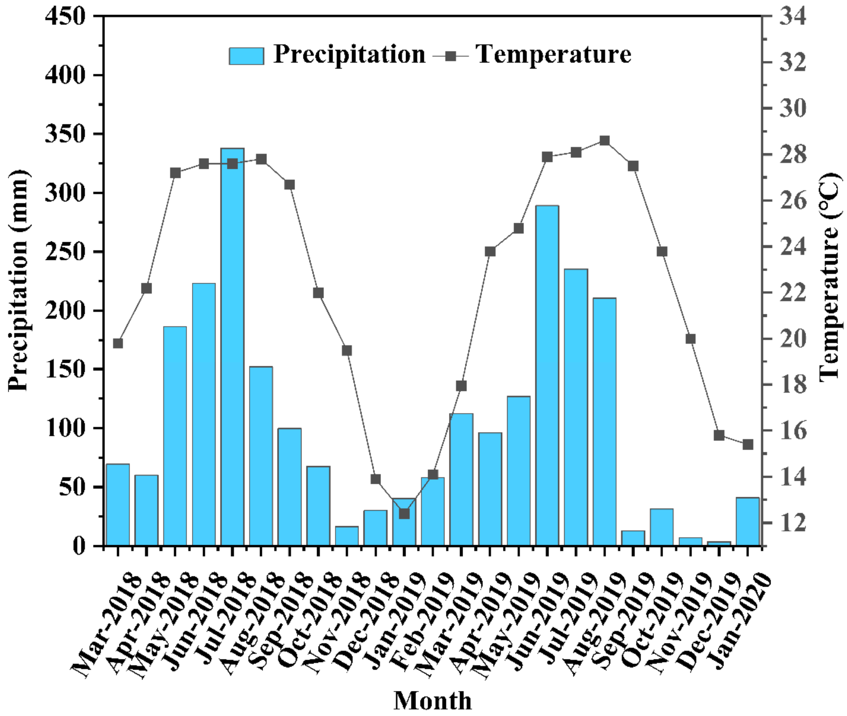

Figure 2. Monthly precipitation (in mm) and temperature (in °C) in Xin'an Village from March 2018 to January 2020.

The soil is acidic clay developed from Quaternary red clay and is classified as a Ferralsols, and cassava was used as the previous crop. The surface soil (0–20 cm) had bulk density of 1.44 g cm^{-3}, pH of 5.73, organic matter of 34.60 g kg^{-1}, total N of 1.49 g kg^{-1}, and available N, P, and K of 149.00, 8.49, and 394.30 mg kg^{-1}, respectively, before planting in 2018. An area of 1012 m^2 was used in this study, which was divided into 12 plots, each at 10 m × 6 m, separated by a 2 m alley. The field experiment adopted a completely randomized block design with four treatments and three replicates for each treatment.

The experimental design was a two-factor, two-level experimental design. The two factors included whether the Fenlong-ridging deep tillage (two levels of non-Fenlong-ridging deep tillage treatment, namely conventional tillage CT and Fenlong-ridging deep tillage treatment FT) and whether biochar was applied (two levels of non-biochar treatment CF and biochar treatment CFB). There were a total of four treatments: CT-CF (this treatment is a conventional measure used in local sugarcane production control), FT-CF, CT-CFB, and FT-CFB. The Fenlong machine is shown in Figure 3. The biochar was derived from straw, and the pyrolysis temperature was 200–250 °C, with the following properties: moisture 31%, pH 7.21, organic matter 4.57%, total N 0.86%, total P 0.19%, and total K 3.96%. The biochar was provided by Guangxi Hannong Biomass Technology Co., Ltd. (Guigang, Guangxi, China).

Figure 3. Snapshot of the Fenlong machine working in the field.

2.2. Sugarcane Planting and Crop Management

The sugarcane cultivar Guitang42, one of the most widely planted cultivars in China with high yield potential, has the characteristics of early maturity, high yield, high sugar content, good ratooning, strong lodging resistance, and excellent comprehensive traits. The sugarcane was planted on 16 March 2018. The row spacing was 120 cm, double-bud planting was adopted, sugarcane seeds were placed in double rows, and the planting density was 140,000 plants ha^{-1}.

Fertilization was carried out according to the consistent application rate of sugarcane planting in Guangxi, China, in which nitrogen, phosphorus, and potassium were applied at 538, 225, and 630 kg per hectare in 2018 and 2019, respectively. Fertilizers include diammonium phosphate, urea, and muriate potash. One-third of the total amount of N fertilizer per hectare was applied as basal dose, and total P and K per hectare were applied as basal dose in the planting ditch. The remaining two-thirds of the total amount of N fertilizer per hectare dose was side-dressed along cane rows in two equal doses during the tillering stage (May and June). Biochar application rate was 500 kg ha^{-1}, mixed with all base fertilizers before planting and applied at a depth of 25 cm. Weeds were controlled by hand hoeing until the elongation stage. The crop had no irrigation, relying on natural rainfall.

2.3. Soil Sampling and Analysis

The soil bulk density (g cm^{-3}) and porosity (%) were measured according to the cutting–ring method. Soil bulk density and soil porosity were calculated following the equation: Soil bulk density (g cm^{-3}) = soil dry weight (g)/cutting–ring volume (cm^3); soil porosity (%) = (1-soil bulk density/soil specific gravity) $\times$ 100. Measurements were made at different soil depths (0–20 and 20–40 cm) at the maturity stage of sugarcane. The measurements were repeated three times in each plot [41].

Disturbed soil samples were collected at the two surface/subsurface layers (0–20 and 20–40 cm) in each plot using a 3 cm diameter soil sampler between three sugarcane rows of newly planted sugarcane on 17 April, 2 July, and 28 October 2018, and ratoon sugarcane on 10 April, 31 August, and 3 November 2019. In addition, before the start of the experiment, soil samples were taken from the divided plots for the determination of soil background values. Bulk soil samples were air-dried and passed through a 2 mm sieve. The soil organic matter content (SOM) was determined by the potassium dichromate external heating method; total N (TN) was determined using the semi-micro-Kjeldahl method; alkali-hydrolyzable nitrogen (AN) was determined using the alkali solution diffusion method; available K (AK) was extracted by NH_4OAc and determined by flame photometric method; and available P (AP) was determined by molybdenum antimony spectrophotometry [42]. Soil TN, AN, AP, AK, and SOM are measured from 0–20 cm depth.

2.4. Plant Sampling

Samples were collected at the seeding, elongation, and maturation stages. Five robust sugarcane plants with representative and consistent growth were randomly selected from each plot, and sugarcane roots were used to determine the root morphological traits. To facilitate root sampling, a rectangular hole was dug with a length from the midline between the 1st and the 2nd plants to the midline between the 2nd and the 3rd plants. The width (25 cm) was half the spacing (50 cm) and a depth of 50 cm; three consecutive plants were collected in the same row in the rectangular hole. The plants were washed with water, and impurities and dead roots were removed. The remaining roots and ground parts were then dried and weighed.

2.5. Agronomic Traits and Yield

The seedling rates (SSR) of newly planted and ratoon sugarcane were recorded on 17 April 2018 and 11 April 2019, respectively. The tillering rates (STR) of newly planted and ratoon sugarcane were measured on 11 May 2018 and 5 June 2019, respectively.

The plant height, stem diameter, and single stem weight of 10 sugarcane plants in each treatment were recorded when the new planting sugarcane and ratooning sugarcane were harvested on 19 January 2019 and 13 January 2020, respectively. The plant height was measured from the base to the sugarcane apex. The stem diameter was measured in the upper third, middle, and seventh sections from the tail to the bottom. For the determination of sugarcane yield, all sugarcanes in each plot were harvested, and the total sugarcane yield was obtained after weighing.

2.6. Root Study

Sugarcane root samples were manually excavated during the seeding, elongation, and maturation stages by loosening the soil around the roots using mechanical hand tools to recover all coarse and fine roots with little or no root damage. During excavation, a smooth flush of low-pressure water was used to obtain substantial horizontal surface root volume along the central part of the roots (taproots). The roots were carefully rinsed with water to remove the adhering soil and air-dried under laboratory conditions. Fresh roots were imaged for root morphology parameters (including total root length, surface area, diameter, tips, and volume) using an Epson root scanner and WinRHIZO analysis software (Reagent Instruments, Quebec City, Canada). During imaging, the root system was carefully spread on the fiber plate (scanner surface) with minimal root overlap and minimal or no damage. This method allows 2D quantification of sugarcane root morphology, and the data are expressed on a per-plant basis.

2.7. Statistical Analysis

The experimental data pertaining to each parameter were statistically assessed by analysis of variance (ANOVA) using SPSS Version 19.0. All data are presented as means. Least significant difference (LSD) at 5% probability ($p > 0.05$) was determined for each studied parameter to compare the treatment means. The two-way interaction effect between tillage × biochar and tillage × planting methods was also determined. An interaction table for the important parameters is provided only when the effects are significant. A schematic diagram represents the overall experimental design (Figure 4).

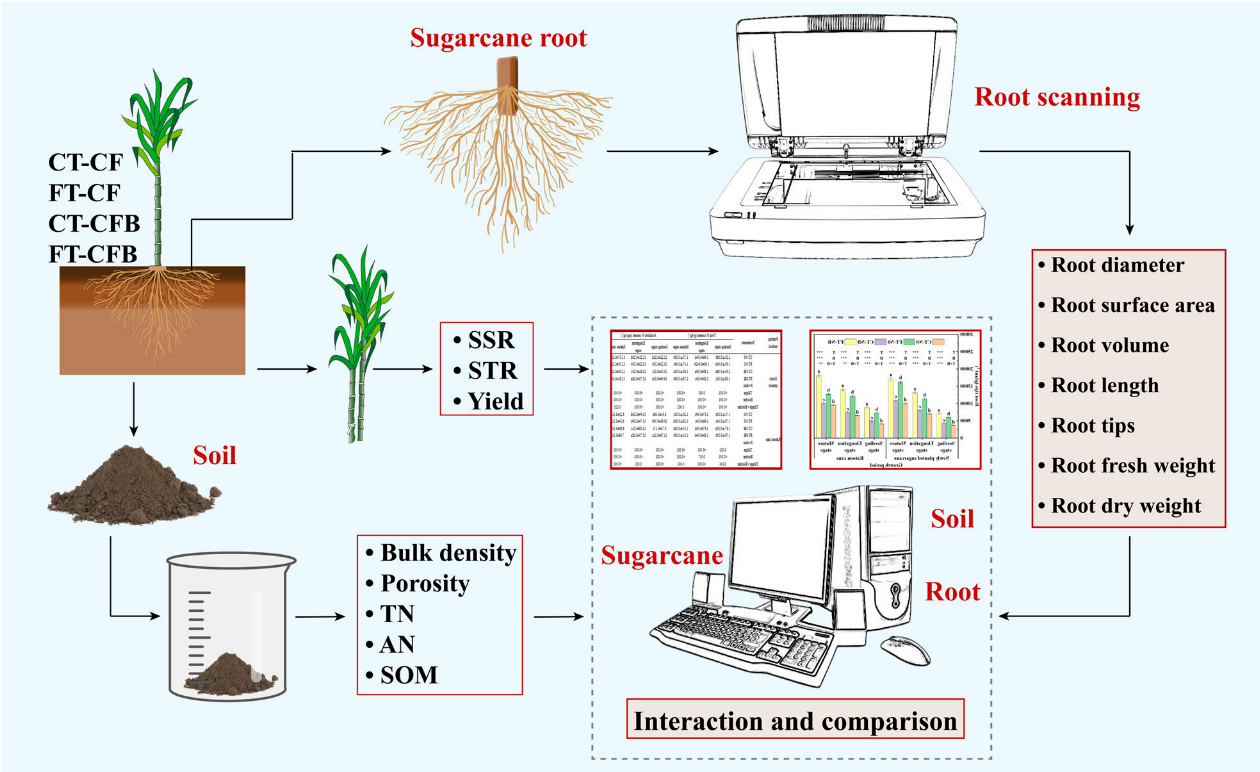

Figure 4. Schematic diagram of the conceptual framework of the study. FT: Fenlong-ridging deep tillage; SSR: sugarcane seedling rates; STR: sugarcane tillering rates; TN: soil total nitrogen content; AN: soil available nitrogen content; SOM: soil organic matter.

3. Results

3.1. The Effects of FT and Biochar on Soil Properties

3.1.1. Soil Bulk Density and Porosity

Bulk density measured at the 0–20 cm and 20–40 cm depths differed significantly among the treatments (Table 1). The bulk density values in the newly planted and ratoon sugarcane followed the order among all the treatments: CT-CF > CT-CFB > FT-CF > FT-CFB. FT-CFB decreased the bulk density by 27% and 33% in the 0–20 cm and 20–40 cm soil layers, respectively, as compared with CT-CF, which decreased the bulk density by 30% and 27%, compared with CT-CF. Moreover, CT-CFB decreased the bulk density by 3% in the 20–40 cm soil layer. The variation in bulk density showed a similar pattern in the soil of newly planted and ratoon sugarcane. Treatment with biochar and FT resulted in the lowest bulk density.

Similarly, porosity measured at the 0–20 cm and 20–40 cm depths of the bulk soil differed significantly among the treatments (Table 1) and decreased in the following order: FT-CFB > FT-CF > CT-CFB > CT-CF. FT-CFB increased the porosity by 18% and 19% in the 0–20 cm and 20–40 cm soil layers, respectively, as compared with CT-CF. Meanwhile, FT-CF increased the porosity by 15% in both layers, while CT-CFB increased the porosity by 3% and 4%. The variation in porosity showed a similar pattern in the newly planted and ratoon sugarcane after the treatments. The biochar and FT treatments had the highest porosity, regardless of soil depth.

However, biochar amendment did not affect the bulk density in the 0–20 cm soil layer, and the interactions between conventional tillage and biochar did not significantly affect the bulk density and porosity in either soil layer (Table 1).

Table 1. The effects of Fenlong-ridging deep tillage and biochar on soil bulk density and porosity.

Planting Method	Treatments	Bulk Density ($g \cdot cm^{-3}$)		Porosity (%)	
		Soil Layer (cm)		Soil Layer (cm)	
		0–20	20–40	0–20	20–40
Newly planted sugarcane	CT-CF	1.14 ± 0.03^{a}	1.23 ± 0.03^{a}	57.14 ± 0.24^{c}	55.58 ± 0.98^{c}
	FT-CF	0.81 ± 0.02^{b}	0.90 ± 0.02^{c}	65.81 ± 0.79^{b}	63.65 ± 0.98^{b}
	CT-CFB	1.15 ± 0.03^{a}	1.19 ± 0.02^{b}	58.67 ± 1.37^{c}	57.69 ± 1.02^{c}
	FT-CFB	0.84 ± 0.02^{b}	0.82 ± 0.02^{d}	67.48 ± 0.64^{a}	66.17 ± 0.98^{a}
	p-value				
	Tillage	<0.001	<0.001	<0.001	<0.001
	Biochar	0.561	<0.001	0.011	0.011
	Tillage×Biochar	0.561	0.161	0.821	0.710
Ratoon sugarcane	CT-CF	1.18 ± 0.06^{a}	1.24 ± 0.04^{a}	54.47 ± 0.79^{c}	51.83 ± 1.50^{c}
	FT-CF	0.86 ± 0.02^{b}	0.89 ± 0.02^{c}	68.06 ± 1.45^{a}	64.20 ± 1.37^{a}
	CT-CFB	1.13 ± 0.04^{a}	1.13 ± 0.04^{b}	57.44 ± 0.79^{b}	56.23 ± 1.51^{b}
	FT-CFB	0.88 ± 0.02^{b}	0.85 ± 0.02^{c}	68.55 ± 1.24^{a}	66.23 ± 1.52^{a}
	p-value				
	Tillage	<0.001	<0.001	<0.001	<0.001
	Biochar	0.537	0.009	0.043	0.004
	Tillage×Biochar	0.152	0.145	0.137	0.178

Different lowercase letters after the means in the same column for different cultivation modes indicate significant differences at $p < 0.05$. CT-CF, conventional tillage-chemical fertilizers; FT-CF, FT-chemical fertilizers; CT-CFB, conventional tillage–application of biochar-based fertilizer; FT-CFB, FT–application of biochar-based fertilizer. Mean ± standard deviations.

3.1.2. Soil Total Nitrogen

The soil total nitrogen (TN) values in the newly planted and ratoon sugarcane field soils decreased in the following order: CT-CFB > FT-CFB > CT-CF > FT-CF (Table 2). CT-CFB had the highest TN during the entire growth period among all the treatments. The TN content of CT-CFB was 0.20 g/kg, 0.78 g/kg, and 0.45 g/kg higher than that of CT-CF, FT-CF, and FT-CFB, respectively in the newly planted sugarcane during the seeding stage. Likewise, the TN content of CT-CFB was 0.21 g kg^{-1}, 0.09 g kg^{-1}, and 0.10 g kg^{-1} higher than that of CT-CF, FT-CF, and FT-CFB, respectively, during the elongation stage. Moreover, the TN content of CT-CFB was 0.14 g kg^{-1}, 0.42 g kg^{-1}, and 0.13 g kg^{-1} higher than that of CT-CF, FT-CF, and FT-CFB, respectively, during the maturation stage.

The variation in TN showed similar trends between the newly planted and ratoon sugarcanes, and both treatments with biochar had higher TN values, whereas the treatment with FT resulted in a lower TN than the treatments with CT. In general, TN in the soil was higher in the newly planted sugarcane than in the ratoon sugarcane field. In this experiment, the TN content of newly planted sugarcane soil first decreased and then increased, whereas that of ratoon sugarcane decreased with time, and TN content was the highest at the seedling stage at both the newly planted and ratoon sugarcane.

Tillage combined with biochar amendment significantly influenced the TN content throughout the sugarcane growth period. Similarly, the interactions between tillage and biochar amendment significantly affected the TN content in the soil for both the newly planted and ratoon sugarcane, with the exception of the ratoon sugarcane during the seedling stage, in which TN content was not significantly affected (Table 2).

Table 2. The effects of Fenlong-ridging deep tillage and biochar on total and available N in soil at the different sugarcane growth stages.

Planting Method	Treatments	Total N ($g \cdot kg^{-1}$)			Available N ($mg \cdot kg^{-1}$)		
		Seeding	Elongation	Maturation	Seeding	Elongation	Maturation
Newly planted sugarcane	CT-CF	2.25 ± 0.07^{b}	1.48 ± 0.04^{c}	1.75 ± 0.05^{b}	287.47 ± 7.06^{d}	292.04 ± 7.34^{d}	132.77 ± 4.17^{d}
	FT-CF	1.65 ± 0.04^{d}	1.60 ± 0.042^{b}	1.47 ± 0.04^{c}	291.58 ± 7.01^{c}	319.34 ± 5.78^{b}	237.04 ± 4.18^{b}
	CT-CFB	2.43 ± 0.06^{a}	1.69 ± 0.04^{a}	1.89 ± 0.05^{a}	293.42 ± 7.29^{b}	305.10 ± 6.68^{c}	185.73 ± 5.14^{c}
	FT-CFB	1.98 ± 0.05^{c}	1.59 ± 0.04^{b}	1.76 ± 0.05^{b}	302.60 ± 7.29^{a}	344.15 ± 6.52^{a}	274.67 ± 4.55^{a}
	p-value						
	Tillage	<0.001	0.003	<0.001	<0.001	<0.001	<0.001
	Biochar	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
	Tillage × Biochar	<0.001	<0.001	0.002	<0.001	<0.001	<0.001
Ratoon sugarcane	CT-CF	1.74 ± 0.06^{b}	1.57 ± 0.04^{b}	1.29 ± 0.03^{c}	333.00 ± 5.77^{d}	352.54 ± 8.97^{d}	117.37 ± 4.62^{d}
	FT-CF	1.70 ± 0.04^{b}	1.48 ± 0.04^{c}	1.26 ± 0.03^{d}	382.40 ± 6.65^{b}	387.36 ± 6.92^{b}	134.83 ± 5.49^{b}
	CT-CFB	1.87 ± 0.05^{a}	1.67 ± 0.04^{a}	1.35 ± 0.03^{a}	350.42 ± 5.95^{c}	383.02 ± 8.99^{c}	131.00 ± 2.82^{c}
	FT-CFB	1.79 ± 0.05^{ab}	1.39 ± 0.04^{d}	1.31 ± 0.03^{b}	398.03 ± 9.43^{a}	399.17 ± 7.08^{a}	140.50 ± 3.00^{a}
	p-value						
	Tillage	0.002	<0.001	<0.001	<0.001	<0.001	<0.001
	Biochar	<0.001	0.017	<0.001	<0.001	<0.001	<0.001
	Tillage × Biochar	0.314	<0.001	0.041	0.638	<0.001	0.005

Different lowercase letters in the same column for different cultivation modes indicate significant differences at $p < 0.05$. CT-CF, conventional tillage- chemical fertilizers; FT-CF, FT-chemical fertilizers; CT-CFB, conventional tillage–application of biochar-based fertilizer; FT-CFB, FT–application of biochar-based fertilizer. The values are mean ± standard deviation.

3.1.3. Soil Available Nitrogen

The soil available nitrogen (AN) showed significant differences between the newly planted and ratoon sugarcanes among the different treatments (Table 2). AN value in both fields decreased in the following order: FT-CFB > FT-CF > CT-CFB > CT-CF. The AN of FT-CFB was the highest during the entire growth period among all the treatments. The AN of FT-CFB was 20%, 5%, and 12% higher than those of CT-CF, FT-CF, and CT-CFB, respectively, during the seeding stage of the ratoon sugarcane. Similarly, the AN of FT-CFB was 15%, 3%, and 6% higher than those of CT-CF, FT-CF, and CT-CFB, respectively, during the elongation stage. Moreover, the AN of FT-CFB was 17%, 4%, and 7% higher than those of CT-CF, FT-CF, and CT-CFB, respectively, during the maturation stage.

The variations in AN showed similar trends for the two planting patterns. The newly planted and ratoon sugarcane treatments with FT resulted in higher AN, followed by treatment with biochar. In general, the AN of the newly planted sugarcane was lower than that of the ratoon sugarcanes. The AN of the newly planted and ratoon sugarcanes first increased and then decreased during the entire growth period. The AN of the newly planted sugarcane was highest during the elongation stage throughout the entire growth period. However, the highest AN value for the ratoon sugarcane was observed during the elongation stage.

Tillage and biochar application significantly affected AN throughout the sugarcane growth period. Moreover, the interactions between tillage and biochar significantly affected the AN during the entire growth period for both planting methods. However, the AN was unaffected during the seeding period in the ratoon sugarcane (Table 2).

3.1.4. Soil Available P and K

The available P (AP) and K (AK) in the soil during the entire growing season were significantly affected by FT and biochar for both the newly planted and ratoon sugarcane (Table 3). There was a significant difference in soil AP and AK among the treatments. AP in soil decreased in the order FT-CFB > FT-CF > CT-CFB > CT-CF. The AP of FT-CFB was 19%, 9%, and 11% higher than that of CT-CF, FT-CF, and CT-CFB, respectively, at the seeding stage for the newly planted sugarcane. The corresponding values were 41%, 19%, and 23% at the elongation stage and 44%, 15%, and 36% at the maturation stage. The AK decreased in the order FT-CFB > CT-CFB > CT-CF > FT-CF. The AK of FT-CFB was 11%, 10%, and

3% higher than that of CT-CF, FT-CF, and CT-CFB, respectively, at the seeding stage for the newly planted sugarcane. The corresponding values were 11%, 10%, and 3% at the elongation stage and 10%, 19%, and 4% at the maturation stage.

Table 3. The effects of Fenlong-ridging deep tillage and biochar on soil available P and K in soil at the different sugarcane growth stages.

Planting Method	Treatments	Available P (mg·kg^{-1})			Available K (mg·kg^{-1})		
		Seeding	Elongation	Maturation	Seeding	Elongation	Maturation
Newly planted sugarcane	CT-CF	11.96 ± 0.34 ^{c}	11.44 ± 0.20 ^{d}	11.27 ± 0.20 ^{d}	714.17 ± 16.64 ^{c}	744.53 ± 17.86 ^{c}	575.79 ± 13.81 ^{c}
	FT-CF	13.07 ± 0.23 ^{b}	13.02 ± 0.24 ^{b}	12.80 ± 0.22 ^{b}	716.28 ± 17.18 ^{c}	736.29 ± 17.66 ^{d}	532.68 ± 12.78 ^{d}
	CT-CFB	13.28 ± 0.23 ^{b}	12.69 ± 0.23 ^{c}	11.87 ± 0.24 ^{c}	768.51 ± 18.44 ^{b}	801.54 ± 19.23 ^{b}	610.41 ± 14.64 ^{b}
	FT-CFB	14.30 ± 0.25 ^{a}	15.858 ± 0.28 ^{a}	13.69 ± 0.24 ^{a}	789.53 ± 18.94 ^{a}	821.56 ± 19.71 ^{a}	635.42 ± 15.24 ^{a}
	p-value						
	Tillage	<0.001	<0.001	<0.001	<0.001	<0.001	0.116
	Biochar	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
	Tillage×Biochar	<0.001	<0.001	0.025	<0.001	<0.001	<0.001
Ratoon sugarcane	CT-CF	8.85 ± 0.13 ^{d}	10.81 ± 0.78 ^{d}	6.17 ± 0.11 ^{c}	985.56 ± 23.64 ^{a}	588.90 ± 14.13 ^{c}	715.74 ± 17.17 ^{c}
	FT-CF	10.53 ± 0.19 ^{b}	13.61 ± 0.24 ^{b}	6.27 ± 0.12 ^{c}	836.66 ± 20.07 ^{b}	569.03 ± 13.65 ^{d}	598.20 ± 14.35 ^{d}
	CT-CFB	9.88 ± 0.14 ^{c}	11.45 ± 0.20 ^{c}	6.80 ± 0.12 ^{b}	1001.67 ± 24.03 ^{a}	612.41 ± 14.69 ^{b}	789.53 ± 18.94 ^{b}
	FT-CFB	11.69 ± 0.18 ^{a}	15.58 ± 0.28 ^{a}	6.99 ± 0.13 ^{a}	989.66 ± 23.74 ^{a}	645.43 ± 15.48 ^{a}	804.54 ± 19.30 ^{a}
	p-value						
	Tillage	<0.001	<0.001	<0.001	0.001	0.207	<0.001
	Biochar	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
	Tillage×Biochar	<0.001	0.001	<0.001	0.002	0.001	<0.001

Different lowercase letters in the same column for different cultivation modes indicate significant differences at $p < 0.05$. CT-CF, conventional tillage-chemical fertilizers; FT-CF, FT-chemical fertilizers; CT-CFB, conventional tillage–application of biochar-based fertilizer; FT-CFB, FT–application of biochar-based fertilizer. The values are mean ± standard deviation.

The variations in available P and K in the soil showed similar trends in the ratoon sugarcane. The treatments with FT resulted in higher AP in the soil. Treatments with biochar resulted in higher AK in the soil. In general, the AK content was lower, and the AP content was higher in the newly planted sugarcane than in the ratoon sugarcanes. During the entire growth period, the AP and AK contents in the soil were highest at the elongation and seedling stages.

The interactions between tillage and biochar significantly affected soil available P and K during the entire growth period for both planting methods (Table 3).

3.1.5. Soil Organic Matter

The soil organic matter (SOM) content during the entire growing season was significantly affected by tillage and biochar for both the newly planted and ratoon sugarcane (Table 4). There was a significant difference in SOM among the treatments. The SOM decreased in the following order: CT-CFB > FT-CFB > CT-CF > FT-CF for all the growing stages. The SOM of CT-CFB was 15%, 33%, and 3% higher than that of CT-CF, FT-CF, and FT-CFB, respectively, at the seeding stage for the ratoon sugarcane. The corresponding values were 16%, 16%, and 2% at the elongation stage and 11%, 15%, and 2% at the maturation stage.

Variations in SOM showed similar trends for the newly planted sugarcane. The treatments with biochar resulted in a higher SOM, whereas FT resulted in a lower SOM. In general, the SOM content of newly planted sugarcane was lower than that of the ratoon sugarcane. The SOM of the newly planted sugarcane first increased and then decreased, whereas the SOM of the ratoon sugarcane increased over time during the entire growth period. The SOM content was the highest at the elongation and maturation stages during the entire growth period.

The interaction between tillage and biochar significantly affected SOM during the entire growth period for both planting methods except for the elongation stage of the newly planted sugarcane (Table 4).

Table 4. The effects of Fenlong-ridging deep tillage and biochar on soil organic matter content at different growth stages of sugarcane.

Planting Method	Treatments	Organic Matter Content ($g \cdot kg^{-1}$)		
		Seeding	Elongation	Maturation
Newly planted	CT-CF	38.48 ± 1.18^{c}	40.11 ± 1.06^{c}	39.53 ± 0.79^{c}
	FT-CF	35.81 ± 0.95^{d}	38.84 ± 1.03^{d}	36.31 ± 0.96^{d}
	CT-CFB	41.56 ± 1.10^{a}	45.64 ± 1.21^{a}	42.37 ± 1.12^{b}
	FT-CFB	40.14 ± 1.02^{b}	44.60 ± 1.16^{b}	43.50 ± 0.91^{a}
	p-value			
	Tillage	<0.001	<0.001	<0.001
	Biochar	<0.001	<0.001	<0.001
	Tillage × Biochar	<0.001	0.924	<0.001
Ratoon sugarcane	CT-CF	37.95 ± 1.01^{c}	39.66 ± 0.93^{c}	43.70 ± 1.16^{c}
	FT-CF	32.69 ± 0.85^{d}	39.77 ± 1.16^{c}	42.00 ± 1.11^{d}
	CT-CFB	43.64 ± 1.16^{a}	46.36 ± 1.26^{a}	48.51 ± 1.08^{a}
	FT-CFB	42.25 ± 0.97^{b}	45.37 ± 1.20^{b}	47.39 ± 1.29^{b}
	p-value			
	Tillage	<0.001	<0.001	<0.001
	Biochar	<0.001	<0.001	<0.001
	Tillage × Biochar	<0.001	<0.001	<0.001

Different lowercase letters in the same column for different cultivation modes indicate significant differences at $p < 0.05$. CT-CF, conventional tillage-chemical fertilizers; FT-CF, FT-chemical fertilizers; CT-CFB, conventional tillage–application of biochar-based fertilizer; FT-CFB, FT–application of biochar-based fertilizer. The values are mean ± standard deviation.

3.2. The Effects of FT and Biochar on Root Growth

3.2.1. Morphology Index

Root traits (length, tips, diameter, surface area, and volume) differed significantly among the treatments for all the growing stages (Figure 5). The values of the root traits for the different treatments decreased in the following order: FT-CFB > FT-CF > CT-CFB > CT-CF. FT-CFB showed better root traits during the entire growth period. As compared with CT-CF, FT-CF, and CT-CFB, FT-CFB at the maturation stage of the newly planted sugarcane increased root diameter by 53%, 17%, and 36% (Figure 5a), respectively; root surface area by 31%, 7%, and 23% (Figure 5b); root volume by 33%, 7%, and 36% (Figure 5c); root length by 39%, 13%, and 35% (Figure 5d); and root tips by 70%, 5%, and 55% (Figure 5e).

Variations in the root traits showed similar trends for the newly planted and ratoon sugarcane. The newly planted and ratoon sugarcane treatments with FT resulted in better root traits, followed by the biochar treatment. In general, the root diameter was higher in newly planted sugarcane than in the ratoon sugarcane, whereas the root surface area, root length, root tips, and root volume of newly planted sugarcane were lower than those of the ratoon sugarcane. Root traits increased with time during the entire growth period, and better root traits were observed at the maturation stage for both planting methods.

Tillage and biochar application significantly improved root traits throughout the entire sugarcane growth period. Similarly, the interactions between tillage and biochar significantly affected the root traits in the newly planted sugarcane, with the exception of a non-significant effect of root diameter at the elongation stage and root tips and root volume at the maturation stage. The interactions between tillage and biochar were significant for root traits in the ratoon sugarcane, with the exception of the root surface area at the seedling stage and root volume at the elongation stage. Figure 6 shows the morphology of sugarcane roots under different treatments.

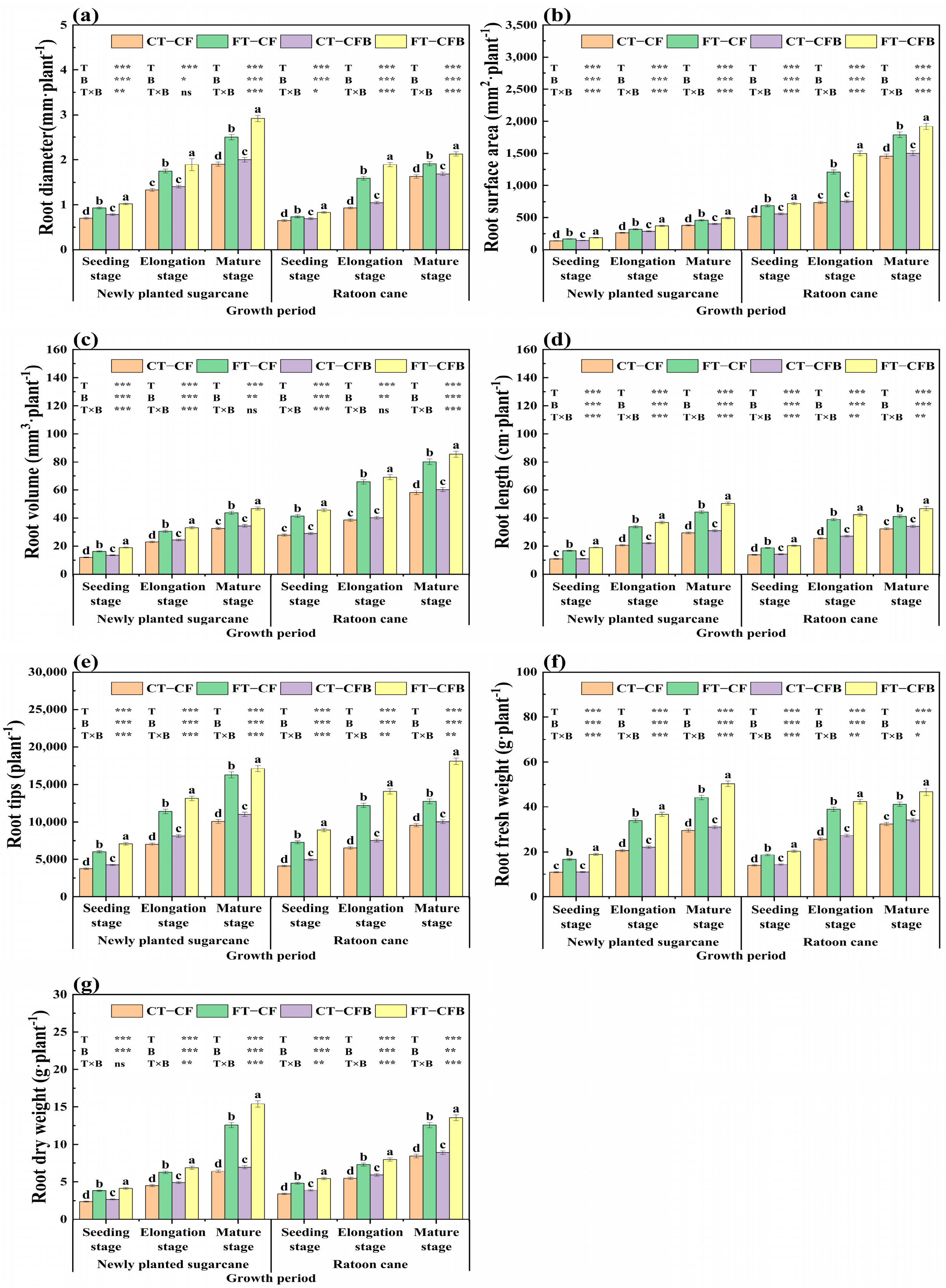

Figure 5. Diagrams of treatment effect results on various root traits at different growth stages of sugarcane: (**a**) diagram of root diameter results at different growth stages; (**b**) diagram of root surface area results at different growth stages; (**c**) diagram of root volume results at different growth stages;

(**d**) diagram of root length results at different growth stages; (**e**) diagram of root tips results at different growth stages; (**f**) diagram of root fresh weight results at different growth stages; (**g**) diagram of root dry weight results at different growth stages. Error bars indicate ± standard deviation. Different letters above the error bars indicate a significant difference between treatments ($p < 0.05$, LSD test). Symbols represent the significance of Wilcoxon signed rank tests: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$, and 'ns' represents non-significant.

Figure 6. Sugarcane root morphology subjected to four treatments in different periods. (**A**) Comparison of root morphology of sugarcane seedlings subjected to CT-CF and FT-CFB treatments; (**B**) comparison of root morphology of sugarcane seedlings subjected to FT-CF and FT-CFB treatments; (**C**) comparison of root morphology of sugarcane seedlings subjected to CT-CFB and FT-CFB treatments; FT-CFFT-CFB (**D**) comparison of root morphology of sugarcane subjected to different treatments at maturation stage. a, b, c, and d indicate CT-CFNB, FT-CF, FCT-CF, and FT-CFB, respectively.

3.2.2. Dry and Fresh Root Weight

There were significant differences in the dry and fresh root weights in both the newly planted and ratoon sugarcanes among the treatments (Figure 5). The values of dry and fresh root weights for the newly planted and ratoon sugarcane plants decreased in the following order: FT-CFB > FT-CF > CT-CFB > CT-CF. The average root fresh weight of FT-CFB was 71%, 14%, and 62% higher than those of CT-CF, FT-CF, and CT-CFB, respectively, at the maturation stage of the newly planted sugarcane (Figure 5f). FT-CFB had significantly higher dry and fresh root weights during the entire growth period than all the other treatments. Similarly, the root dry weight of FT-CFB was 139%, 22%, and 121% higher than those of CT-CF, FT-CF, and CT-CFB, respectively, at the maturation stage of the ratoon sugarcane (Figure 5g).

The variations in root dry and fresh weight showed similar trends in the newly planted and ratoon sugarcane. Treatments with FT resulted in the highest dry and fresh root weights, followed by biochar treatment. In general, the dry and fresh root weights of the newly planted sugarcane were lower than those of the ratoon sugarcane. Dry and fresh root weights increased with time during the entire growth period, and the highest values of dry and fresh root weights were observed at the maturation stage for both planting methods.

Tillage and biochar application significantly influenced dry and fresh root weights throughout the sugarcane growth period. Moreover, the interaction between tillage and biochar was significant for both weights during the entire growth period in both planting methods; however, the dry root weight was unaffected during the seeding period in the newly planted sugarcane.

3.3. The Effects on Agronomic Traits and Sugarcane Yield

Agronomic Traits and Sugarcane Yield

There were significant differences in agronomic traits (SSR and STR) and sugarcane yield between the newly planted and ratoon sugarcane among the treatments (Table 5). SSR and sugarcane yield in both planting methods decreased as follows: FT-CFB > CT-CFB > FT-CF > CT-CF. The STR at the newly planted sites were FT-CFB > CT-CFB > FT-CF > CT-CF, while for ratoon sugarcane, the order was FT-CFB > FT-CF > CT-CFB > CT-CF. FT-CFB recorded the highest SSR, STR, and sugarcane yield during the entire growth period. The SSR of FT-CFB were 67%, 33%, and 14% higher than those of CT-CF, FT-CF, and CT-CFB, respectively, for the newly planted sugarcane. Similarly, the STR of FT-CFB were 34%, 14%, and 13% higher than those of CT-CF, FT-CF, and CT-CFB, respectively. Moreover, sugarcane yield with FT-CFB was 58%, 33%, and 4% higher than that with CT-CF, FT-CF, and CT-CFB, respectively.

Table 5. The effects of Fenlong-ridging deep tillage and biochar on agronomic traits and yield.

Planting Method	Treatments	Seedling Rate (%)	Tillering Rate (%)	Yield (kg·ha^{-1})
Newly planted sugarcane	CT-CF	31.83 ± 1.07 ^{d}	51.23 ± 2.05 ^{d}	109,997 ± 2585 ^{c}
	FT-CF	39.80 ± 1.33 ^{c}	60.08 ± 2.18 ^{c}	130,773 ± 3074 ^{b}
	CT-CFB	46.45 ± 1.12 ^{b}	60.91 ± 2.44 ^{b}	167,499 ± 3937 ^{a}
	FT-CFB	53.16 ± 1.89 ^{a}	68.38 ± 3.11 ^{a}	173,679 ± 3886 ^{a}
	p-value			
	Tillage	<0.001	<0.001	<0.001
	Biochar	<0.001	<0.001	<0.001
	Tillage×Biochar	0.010	0.008	0.008
Ratoon sugarcane	CT-CF(a)	37.13 ± 1.69 ^{d}	56.44 ± 2.26 ^{d}	92,743 ± 2179.94 ^{c}
	FT-CF(b)	42.42 ± 1.44 ^{c}	63.04 ± 2.52 ^{b}	112,256 ± 2638.61 ^{b}
	CT-CFB(c)	43.81 ± 1.47 ^{b}	60.88 ± 2.43 ^{c}	114,864 ± 3512.61 ^{b}
	FT-CFB(d)	67.50 ± 2.26 ^{a}	72.35 ± 2.89 ^{a}	123,425 ± 2858 ^{a}
	p-value			
	Tillage	<0.001	<0.001	<0.001
	Biochar	<0.001	<0.001	<0.001
	Tillage×Biochar	<0.001	<0.001	0.028

Different lowercase letters in the same column for different cultivation modes indicate significant differences at $p < 0.05$. CT-CF, conventional tillage-chemical fertilizers; FT-CF, FT-chemical fertilizers; CT-CFB, conventional tillage–application of biochar-based fertilizer; FT-CFB, FT–application of biochar-based fertilizer. The values are mean ± standard deviation.

Variations in the agronomic traits and sugarcane yield showed similar trends in both the newly planted and ratoon sugarcane. The treatments with biochar resulted in higher SSR, STR, and sugarcane yield as compared with those without. Meanwhile, FT resulted in a higher increase in these traits. In general, the seedling and STR of newly planted sugarcane were lower than those of the ratoon sugarcane, whereas the yield of newly planted sugarcane was higher than that of the ratoon sugarcane.

SSR, STR, and sugarcane yield were significantly affected by tillage and biochar application in all the growing stages for both planting methods. Furthermore, the interaction between tillage and biochar significantly affected sugarcane agronomic traits and yield in the newly planted and ratoon sugarcanes (Table 3). Morphology of sugarcane at the maturation stage subjected to different treatments is shown in Figure 7.

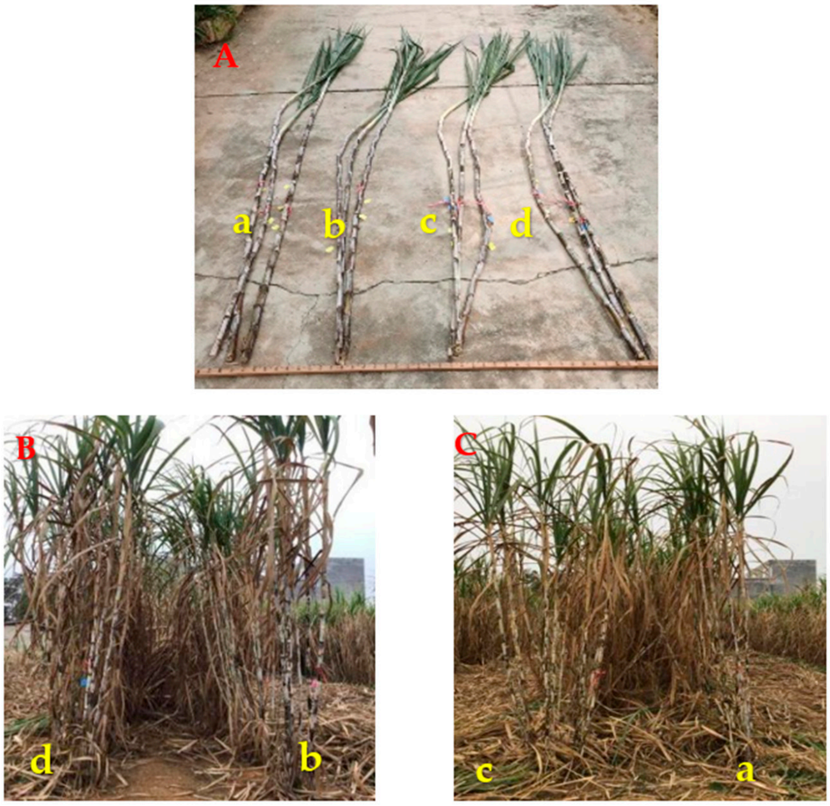

Figure 7. Morphology of sugarcane at maturation stage subjected to different treatments. (**A**) Morphological comparison of sugarcane harvested at maturation stage subjected to four different treatments; (**B**) at maturity, the growth of sugarcane subjected to FT-CFB and FT-CF treatments in the field; (**C**) at maturity, the growth of sugarcane subjected to CT-CFB and CT-CF treatments in the field. (a) Morphology of sugarcane at maturity stage under CT-CF treatment, (b) morphology of sugarcane at maturity stage under FT-CF treatment, (c) morphology of sugarcane at maturity stage under CT-CFB treatment, and (d) morphology of sugarcane at maturity stage under FT-CFB treatment.

4. Discussion

4.1. FT Improve Sugarcane Growth and Yield

FT breaks the hardpan under the plow layer and creates a soil layer that is suspended and loosened, which leads to more favorable hydrothermal conditions, increases the availability of nutrients, water, and oxygen, and thus enhances microbial activities, thereby improving plant photosynthetic efficiency and crop yield [43–46]. FT has the characteristics of deep tillage and rotary grinding, which increase soil porosity and decrease soil bulk density [20,41,47]. Compared with traditional rotary tillage, FT (especially for more than two years) decreased the soil bulk density and increased the soil porosity in 30–40 cm soil depth after maize maturity [48]. Ma et al. [49] found soil bulk density in sweet sorghum farmland significantly decreased, and soil porosity under FT was significantly higher than that under CK. In this study, soil physical qualities, such as soil bulk density and porosity, were improved by FT. There were significant differences in the soil bulk density and porosity between the conventional and FT. A reduction in soil bulk density, an increase in soil porosity and water storage, and an improvement in available N and P after FT treatment indicated that FT could play an active role in the storage of soil nutrients [20,44–46,50].

Zhu et al. [46] found the contents of organic matter, total nitrogen, available phosphorus, and available potassium were higher in soil under FT than those under conventional tillage, which indicates the activation of soil nutrients was greater in FT soil. In this study, FT significantly affected AN, AK, and AP throughout the sugarcane growth period, as compared with conventional tillage. FT could significantly increase soil nutrient availability and uptake by sugarcane plants, especially N metabolism and amino acid synthesis, thereby providing a material basis for protein synthesis, improving the vascular bundle structure, and promoting the activities of enzymes related to N metabolism and root activity, facilitating plant growth and development on the ground [18,20,44]. FT created a better soil environment for cassava growth than CT, thus promoting the formation of more stable rhizosphere fungal community structures, which had an important relationship with soil pH, activity of urease, available nitrogen, available phosphorus, organic matter, and clay [51,52] Duan et al. [44] found the total biomass weight (TW) of sugarcane plants were 9.1% and 21.7% greater under FT than those under CK and found that FT promoted the activity of endophytic microbes in the roots, and these diverse microbial taxa might have an effect on sugarcane yield and soil chemical properties. Chlorophyll content and the photosynthetic rate increased, with significantly higher activity of photosynthetic enzymes, including NADP-malate dehydrogenase (NADP-MDH), phosphoenolpyruvate carboxylase (PEPC), and ribulose-1,5-bisphosphate carboxylase (RuBPC) under FT compared to CK. Sugarcane height, stem diameter, single stem weight, effective stem number, and yield significantly increased under FT compared to that under CK [46,50]. Our results revealed that the sugarcane root index, SSR, tillering rate, and yield of FT in newly planted and ratoon sugarcane were significantly higher than those of the control treatment. A possible explanation is that FT can create a soil environment suitable for microbes and crop growth by enhancing nutrient availability to sugarcane, thus improving root growth, nutrient absorption, and sugarcane yield [20,50,53,54]. It seems that Fenlong-ridging deep tillage combined with chemical fertilizer mixed with biochar (FT-CFB) application, compared with the farmers' conventional tillage with chemical fertilizer without biochar (CT-CF), is a new promising farm management practice for sustainably increasing sugarcane yield in the newly planted sugarcane and also in ratoon sugarcane in the red soil region of south China.

4.2. FT Needs Fertilizers to Improve Sugarcane Growth and Yield

Fertilization is necessary to supply sugarcane with sufficient amounts of nutrients. After deep tillage and subsoil disturbance, mineralization of organic matter increases, and subsequent leaching occurs due to enhanced water infiltration, whereas nutrients in the soil layer become diluted due to mixing with subsurface soil [55]. Our results showed that the TN and SOM contents of FT soil were significantly lower than those of the control treatment. Deep tillage mechanically mixed topsoil with the subsoil, and TN and SOM in the soil were significantly reduced [56]. FT increased soil porosity, water retention, and thermal capacity, thus accelerating SOM mineralization [20]. On the other hand, the roots of sugarcane after FT treatment were more developed, as they can penetrate deeper into the subsoil layer to explore nutrients and water. Therefore, it is necessary to combine FT treatment with appropriate fertilizer application to sustain sugarcane growth and yield. However, the production of sugarcane is often accompanied by a large loss of applied N, which poses adverse environmental impacts [25]. Biochar has been used to produce slowly released fertilizers that can prevent nutrient loss and improve the efficiency of nutrient utilization [32]. Therefore, it is important to study how to rapidly improve soil aggregate structure using biochar to increase sugarcane yield after FT.

4.3. FT Integrated with Biochar and Fertilization Improve Sugarcane Growth and Yield

Biochar was reported to enhance soil nitrification in Scots pine forests, and charcoal exhibits important characteristics that affect the regulatory steps in N cycling [57]. Our results showed that biochar application increased soil TN, AN, AP, AK, and SOM as compared to the control. This might be because biochar can retain nutrients and SOM from loss by leaching or mineralization, thus increasing plant-available nutrients [58–60]. Deep tillage combined with biochar-based fertilization could also improve the formation and stability of large aggregates due to enhanced humus formation and accumulation [38,61–63]. Our study also showed that the interaction between FT and biochar-based fertilizers significantly affected TN, AN, AP, AK, and SOM, both in the newly planted and ratoon sugarcane. Biochar absorbed NH_4-N, prevented N loss, and increased its availability [64]. Biochar also increased microbial growth and activity, likely due to hydrothermal environment and air conditions [65,66]. Furthermore, FT increased the availability of soil nutrients and microbial growth and activity [44,45]. Overall, the interactions between FT and biochar-based fertilizers can reduce bulk density and increase soil porosity, AN, AP, AK, and SOM.

Root growth is strongly limited by the soil environment; increased root hair proliferation, root length, and root number have been observed in loosed soil conditions [54]. FT deep tillage breaks the hardpan under the plow layer and up to the subsoil can alleviate root entry pressure, thus increasing the rooting depth, water, and nutrient uptake [17,44,67,68]. Li et al. [20] found that FT resulted in more sugarcane root hairs and increased root length and density compared with conventional tillage. Biochar improves soil structure and increases soil water retention, which increases water supply for root growth and reduces mechanical resistance [69]. Deep tillage combined with biochar was reported to promote the root growth of crops [70]. Our results showed that FT deep tillage combined with biochar significantly increased root diameter, root surface area, root volume, root tip number, root length, and fresh and dry root weight compared with the control. FT provides an environment that is suitable for root growth [44,67,68] and promotes the development of a sugarcane root system, whereas biochar stimulates plant growth and increases the demand for nutrients and water, thereby increasing root biomass [71]. In summary, biochar and FT enhanced the root growth of sugarcane because of their synergistic effect.

There is a correlation between the aboveground and underground parts of crops, and a good root structure can promote the accumulation of sugar and yield [72]. Our experiments showed that the interactions between tillage and biochar significantly affected the sugarcane yield in newly planted and ratoon sugarcane. FT with biochar significantly increased sugarcane yield as compared with that of the control. This might be because FT and biochar jointly increase soil porosity and promote the formation of soil aggregates [44,45,73,74]. Moreover, a more favorable soil environment promoted the growth of roots and microorganisms, which, in turn, improved the nutrient utilization rate [67,75]. The more developed the root system of the crop is, the stronger the ability to absorb water and nutrients, ultimately improving the rate of sugarcane emergence and tillering and forming the basis for the high yield of the crop [76]. Altogether, FT and biochar applications potentially increase sugarcane yield. That FT integrated with biochar and fertilization is promising for increasing sugarcane yield in the newly planted and ratoon sugarcanes.

5. Conclusions

The integration of FT with fertilization and biochar amendment significantly improved soil physical and chemical properties, increased soil storage for nutrients, and enhanced root growth and nutrient uptake, thus leading to higher sugarcane yield. FT breaks the hardpan under the shallow A-horizon soil layer and facilitates root penetration into the deeper soil layers for nutrients. The use of biochar as a soil amendment can maintain favorable soil conditions, preventing nutrient loss and promoting microbial growth and activity. The results of the present study showed that Fenlong-ridging deep tillage combined with chemical fertilizer mixed with biochar (FT-CFB) application presented significantly higher sugarcane root fresh and dry weights and higher yield and thus is a new promising farm management practice for sustainably increasing sugarcane yield in the newly planted sugarcane also in ratoon sugarcane in the red soil region of south China. (Figure 8).

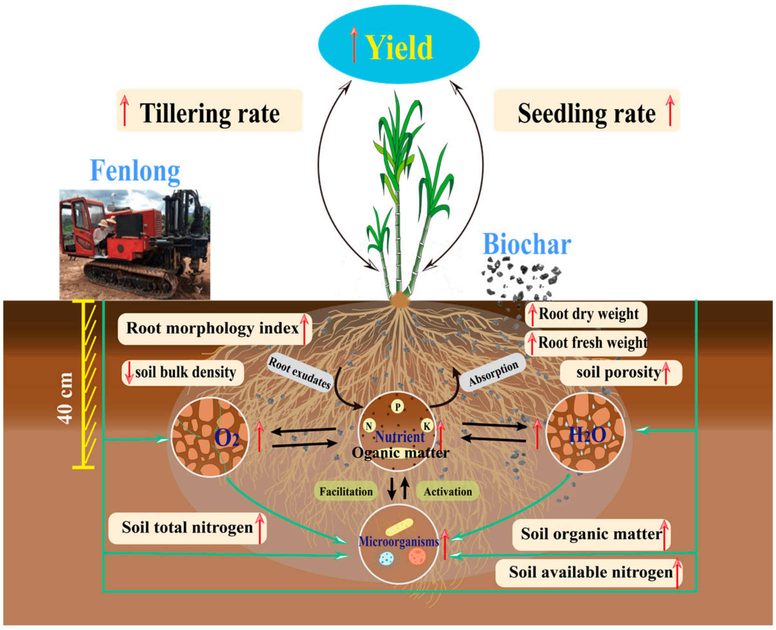

Figure 8. Theoretical model of interactions between FT and biochar to increase sugarcane yield.

Author Contributions: Conceptualization, J.X., S.Z. and S.L.; data curation, J.X., S.Z., S.H., L.W., L.C. and R.L.; software, J.X., S.Z., S.H., L.W., L.C. and R.L.; methodology, S.H., Z.L., B.W., Z.H. and S.L.; validation, S.H., Z.L., B.W., Z.H. and S.L.; formal analysis, S.H., Z.L., B.W., Z.H. and S.L.; investigation, S.H., Z.L., B.W., Z.H. and L.W.; resources, Z.L., S.H. and S.L.; writing—original draft preparation, J.X., S.Z., S.H., L.W., L.C., R.L. and S.L.; writing—review and editing, J.X., S.Z., S.H., L.W., L.C., R.L., Z.L., B.W., Z.H. and S.L.; supervision, S.L.; project administration, S.L.; funding acquisition, S.L. All authors have read and agreed to the published version of the manuscript.

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