

Article

The Effects of Different Straw-Returning Methods on Soil Organic Carbon Transformation in Rice–Rape Rotation Systems

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Abstract

Effective management of straw in rice (*Oryza sativa* L.)–rape (*Brassica napus* L.) rotation systems is essential for optimising resource efficiency and improving soil quality. This two-year study investigated the impact of seven straw treatment methods on soil organic carbon (SOC) dynamics. The treatments examined were as follows: (1) control (CK); (2) rice straw (SF); (3) rapeseed straw (YF); (4) rice-straw-derived biochar (SB); (5) rapeseed-straw-derived biochar (YB); (6) mixed straw (YSF); (7) mixed biochar (YSB). Soil properties, enzyme activities and carbon fractions were subsequently analysed. During the canola growing season, the application of rice straw biochar increased oxidisable carbon (ROC), dissolved organic carbon (DOC) and microbial biomass carbon (MBC) by 25.7%, 61.7% and 67.2%, respectively, compared to the control. Notably, SB was more effective than unprocessed rice straw (SF) at increasing SOC and ROC. Furthermore, SB demonstrated superior performance in enhancing ROC (56.4%), MBC (36.0%) and DOC (12.2%) compared to hybrid biochar (YSB). SB consistently exhibited a higher carbon accumulation trend than the rapeseed-derived treatments (YF, YB and YSB). The results of the study indicated that applying rice straw biochar during the oilseed rape growing season was effective in increasing variable carbon pools and soil organic carbon accumulation.

Keywords: rice–rape rotation; straw returning; biochar returning; soil organic carbon



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1. Introduction

Farmland is extensively acknowledged as a significant carbon reservoir, exerting a pivotal influence on the global carbon cycle [1]. The rotation facilitates the accumulation of soil organic carbon [2]. Furthermore, the findings of the study demonstrated that the rice–rape rotation system resulted in a substantial increase in soil microbial biomass carbon and soil organic carbon content, in comparison to alternative rotation systems [3]. Nevertheless, the rice–rapeseed rotation system results in the generation of a substantial quantity of crop residues [4]. In the context of agriculture, the improper management of rice and rapeseed straws, which are considered as agricultural waste, has the potential to result in resource wastage and adverse environmental consequences [5]. The incineration of straw in situ is a prevalent method of disposal, as exemplified by the practice of farmers in India who

utilise this approach for the disposal of straw [6]. However, this practice can result in a number of adverse environmental consequences, including the loss of soil organic matter, a reduction in soil fertility, and an increased risk of soil erosion [7]. The reinstatement of rice straw in the field has been demonstrated to have a positive effect on the quantity of soil organic carbon [8]. It is imperative to ensure the maintenance of soil nutrient content. However, it should be noted that untreated straw is susceptible to rapid decomposition by microorganisms, resulting in the loss of nutrients and the emission of greenhouse gases [9]. Charcoal produced from straw, known as biochar, has been shown to have a significant impact on stability and the reduction in greenhouse gas emissions, including carbon dioxide, methane and nitrous oxide [10]. In addition, biochar has been demonstrated to promote the stabilisation of soil organic carbon [11]. Biochar is characterised by its high carbon content, which typically exceeds 60%, and due to its aromatic carbon structure and porous nature, it exhibits high stability and long-term carbon sequestration capacity. The stability of biochar enables it to remain in the soil for extended periods of time, ranging from decades to thousands of years. This process contributes to a significant reduction in the concentration of carbon dioxide in the atmosphere [12]. It has been demonstrated that the process of long-term fertilisation has the capacity to result in the sequestration of soil organic carbon [13]. While tillage practices and crop rotation systems have been shown to have a significant impact on soil physical properties, prolonged rice–rapeseed rotation has been demonstrated to have an adverse effect on these properties [14].

The effective management of rice and rapeseed straw residues in rice–rapeseed rotation systems presents a major challenge for sustainable agricultural development. Studies indicate that straw incorporation significantly enhances soil organic carbon (SOC) sequestration and improves soil structural stability [15]. Furthermore, rice straw has been shown to increase the concentration of humic substances and labile organic carbon fractions, thereby improving soil fertility and augmenting SOC storage capacity [16,17]. Zhu et al. demonstrated that incorporating rapeseed straw as an exogenous carbon input enhances soil tilth conditions for subsequent rice cultivation [18]. The rational management of rice and canola straw residues has been shown to improve soil health while reducing fertiliser requirements, lowering production costs and improving economic returns [19]. In recent years, advances in the valorisation of agricultural waste have led to the increasing adoption of straw and biochar amendments as a viable strategy for improving soil fertility and supporting sustainable agricultural practices. Therefore, this experiment uses the rapeseed and rice straw harvested from the experimental field as raw materials to be returned to the field and investigates the effects of single and mixed applications of straw and biochar on soil organic carbon transformation in rice–rapeseed rotations.

2. Materials and Methods

2.1. Experimental Site Characterization

The study site was located in Guilin City (25° N, 110° E), Guangxi Zhuang Autonomous Region, China, within a subtropical monsoon climate zone. The region has an average annual temperature of 18–20 °C, with annual rainfall ranging from 1888 to 1890 mm. Climatic conditions are also characterised by 76% mean relative humidity, 1447.1 annual sunshine hours, pronounced seasonality (long summer/short winter) and extended frost-free periods. The experimental soil samples were collected from a rice–rapeseed double-crop system at the Guilin Agricultural Science Research Centre (25°04′13″ N, 110°28′36″ E) and the soil texture was silty clay loam. A 2-year field trial was conducted from 2022 to 2023 and the basic characteristics of the soil in the plough layer (0–20 cm) before the trial in December 2021 are shown in Table 1.

Table 1. Basic properties of soil.

pH	Cation Exchange Capacity CEC (g·kg ^{−1})	Electrical Conductivity EC (μm·cm ^{−1})	Acid Phosphatase AP (mg·kg ^{−1})	Available Potassium AK (mg·kg ^{−1})	Alkali-Hydrolysable Nitrogen AN (mg·kg ^{−1})
7.32 ± 0.04	5.02 ± 0.30	85.53 ± 1.04	128.57 ± 1.46	5.67 ± 0.19	157.19 ± 6.21

Note: All data are expressed as the mean ± standard deviation (SD).

2.2. Experimental Methods

2.2.1. Experimental Design

The field study was conducted from November 2021 to October 2023 in a long-term experimental field at the Guangxi Guilin Agricultural Science Research Centre (25°04′13″ N, 110°28′36″ E). All crop residues used in the experiment (rice straw and rapeseed straw) were collected from the same field during the study period. As illustrated in Table 2, the experiment was configured with seven distinct treatments: CK (during the rice–rapeseed rotation period, no additional straw or biochar were applied), SF (the application of rice straw was confined exclusively to the period prior to the planting of rapeseed throughout the cycle of rice–rapeseed cultivation), YF (the application of rapeseed straw was confined to the period prior to rice planting, within the context of the rice–rapeseed rotation), SB (biochar derived from rice straw was applied exclusively prior to the planting of rapeseed throughout the rice–rapeseed rotation), YB (biochar derived from rapeseed straw was applied exclusively prior to the planting of rice, throughout the rice–rapeseed rotation), YSF (rice straw biochar was applied before oilseed rape planting, and rape straw was applied before rice planting throughout the rice straw–oilseed rape rotation), YSB (rice straw biochar was applied before oilseed rape planting, and rape straw biochar was applied before rice planting throughout the rice straw–oilseed rape rotation).

Table 2. Experimental design.

Treatment	Rape Season Planting Period	Rice Season Planting Period
CK	-	-
YF	-	Rape straw
YB	-	Rape straw biochar
SF	Rice straw	-
YSF	Rice straw	Rape straw
SB	Rice straw biochar	-
YSB	Rice straw biochar	Rape straw biochar

A completely randomised block design with three replications for each treatment was utilised, and the size of each small sample plot was 20 m² (3 m × 6.5 m), with additional 1 m wide protection rows between adjacent experimental fields. The amount of straw and biochar applied to each sample plot was 12 kg of rice straw, 3.6 kg of rapeseed straw, 3.6 kg of rice straw biochar, and 1.08 kg of rapeseed straw biochar. The straw was air-dried under ambient conditions, manually segmented into 2 cm fragments and oven-dried at 60 °C for 48 h. After mechanical grinding and sieving through a 60-mesh sieve, the processed straw was incorporated into the soil by rotary tillage to a depth of approximately 20 cm.

The fertilisation process was executed in accordance with the established protocols for conventional fertiliser application. During the oilseed rape season, the dosage of nitrogen (N), phosphorus (P₂O₅) and potassium (K₂O) fertilisers was 0.018, 0.011 and 0.011 kg/m², respectively. The base fertiliser compound fertiliser was 0.075 kg/m², and the subsequent application of urea was 0.015 kg/m². In the rice season, the dosages of N, P₂O₅ and K₂O were 0.018, 0.009 and 0.019 kg/m², respectively.

2.2.2. Soil Sample Collection

Soil profile samples were collected at four different growth stages per year: rapeseed shoot (January 2022 and December 2022), flowering (March 2022 and March 2023) and maturity (April 2022 and May 2023) and rice maturity (September 2022 and September 2023). For each sampling plot, three random sampling points were selected. At each point, plough layer soil (0–20 cm depth) was collected using a soil auger (overall length of one meter, the indenter is spiral in shape and has a diameter of 6 cm), with approximately 1 kg of soil obtained per sampling location. The samples from replicate points were then thoroughly mixed to form a composite representative sample, which was subsequently reduced to the required quantity using the quartering method [20].

2.2.3. Basic Properties and Characterization of Returned Materials

A specific quantity of rice straw and rapeseed straw powder was meticulously measured, placed within a crucible, and thoroughly covered. The crucible was then subjected to a pyrolysis process in a muffle furnace at a temperature of 600 °C for a duration of two hours, with the presence of limited oxygen. Following a period of cooling to room temperature, the sample was weighed and sieved through a 60-mesh sieve. Thereafter, it was placed in a self-sealing bag and stored in a dry and cool place. The fundamental properties of the materials returned are enumerated in Table 3. The carbon–nitrogen ratio of the rice straw (SF) was found to be significantly lower than that of rape straw (YF). The pH level of the rice straw biochar (SB) was found to exceed that of the rape straw biochar (YB). Furthermore, the yield was observed to be higher for SB, while the carbon percentage was found to be lower in comparison to YB. The process of preparing the straw into biochar resulted in an increase in the percentage of elemental carbon (C) and a decrease in the percentage of elemental hydrogen (H) within the biochar. As demonstrated in Figure 1, the X-ray diffraction (XRD) patterns of SB and YB exhibited broad diffraction peaks at 20–30°, indicative of the predominance of amorphous carbonaceous structures in the biochar matrix. The diffraction peaks observed in SB were found to be exclusively related to KCl. The peaks observed in YB at 28.2°, 40.42°, etc., were found to be associated with KCl, while the peaks at 29.28°, etc., were found to be associated with CaCO₃.

Table 3. Basic properties of test materials.

	pH	Agricultural Productivity (%)	C (%)	H (%)	O (%)	N (%)	C/N	C/H
SF	-	-	43.12	6.00	-	1.36	31.71	7.19
YF	-	-	40.09	6.59	-	0.44	91.11	6.08
SB	10.15	30.64	60.44	3.75	34.39	1.42	42.55	16.11
YB	10.03	27.42	68.31	3.76	27.6	0.33	206.08	18.17

2.2.4. Determination Methods

The pH of the soil was measured potentiometrically using a glass electrode pH meter (FE28-Standard, Mettler Toledo, Switzerland) that had been calibrated in advance [21]. The soil-to-water ratio used for this was 1:2.5. The cation exchange capacity (CEC) was determined via the barium chloride–sulfuric acid compulsory exchange method [21]. The soil alkaline nitrogen (AN) was ascertained through the utilisation of the alkaline diffusion method [22]. The rapid-acting phosphorus (AP) was determined by the sodium carbonate extraction-molybdenum antimony anti-spotting method [22]. The soil-available potassium (AK) present in the soil sample was measured using flame photometric detection, following the extraction of the sample with ammonium acetate [22]. Water was added in a 1:5 (m/V) ratio, and the extract was extracted by shaking at 20 °C ± 1 °C. The conductivity (EC) of the extract was then determined [23]. The activity of soil catalase was determined

by means of a hydrogen peroxide-potassium permanganate titration method [24]. The assessment of soil sucrase activity was conducted by means of the 3,5-dinitrosalicylic acid colourimetric method [24]. The soil urease was determined by a sodium phenol-sodium hypochlorite colourimetric method [25]. The quantification of soil organic carbon (SOC) was accomplished through the implementation of potassium dichromate oxidation and spectrophotometry [23]. The readily oxidised carbon (ROC) was determined by 333 mmol L⁻¹ KMnO₄ oxidation [23]. The estimation of soil microbial biomass carbon (MBC) was accomplished by employing chloroform fumigation extraction [26]. The quantification of soil dissolved organic carbon (DOC) was performed using a TOC (Multi N/C 3100, Analytik Jena, Jena, Germany) analyser [26].

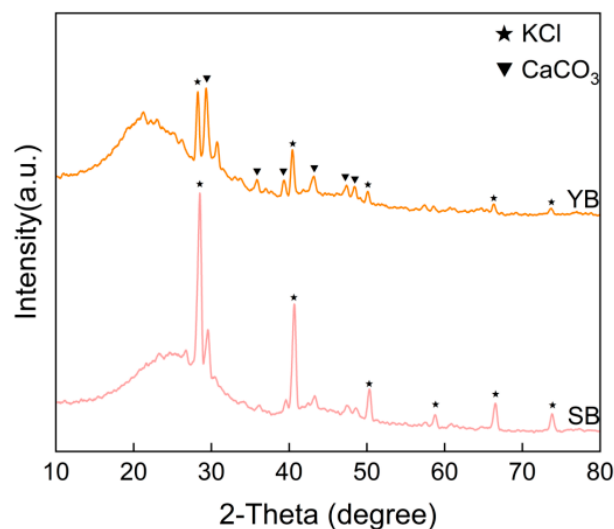


Figure 1. Biochar X-ray diffractometer pattern.

2.2.5. Data Processing

The data processing, plotting, and tabulation stages were conducted utilising SPSS 27, Origin Pro 2024 and Excel 2021 software. All data were expressed as the mean $\pm$ standard deviation (SD). One-way analysis of variance (ANOVA) was employed to ascertain the statistical significance of variations in outcomes among different treatments for a given incubation time, with a significance level of $p < 0.05$ (LDS post hoc test) ($n = 3$). The correlations between soil organic carbon fractions and soil enzyme activities and other physicochemical factors were analysed using OriginPro 2024 (OriginLab Corporation, Northampton, MA, USA) plotting (Pearson correlation analysis).

3. Results

3.1. Effects of Different Treatments of Straw and Biochar on Basic Soil Properties

The impacts of two-year straw and biochar amendments on fundamental soil properties are presented in Figure 2. The application of diverse treatments yielded no substantial alteration in soil pH when compared to the control (CK). The pH of the soil drops a lot as the rice maturity stage. In comparison with the CK control, the YSF, SB and YSB field return treatments exhibited a marked increase in soil AN content. The SB field return treatment demonstrated the most significant increase. The application of SF, SB and YSF treatments resulted in a significant increase in soil AK compared to the CK control. The application of YSB resulted in a substantial augmentation of the CEC content during the phase of rice maturation. Following a period of two years, the application of SB treatment resulted in a substantial increase in CEC content within the soil matrix. The AP content of the treatments attained its maximum value at the flowering stage in 2023, exhibiting an initial upward

trend, followed by a subsequent downward trend. Soil EC exhibited a substantial increase in response to the application of SF, YSF and YSB.

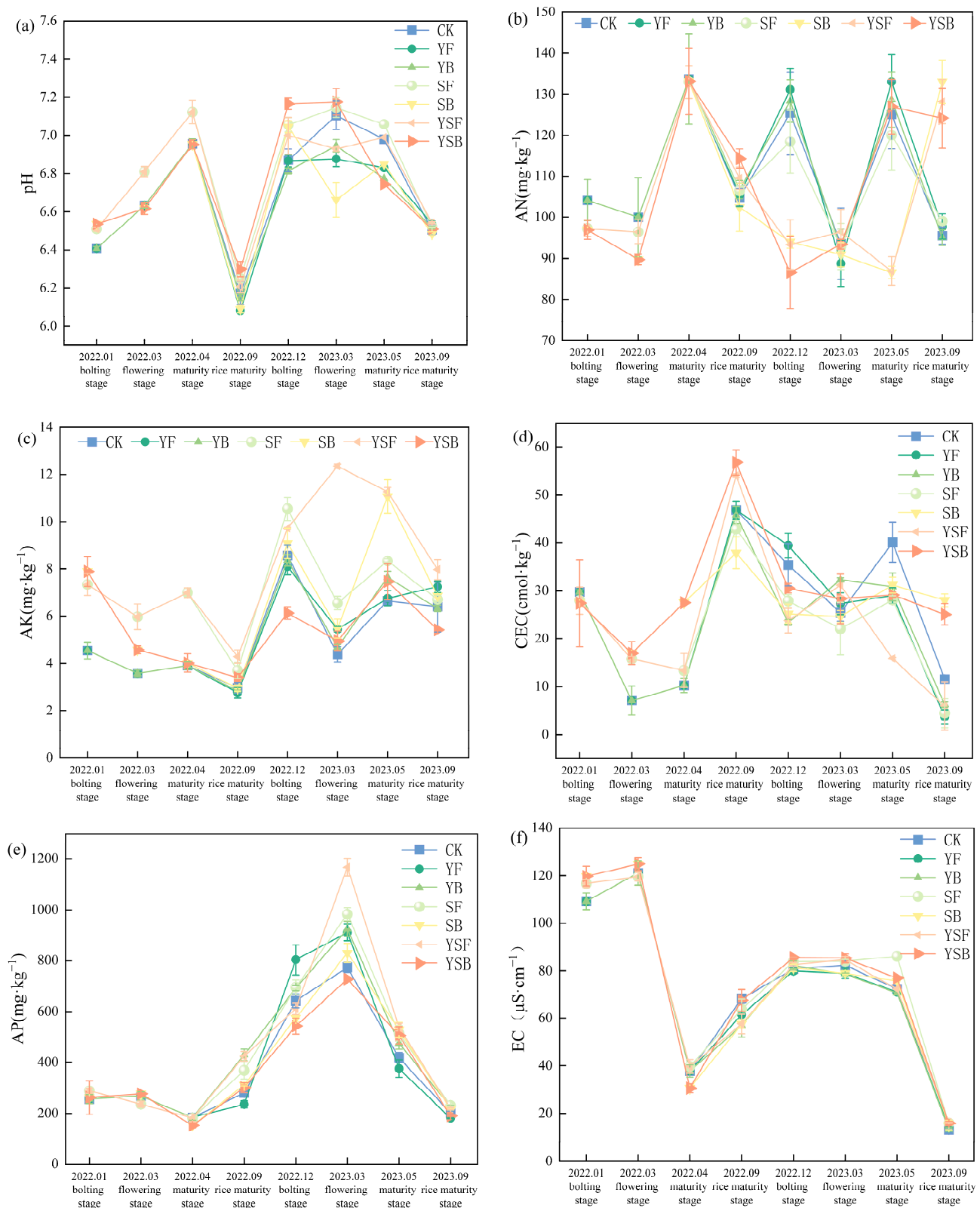


Figure 2. Effect of different straw and biochar reduction treatments on basic soil properties. (a) Acidity pH; (b) available nitrogen AN; (c) available potassium AK; (d) cation exchange capacity CEC; (e) available phosphorus AP; (f) electrical conductivity EC.

3.2. Changes in Soil Enzyme Activities with Different Straw and Biochar Return Treatments

As demonstrated in Figure 3, there is a dynamic interplay between soil sucrase, urease and catalase levels during the oilseed rape and rice seasons. As demonstrated in Figure 3a, soil sucrase activity exhibited substantial seasonal variations across all treatment groups. In April 2022, a significant decrease in soil sucrase was observed in the oilseed rape straw biochar, oilseed rape straw and blank groups in comparison to March 2022. The highest levels of soil sucrase activity were observed in March 2023 and May 2023 for each treatment. It was observed that, during the months of September 2022 and September 2023, there was a notable absence of significant soil sucrase activity. As demonstrated in Figure 3b, soil urease activity exhibited significant seasonal fluctuations, reaching a peak in September 2022. The application of rice straw biochar and rice–oilseed rape straw biochar resulted in reduced soil urease activity. The lowest recorded value of soil urease activity was observed in May 2023, and the application of oilseed rape straw resulted in a significant reduction in soil urease activity. As demonstrated in Figure 3c, soil catalase activity exhibited a tendency to initially increase and subsequently decrease in accordance with the duration of each treatment's reintroduction to the field. The activity of soil peroxidase exhibited a significant increase to a peak value in April 2022, subsequently decreasing to a minimum value in September 2022. Following a two-year field experiment, the application of rice straw biochar resulted in a significant enhancement of peroxidase activity by 49.19% in comparison with the control group (CK).

3.3. Changes in Soil Organic Carbon with Different Straw and Biochar Return Treatments

As demonstrated in Figure 4, the content of SOC exhibited an upward trend in accordance with the time of straw and biochar return to the field. The soil organic carbon content of the oilseed rape season was found to be significantly lower in comparison to the other periods in March 2022. An increase in soil organic carbon content was observed from September 2022 to December 2022, coinciding with the return of the YSB to the field treatment soil. The increase in soil organic carbon content was found to be 43.24%. Conversely, soil organic carbon exhibited less variability from December 2022 to May 2023, and the disparities in soil organic carbon content among treatments were not statistically significant. The utilisation of straw and biochar in a rice–rape rotation has been demonstrated to have a significant impact on the soil's SOC content over time in comparison with the pre-application state. Specifically, the application of rice straw biochar was shown to enhance the SOC content more effectively than rice straw, while the use of rape straw biochar was observed to yield superior results compared to rape straw. Furthermore, the combination of rice–rapeseed straw biochar has been found to demonstrate the most substantial enhancement in SOC content when compared to rice–rapeseed straw.

3.4. Changes in Soil Active Carbon Fractions by Different Treatments of Straw and Biochar Returned to the Field

As demonstrated in Figure 5, there was a dynamic shift in soil MBC in each treatment during the oilseed rape and rice seasons. The soil MBC content exhibited a tendency to decrease, subsequently followed by a gradual increase with the time of field return. The most significant change was observed in the CK treatment, which was implemented from December 2022 to May 2023. The MBC content attained its zenith in March 2023, marking an escalation of 60.25% in comparison with December 2022. In September 2023, the MBC content of the SB return treatment attained a maximum value of 765.89 mg·kg^{−1}.

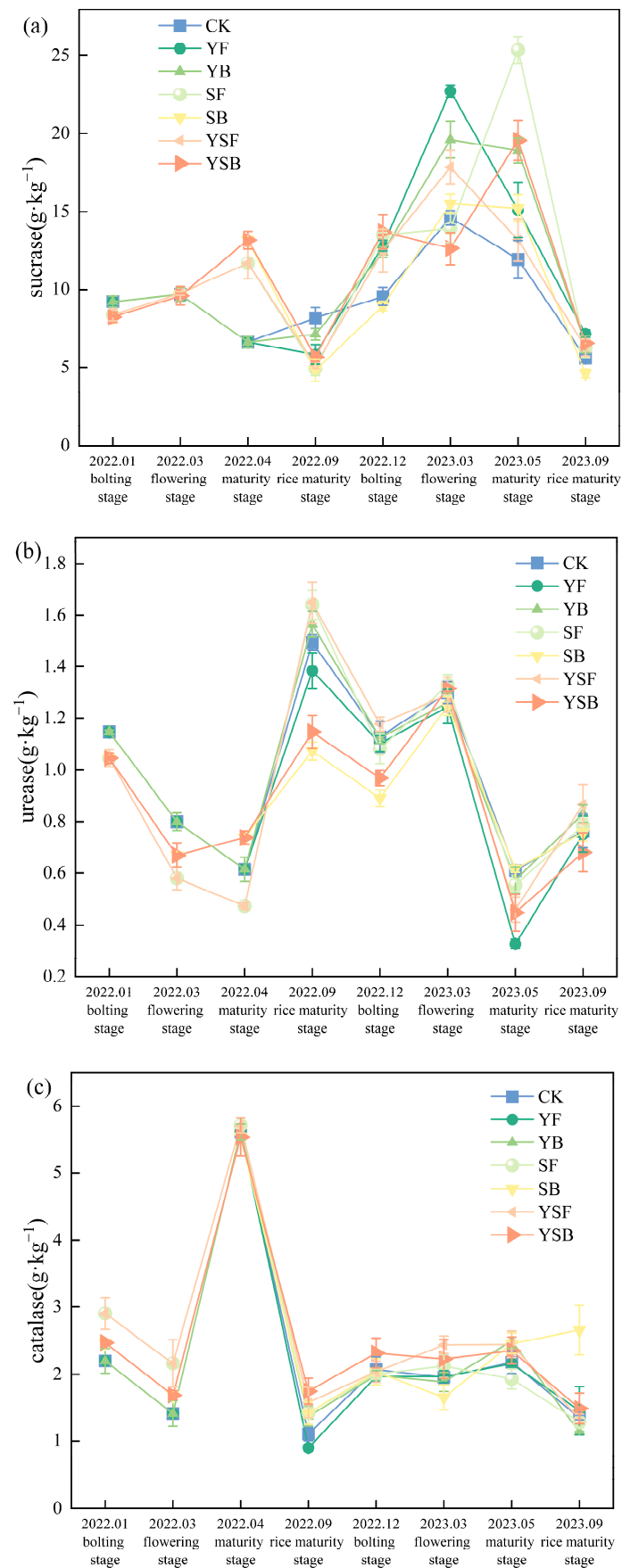


Figure 3. Changes in soil enzyme activities under different returning treatments of straw and biochar. (a) Soil sucrase activity; (b) soil urease activity; (c) soil catalase activity.

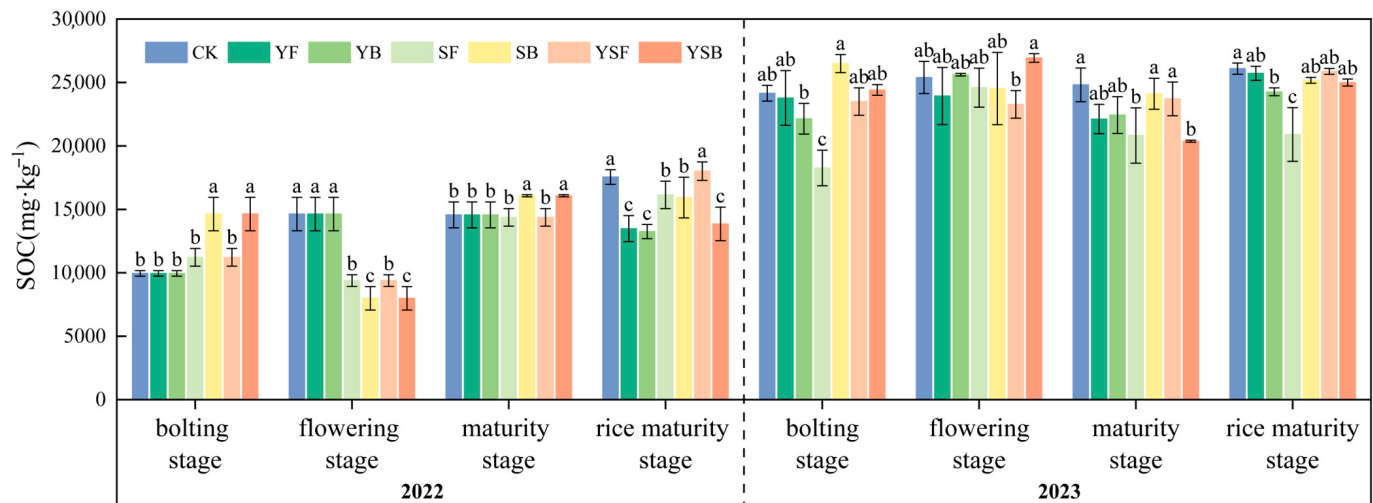


Figure 4. Changes in soil organic carbon by different return treatments of straw and biochar to the field. Different lowercase letters indicate that the differences between treatments are significant at the 0.05 level.

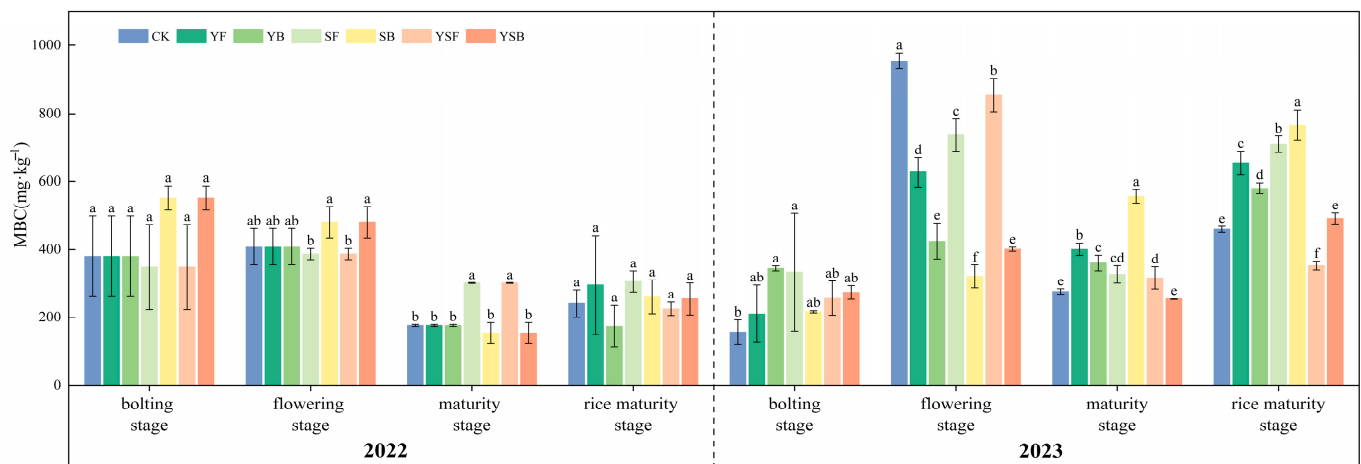


Figure 5. Changes in soil microbial biomass carbon with different straw and biochar restocking treatments. Different lowercase letters indicate that the differences between treatments are significant at the 0.05 level.

The alterations in soil DOC resulting from the implementation of straw and biochar are demonstrated in Figure 6. The impact of diverse straw and biochar treatments on DOC content exhibited significant variation ($p < 0.05$). With the exception of the SF and YSF treatments, the soil DOC content exhibited a significant “W”-shaped trend with the time of field return, reaching its maximum value in January 2022. Conversely, the soil DOC content of the SF and YSF treatments exhibited a significant “W”-shaped trend with the time of field return, also attaining its maximum value in January 2022. Following the initial peak in January 2022, soil DOC content demonstrated significant variability from January 2022 to April 2022, with comparatively minor fluctuations from March 2023 to September 2023 for CK and straw return. Following a two-year field experiment, the SB amendment treatment resulted in a statistically significant increase ($p < 0.05$) in soil DOC content, reaching the maximum observed concentration among all treatments.

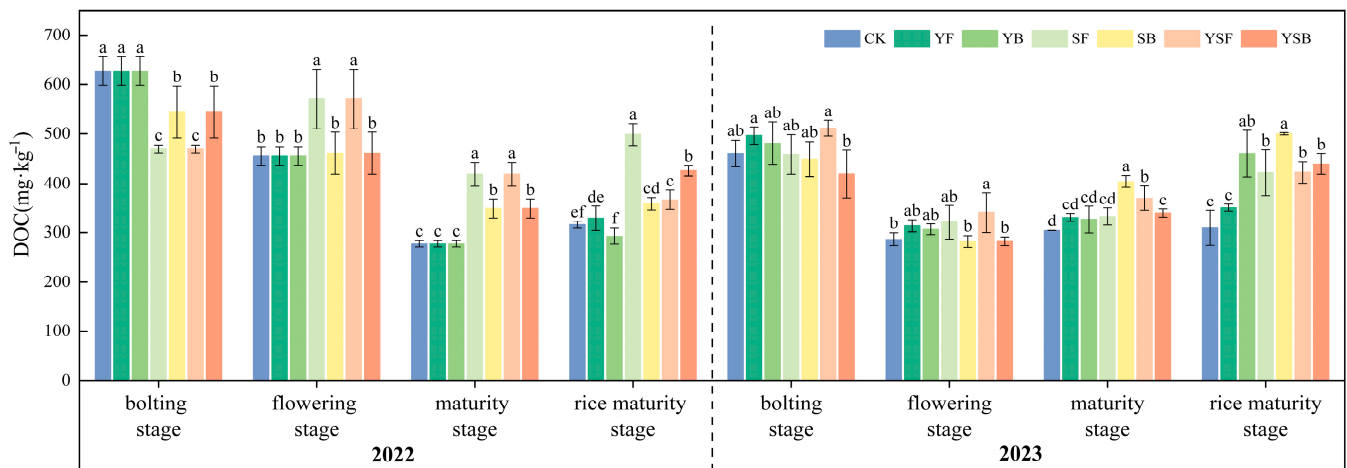


Figure 6. Changes in soil soluble organic carbon due to different treatments of straw and biochar for land reclamation. Different lowercase letters indicate that the differences between treatments are significant at the 0.05 level.

As demonstrated in Figure 7, the dynamics of soil ROC during the oilseed rape and rice seasons are illustrated. The data demonstrate a gradual increase in soil ROC content from January 2022 to September 2022, followed by a substantial surge of 62.81% to 75.22% from September 2022 to March 2023, reaching a maximum value in March 2023. Following the conclusion of the two-year field experiment, it was determined that the application of rice–oilseed rape straw biochar resulted in a significant reduction in soil ROC content.

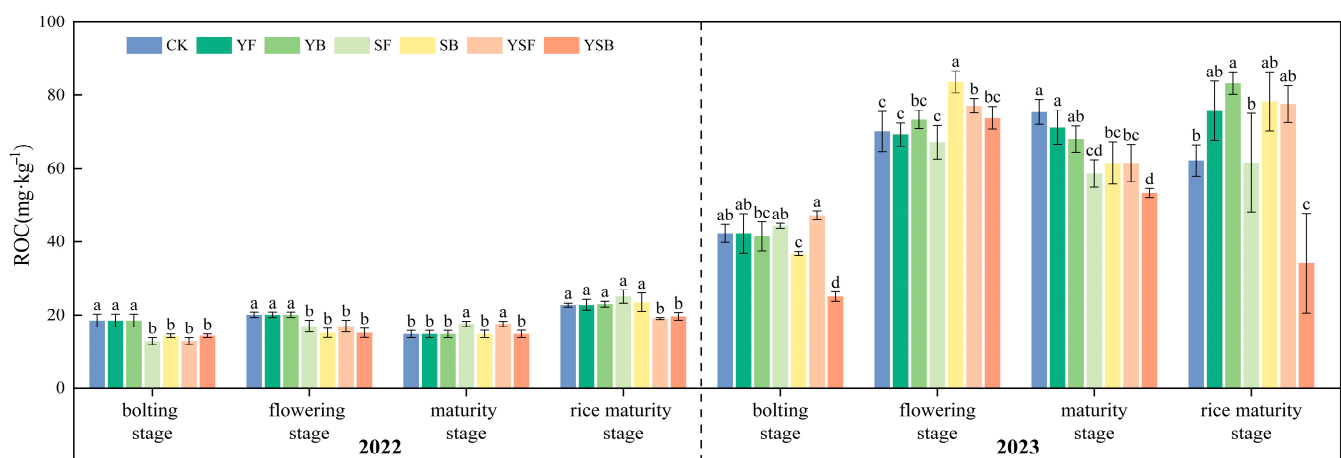


Figure 7. Changes in soil readily oxidizable organic carbon by different treatments of returning straw and biochar to the field. Different lowercase letters indicate that the differences between treatments are significant at the 0.05 level.

3.5. Correlation Analysis Between Soil Carbon Components and Physicochemical/Enzymatic Properties

As illustrated in Figure 8, a correlation exists between soil organic carbon and active carbon fractions on the one hand, and soil basic properties and soil enzyme activities on the other, following the application of straw and biochar under a rice–rape rotation. Sucrase activity exhibited a highly significant positive correlation with SOC and ROC. Furthermore, soil organic carbon (SOC) exhibited statistically significant correlations ($p < 0.01$) with multiple edaphic parameters, including pH, AK, AP, EC, sucrase activity, ROC and DOC. ROC was also found to be highly significantly correlated with AK, AP, sucrase, MBC, DOC and SOC.

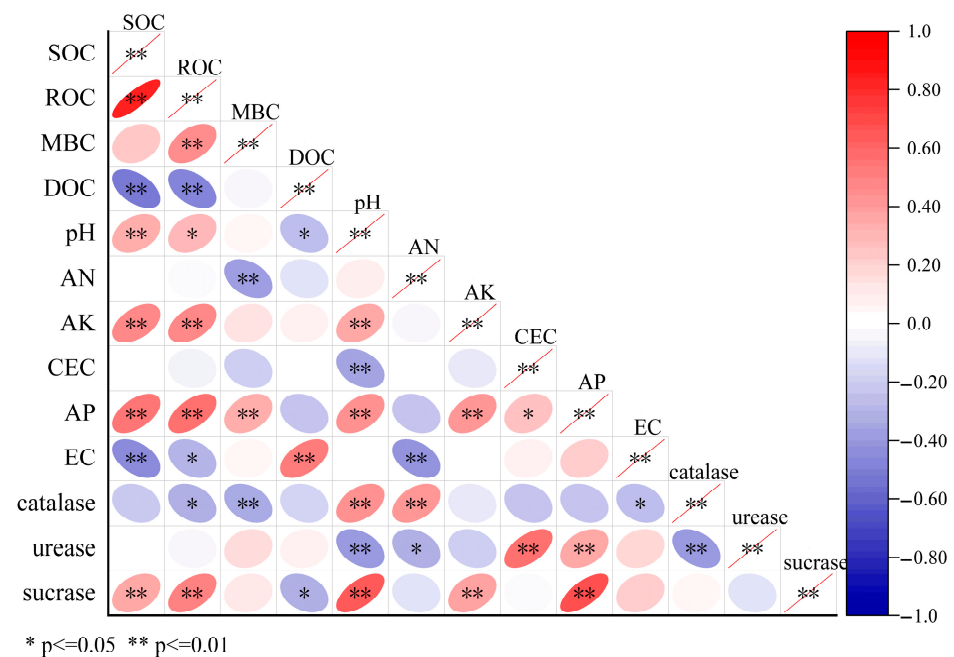


Figure 8. Correlation analysis between soil carbon components and physicochemical/enzymatic properties. Note: ** indicates a highly significant correlation at the 0.01 level (two-tailed); * indicates a significant correlation at the 0.05 level (two-tailed).

4. Discussion

4.1. Effects of Different Returning Treatments on Basic Properties of Rice–Rapeseed Rotation Farmland

It is evident that soil pH exerts a pivotal function in the regulation of biogeochemical reactions within soil [27]. The addition of exogenous organic matter, such as straw and biochar, has been demonstrated to exert a positive or negative priming effect on the mineralisation of SOC. This dynamic process contributes to the maintenance of a balanced total SOC content [28]. The findings of this experimental study demonstrated that the impact of various treatments on soil pH did not exhibit a significant difference. However, soil pH exhibited a highly significant positive correlation ($p < 0.01$) with basic soil properties such as soil organic carbon (SOC), ammonium potassium (AK), available phosphorus (AP), catalase and sucrase. Conversely, soil pH demonstrated a highly significant negative correlation ($p < 0.01$) with soil cation exchange capacity (CEC) and urease. As demonstrated by Wang et al. [29], the conversion and stabilization of organic carbon can be influenced by soil pH, through the regulation of soil enzyme activities. Soil pH can also regulate the decomposition and transformation of organic carbon by influencing the structure and function of microbial communities [30]. This finding suggests that pH plays a pivotal role in affecting changes in soil SOC and the active organic carbon fraction content. Following the process of rice cultivation, a significant decrease in soil pH is observed. This decline can be attributed to the promotion of decomposition of organic matter and reduction in iron in the soil by flooding, which results in the further release of H^+ ions and an increase in acidification [31].

It is imperative to acknowledge the pivotal role of nitrogen, phosphorus and potassium in facilitating optimal plant growth and sustaining optimal microbial activity [32]. Straw and biochar have been found to be rich in nitrogen, phosphorus, potassium and other essential nutrients. Their incorporation into soil has been demonstrated to enhance organic matter content, stimulate biological activity and improve nutrient availability [33]. In this experimental study, the effects of SB, YSF and YSB on improving soil nutrient content were investigated. The results demonstrated that, in comparison with the CK control, the YSF, SB

and YSB field return treatments exhibited a marked increase in soil AN content. The SB field return treatment demonstrated the most significant increase. These findings suggest that SB, SF and YSF have significant effects on improving soil nutrient content. The incorporation of straw into paddy fields has been shown to have a significant effect on mitigating nitrogen loss [34]. Similarly, the application of biochar to soil has been demonstrated to enhance its nitrogen retention capacity, thereby reducing nitrogen loss and, consequently, improving nitrogen use efficiency [35,36]. The judicious utilisation of rice straw biochar has been demonstrated to enhance rice yield while concomitantly reducing the reliance on chemical fertilisers. This approach constitutes a sustainable agricultural management strategy. The return of straw to the field has been demonstrated to increase soil phosphorus availability. Cao et al. demonstrated that crop straw not only increases directly available phosphorus for crops but also provides a long-term slow-release phosphorus source for crops and soil microorganisms [37]. The capacity of biochar to introduce AP into soil is dependent on the quantity and form of P present in the biochar [38]. The reintroduction of straw to the field has been demonstrated to facilitate the absorption of potassium by plants, thereby effectively supplementing the soil's potassium levels and enhancing its overall nutrient content [39]. Straw biochar has been found to contain significant amounts of available nitrogen and available phosphorus, and the high content of available potassium has been demonstrated to increase soil potassium concentration. The application of straw biochar has been demonstrated to enhance the absorption of nutrients from the soil [40].

Biochar has been shown to possess a high CEC, which has the potential to significantly enhance the cation exchange capacity of the soil. The utilisation of biochar has been demonstrated to enhance the CEC of soil, thereby augmenting its capacity for carbon storage through the augmentation of its organic matter content [41]. Soils with higher organic carbon content characteristically exhibit higher CEC, a factor that contributes to the maintenance of soil nutrient balance and the enhancement of soil fertility [42]. The present experimental study found that the CEC of SB and YSB treatments was significantly higher than that of CK. The findings of Chintala et al.'s cultivation study demonstrated that biochar can effectively enhance soil pH, EC and CEC [43]. The measurement of soil EC has been demonstrated to serve as a significant indicator of soil nutrient content [44]. The present experimental study demonstrated that soil EC was significantly increased by SF, YSF and YSB. This phenomenon may be attributed to the incorporation of organic matter into the soil, facilitated by the return of straw and biochar. Kim et al. demonstrated that the presence of organic matter in soil results in an increase in its ion content, thereby causing an elevation in the EC of the soil [45]. Straw is characterised by a high nutrient content, including nitrogen, phosphorus and potassium. During the process of decomposition, these nutrients are released into the soil, thereby increasing its cation exchange capacity [46].

4.2. Effects of Different Returning Treatments on Soil Enzyme Activities in Rice–Rape Rotation Farmland

It has been demonstrated that soil enzymes are capable of catalysing the decomposition of plant residues. This process involves the conversion of large organic molecules into small soluble carbon molecules, thereby accelerating the mineralisation of organic carbon [47]. Invertase is a vital soil enzyme that can catalyse the hydrolysis of sucrose in plant tissues. It is a pivotal enzyme in the carbon cycle [48]. The findings of the research indicate that, in April 2022, the activity of soil invertase in rapeseed straw biochar, rapeseed straw and the control group, which served as a baseline, was significantly lower than that observed in March 2022. This phenomenon may be attributable to the substantial absorption of nutrients by rapeseed plants during their mature stage of development. This process has been observed to result in a decline in the readily degradable carbon present within the soil matrix, including components such as root exudates [49]. The activity of soil invertase

reached its peak in March and May 2023 for each treatment. This finding is analogous to the results reported by Luo et al. [50]. It has been demonstrated that the demand for sucrose decomposition by rapeseed increases during the flowering and mature stages [51]. Consequently, this results in an increase in invertase activity. Concurrently, the ambient temperature is optimised to ensure the efficiency of the enzymatic reactions. The relatively low levels of soil invertase activity observed in September 2022 and 2023 may be attributed to oxygen deficiency during the waterlogged rice-growing season. This deficiency has been shown to suppress aerobic microbial activity and consequently reduce invertase production [52].

Research has demonstrated that soil urease activity exhibits significant seasonal variations, reaching its peak in September 2022. The application of rice straw biochar and rice–rapeseed straw biochar resulted in a comparatively minor increase in soil urease activity. This phenomenon may be attributed to the substantial input of organic matter derived from residual roots and straw during the maturation stage of rice cultivation, which serves as a critical substrate for soil biogeochemical processes. It has been established that these organic substances fulfil the role of carbon sources and energy sources for microorganisms. Stimulation of their proliferation is observed, as is promotion of the synthesis and secretion of urease [53]. Rice straw biochar has been shown to exhibit high carbon stability and low nitrogen content. During the process of microbial decomposition, it has been observed to be responsible for the fixation of inorganic nitrogen in the soil [11]. The consequence of this is the production of a relatively low urease substrate, which in turn results in the inhibition of urease activity. In May 2023, the activity of soil urease reached its lowest recorded value, and the application of rapeseed straw resulted in a significant reduction in soil urease activity. This phenomenon may be attributable to the substantial absorption of soil nitrogen by the cultivated crops [54]. A reduction in the urea substrate, in conjunction with water stress during the dry season, has been shown to inhibit urease activity. At this particular juncture, it is conceivable that rapeseed straw may undergo a process of decomposition, which has been observed to result in the secretion of inhibitory substances. This phenomenon has been shown to induce a decline in urease activity [55].

Oxidative enzymes, including catalase, play a pivotal role in the humification process by facilitating the transformation of organic matter into stable forms through oxidation reactions. This process is instrumental in enhancing the stability of soil organic carbon [47]. In the rice–rape rotation system, the effects of different returning treatments on soil enzyme activities demonstrate significant inter-annual and seasonal differences, primarily due to the dynamics of carbon sources, microbial responses and temperature variations. The findings of the research indicate that in April 2022, all return-to-field treatments significantly increased the activity of catalase. Conversely, in September 2022, these treatments significantly decreased the activity of catalase. This phenomenon may be attributed to the decomposition of organic matter during the maturation period of rapeseed, which in turn stimulates the activity of aerobic microorganisms [56]. The process is characterised by the accumulation of hydrogen peroxide, which in turn promotes the synthesis of catalase. However, following the rice season and the occurrence of flooding, the soil became anaerobic, thereby restricting the production of catalase and reducing the demand for it. This was due to the domination of anaerobic microorganisms over the metabolic pathways, which resulted in a decline in catalase activity. Following the conclusion of the two-year field trials, it was determined that the soil treated with rice straw biochar exhibited the highest catalase content. This phenomenon can be attributed to the highly aromatic nature of rice straw biochar, its slow rate of decomposition and its capacity to release stable carbon sources on a continuous basis [57]. The process of accumulating organic matter in the soil has been shown to have a number of important consequences. Firstly, it provides rich

substrates for microorganisms, which in turn promotes their metabolic activities. This, in turn, has been demonstrated to enhance the activity of enzymes such as catalase in the soil [58].

4.3. Effects of Different Return Treatments on SOC Transformation in Rice–Rape Rotation Farmland

It is evident that minor alterations in SOC can exert a substantial influence on carbon cycle feedbacks, thus underscoring their critical role in the process of soil carbon sequestration [59]. The findings of this experimental study demonstrated that all treatments in the rice–rape rotation field trial exhibited a significant increase in soil organic carbon content. However, the difference between the effects of straw and biochar return on SOC content was not significant in comparison with CK. This was due to the fact that the inputs of SOC in the field trial were mainly from crop apoplasts, roots, and secretions, and the inputs were substantial. The increase in the amount of crop growth, root, weed and litter returned to the field resulted in an increase in the total organic carbon content of the soil [60]. In addition, the exogenous addition of straw and biochar resulted in a relatively small enhancement of soil SOC content. It can be hypothesised that the higher soil organic carbon content observed in the rice–rape rotation system is indicative of higher root biomass, greater carbon sequestration capacity and lower carbon release [61]. The incorporation of rice straw biochar proved to be a more efficacious method of increasing the soil's organic carbon content when compared with the rice straw addition treatment.

Soil-active organic carbon constitutes a minor proportion of total soil organic carbon. However, it directly participates in the biochemical transformation process in the soil, serving as the carbon source for soil microbial activities and the driving force for soil nutrient flow [62]. Soil MBC constitutes a negligible proportion of the soil; however, it is a reliable indicator of the quantity of soil microorganisms and is a significant metric for evaluating the quantity and activity of these organisms, as well as soil fertility [63]. Following two years of field experiments, the MBC content in the SB treatment reached a maximum value of 765.89 mg·kg⁻¹. The application of straw biochar resulted in a substantial increase in the MBC of the soil surface, leading to the stabilisation of the slow release of carbon. Furthermore, the formation of an organic–mineral complex on the surface of the biochar ensured the continuous feeding of the microbial community [64]. Following a period of two years, the rate of carbon release was optimally balanced with the efficiency of microbial utilisation. Furthermore, the maximum accumulation of MBC was achieved. This is attributable to the fact that SB is generated by high-temperature pyrolysis of straw, and its aromatic carbon structure is highly stable and difficult to be decomposed directly by microorganisms in a short period of time [65]. The MBC continued to accumulate due to the stability of SB, significantly outperforming the other treatments at 2 years. Odugbenro et al. [66] discovered that the high porosity, large internal surface area and abundance of microporous structures in biochar can enhance soil aggregate stability, thus facilitating the immobilisation and long-term storage of soil MBC. The YSF and YSB treatments demonstrated significantly lower mean concentrations in comparison to the other treatments. This phenomenon may be attributed to microbial community competition induced by frequent carbon source alternation. As demonstrated by Yan et al. [67], environmental conditions have been shown to exert a substantial influence on the composition and distribution of microbial communities. Moreover, emerging evidence suggests that microbial community dynamics are modulated by multiple factors, particularly carbon source variability and transition frequency [68].

DOC has been identified as a significant constituent of soil organic carbon. The concentration and dynamic fluctuations of the phenomenon under investigation exert a direct influence on the storage and cycling of soil carbon [69]. In this experiment, the

soil DOC content showed a “W” shape trend of increase and decrease with the growth cycle of crops under the treatment of returning straw and biochar to the field, and the SB treatment had the best effect on increasing the soil DOC content. This phenomenon may be attributable to alterations in DOC content, consequent to variations in carbon input dynamics and the modulation of microbial–crop interactions [70]. Straw DOC is subject to rapid depletion, whereas rice straw biochar has the capacity to provide a stable carbon source over time, resulting in a high DOC content after a period of two years [71].

Changes in the amount of oxidizable organic carbon in soil are indicative of changes in the dynamics of soil carbon pools [72]. It is evident that soil oxidizable organic carbon is of significance in enhancing soil quality, sustaining soil fertility, and preserving the equilibrium of soil carbon pools [73]. The experiment demonstrated that the application of rice–oilseed rape straw biochar resulted in diminished efficacy in enhancing soil ROC content within a rice–rape rotation. The experiment demonstrated that a single application of straw and biochar was more efficacious than a mixed treatment in the context of rice–rape rotation. This may be due to the fact that seasonal mixing may not adequately account for seasonal variations in soil microbial activity [74], resulting in a less pronounced synergistic effect of biochar and straw. The following study investigates the effects of different return treatments on the enhancement of soil ROC content by oilseed rape straw biochar, oilseed rape straw, rice straw biochar and rice–oilseed rape straw. The study demonstrated that the application of rice–rape straw biochar resulted in a decrease in soil ROC content in comparison with the control group. This phenomenon may be attributable to the fact that biochar has been demonstrated to retard the renewal of organic carbon and possesses a greater potential to sequester carbon and augment sinks in comparison to the direct return of straw to the field. However, the high adsorption capacity of biochar leads to microbial entrapment in its pore network, reducing microbial access to organic substrates and thereby lowering biochar degradation rates [75].

The implementation of a correlation analysis revealed a statistically significant positive relationship ($p < 0.01$) between soil sucrase activity and both SOC and ROC content. This finding suggests the presence of a substantial correlation between the activity of enzymes present in soil and the quantity of carbon in soil that is considered to be organic. ROC is an active component of SOC, and its accumulation contributes directly to the stability of the SOC pool. For instance, as Zhu et al. discovered, there is a demonstrable correlation between enzyme activity and SOC [76]. This is a synergistic cycle effect involving “microbes, enzymes and carbon substrates”, where sucrase hydrolyses sucrose to produce glucose and fructose, which provide fast-acting energy for microorganisms and drive MBC proliferation. Accelerating MBC turnover promotes the input of microbial residues, while microbially secreted extracellular polysaccharides (EPSs) can physically sequester ROC and reduce its mineralisation rate by forming microaggregates through cementation [77]. This further prolongs the organic carbon turnover cycle, forming a positive cyclic pathway for carbon sequestration. It has been demonstrated that regulating sucrase activity is crucial for enhancing the carbon sequestration potential of rice paddies. A significant correlation was observed between pH and the three enzymes. In their seminal study, Jakob et al. discovered that soil enzyme activity exhibited a high degree of sensitivity to pH changes, and was also influenced by temperature [78]. This resulted in significant seasonal fluctuations in soil enzyme activity. The highly significant negative correlation between pH and urease ($p < 0.01$) is rooted in the neutral optimum property of pH. At higher pH levels, NH_3 volatilisation leads to a loss of substrate (NH_4^+), which in turn reduces urease activity. Additionally, the OH[−] dissociation of the urease bis-Ni²⁺ active centre may result in the inactivation of the catalytic site [79]. The present study demonstrates a highly significant positive correlation ($p < 0.01$) between pH and catalase, which may reflect the former’s

alkaline stability and the latter's high pH-induced oxidative stress [80]. The highly significant positive correlation between pH and sucrase ($p < 0.01$) was then the result of a balance between fungal acidic adaptation and bacterial alkaline compensation, with attenuation of fungal secretion offset by bacterial compensatory secretion [81]. The findings of this study indicate that soil pH has a synergistic effect on catalase and sucrase activities. In contrast, the buffering of alkaline soils with additional organic matter is crucial for the preservation of urease function. The results of the study demonstrated a significant and positive correlation between EC and sucrase and urease, suggesting that elevated salinity inhibits microbial secretion of extracellular enzymes. The findings indicate that urease and sucrase can serve as correlative enzymes for the carbon and nitrogen cycles. In the rice–rapeseed rotation system, SOC has been shown to act as a regulatory hub, thereby influencing soil fertility and ecological functions via significant correlations with physical, chemical and biological indicators. Firstly, the correlation between SOC and pH, AK and AP reflects the bidirectional effect of organic matter on nutrient cycling. Secondly, it is evident that soil with higher SOC content generally exhibits higher MBC, which in turn may further encourage the expression and activity of sucrase [82]. The findings of this study indicated that SOC interacted with soil physicochemical properties and enzyme activities. Furthermore, the application of SB led to an improvement in the composite indexes, which further promoted the transformation of organic carbon fractions under rice straw–oilseed rape rotation.

5. Conclusions

The study demonstrated that the application of rice straw biochar field return could enhance the sequestration of organic carbon in rice and rape rotation systems fields. The impact of various field return treatments, including straw and biochar, on soil-active organic carbon exhibited significant variation. In comparison with the control group (CK), the implementation of a single application of rice straw biochar resulted in a substantial enhancement of the soil microbial biomass carbon (MBC), soluble organic carbon (DOC) and readily oxidizable organic carbon (ROC) contents. Furthermore, the application of rice straw biochar to the field has been shown to enhance soil catalase activity, accelerate the decomposition of organic matter and nutrient cycling and promote plant growth. Conversely, the application of rice straw biochar had a substantial impact on soil nutrients, particularly on soil cation exchange capacity (CEC), which enhanced the adsorption and retention capacity of soil nutrients. The application of rapeseed straw in isolation or in combination with rapeseed straw biochar within the field environment led to a significant increase in soil sucrase activity and soil readily oxidizable organic carbon (ROC) content. However, this application exhibited a comparatively lesser effect on soil carbon fixation in comparison to the utilisation of rice straw biochar within the field environment. The utilisation of straw and biochar has been demonstrated to mitigate soil alkalisation and augment soil pH, thereby enhancing soil basic properties and, consequently, optimising soil fertility. The application of rice straw biochar during the oilseed rape planting period was found to be most favourable to the conversion of soil organic carbon fractions in the field under rice–rape rotation.

The pore structure of biochar has been demonstrated to enhance the water-holding capacity of soil, alleviate drought during the rice season and stains during the rape season and can be effective in retaining water and combating drought. The utilisation of rice–oilseed rape straw in the production of biochar in situ offers a solution to the problem of open burning, while concurrently reducing the amount of nitrogen fertiliser required. It is imperative to provide a robust argument for the exploration of soil carbon sequestration. The study demonstrates that the process of soil carbon sequestration is both reliable

and effective in reducing emissions and sequestering carbon. The experimental findings demonstrate that biochar application enhances the conversion of soil carbon fractions, as well as soil carbon sequestration. This may result in the incorporation of biochar carbon sequestration into agricultural carbon trading. The experimental period of this study was relatively brief, spanning a duration of two years. This is due to the fact that long-term positional observations of a duration exceeding ten years are not available. Furthermore, the sustained improvement effects of biochar, such as its capacity for carbon sequestration stability and nutrient slow-release capacity, remain ambiguous. The yield increase effect of biochar on rice and oilseed rape was found to be inconsistent, and its effect on crop yield, among other factors, has yet to be the subject of detailed study. Further investigation into this area could yield valuable insights into the long-term biochar return to the field response mechanism.

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