

Article

Straw-Derived Synthetic Humic Acid Improves Soil Structure, Nutrient Availability, Humification, and Crop Productivity in a Compacted Alkaline Farmland of the Yellow River Floodplain

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Abstract

Sustainable crop residue management in alkaline agroecosystems is challenging due to trade-offs among carbon stabilization, nutrient availability, and microbial activity. To identify an optimal upcycling strategy for compacted alkaline farmland, a two-year wheat–maize rotation experiment in the Yellow River floodplain compared four treatments: no organic amendment (CK), direct straw return (CS), straw-derived biochar (CB), and straw-derived synthetic humic acid (CH). Results showed that CH produced the most balanced improvements across all dimensions. Compared to CK (pH 8.62) and CB (pH 9.16), CH significantly reduced soil pH to 8.03, enhancing alkaline buffering. CH achieved the highest available phosphorus (2.36 mg kg^{−1}), macroaggregate proportion (19.40%), and microbial biomass carbon (91.77 mg kg^{−1}). Enhanced humification was evidenced by superior HA content (5.82 mg kg^{−1}) and an HA/FA ratio of 1.90 in the 0–20 cm layer. Agronomically, CH achieved the highest annual grain production (ATGP, 12.11 × 10³ kg ha^{−1}, comprising 5.65 × 10³ kg ha^{−1} for wheat and 6.46 × 10³ kg ha^{−1} for maize) and maximum Integrated Sustainability Score (ISS = 1.000). These findings suggest that converting straw into synthetic humic acid effectively bridges the gap between unstable raw residues and inert biochar, serving as a promising alternative pathway for improving soil structure, nutrient availability, and productivity in compacted, alkaline floodplain farmland.

Keywords: biomass upcycling; straw utilization; synthetic humic acid; resource use efficiency; alkaline soil amelioration; Yellow River floodplain



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1. Introduction

The use of land for agricultural purposes is often limited by severe environmental constraints, making sustainable production increasingly challenging [1–3]. The historical Yellow River floodplain is an important agricultural region of the North China Plain, but its use for agricultural purposes is often limited by several interacting soil factors [4,5]. In addition to low soil organic matter and structural degradation, these farmlands are influenced by long-term hydrological disturbance, alternating wetting–drying cycles, and intensive cultivation. In low-lying areas, crop production may be affected by temporary

waterlogging during the rainy season and subsequent moisture shortage during drying periods. Such conditions place greater demands on soil structure, nutrient buffering, and biological functioning [4,5].

The soils of this region also commonly exhibit alkaline conditions and management-related compaction, both of which restrict crop performance [4–7]. Weak aggregation, elevated bulk density, restricted root-zone development, and low nutrient availability may occur simultaneously in floodplain cropland [4,6,7]. Under alkaline conditions, phosphorus availability is particularly constrained because a substantial proportion of soil P may remain in sparingly available forms [8–10]. Therefore, amendment strategies in these soils should be evaluated not only for their capacity to add carbon, but also for their ability to alleviate alkaline stress, improve structural stability, sustain microbial functioning, and support crop production in an integrated manner.

Returning crop residues to the field is widely practiced to maintain soil organic matter and support soil fertility [11]. However, direct straw incorporation often shows limited short-term effectiveness because crop residues usually have a high C/N ratio and a recalcitrant lignocellulosic structure [12–14]. In compacted and nutrient-constrained soils, this may temporarily immobilize nitrogen, delay nutrient release, and reduce the short-term agronomic value of residue return [12,14,15]. Converting residues into biochar is another common utilization pathway that can increase soil carbon stocks and modify soil physicochemical properties [16,17]. However, straw-derived biochar is often characterized by alkaline properties and may modify soil pH [16–18], and its application to already alkaline farmland may intensify high-pH conditions and reduce nutrient availability, particularly phosphorus availability [8–10,17,18]. These limitations suggest the need for an alternative residue-conversion pathway that can promote carbon transformation and nutrient regulation without further increasing soil pH or exacerbating alkaline-related issues such as nutrient fixation.

Synthetic humic acid derived from agricultural residues has emerged as a promising amendment for degraded cropland [19–23]. Compared with raw straw, it contains more transformed and functionally active organic components [23,24]. In addition, unlike alkaline biochar, it may improve soil condition without further intensifying alkaline stress [21,25,26]. Previous studies have linked straw-derived synthetic humic materials to improved aggregation, carbon transformation, nutrient retention, and humification in soil [21,24,26–29]. Related evidence has also suggested their potential contribution to the rehabilitation of degraded cropland [21,24,26]. These properties are particularly relevant in the Yellow River floodplain, where soil rehabilitation requires simultaneous improvement in structure, nutrient status, biological activity, and carbon transformation. However, field-based evidence directly comparing direct straw return, straw-derived biochar, and straw-derived synthetic humic acid within the same alkaline floodplain system remains limited, particularly when soil chemical, structural, biological, humification, and productivity responses are considered together.

Accordingly, this study evaluated the effects of three straw-utilization pathways—direct straw return, straw-derived biochar, and straw-derived synthetic humic acid—on soil properties and crop productivity in a compacted alkaline farmland of the Yellow River floodplain. We hypothesized that, relative to direct straw return and biochar, synthetic humic acid would more effectively: (i) improve aggregate-size distribution and biologically active carbon fractions; (ii) alleviate soil alkalinity and maintain higher nutrient availability; and (iii) promote humification in both surface and subsurface soil. The objective was to identify a more suitable residue-management pathway for rehabilitating compacted alkaline floodplain soil through both direct measurement of soil responses and comprehensive evaluation of various soil physical, chemical, and biological indicators alongside crop yield.

2. Materials and Methods

2.1. Site Description and Environmental Design

The field experiment was conducted from June 2023 to October 2024 in the historical Yellow River floodplain region (33°21' N, 116°41' E, altitude: 17 m). The site is located in a warm temperate monsoonal climate zone. The site is representative of low-lying floodplain cropland that is subject to frequent alternation between spring drought and summer waterlogging [4,5]. The experimental procedure is outlined in Supplementary Material S1 (Figure S3). The initial physicochemical properties of the experimental soil (0–20 cm) are summarized in Table 1 (Part A). These properties indicate typical alkaline conditions (pH 8.60) and a high bulk density (1.58 g cm^{-3}) that exceeds the critical threshold for root restriction in silty soils [6].

Table 1. Basic properties of the initial soil and the residue-derived materials used in this study.

Part A. Initial Physicochemical Properties of the Experimental Soil (0–20 cm) Before Treatment Application					
Parameter	Unit	Value			
Clay	%	42.00			
Silt	%	45.00			
Sand	%	13.00			
Texture	–	Silty clay loam			
Bulk density	g cm ^{−3}	1.58			
pH (H ₂ O)	–	8.60			
EC	mS cm ^{−1}	0.55			
SOC	g kg ^{−1}	6.22			
Total nitrogen (TN, Nt)	g kg ^{−1}	1.38			
Easily hydrolyzable nitrogen (EHN)	mg kg ^{−1}	7.06			
AP	mg kg ^{−1}	2.17			
AK	mg kg ^{−1}	68.70			
Total salt	g kg ^{−1}	1.83			
Saturated hydraulic conductivity	cm s ^{−1}	2.03 × 10 ^{−6}			
Part B. Basic Properties of the Residue-Derived Materials Applied or Prepared in This Study					
Parameter	Unit	Wheat Straw	Corn Straw	Biochar	Synthetic Humic Acid
Carbon (C)	%	42.50 ± 1.20	44.80 ± 1.50	83.20 ± 6.51	50.50 ± 4.73
Nitrogen (N)	%	0.48 ± 0.05	0.72 ± 0.08	1.35 ± 0.06	2.14 ± 0.13
C/N ratio	%	88.5	62.2	61.6	23.6
N/S ratio	%	1.92	4.80	2.81	6.90
Hydrogen (H)	%	4.90 ± 0.56	5.41 ± 0.63	1.53 ± 0.11	6.51 ± 0.77
Oxygen (O)	%	44.80 ± 1.65	47.30 ± 1.35	13.60 ± 0.94	40.60 ± 1.21
Sulfur (S)	%	0.25 ± 0.04	0.15 ± 0.03	0.48 ± 0.05	0.31 ± 0.06
Cellulose	%	38.20 ± 2.10	35.40 ± 1.80	N/A *	N/A *
Hemicellulose	%	24.50 ± 1.40	22.10 ± 1.20	N/A *	N/A *
Lignin	%	15.80 ± 1.10	12.50 ± 0.90	N/A *	N/A *
Ash	%	6.50 ± 0.40	5.20 ± 0.30	-	-
pH (H ₂ O)	–	7.15	6.28	10.70	4.55
EC	mS cm ^{−1}	0.94	0.82	4.00	-
Humic acid (HA)	%	-	-	-	31.2
Fulvic acid (FA)	%	-	-	-	12.6

Note: N/A: Not applicable. * The crystalline structure of cellulose and the phenolic networks of lignin are fundamentally depolymerized and transformed into aromatic and humic-like structures during high-temperature pyrolysis and supercritical ammonification processes, making traditional fiber analysis inapplicable.

According to the World Reference Base for Soil Resources (WRB), the soil is classified as a Calcaric Fluvisol, characterized as a compacted silty clay loam with an alkaline

reaction and low organic carbon. Baseline physicochemical properties (0–20 cm) prior to treatment application are summarized in Table 1. A randomized block field experiment was established under a winter wheat–summer maize rotation system. Winter wheat (*Triticum aestivum* L., cv. Zhongmai 578) was sown on 15 October 2023 and harvested on 5 June 2024. Summer maize (*Zea mays* L., cv. Huaiyu 7967) was sown on 15 June 2024 and harvested on 5 October 2024. Four treatments were implemented with three replicates each: (1) CK: no organic amendment (control); (2) CS: direct straw return; (3) CB: straw-derived biochar; and (4) CH: straw-derived synthetic humic acid. Fertilizer application, irrigation, and pest management followed local conventional practices and were applied uniformly across all treatments to ensure that observed differences were solely attributable to the amendment pathways. All organic amendments (CS, CB, and CH) were manually broadcast onto the soil surface at an equivalent carbon rate approximately one week before sowing. Immediately after broadcasting, the materials were mechanically incorporated into the topsoil (0–20 cm depth) using a tractor-drawn rotary tiller to ensure uniform mixing. Conventional NPK fertilizers were applied simultaneously according to local practices.

2.2. Preparation and Characterization of Amendments

While both wheat and corn straws are abundant in this rotation system (properties shown in Table 1 Part B), wheat straw was specifically selected as the primary feedstock for preparing the biochar (CB) and synthetic humic acid (CH) treatments in this study. This selection was based on its higher C/N ratio and more recalcitrant lignocellulosic structure, which typically present greater challenges for direct decomposition in alkaline soils. Wheat and corn straw were collected locally as raw materials. Their basic chemical properties are presented in Table 1 (Part B). For the CB treatment, biochar was produced by pyrolysis under oxygen-limited conditions at 500–600 °C with a heating rate of 10 °C min^{−1}. For the CH treatment, straw-derived synthetic humic acid was synthesized via a novel supercritical ammonification process developed in our laboratory. Briefly, air-dried crop straw was crushed and mixed with aqueous ammonia (concentration: 10%) at a solid-to-liquid ratio of 1:10 (*w/v*). The mixture was then transferred into a sealed high-pressure autoclave reactor and rapidly heated to 150 °C. Under these conditions, the system generated a self-pressurized supercritical environment of 12 MPa. After a short reaction time of 2 min, the reactor was rapidly cooled to room temperature. This unique *de novo* thermochemical process was specifically designed to disrupt the recalcitrant lignocellulosic structure while directly incorporating nitrogen-containing functional groups into the carbon matrix, thereby promoting rapid humification without the need for traditional prolonged composting. The final highly reactive humic product was collected, dried, and ground for field application. This product is currently a laboratory-synthesized prototype developed by our research group and has not yet been commercialized or patented.

To confirm the successful humification and address the chemical mechanism, the product was analyzed for its humic substance content. Based on the classic alkaline-extraction and acid-precipitation method (International Humic Substances Society protocols), the synthetic humic acid (CH) contained a high proportion of extractable humic substances, specifically yielding 31.2% humic acid (HA) and 12.3% fulvic acid (FA) by dry weight. This confirms its classification as a synthetic humic material.

Chemically, the conversion of straw lignocellulose into humic acids during this supercritical ammonification involves two primary reaction pathways. First, high-temperature and high-pressure water facilitates the depolymerization (hydrolysis) of cellulose into reducing sugars and furfurals, while lignin is cleaved into reactive phenolic monomers. Second, these reactive intermediates undergo spontaneous polycondensation and Maillard-type

reactions in the presence of ammonia (NH₃). The simplified chemical reaction pathways can be expressed as follows:

- (1) Depolymerization: Lignocellulose + H₂O $\xrightarrow{150^{\circ}\text{C}, 12\text{ MPa}}$ Phenolic monomers + Reducing sugars/Furfurals
- (2) Polycondensation: Phenolic monomers + Sugars/Furfurals + NH₃ $\xrightarrow{\text{Maillard/Polymerization}}$ N-enriched Synthetic Humic Acid (N-AHA) + H₂O

This process effectively restructures the aliphatic chains into aromatic, highly functionalized humic-like polymers.

The characteristics of residue-derived materials were determined as follows: The elemental compositions (C, H, O, N, and S) were quantified using an automated elemental analyzer (Vario EL III, Elementar, Langenselbold, Germany). Ash content was determined by heating the samples in a muffle furnace at 550 °C for 6 h. The lignocellulosic components (cellulose, hemicellulose, and lignin) of the raw straw were determined using the Van Soest detergent fiber analysis method [30]. The pH and electrical conductivity (EC) of biochar and synthetic humic acid were measured in a 1:10 (*w/v*) water suspension using a pH meter (Model: DLX-PH0501; DELIXI Electric, Wenzhou, China) and a conductivity meter (Model: ZS; Xinglianying, Guangdong, China), respectively. The supercritical ammonification process achieved an overall solid mass yield of approximately 71% (dry basis) from the raw wheat straw. The recovered solid product had a final moisture content of approximately 20%, and its detailed final chemical composition (including HA and FA fractions, pH, and EC) is thoroughly characterized in Table 1.

2.3. Soil Sampling and Analytical Procedures

Soil samples (0–20 cm and 20–40 cm) were collected on 15 June and 15 October in both 2023 and 2024. Soil physical and chemical properties were determined according to standard protocols:

Physical properties: Soil texture (clay, silt, and sand fractions) was determined by the pipette method after removing organic matter and carbonates. Bulk density (BD) was measured using the stainless-steel core method (100 cm³).

Soil physical, chemical, and biochemical properties, including fiber fractions of straw materials, available phosphorus, soil organic carbon, microbial biomass carbon, dissolved organic carbon, and humic substance fractions, were determined using standard and widely adopted methods [30–36]. The integrated sustainability assessment was conducted following a multifunctionality-based evaluation framework [37].

Chemical properties: Soil pH and EC were determined in a 1:2.5 soil-to-water suspension [34]. Total nitrogen (TN) was measured using the micro-Kjeldahl method. Total salt content was determined by the residue-on-evaporation method. To determine easily hydrolyzable nitrogen (EHN), the alkaline hydrolysis diffusion method was used [34]. Available phosphorus (AP) was determined using 0.5 M NaHCO₃ extraction followed by colorimetric analysis [31]. Available potassium (AK) was determined by 1.0 M NH₄OAc extraction and flame photometry [34].

Carbon and Humification indices: Dissolved organic carbon (DOC) was measured after water extraction (1:5 ratio) followed by filtration through a 0.45-μm membrane [35]. Humic substances (HA and FA) were separated by acidification and alkali extraction according to the standard IHSS method [36], then quantified using the TOC analyzer ((TOC-L, Analytik, Jena, Germany)) or dichromate oxidation.

2.4. Sustainability Assessment Metrics

$$X' = \frac{X - X_{min}}{X_{max} - X_{min}} \quad (1)$$

where X is the observed value for a given treatment, and X_{min} and X_{max} are the minimum and maximum values of that indicator across all treatments.

For soil pH, inverse normalization was applied because a lower pH was considered more favorable under the alkaline soil conditions of this study:

$$X' = \frac{X_{max} - X}{X_{max} - X_{min}} \quad (2)$$

The *ISS* (Integrated Sustainability Score) for each treatment was calculated as the arithmetic mean of the six normalized dimensions [37]:

$$ISS = \frac{1}{n} \sum_{i=1}^n X' \quad (3)$$

where $n = 6$.

In addition, Resource Use Efficiency (*RUE*) was separately calculated as a relative productivity indicator based on annual total grain production (*ATGP*). For comparative presentation, normalized *RUE* was expressed as follows [37]:

$$RUE = \frac{ATGP_i}{ATGP_{max}} \quad (4)$$

where $ATGP_i$ is the *ATGP* of treatment i , and $ATGP_{max}$ is the maximum *ATGP* observed among treatments [36]. Thus, normalized *RUE* ranged from 0 to 1, with the highest-performing treatment assigned a value of 1.000.

The raw data, normalization procedures, and calculation results used for *ISS* and *RUE* are provided in the Supplementary Materials.

2.5. Crop Growth Measurement and Yield Calculation

During the harvest stages of winter wheat and summer maize, agronomic traits and yield components were systematically measured for each plot. Ten representative plants per plot were randomly selected to measure plant height (from the ground to the top of the panicle/tassel), panicle/ear length, and panicle/ear diameter using a graduated ruler and digital calipers. The total grain number per panicle/ear was recorded after manual counting.

The grain yield was determined by harvesting all plants within a 2 m × 2 m representative quadrat in each plot. The grains were air-dried to a constant weight, and the final yield was adjusted to a standard moisture content (12.5% for wheat and 14% for maize). Annual total grain production (*ATGP*) was calculated as the sum of wheat and maize grain yields within one rotation cycle.

2.6. Statistical Analysis

All experimental data were expressed as mean ± standard deviation. Differences among treatments were evaluated using one-way analysis of variance (ANOVA) followed by the least significant difference (LSD) test at $p < 0.05$. The significance of year (Y), treatment (T), and their interaction (Y × T) was evaluated for crop yield data. Statistical analyses and graphical presentations were performed using SPSS 25.0 (IBM Corp., Armonk, NY, USA) and specialized visualization software Python, Version 3.x (Python Software Foundation, Wilmington, DE, USA).

3. Results

3.1. Soil pH and Nutrient Availability

Different residue-utilization pathways produced distinct effects on the soil chemical environment (Tables 1 and S2). Throughout the experimental period, CH consistently demonstrated a superior capacity to mitigate soil alkalinity compared to other treatments (Figure 1A). By the final sampling stage (October 2024), CH reduced soil pH to 8.03, significantly lower than the control (CK, 8.62). Conversely, CB maintained a higher pH (9.16) throughout the study, indicating that carbonization may intensify alkaline stress in these floodplain soils.

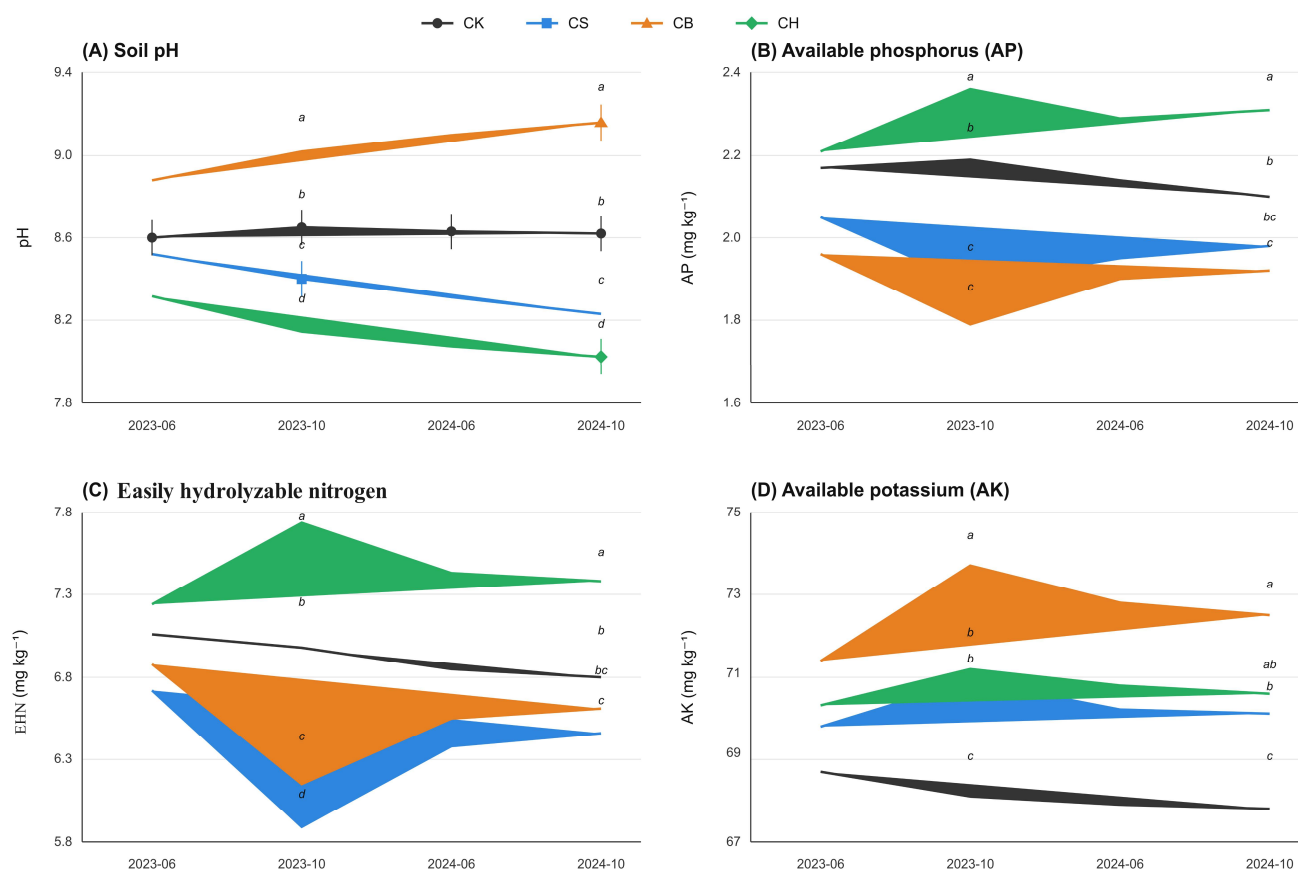


Figure 1. Effects of different straw-utilization pathways on soil pH and nutrient availability during the experimental period. Panels show changes in (A) soil pH, (B) available phosphorus (AP), (C) easily hydrolyzable nitrogen (EHN), and (D) available potassium (AK) under different treatments. CK, no organic amendment; CS, direct straw return; CB, straw-derived biochar; CH, straw-derived synthetic humic acid. Values are means $\pm$ standard deviation. Different lowercase letters indicate significant differences among treatments at the same sampling stage.

Nutrient availability responded differently to the amendment pathways (Figure 1B–D). CH maintained significantly higher available phosphorus (AP, 2.36 mg kg^{-1}) and easily hydrolyzable nitrogen (EHN) than all other treatments. Notably, CB showed the lowest AP solubility (Figure 1B), likely due to its high pH. However, CB contributed to the highest available potassium (AK) levels (Figure 1D), consistent with its mineral-rich composition. Overall, CH proved most effective in simultaneously alleviating alkalinity and maintaining a balanced nutrient supply.

3.2. Soil Aggregate Distribution and Structural Indicators

Soil structural stability was significantly modified by the amendments (Figure 2; Table S3). While all organic treatments increased aggregation relative to CK, CH exerted the most pronounced effect on particle binding. Specifically, CH achieved the highest macroaggregate proportion (19.40%) at the end of the experiment, significantly outperforming CS and CB (Figure 2B). The reduction in the silt–clay fraction under CH further confirms its role in promoting structural reorganization (Figure 2C). These results suggest that the humification-based pathway (CH) provides stronger structural resilience in compacted floodplain farmland than either raw straw return or biochar application.

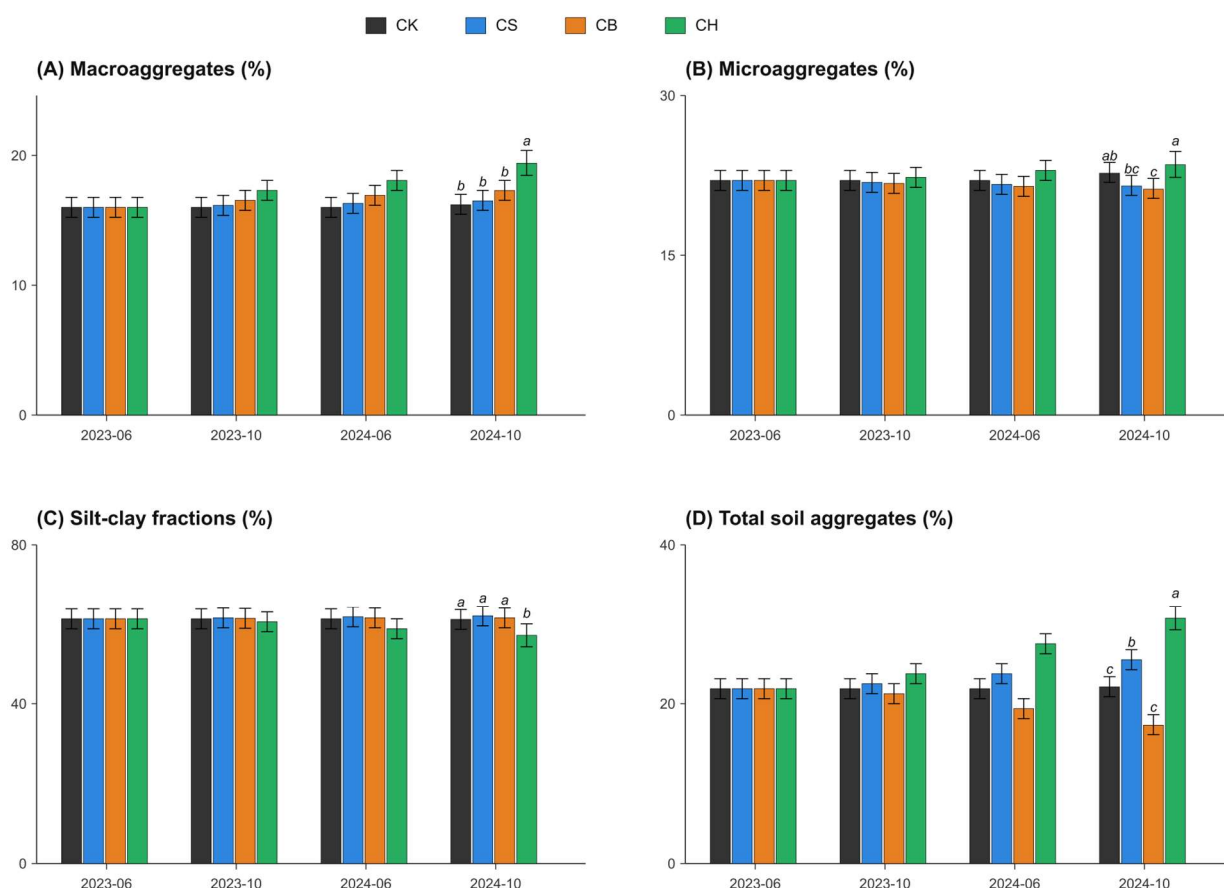


Figure 2. Effects of different straw-utilization pathways on soil aggregate-size distribution and structural improvement. Panels show treatment effects on (A) total aggregates, (B) macroaggregates, (C) microaggregates, and (D) silt–clay fraction. CK, no organic amendment; CS, direct straw return; CB, straw-derived biochar; CH, straw-derived synthetic humic acid. Values are means $\pm$ standard deviation. Different lowercase letters indicate significant differences among treatments.

3.3. Carbon Fractions and Microbial Biomass Carbon

Amendments substantially increased soil carbon pools, but the functional quality of carbon accumulation differed among treatments (Figure 3; Table S4). All treatments improved soil organic carbon (SOC), with CB and CH showing the highest total accumulation (Figure 3A). However, the biologically active carbon pool was most stimulated under CH, which recorded the highest dissolved organic carbon (DOC, 3.35 mg kg^{-1}) and microbial biomass carbon (MBC, 91.77 mg kg^{-1}) (Figure 3B,C). Notably, CB displayed negligible MBC improvement compared to CK, despite its high SOC contribution. Humic carbon (HC) followed a similar trend, with CH creating the largest stable humified carbon sink (Figure 3D).

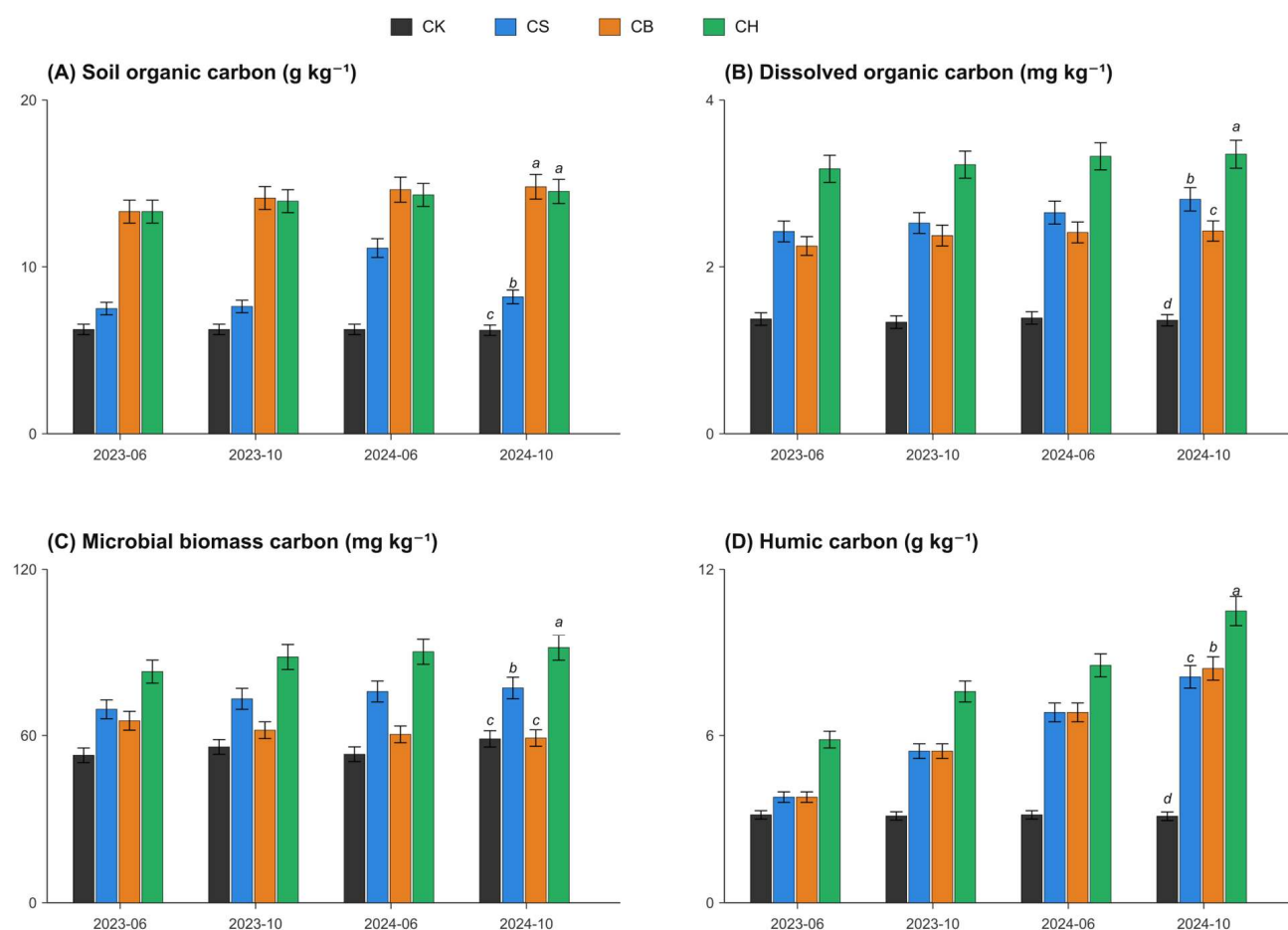


Figure 3. Effects of different straw-utilization pathways on soil carbon fractions and microbial biomass carbon during the experimental period. Panels show changes in (A) soil organic carbon (SOC), (B) dissolved organic carbon (DOC), (C) microbial biomass carbon (MBC), and (D) humic carbon (HC) under different treatments. CK, no organic amendment; CS, direct straw return; CB, straw-derived biochar; CH, straw-derived synthetic humic acid. Values are means $\pm$ standard deviation. Different lowercase letters indicate significant differences among treatments at the same sampling stage.

3.4. Humification in Surface and Subsurface Soil Layers

The conversion pathways significantly influenced humification intensity throughout the soil profile (Figure 4; Table S5). In the surface layer (0–20 cm), CH achieved the highest HA content (5.82 mg kg⁻¹) and an HA/FA ratio of 1.90, compared to 1.20 and 1.10 for CB and CS, respectively (Table S6). A distinctive pattern was observed in the subsurface layer (20–40 cm), where CH maintained significantly higher HA and FA contents than all other treatments at the final sampling date (Figure 4C,D). These findings indicate that the influence of synthetic humic acid extends deeper into the soil profile than raw straw or biochar, promoting humification across both surface and subsurface layers.

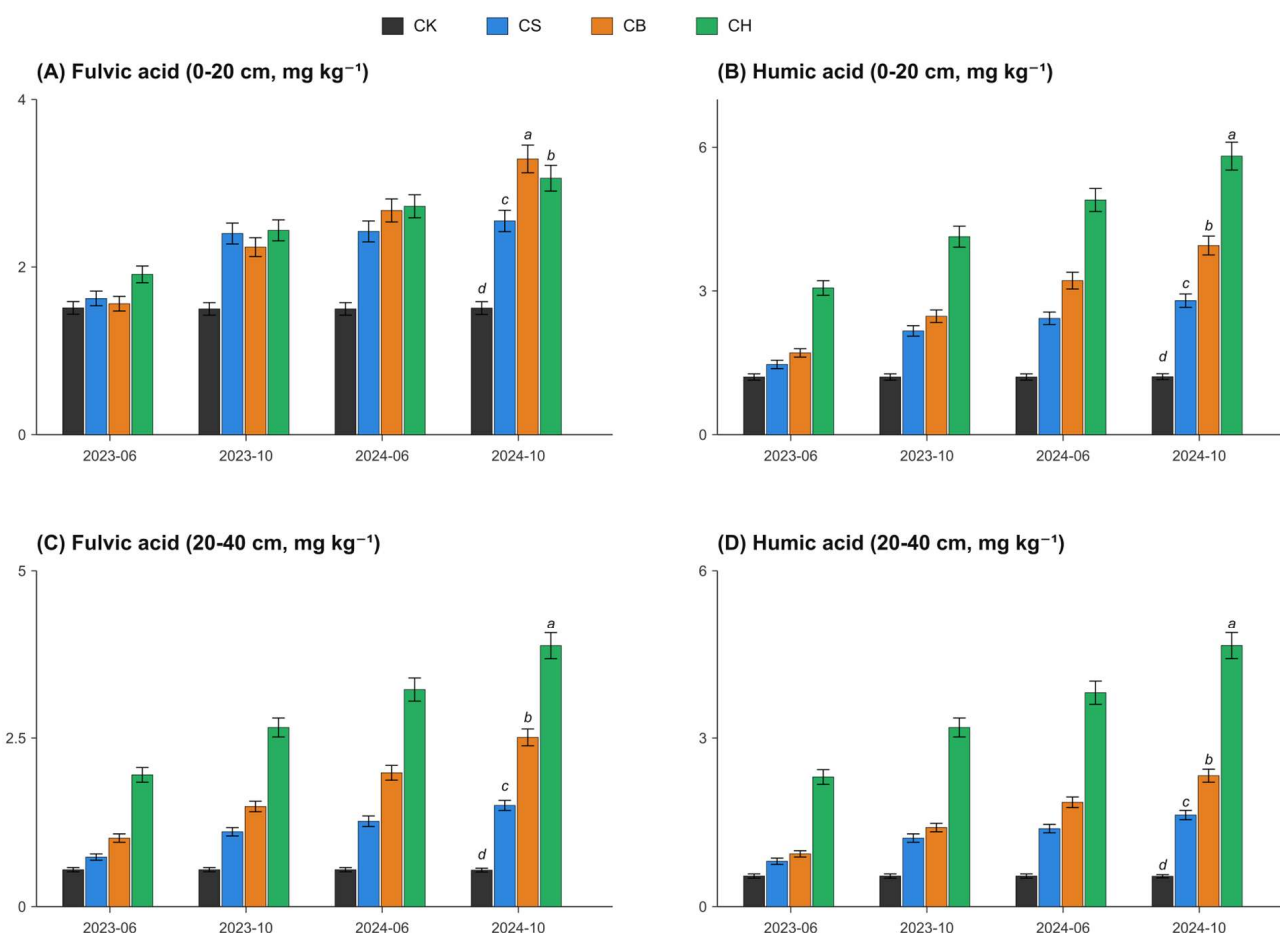


Figure 4. Effects of different straw-utilization pathways on fulvic acid and humic acid contents in surface and subsurface soil layers during the experimental period. Panels show changes in (A) fulvic acid (FA) in the 0–20 cm soil layer, (B) humic acid (HA) in the 0–20 cm soil layer, (C) FA in the 20–40 cm soil layer, and (D) HA in the 20–40 cm soil layer. CK, no organic amendment; CS, direct straw return; CB, straw-derived biochar; CH, straw-derived synthetic humic acid. Values are means $\pm$ standard deviation. Different lowercase letters indicate significant differences among treatments at the same sampling stage.

3.5. Crop Growth Traits and Productivity

Agronomic performance mirrored the observed soil improvements (Tables 2 and S7). CH achieved the highest grain yields for both wheat and maize in each year of the rotation cycle. In 2024, grain yields under CH reached 5.65 and $6.46 \times 10^3 \text{ kg ha}^{-1}$ for wheat and maize, respectively, resulting in the highest annual total grain production (ATGP, $12.11 \times 10^3 \text{ kg ha}^{-1}$). Conversely, CB resulted in lower wheat and maize yields than CH and CS, often remaining statistically similar to the control (CK) (Table 2). This suggests that the nutrient limitations associated with biochar in alkaline soil restricted its potential productivity benefits.

Table 2. Effects of different straw-utilization pathways on crop growth traits and grain yield of wheat and maize.

Part A. Wheat													
Year	Treatment	Plant Height (cm)		Panicle Length (cm)		Total Grains per Panicle		1000-Kernel Weight (g)		Grain Yield (10 ³ kg ha ⁻¹)			
2023	CK	85.20 ± 4.25 a		6.32 ± 0.32 b		20.60 ± 0.98 b		27.70 ± 1.39 a		4.98 ± 0.24 b			
2023	CS	86.30 ± 4.26 a		6.55 ± 0.31 b		20.80 ± 1.13 b		27.90 ± 1.41 a		5.07 ± 0.21 b			
2023	CB	82.10 ± 4.22 ab		5.83 ± 0.29 bc		20.50 ± 1.02 b		28.60 ± 1.44 a		4.83 ± 0.21 b			
2023	CH	92.60 ± 4.25 a		7.25 ± 0.37 a		22.80 ± 1.15 a		31.50 ± 1.52 a		5.52 ± 0.20 a			
2024	CK	85.30 ± 4.20 a		6.33 ± 0.34 ab		20.50 ± 1.08 b		27.80 ± 1.38 ab		4.99 ± 0.23 b			
2024	CS	87.20 ± 4.23 a		6.62 ± 0.35 a		20.90 ± 1.10 b		28.10 ± 1.40 ab		5.08 ± 0.27 b			
2024	CB	81.90 ± 4.25 ab		5.82 ± 0.28 b		20.40 ± 1.15 b		29.10 ± 1.53 a		4.82 ± 0.23 b			
2024	CH	93.50 ± 4.24 a		7.26 ± 0.36 a		23.20 ± 1.17 a		31.60 ± 1.51 a		5.65 ± 0.27 a			
Part B. Maize													
Year	Treatment	Plant Height (m)		Stem Diameter (cm)		Ear Diameter (cm)		1000-Kernel Weight (g)		Grain Yield (10 ³ kg ha ⁻¹)		ATGP (10 ³ kg ha ⁻¹)	
2023	CK	2.46 ± 0.03 b		7.65 ± 0.05 c		13.70 ± 1.25 b		197 ± 10 c		6.16 ± 0.45 a		11.10 ± 0.21 a	
2023	CS	2.52 ± 0.04 b		8.09 ± 0.06 b		14.80 ± 1.12 b		203 ± 12 b		6.23 ± 0.41 a		11.30 ± 0.25 a	
2023	CB	2.39 ± 0.03 c		7.37 ± 0.06 d		14.70 ± 1.27 b		205 ± 11 b		6.08 ± 0.37 a		10.90 ± 0.23 b	
2023	CH	2.63 ± 0.05 a		8.26 ± 0.06 a		17.20 ± 1.16 a		218 ± 10 a		6.38 ± 0.39 a		11.90 ± 0.26 a	
2024	CK	2.45 ± 0.03 c		7.65 ± 0.04 c		13.60 ± 1.23 b		195 ± 8 c		6.15 ± 0.38 a		11.10 ± 0.21 b	
2024	CS	2.53 ± 0.04 b		8.12 ± 0.05 b		14.90 ± 1.05 b		205 ± 12 b		6.25 ± 0.40 a		11.30 ± 0.23 b	
2024	CB	2.38 ± 0.04 c		7.35 ± 0.05 d		14.60 ± 1.08 b		203 ± 10 b		6.03 ± 0.39 a		10.90 ± 0.28 b	
2024	CH	2.65 ± 0.05 a		8.28 ± 0.06 a		17.30 ± 1.13 a		223 ± 11 a		6.46 ± 0.43 a		12.10 ± 0.25 a	
ANOVA Summary													
Source of Variation	Wheat Plant Height	Wheat Panicle Length	Wheat Total Grains per Panicle	Wheat 1000-Kernel Weight	Wheat Yield	Maize Plant Height	Maize Stem Diameter	Maize Ear Diameter	Maize 1000-Kernel Weight	Maize Yield	ATGP		
Year (Y)	ns	ns	ns	ns	*	ns	ns	ns	ns	*	**		
Treatment (T)	*	*	*	**	**	**	*	*	**	**	**		
Y × T	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns		

Note: Values are presented as mean $\pm$ variation estimates from three replicates. Different lowercase letters within the same year and column indicate significant differences among added treatments at $p < 0.05$. ATGP, annual total grain production; ns, not significant. For the ANOVA results, * and ** indicate significance at $p < 0.05$ and $p < 0.01$, respectively.

3.6. Integrated Sustainability Assessment and Resource Use Efficiency

The systemic performance of the residue pathways was evaluated using the multi-functional scorecard [36] (Figure 5; Table S6). CH achieved the maximum relative score in all six dimensions: pH mitigation, P availability, structural resilience, microbial activity, humification quality, and yield efficiency (Figure 5A). The final Integrated Sustainability Score (ISS) followed the order: CH (1.000) > CS (0.380) > CK (0.231) > CB (0.119). Similarly, the normalized Resource Use Efficiency (RUE) confirmed CH as the most efficient treatment (1.000) for grain production (Figure 5B), reinforcing the conclusion that straw-derived synthetic humic acid is a superior strategy for rehabilitating compacted alkaline floodplain agroecosystems.

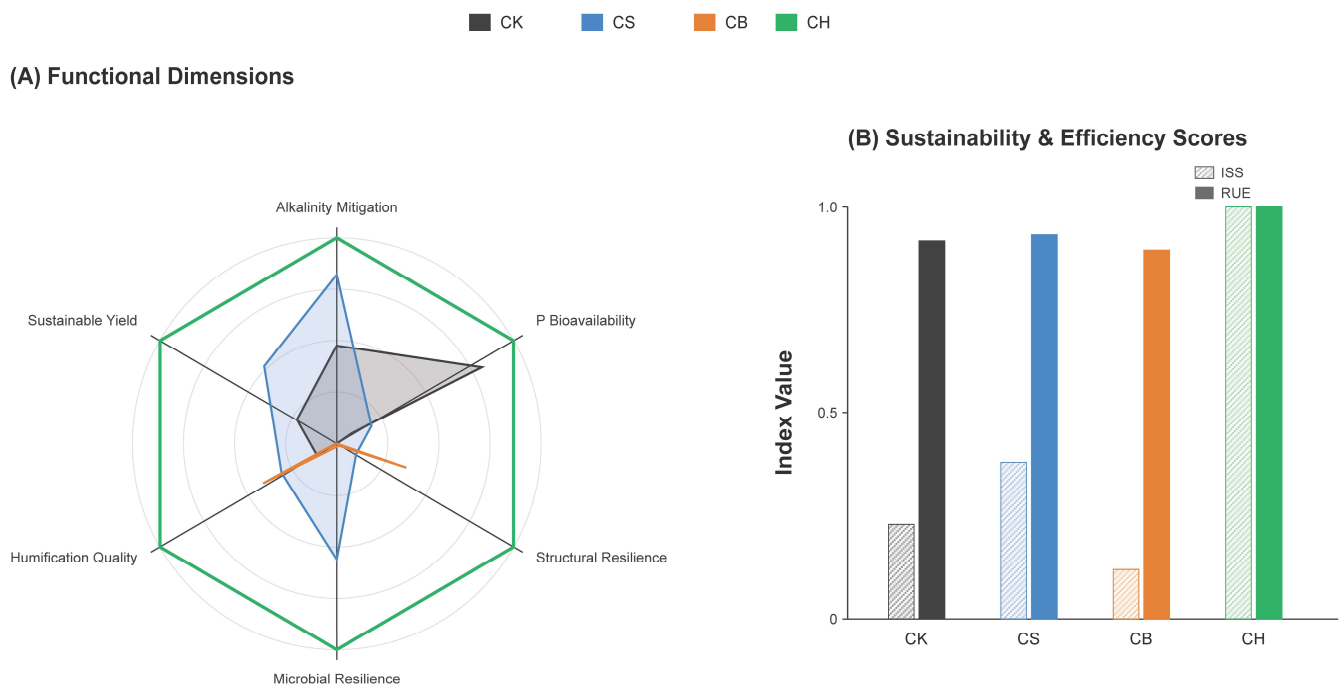


Figure 5. Integrated sustainability scorecard and relative production efficiency of different straw-utilization pathways. Panel (A) shows the radar-chart comparison of six normalized dimensions, including pH buffering, phosphorus availability, aggregate improvement, microbial activity, humification, and yield efficiency. Panel (B) shows normalized Resource Use Efficiency (RUE) based on annual total grain production (ATGP). CK, no organic amendment; CS, direct straw return; CB, straw-derived biochar; CH, straw-derived synthetic humic acid. All indicators in the scorecard were normalized to a 0–1 scale using the min–max method, with higher values indicating better relative performance. For soil pH, inverse normalization was applied because a lower pH was considered more favorable under the alkaline soil conditions of this study.

4. Discussion

4.1. Differential Effects on Biogeochemical Cycling and Nutrient Availability

The study reveals that residue pathways differ markedly in regulating soil chemistry in alkaline floodplain farmland. CH was the most effective in reducing pH and maintaining easily hydrolyzable nitrogen (EHN) and phosphorus (AP) availability (Figure 1). This aligns with our first hypothesis that humification-based conversion can alleviate alkaline stress better than carbonization. Unlike alkaline biochar (CB), which tends to intensify high-pH constraints and limit P solubility by promoting Ca-P precipitation [8–10,17,18], the abundant acidic functional groups (e.g., carboxyl and phenolic groups) in CH provide essential buffering [26]. This pH regulation is crucial for unlocking “legacy phosphorus” in alkaline soils, where P availability is traditionally restricted [8–10].

While direct straw return (CS) gradually contributes nutrients, its effectiveness is often hindered by the high C/N ratio and recalcitrant lignocellulosic structure of fresh residues, leading to temporary nutrient immobilization [12–14]. Our findings are consistent with recent syntheses showing that straw return does not always translate into efficient carbon sequestration when microbial stoichiometric demands are not adequately met [11,13,14]. In contrast, the transformed character of synthetic humic acid promoted a more active dissolved carbon pool (DOC) and microbial biomass (MBC). This microbial activation suggests that CH acts as a “metabolic primer,” enhancing the biogeochemical cycling of nutrients rather than serving mainly as a passive carbon sink like CB [21,24,29].

4.2. Soil Structural Evolution and Profile Humification Processes

Soil structural recovery is critical for rehabilitating compacted floodplain soils, where weak aggregation restricts root-zone development [4,6,7,15]. CH produced the strongest increase in macroaggregates (Figure 2), supporting our second hypothesis. This structural improvement is likely driven by the synergy between chemically active humic substances and biological binding. Humic substances act as a powerful organo-mineral glue, promoting the formation of water-stable macroaggregates [27–29]. The higher HA/FA ratio under CH (Table S6) further reflects a qualitative shift in carbon transformation, moving from simple residue decomposition to advanced humification.

A distinctive finding was the promotion of humification in both the surface (0–20 cm) and subsurface (20–40 cm) layers under CH (Figure 4). This finding is consistent with the reported profile-specific distribution of dissolved organic matter in fluvo-aquic soils [38]. Thermochemical humification aims to reconstruct lignocellulosic biomass into reactive humic-like substances rather than the inert aromatic matrices typical of pyrolytic chars [19,21,29]. The observed subsurface HA accumulation suggests that CH-derived colloids or soluble fractions possess higher mobility than biochar or raw straw, allowing them to influence deeper soil layers [39,40]. This “profile-wide” improvement is essential for alleviating subsoil compaction, enhancing root-zone moisture retention, and promoting deeper nutrient acquisition—a combination that direct straw return (CS) failed to achieve within the two-year study period.

4.3. Linking Soil Health to Agronomic Productivity and Sustainability

The agronomic results demonstrate that the integrated soil improvements under CH translated into superior grain yields (Table 2). The highest ISS and RUE for CH (Figure 5) indicate a balanced optimization of chemical, physical, and biological functions. In multi-constrained alkaline environments, isolated gains (e.g., total SOC increase under CB) are often offset by trade-offs such as phosphorus fixation or pH spikes [8–10,17,18]. CH avoided these trade-offs by providing a synchronized supply of nutrients and structural stability.

From a broader perspective, converting wheat straw into nitrogen-enriched synthetic humic acid represents a transition from linear biomass disposal to a more circular bioeconomy-oriented utilization pathway [20,21,41]. Such functionalized residue upcycling aligns with the goals of “climate-smart agriculture” by simultaneously enhancing carbon sequestration and resource use efficiency [2,3]. While biochar remains a valuable tool for long-term carbon storage [16,18], humification-based pathways appear more suited for the immediate fertility needs and structural rehabilitation of the Yellow River floodplain agroecosystems.

4.4. Integrated Mechanism and Management Implications for Floodplain Farmland

The systematic comparison of four pathways provides a clear mechanistic hierarchy for residue management in compacted alkaline farmlands. Our results demonstrate that the Research Purpose (identifying a compatible strategy) is met through the Research Content (comparing conversion pathways) by revealing that CH addresses the “alkalinity-compaction-productivity” triad more effectively than CS or CB. Specifically, the synthetic humic acid pathway bridges the gap between the rapid but unstable nutrient release of raw straw and the stable but inert carbon storage of biochar.

Furthermore, while this study primarily focused on aggregate stability and pH buffering, sodium (Na^+) dispersion is also a critical factor in alkaline soil degradation. The highly functionalized nature of synthetic humic acid may provide active binding sites for cation exchange, potentially mitigating sodium-induced structural damage. The specific interactions between humic treatments and exchangeable sodium dynamics warrant targeted

investigation in future studies. The superiority of CH is anchored in three interconnected mechanisms: (i) Chemical Alleviation, where synthetic humic acid acidic groups lower pH to unlock fixed P; (ii) Physical Restructuring, where humic colloids promote macroaggregate stability to relieve compaction; and (iii) Biological Stimulation, where labile carbon fractions increase microbial biomass. This synergy results in a system that is not only productive (High RUE) but also structurally and chemically resilient (High ISS). For the management of Yellow River floodplain cropland, we suggest that while direct straw return remains a baseline practice, the targeted application of straw-derived synthetic humic acid offers a high-efficiency alternative for rapid soil rehabilitation. Future deployment should integrate rigorous life-cycle assessments (LCA) and cost–benefit analyses [41]. While the initial capital investment for supercritical ammonification equipment is higher than for traditional composting, its ultrafast reaction time (2 min) and the resulting significant yield increases suggest a promising long-term economic return that warrants detailed regional evaluation [20,21,41].

5. Conclusions

This two-year field study showed that wheat-straw upcycling pathways differed markedly in their agronomic performance under alkaline floodplain conditions. Direct straw incorporation increased fresh organic input but was constrained by early-stage nitrogen immobilization, whereas straw-derived biochar mainly contributed stable carbon and showed limited benefits for pH buffering, phosphorus availability, and microbial activity in the tested soil. In contrast, nitrogen-enriched synthetic humic acid produced by supercritical ammonification more effectively reduced soil alkalinity, increased available phosphorus, improved microbial biomass, and enhanced crop productivity and resource use efficiency. The integrated sustainability assessment further indicated that synthetic humic acid provided the most balanced performance across soil chemical, biological, and agronomic dimensions, including pH buffering, carbon stabilization, nitrogen retention, phosphorus unlocking, microbial resilience, and resource use efficiency. These results suggest that, in alkaline agroecosystems, the functional quality of residue-derived carbon may be more important than carbon stability alone. Overall, converting wheat straw into nitrogen-enriched synthetic humic acid appears to be a promising sustainable agricultural practice for improving soil biochemical functioning and crop performance in alkaline agricultural soils. Future studies should further evaluate the long-term stability, economic feasibility, and broader regional applicability of this approach. However, it is important to note that these findings are based on a two-year field experiment at a single site. The full environmental and economic viability of scaling up supercritical ammonification technology requires further long-term, multi-site trials and a comprehensive Life Cycle Assessment (LCA).

Supplementary Materials: The following supporting information can be downloaded at <https://www.mdpi.com/article/10.3390/agriculture16141536/s1>.

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Abbreviations

The following abbreviations are used in this manuscript:

CK	control with conventional NPK fertilizer only
CS	direct straw return plus NPK
CB	straw-derived biochar plus NPK
CH	synthetic humic acid plus NPK
NPK	nitrogen, phosphorus, and potassium fertilizer
RUE	resource use efficiency
ISS	Integrated Sustainability Score
SOC	soil organic carbon
EHN	easily hydrolyzable nitrogen
AP	available phosphorus
MBC	microbial biomass carbon
C/N	carbon-to-nitrogen ratio
HC	humified carbon
DOC	dissolved organic carbon
AK	available potassium
HA	humic acid
FA	fulvic acid
ATGP	annual total grain production
LCA	life-cycle assessment
EC	electrical conductivity
TC/TN	total carbon/total nitrogen

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