

Article

Strip Tillage and No Tillage with Integrated Agronomic Practices Improve Maize Yield and Modulate Humus Fractions and Humic Acid Molecular Properties in Sloping Farmlands of Northeast China

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Abstract

Conventional ridge tillage has triggered severe soil organic carbon depletion and soil erosion in sloping maize fields of humid northeast China, posing a persistent threat to black soil health and regional grain security. As representative conservation tillage systems integrated with full straw residue retention, no tillage and strip tillage exhibit prominent potential in soil protection, and their soil-improving benefits are inseparable from continuous straw carbon input; however, their regulatory effects on humus fractions and humic acid molecular properties in erosion-prone sloping farmlands remain largely unclarified. This study aimed to screen the optimal integrated tillage–cultivation mode for sloping farmlands in the northeast China black soil region and to reveal how tillage systems coupled with incremental agronomic practices affect maize yield, humus composition, and humic acid molecular characteristics in Albic soil, a representative degraded soil type of the regional black soil system. A 2-year field experiment was conducted in a typical sloping farmland of Jilin Province, with conventional ridge tillage set as the control. Five incremental integrated management practices (from baseline practice to fertilizer reduction, straw decomposition promotion, and 5–10% higher planting density) were arranged under both under no-tillage and strip-tillage systems. We analyzed dissolved organic matter fluorescence properties, carbon content of humus fractions, and humic acid molecular structural features, and performed principal component analysis for comprehensive performance evaluation of all treatments. This study demonstrates that optimized strip tillage, supported by full straw C input as an indispensable prerequisite, combined with straw decomposition promotion and a 10% planting density increase can synchronously boost soil fertility and maize yield, providing a scientific and practical tillage strategy for sustainable black soil conservation of sloping Albic farmlands in humid northeast China. Strip tillage achieved a 6.78% higher average maize yield than NT, and the maximum yield was recorded with ST5 (strip tillage combined with straw decomposition promotion and 10% planting density increase). Both no tillage and strip tillage significantly increased C_{DOM} content, humification index and autochthonous contribution, optimized humus

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component distribution with elevated humic acid carbon content, humic acid carbon-to-fulvic acid carbon ratio and humic acid carbon-to-total organic carbon ratio, and enhanced humic acid aromaticity, thermal stability, and hydrophobicity. The principal component analysis results indicated that ST5 ranked first in comprehensive performance, while conventional ridge tillage ranked the lowest among all treatments. Strip tillage integrated with straw decomposition promotion and 10% increased planting density effectively modulated humus fractions, improved humic acid molecular stability, and synchronously increased maize yield. This integrated management regime provides a scientific and practical tillage strategy for sustainable black soil conservation and high-efficiency maize production in sloping Albic farmlands of humid northeast China.

Keywords: strip tillage; no tillage; maize; humus composition; humic acid

1. Introduction

The black soil region in northeast China is a national strategic grain production base dominated by maize, with sloping farmland accounting for a considerable proportion. A typical degraded soil subtype widely developed on sloping lands within the black soil region, Albic soil is characterized by a shallow fertile layer, severe organic carbon depletion, and high erosion sensitivity, making it a key target of regional black soil conservation efforts. Over 60% of such sloping farmlands suffer from severe soil erosion, which reduces maize yield by 9–22% and is accompanied by progressive thinning of the black soil layer and soil organic carbon depletion [1]. Albic soil degradation and accelerated erosion arise from a suite of interacting agronomic drivers rather than a single dominant practice. Long-term conventional ridge tillage (CT), characterized by intensive soil disturbance and prevalent crop residue removal or burning and compounded by prolonged continuous maize monoculture, imbalanced organic residue budgets, suboptimal fertilization management, and a pervasive organic matter deficit across the agroecosystem, has caused severe black soil degradation and exacerbated soil erosion by accelerating soil organic carbon (SOC) loss, reducing microbial diversity, and destabilizing soil aggregates [2], seriously endangering regional food security and ecological sustainability. As the core component of soil organic matter (SOM), humus (HS) plays an irreplaceable role in regulating soil fertility, improving soil physicochemical properties, and promoting C sequestration; its composition and humic acid (HA)'s molecular structure directly determine soil C pool stability and nutrient supply capacity. One agronomic measure within the broader management system of agroecosystem organic matter balance, total straw returning, a pivotal approach to supplement SOM, is widely promoted in agriculture, and its ability to enhance SOM stability and optimize nutrient cycling in degraded soils is increasingly recognized [3,4]. However, the balance of organic matter input, transformation, and loss is the core determinant of SOM dynamics. In the presence of a sustained organic matter deficit, straw returning alone cannot guarantee SOM restoration or soil fertility stabilization, and its beneficial effects can only be fully realized with the coordination of appropriate tillage practices. Strip tillage (ST) and no tillage (NT), integrated conservation tillage systems that couple reduced soil disturbance with full crop residue retention, show great potential in protecting black soil, improving soil fertility, preserving soil integrity, and mitigating erosion [5]. Nevertheless, their adoption in humid, erosion-prone sloping farmlands remains limited due to uncertainties in balancing short-term crop productivity and long-term soil health.

Accumulating evidence indicates that NT combined with straw returning effectively increases SOC content and HS accumulation under most field conditions. For instance,

studies in black soil regions showed conservation tillage (NT, subsoiling) with straw returning significantly raised dissolved organic matter (DOM) content and altered its fluorescence characteristics. DOM is an operationally defined soluble organic matter pool comprising abundant labile non-humic fractions and partial humic-like components, and it is highly sensitive to tillage disturbance [5]. Specifically, fluorescence indices (fluorescence index (FI), autochthonous contribution (BIX) and humification index (HIX)) derived from 3D-EEM spectroscopy reflect the source and humification degree of DOM. It is widely documented that NT promotes more stable HA molecules through preferential decomposition of labile aliphatic fractions. Straw-returning modes also influence HA oxidation, aromatization, and humification. Beyond black soils, conservation tillage (NT, ST) with straw incorporation restored soil structure, increased water-stable aggregates, and enhanced C sequestration in fragile ecosystems (e.g., Brazilian sandy coastal soils [6], Ethiopian erosion-prone highlands [7]). These practices also optimized nutrient availability in a context-dependent manner: NT enhanced cation exchange capacity and mitigated soil acidity in tropical regions [6], while ST improved phosphorus solubility via localized acidification [8]. For maize productivity and nutrient cycling, NT accumulated surface SOC by 15–20% in long-term trials, but delayed early-season N availability, requiring starter fertilizers [5], whereas CT temporarily boosted nutrient accessibility, but depleted SOC by 2.4 g kg^{-1} over five years [9]. In northeast China, short-term implementation of NT initially reduced maize yields by 9–12%, but outperformed CT after four years due to improved water retention [10]. NT with straw mulching increased yields by 0.91–3.1% under reduced N input [11], but might reduce yields under high fertility via nutrient immobilization [12]. ST, combining tilled sowing rows and untilled inter-rows, balanced soil conservation and productivity, outperforming NT in cold regions (3–26% yield increase) while cutting input costs [13,14]. Regarding soil HS and aggregate properties, NT shifted HS toward hydrophobic, aromatic structures, enhancing water retention and nutrient supply [15]. Li et al. [16] found that NT increased HS C content in water-stable aggregates (0–20 cm, 20–40 cm), enhanced aliphatic, methoxyl, and hydrophobic C in $>2 \text{ mm}$ aggregates (improving C stability), and increased alkyl, O-alkyl, and methoxyl/N-alkyl C in the 0–20 cm layer, confirming its superiority for C sequestration and stability. However, systematic studies on the regulatory effects of ST on HS composition and HA molecular structure remain limited, particularly in humid sloping farmlands with severe erosion risks.

Extensive studies have investigated the responses of SOC fractions and HS properties to conservation tillage practices in the northeast China black soil region, yet the majority of this evidence was collected from flat farmlands with well-developed Mollisol profiles, which are characterized by low erosion risk and distinct hydrothermal conditions compared with sloping landscapes [1,15,16]. Although prior work has confirmed that sloping farmlands suffer more severe SOC depletion and soil structural degradation, research on tillage-driven HS regulation in erosion-prone sloping Albic soils—a representative degraded soil subtype with shallow fertile layers and high erodibility—remains notably scarce, and the regulatory mechanisms underlying HS transformation under humid sloping conditions remain poorly resolved. Regarding HS characterization methodology, existing studies have generally adopted single analytical approaches: some have examined DOM fluorescence properties as a sensitive proxy for tillage-induced SOM dynamics [1], while others have quantified the C content of solid-phase HS fractions or characterized individual structural features of HA via elemental analysis or Fourier-transform infrared (FTIR) spectroscopy [16]. However, few studies have integrated dissolved-phase DOM optical profiling, quantitative fractionation of full solid-phase HS components, or multi-dimensional molecular characterization of HA to systematically decipher how tillage systems coupled with incremental agronomic practices modulate HS turnover. Building on the two research issues identified above, we propose two testable hypotheses: (1) relative

to CT, both NT and ST combined with full straw return can optimize HS fraction distribution and enhance HA molecular stability in erosion-prone sloping Albic soil, and ST will deliver stronger beneficial effects than NT by balancing soil aeration in seeding rows and organic matter protection in inter-rows; and (2) the stepwise integration of optimized agronomic practices (fertilizer reduction, straw decomposition promotion, and moderately increased planting density) can deliver concurrent improvements in both maize yield and soil HS quality, and there exists an optimal integrated tillage–cultivation mode suitable for local sloping farmlands. To test the above hypotheses, the present study was conducted in a typical sloping farmland in Shulan City, Jilin Province, China, with CT as the control. Under NT and ST systems for maize production, combined with comprehensive cultivation techniques and full straw return, systematic analysis of DOM was conducted via three-dimensional excitation–emission matrix (3D-EEM) fluorescence spectroscopy, with FI, BIX, and HIX employed as the key evaluation indices to reflect the source and humification status of dissolved-phase organic matter. The C content of HS fractions was quantitatively determined, and the molecular structure of HA was characterized through FTIR spectroscopy, elemental analysis, and differential thermal–thermogravimetric analysis (DT–TGA). A cumulative additive split-plot field experiment was established to systematically compare soil HS properties, HA molecular structure, and maize yield across different tillage–cultivation modes, with the aim of systematically revealing the regulatory effects of NT/ST systems with gradient agronomic practices on DOM fluorescence properties, HS fractions, and multidimensional HA molecular characteristics in sloping Albic soil and comprehensively evaluating the overall performance of all tillage–cultivation combinations and identifying the optimal strategy for integrated maize yield improvement and soil HS quality enhancement.

2. Materials and Methods

2.1. Materials

The medium-maturing maize hybrid HA9306 was obtained from Jilin Hongxiang Seed Industry Co., Ltd., Changchun, China. Experimental fertilizers and microbial agents included a compound fertilizer (N-P₂O₅-K₂O 25-10-15) from Jilin Jidanli Agricultural Co., Ltd., Jilin, China, an agricultural microbial agent (containing *Bacillus subtilis* and *Bacillus mucilaginosus*, effective viable count >500 million CFU g⁻¹) from Sinochem Modern Agriculture (Jilin) Co., Ltd., Changchun, China, and the microbial agent Tailong Nonghaokang from Inner Mongolia Nonghaokang Agricultural Biotechnology Co., Ltd., Hohhot, China.

2.2. Experimental Design

A two-year (April 2024–December 2025) field experiment with continuous maize monoculture was conducted at Zhongcheng Wang Family Farm, Tiande Township, Shulan City, Jilin Province, China. The test soil is classified as Albic soil (Albic Luvisols), a typical degraded soil type extensively distributed in the sloping farmlands of the northeast China black soil region, with an elevation of 214.4 m a.s.l. (44°30'58" N, 126°42'16" E). Prior to the formal experiment, maize was verified as the sole preceding crop. The entire experimental site had been managed under continuous maize monoculture with conventional ridge tillage and full straw removal after harvest for more than 10 consecutive years. No crop rotation, fallow or other land-use changes occurred during this period. The experimental site had an average slope gradient of 9.7°, representative of typical erosion-prone sloping farmland of the Albic soil subtype within the northeast China black soil region, which is highly consistent with the dominant land type facing black soil degradation and erosion risks in the study area. Prior to treatment implementation in April 2024, composite soil samples were collected from the 0–20 cm topsoil layer in each replicate

block to determine baseline soil physicochemical properties. The initial soil properties at 0–20 cm depth were as follows: pH 5.82 (measured in a 1:2.5 soil/water suspension), silty loam texture, 132.6 mg kg⁻¹ alkali-hydrolyzable nitrogen (available N), 38.4 mg kg⁻¹ available phosphorus (Olsen-P), 138.5 mg kg⁻¹ available potassium, and 1.22 g cm⁻³ soil bulk density. The 0–20 cm soil layer was selected as the experimental focus based on the following scientifically grounded considerations. The experimental soil is typical sloping Albic soil in the northeast China black soil region, characterized by an extremely thin fertile topsoil and compact, organic-poor Albic illuvial horizon below 20 cm. Maize root activity and effective agronomic nutrient supply are almost entirely confined within the 0–20 cm plough zone under local sloping farmland production conditions. In the 2024 growing season, total precipitation was 568.2 mm and the mean daily air temperature was 20.1 °C. In the 2025 growing season, total precipitation was 612.7 mm and the mean daily air temperature was 19.8 °C. The two-year climatic conditions were generally consistent with the long-term average climate of the study region.

This study adopted a cumulative additive split-plot design with three randomized complete blocks as biological replicates. The design did not satisfy the orthogonality assumption of standard full factorial experiments and was selected to screen the optimal integrated tillage–cultivation mode for local sloping farmlands, rather than to quantify the independent effect of each single agronomic factor. Crucially, the five subplot management levels were constructed via sequential additive superposition of multiple agronomic parameters (fertilizer dosage, microbial inoculation, straw decomposition promotion, planting density), rather than separate, independent orthogonal subplot factors. These superimposed subplots contained mixed agronomic variables simultaneously, meaning the independent contribution of any individual agronomic measure could not be statistically partitioned or quantified separately from combined treatment effects. We explicitly clarified that this design did not possess factorial orthogonality: the five subplot treatments were sequential additive combinations of agronomic technologies rather than orthogonal factorial levels, so the independent main effects and interaction effects of individual agronomic measures could not be strictly partitioned via conventional factorial ANOVA. Whole-plot factor: tillage system, with three levels—NT, ST, and CT (served as the control). Subplot factor: integrated agronomic management gradient, with five additive levels assigned exclusively within NT and ST whole plots. The five additive sub-treatments under NT and ST were set as a stepwise technology integration sequence based on local baseline practice.

NT1/ST1: Baseline practice. Local conventional NT/ST management with a planting density of 65,000 plants ha⁻¹, 1000 kg ha⁻¹ compound fertilizer (N-P₂O₅-K₂O 25-10-15) as basal fertilizer, and 50 kg ha⁻¹ agricultural microbial agent as seed fertilizer.

NT2/ST2: Baseline + fertilizer reduction. Reduced basal compound fertilizer to 400 kg ha⁻¹, supplemented with 400 kg ha⁻¹ microbial agent and 20 kg ha⁻¹ ZnSO₄ as seed fertilizer.

NT3/ST3: T2 + straw decomposition promotion. Powdered microbial inoculant was diluted with fine soil, incorporated into the sowing zone at the V4–V6 seedling stage, and rotary-tilled into idle strips to bury straw at 25–30 cm depth.

NT4/ST4: T3 + 5% increased planting density. Planting density adjusted to 68,250 plants ha⁻¹.

NT5/ST5: T3 + 10% increased planting density. Planting density adjusted to 71,500 plants ha⁻¹.

In total, 11 treatment combinations were included, and 3 replicates yielded 33 experimental plots. Each subplot measured 8 m × 10 m (80 m²), with 0.5 m protective rows between adjacent subplots and 1 m buffer zones between blocks to eliminate edge effects. Whole plots were randomly arranged within each block, and sub-treatments were randomly allocated within the corresponding NT and ST whole plots. A schematic diagram

of the cumulative additive split-plot experimental layout is provided in Figure S1, which illustrates the spatial arrangement of blocks, whole plots, subplots, treatment allocation, and randomization. Each independent field subplot subjected to independent tillage operations and integrated agronomic management practices is explicitly defined as the actual experimental unit, with $n = 3$ independent biological replicates per treatment corresponding to the three randomized complete blocks. All non-experimental agronomic practices (pest control, weed management, supplementary irrigation) were uniformly implemented across all plots to avoid confounding effects. Detailed field operations for each tillage system are described below.

NT: After the autumn combine harvest, maize straw was chopped (<25 cm) and spread on the soil surface. One to two days before spring sowing, a wide–narrow row pattern was adopted, with straw moved from sowing (50 cm) to idle strips (80 cm) using a straw grader. Sowing, fertilization, covering, and compaction were completed simultaneously with a no-till planter when the 5 cm soil temperature stabilized at ≥ 10 °C. Planting density was 65,000 plants ha⁻¹ (27 cm spacing), with 1000 kg ha⁻¹ base compound fertilizer (N-P₂O₅-K₂O 25-10-15) plus 50 kg ha⁻¹ “mouth fertilizer” (agricultural microbial agent).

ST: After the autumn combine harvest, maize straw was chopped (<25 cm), spread, and moved from sowing to fallow strips with a straw grader, followed by partial tillage (< 10 cm depth) in sowing strips. In spring, sowing, fertilization, covering, and compaction were performed simultaneously with a no-till planter at 5 cm soil temperature ≥ 10 °C, with deep cultivation (25–30 cm) conducted specifically at the V4–V6 seedling stage. Planting density and fertilization were consistent with NT.

CT: After the autumn combine harvest, straw was incinerated. Spring soil preparation involved fertilization, ridging, and compaction (tillage depth: 18 cm). Planting density and fertilization were the same as for NT and ST. This straw incineration measure for CT strictly reproduced the long-term dominant traditional farming custom on sloping Albic farmlands in Jilin’s black soil region. In local real maize production, conventional ridge tillage has always been matched with straw burning as a unified set of farm operations for decades. By contrast, newly popular no tillage and strip tillage (NT/ST) are promoted as complete conservation tillage packages that mandate full maize straw return as a necessary supporting agronomic practice. We designed CT to fully simulate the authentic conventional production system used by local farmers rather than constructing artificial single-factor control groups, which unavoidably generated straw organic C input as a confounding covariate between CT and NT/ST treatments.

The full correspondence between treatment codes and management measures is summarized in Table 1.

Table 1. Treatment codes and management measures

Treatment Code	Planting Density (Plants ha ⁻¹)	Basal Compound Fertilizer (kg ha ⁻¹)	Microbial Agent (Basal + Seed-Fertilizer)	ZnSO ₄ Addition	Straw Decomposition Promotion	Density Increase Rate
CT	65,000	1000	50 kg ha ⁻¹ seed-fertilizer only	–	–	0
NT1/ST1	65,000	1000	50 kg ha ⁻¹ seed-fertilizer only	–	–	0
NT2/ST2	65,000	400	400 kg ha ⁻¹ basal + 50 kg ha ⁻¹ seed-fertilizer	✓	–	0
NT3/ST3	65,000	400	400 kg ha ⁻¹ basal + 50 kg ha ⁻¹ seed-fertilizer	✓	✓	0
NT4/ST4	68,250	400	400 kg ha ⁻¹ basal + 50 kg ha ⁻¹ seed-fertilizer	✓	✓	5%

NT5/ST5	71,500	400	400 kg ha ⁻¹ basal + 50 kg ha ⁻¹ seed-fertilizer	√	√	10%
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Note: “√” indicates that the measure is included in the corresponding treatment. All NT and ST treatments adopted full maize straw return after autumn harvest, while CT adopted straw incineration following local convention.

2.3. Soil Sampling and Sample Preparation

Soil samples were collected in late October 2025, immediately after maize physiological maturity and grain harvest. Given that soil HS fractions and HA molecular structure are relatively stable, slow-varying components of SOM, their response to tillage and straw management practices relies on cumulative treatment effects to be fully expressed. Therefore, all results presented were determined using soil samples collected in 2025, after two consecutive years of continuous tillage and agronomic management implementation. Short-term (one-year) treatments usually produce weak and fluctuating signals that are easily confounded by seasonal climatic variation and initial soil heterogeneity. Therefore, following the common practice in similar HS regulation studies in black soil regions, all soil property results presented in the main text were determined using soil samples collected in 2025, after two consecutive years of continuous tillage and agronomic management implementation, to capture stable cumulative treatment effects. Sampling was performed on the 0–20 cm plough layer using a 5 cm-diameter soil auger following the five-point sampling method. Five subsamples were randomly distributed across the entire 80 m² subplot to cover the microspatial heterogeneity of soil properties and thoroughly homogenized to generate one composite sample per plot. This composite sampling strategy effectively reduces random sampling error caused by small-scale spatial variability in SOM fractions. Each composite sample directly corresponded to one field replicate, with three randomized complete blocks serving as independent biological replicates for each treatment. The three blocks were arranged along the slope gradient to cover the main spatial heterogeneity of the experimental site, ensuring the representativeness of the replication design.

After removing visible plant residues, roots, and gravel, the 2025 soil samples were passed through a 2 mm sieve. One portion of the fresh sample was stored at 4 °C for DOM analysis. The remaining portion was air-dried at room temperature in darkness for subsequent HS composition and HA characterization.

2.4. 3D-EEM Fluorescence Spectroscopy of DOM

Fresh soil samples were suspended in distilled water at a 1:30 (w v⁻¹) solid-to-liquid ratio and shaken at 25 °C for 24 h. The mixture was then centrifuged at 12,000 rpm for 15 min, and the supernatant was filtered through a 0.45 µm membrane to obtain DOM samples. DOM C content was measured with a vario TOC cube analyzer (Elementar Analysensysteme GmbH, Langenselbold, Germany). 3D-EEM fluorescence of DOM was collected using a Hitachi F-7000 spectrometer (Tokyo, Japan) with Ex 200–550 nm and Em 250–550 nm, following Wang et al. [17]: Ex/Em slits 5 nm, scanning speed 2400 nm min⁻¹. EEMs were corrected by subtracting an ultrapure water blank to minimize scattering, and spectra were plotted using MATLAB 2020 (MathWorks, Natick, MA, USA).

The HIX was calculated as the ratio of integrated fluorescence intensities at Em 435–480 nm and 330–375 nm (Ex 260 nm; [8]) to characterize DOM humification degree: higher values indicate more advanced humification, reflecting conversion of labile, low-molecular-weight OM (e.g., proteins, carbohydrates) to stable, high-molecular-weight DOM with complex aromatic structures. The BIX, a quantitative indicator of autochthonous DOM contribution, was the ratio of Em 380 nm to Em 430 nm (Ex 310 nm; [18]), representing the

proportion of freshly produced biogenic OM. A BIX > 1.0 indicates dominant labile biogenic OM (e.g., microbial metabolites), while a BIX < 0.8 indicates more recalcitrant geochemically transformed OM (e.g., aged HS). The FI distinguishes OM sources: the ratio of E_m 450 nm to E_m 500 nm (E_x 370 nm). An FI < 1.4 indicates allochthonous OM (terrestrial plant detritus, high aromaticity), while an FI > 1.9 indicates autochthonous OM (in situ biological processes, high bioavailability).

2.5. Extraction of HS Fractions and Their C Determination

HS fractions were extracted via Zhou et al.'s [19] protocol with minor modifications for consistency. Air-dried, homogenized soil samples were sieved through a 0.15 mm mesh, and 5.0 g aliquots were transferred to polyethylene centrifuge tubes. WSS were extracted twice with deionized water (1:5 w v⁻¹) in a 70 °C water bath shaker (200 rpm) for 1 h each. After centrifugation (4000× g, 15 min), supernatants were pooled and diluted to 50 mL with deionized water. The residue was alkaline-extracted with 0.1 M Na₄P₂O₇·10 H₂O and 0.1 M NaOH (1:5 w v⁻¹) under the same conditions, and the dark-brown supernatant was designated humic-extracted acid (HE). The residue was washed 4–5 times with deionized water until neutral (pH 6.5–7.0), then oven-dried (60 °C), ground, and sieved (0.15 mm) to obtain Hu.

To isolate HA and FA, 30 mL of HE was acidified to pH 1.0 with 6 M HCl and stood overnight to precipitate HA. Centrifugation (4000× g, 15 min) separated HA (dark precipitate) and FA (clear supernatant). HA was redissolved in 0.1 M NaOH (70 °C) to pH 6.8–7.2. C_{HE} and C_{HA} were determined via the K₂Cr₂O₇ volumetric method: $C_{FA} = C_{HE} - C_{HA}$, and the C_{HA}/C_{FA} ratio was calculated. Purified HA was electrodialyzed to remove electrolytes, concentrated by rotary evaporation (≤40 °C), lyophilized to powder, ground, and sieved (0.01 mm) for characterization.

2.6. Analysis Methods

The logK coefficient of the HE alkaline extract was calculated as $\log(A_{400}) - \log(A_{600})$ from absorbance values at 400 and 600 nm using a TU-1900 UV-visible spectrophotometer (Beijing Purkinje General Instrument Co., Ltd., Beijing, China). Elemental compositions (C, H, O, and N) of solid HA samples were determined with a PE 2400II CHNS/O elemental analyzer (PerkinElmer, Waltham, MA, USA), and H/C, C/N, and O/C molar ratios were calculated from the results. Solid HA structural characteristics were analyzed via an FTIR-850 Fourier-transform infrared (FTIR) spectrometer (Tianjin Gangdong Sci & Tech Development Co., Ltd., Tianjin, China) over 400–4000 cm⁻¹, with spectra processed using FTIR 850 software. HA thermal stability was assessed with an HQT-2 thermogravimetric analyzer (Beijing Hengjiu Experimental Equipment Co., Ltd., Beijing, China): 5–7 mg samples were heated from 35 °C to 700 °C at 15 °C min⁻¹ under 60 mL min⁻¹ air flow, and DT-TGA data were recorded via instrument software. Solid-state ¹³C-CPMAS-NMR spectra of 100 mg HA samples were obtained with a Bruker AV400 spectrometer (Bruker BioSpin, Fällanden, Switzerland) at 100 MHz, with parameters of 8 kHz spinning rate, 50 Hz line broadening, 2 ms contact time, 5 s relaxation delay, and ¹H 90° pulse. Relative C abundance was calculated from the integrated area of five functional groups. All derived structural parameters and molar ratios (e.g., FTIR peak intensity ratios, thermal stability indices, C functional group ratios) were calculated individually for each biological replicate rather than from pooled samples to preserve statistical independence and properly propagate variability from soil sampling, HA extraction, and instrument measurement.

2.7. Statistical Analyses

This study adopted a cumulative additive split-plot design with an unbalanced and non-orthogonal superimposed subplot structure: CT only included one control treatment,

while NT and ST each contained five gradient sub-treatments with mixed stacked agronomic parameters. Since multiple agronomic variables were simultaneously mixed within each incremental subplot and no independent single-factor control groups were set, standard factorial ANOVA could not be used to separate the independent main effect or interaction of any individual agronomic parameter (fertilizer reduction, straw decomposition promotion, planting density). To match this design feature and align with the research objective of optimal tillage–cultivation mode screening, a two-step ANOVA strategy was employed, as follows. (1) One-way ANOVA across all treatments for integrated mode comparison. Treating each of the 11 tillage-management combinations as a complete integrated technical regime, one-way ANOVA was performed across all 11 treatments, with treatment as the fixed factor and block as the random factor (Table S8). Duncan’s multiple range test ($p < 0.05$) was used for pairwise comparison between all individual tillage-management combinations. (2) Split-plot ANOVA for tillage main effect verification. To verify the overall main effect of tillage systems and comply with the split-plot design logic, split-plot ANOVA was conducted using three baseline treatments (NT1, ST1, CT) with consistent agronomic management. Given that the sub-treatments were cumulative additive gradients rather than independent factorial factors, this study did not focus on decomposing the independent effect and interaction of each agronomic measure, but prioritized the pairwise comparison of integrated modes. Considering the limited statistical power of normality and homogeneity tests with only three biological replicates, we supplemented multiple lines of evidence to support the application of parametric analysis. First, all measured soil biogeochemical and crop yield indicators are widely recognized to follow an approximately normal distribution in arable Mollisols, which is a common basis for statistical analysis in soil ecology research. Second, the five-point composite sampling strategy effectively reduced microspatial heterogeneity within each plot: all datasets showed moderate variability (most coefficients of variation $< 10\%$) without extreme outliers or severely skewed distributions. The Shapiro–Wilk test and Levene’s test were applied prior to ANOVA as auxiliary checks for data normality and homogeneity of variance, respectively. To further confirm the robustness of our results, we additionally conducted the nonparametric Kruskal–Wallis H test on all core indicators, and the significance pattern of inter-treatment differences was highly consistent with the ANOVA results. Principal component analysis (PCA) was performed on all 11 treatments using 18 core indicators to comprehensively evaluate the overall performance of each tillage–cultivation mode. All data derived from the 2025 soil sampling campaign are presented as means $\pm$ standard deviation of three biological replicates. Notably, each biological replicate corresponds to an independent field plot subjected to independent tillage and management operations; thus, the observational units (plot-level measurements) satisfy the independence assumption of parametric ANOVA. The non-orthogonal and structurally nested relationship exists only among treatment levels in the additive gradient.

All spectral and thermogravimetric determinations were conducted independently for each of the three field biological replicates. For each soil sample, HA was extracted separately and then subjected to instrumental analysis, with 2–3 technical replicates per sample. Technical replicate values were averaged prior to data processing to minimize instrumental noise. All derived structural parameters and molar ratios (e.g., FTIR peak intensity ratios, thermal stability indices, C functional group ratios) were calculated individually for each biological replicate, rather than from pooled samples, to preserve statistical independence and properly propagate variability from soil sampling, HA extraction, and instrumental measurement.

3. Results

3.1. Maize Yield and Its Constituent Factors

All results presented in this section were determined using soil samples collected in late October 2025 after two consecutive years of continuous tillage and integrated agromonomic management implementation. No cross-year data averaging was performed. As shown in Table 2, split-plot ANOVA based on baseline treatments (NT1, ST1, CT) showed that tillage system had a significant effect on maize yield ($p < 0.05$). NT and ST baseline treatments achieved significantly higher yield than CT. Overall, ST treatments had a 6.78% higher average yield than NT treatments. Among the NT group, NT1 yielded the highest, followed by NT3 and NT5, with NT2 the lowest. For ST, ST5 produced the maximum yield, followed by ST4 and ST2, with ST3 the lowest. ST4 and ST5 were 16.5% and 22.3% higher than ST3, respectively, while NT4 and NT5 slightly decreased compared to NT3.

Table 2. Mean values of maize yield and constituent factors under different tillage practices combined with integrated management strategies

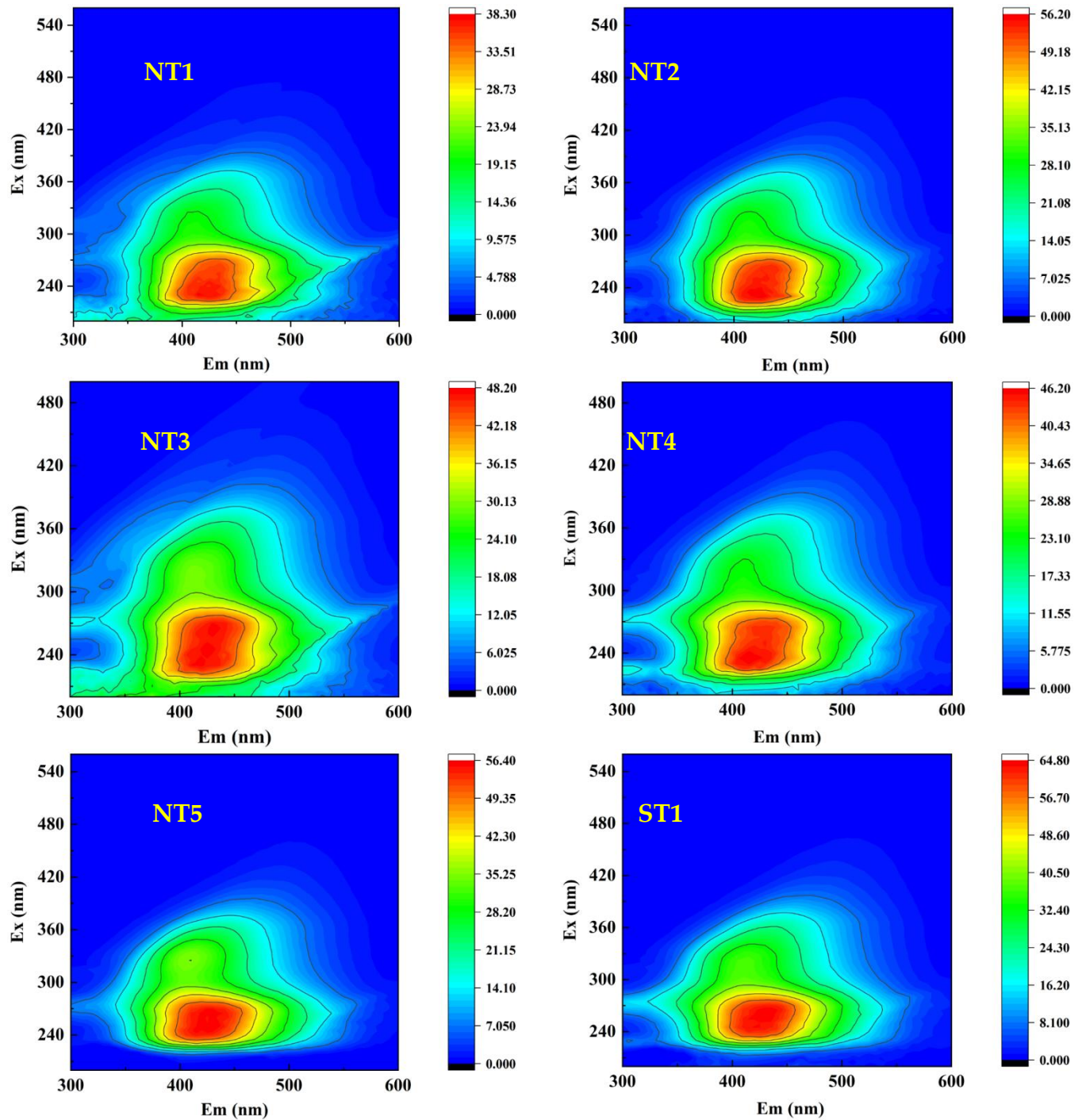
Tillage System	Treatments	Number of Spikes per Row	Number of Grains per Row	Kernel Number per Spike	Percentage of Dented Grains (%)	Hundred-Grain Weight (g)	Maize Yield (kg ha ⁻¹)	Maize Yield Ave. (kg ha ⁻¹)
No-tillage (NT) system	NT1	19.1	41.1	783.1	9.4	33.0	10,769.4	9996.0
	NT2	16.9	41.5	702.0	14.3	33.5	8941.4	
	NT3	17.3	39.9	691.0	9.9	32.7	10,132.3	
	NT4	17.7	41.5	732.6	10.5	34.9	10,030.1	
	NT5	17.3	41.2	711.4	12.9	33.5	10,107.0	
Strip-tillage (ST) system	ST1	16.7	42.9	714.4	2.7	33.2	10,258.3	10,673.9
	ST2	17.5	39.5	690.5	15.5	32.7	10,556.9	
	ST3	17.6	39.4	693.4	12.8	32.2	9609.9	
	ST4	16.9	41.1	696.5	10.8	33.5	11,193.8	
	ST5	18.7	39.9	744.3	12.1	35.1	11,750.5	
Conventional tillage (CT, control)	CT	17.6	41.7	734.4	8.7	35.9	9821.1	9821.1

Note: Treatments are grouped by tillage system for intuitive cross-system comparison. NT1/ST1 represents local conventional NT and ST for maize cultivation at a density of 65,000 plants ha⁻¹. NT2/ST2 integrates fertilizer reduction based on NT1/ST1. NT3/ST3 adds straw decomposition promotion to NT2/ST2. NT4–NT5 and ST4–ST5 are modified from NT3/ST3: NT4/ST4 with a 5% higher planting density (68,250 plants ha⁻¹), and NT5/ST5 with a 10% higher density (71,500 plants ha⁻¹). The system-level average values are retained only as descriptive summary statistics (NT = mean of 5 sub-treatments, ST = mean of 5 sub-treatments, CT = single control treatment) for intuitive overview.

Regarding yield components, NT1 had the highest spike row number and ST1 had the lowest. Grains per row ranged from 39.4 to 42.9, with ST1 the highest. NT1 had the highest kernel number per spike, followed by ST5, with the lowest in ST2 (690.5) and NT3 (691.0). ST1 and NT1 had the lowest dented grain proportion in their respective series, and all NT sub-treatments had higher grain damage than CT. CT had the highest hundred-grain weight (35.9 g), followed by ST5 and NT4, with the lowest in ST3 and NT3.

3.2. 3D-EEM Fluorescence Spectra of DOM

Figure 1 and Table 3 depict C_{DOM} content and DOM fluorescence indicators under NT, ST, and CT. In NT, C_{DOM} content increased with optimized agronomic practices and higher planting density, with NT1 having the lowest and a gradual rise from NT3 to NT5. ST showed a similar, but broader C_{DOM} trend, increasing from ST1 to ST5, while CT had the lowest C_{DOM} content.



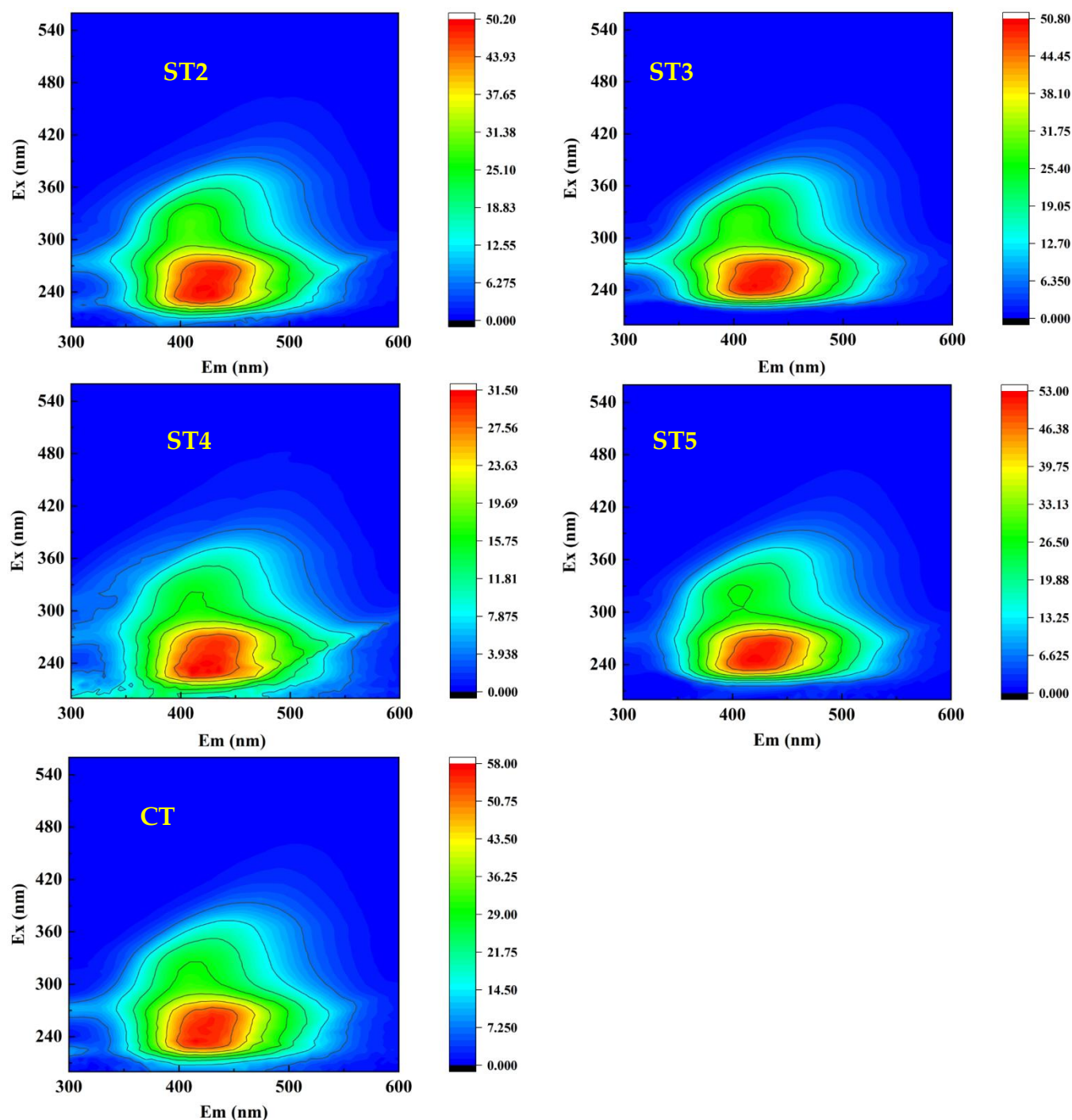


Figure 1. 3D-EEM fluorescence spectra of DOM under different tillage practices combined with integrated management strategies. Note: Each spectrum plots excitation wavelength (200–500 nm) on the vertical axis and emission wavelength (300–600 nm) on the horizontal axis, with fluorescence intensity represented by the color gradient (higher values indicate greater C_{DOM} , abundance). Two core fluorescent DOM fractions are distinguishable in the spectra: (1) protein-like fluorescence region ($Ex/Em \approx 220\text{--}280\text{ nm}/300\text{--}380\text{ nm}$), corresponding to labile autochthonous DOM (tryptophan- and tyrosine-like substances) derived from microbial metabolism and crop root exudates, which is linked to the BIX for autochthonous contribution evaluation; (2) humic-like fluorescence region ($Ex/Em \approx 250\text{--}350\text{ nm}/380\text{--}550\text{ nm}$), representing recalcitrant, high-aromaticity DOM components (fulvic acid- and humic acid-like substances), which reflects the DOM humification degree quantified by the HIX. Elevated fluorescence intensity in the humic-like region and red shifts of peak positions indicate enhanced DOM humification and molecular complexity, and increased protein-like

peak intensity reflects greater accumulation of microbially derived fresh DOM. The 11 panels correspond to 5 incremental management levels under no tillage (NT1–NT5), 5 levels under strip tillage (ST1–ST5), and conventional ridge tillage (CT) as the control.

Table 3. C_{DOM} content and DOM fluorescence indices (FI, BIX, HIX) under different tillage practices combined with integrated management strategies

Tillage System	Treatments	C_{DOM} Content (mg/L)	Optical Indices of DOM		
			Fluorescence Index (FI)	Autochthonous Contribution (BIX)	Humification Index (HIX)
No-tillage (NT) system	NT1	0.36 ± 0.02 g	2.39 ± 0.08 ab	0.77 ± 0.08 d	5.53 ± 0.24 j
	NT2	0.38 ± 0.03 g	2.30 ± 0.09 cd	0.77 ± 0.09 d	5.66 ± 0.15 i
	NT3	1.52 ± 0.13 f	2.30 ± 0.15 cd	0.78 ± 0.04 cd	7.03 ± 0.24 e
	NT4	2.22 ± 0.18 e	2.25 ± 0.09 d	0.86 ± 0.11 bc	7.16 ± 0.31 d
	NT5	3.71 ± 0.24 c	2.32 ± 0.11 c	0.89 ± 0.09 b	8.04 ± 0.45 b
Strip-tillage (ST) system	ST1	0.30 ± 0.02 hi	2.41 ± 0.12 a	0.81 ± 0.07 c	5.73 ± 0.16 h
	ST2	0.32 ± 0.02 h	2.25 ± 0.14 d	0.85 ± 0.06 bc	6.24 ± 0.21 g
	ST3	3.55 ± 0.25 d	2.33 ± 0.11 c	0.90 ± 0.09 b	6.41 ± 0.24 f
	ST4	6.14 ± 0.44 b	2.37 ± 0.07 b	0.91 ± 0.06 ab	7.12 ± 0.38 d
	ST5	11.3 ± 0.45 a	2.41 ± 0.09 a	0.93 ± 0.16 a	9.81 ± 0.51 a
Conventional tillage (CT, control)	CT	0.26 ± 0.01 i	2.29 ± 0.05 cd	0.79 ± 0.09 cd	7.67 ± 0.42 c

Note: Treatments are grouped by tillage system for intuitive cross-system comparison. Data are expressed as means $\pm$ standard deviation with $n = 3$ independent field biological replicates (three randomized complete blocks). Each replicate corresponds to one independent experimental plot. Composite soil samples collected via the five-point sampling method within each plot were used for all determinations, and technical replicates of spectral scanning and chemical measurement were averaged prior to statistical analysis to avoid pseudo-replication. Abbreviations: C_{DOM} = C content of dissolved organic matter; DOM = dissolved organic matter. Different lowercase letters indicate significant differences among all 11 treatments by one-way ANOVA followed by Duncan's multiple range test ($p < 0.05$).

DOM FI (all >1.9) uniformly indicated that DOM across all tillage and management systems was predominantly derived from in situ autochthonous microbial processes. The inter-treatment variation of FI values was relatively narrow in magnitude and did not follow a consistent pattern aligned with the incremental agronomic management gradient. Numerically, FI peaked at NT1 in the NT series and showed a fluctuating trend across ST sub-treatments; however, given the small amplitude of variation, these minor fluctuations were considered to partially reflect instrumental and analytical noise and were not interpreted as ecologically meaningful treatment responses. BIX increased with enhanced management— 0.77 (NT1) to 0.89 (NT5) in NT, and 0.81 (ST1) to 0.93 (ST5) in ST—indicating promoted autochthonous microbial DOM production. CT (BIX = 0.79) was lower than NT4, NT5, and all ST sub-treatments. HIX increased with technological integration and higher density: 5.53 (NT1) to 8.04 (NT5) in NT, peaking at ST5 in ST. Notably, CT (HIX = 7.67) was higher than NT1–NT4 and ST1–ST4 despite having the lowest C_{DOM} content.

3.3. HS Composition

As shown in Figure 2, NT4 had the highest C_{WSS} content in the NT series, while NT1 and NT2 shared the lowest. In the ST series, ST1 had the highest C_{WSS} , with ST3 the lowest. All NT and ST treatments had significantly higher C_{WSS} than CT. For C_{HE} , NT5 was the

highest in the NT series, while NT1 was the lowest. In the ST series, ST1 had the highest C_{HE} and ST3 had the lowest—significantly lower than that of CT. Regarding C_{HA} , NT4 was the highest in the NT series, followed by NT5. In contrast, NT3 displayed the lowest C_{HA} in the NT series, which was statistically comparable to that of CT. In the ST series, C_{HA} increased consistently from ST1 to ST5 (all higher than CT), with ST5 the highest. For C_{Hu} , the NT series showed a trend of increasing from NT1 to NT4, then decreasing in NT5, and all NT treatments were significantly higher than CT. In the ST series, ST3 had the highest C_{Hu} (significantly higher than CT), while ST4 and ST5 were lower than CT.

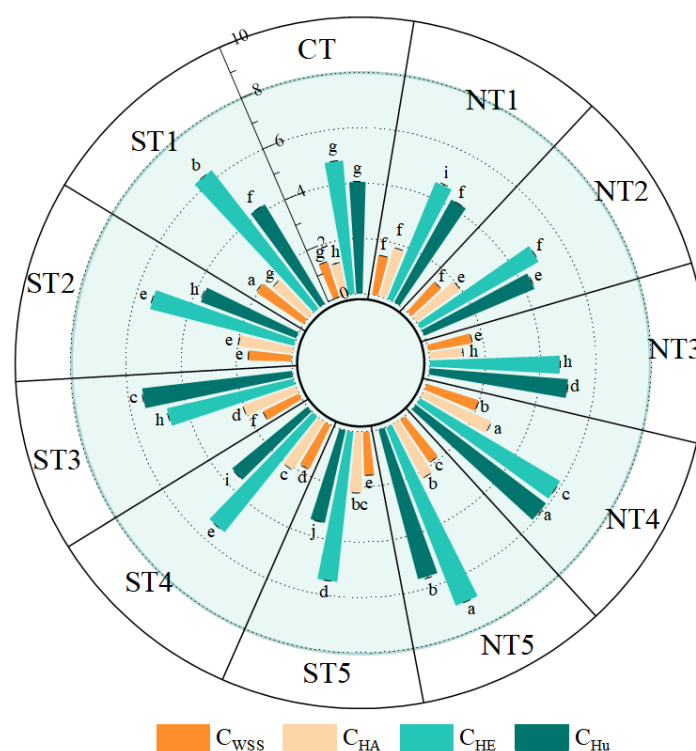


Figure 2. Effects of different tillage practices combined with integrated management strategies on HS composition. Note: Different lowercase letters indicate statistically significant differences ($p < 0.05$) in C content of HS fractions (C_{WSS} , C_{HA} , C_{HE} , and C_{Hu}) across treatments.

3.4. C_{HA}/C_{FA} , $HA\ E_4/E_6$, TOC, and C_{HA}/TOC

The $HA\ E_4/E_6$ ratio indicates structural complexity, with a higher ratio denoting lower aromaticity, higher aliphaticity, and a simpler structure [20]. As shown in Figure 3a, in the NT system, the E_4/E_6 ratio increased progressively from NT1 to NT3, then steadily declined to NT5, with NT3 the highest and NT5 the lowest. In ST treatments, the ratio rose from 4.93 (ST1) to a peak of 5.86 (ST2), then declined to 4.50 (ST5). Compared with CT, E_4/E_6 ratios were higher in NT1–NT4 and ST1–ST3, but lower in NT5 and ST4–ST5. The C_{HA}/C_{FA} ratio, a key indicator of HS quality with more stable and fertility-beneficial HA than FA [21], presented a U-shaped trend in both systems. In NT, the ratio dropped to the minimum at NT3 and then increased, peaking at NT5. In ST, it decreased from ST1 to ST2, followed by a continuous rise to ST5. CT had the lowest C_{HA}/C_{FA} ratio (comparable to NT3), while NT5 and ST5 showed the highest ratios across all treatments.

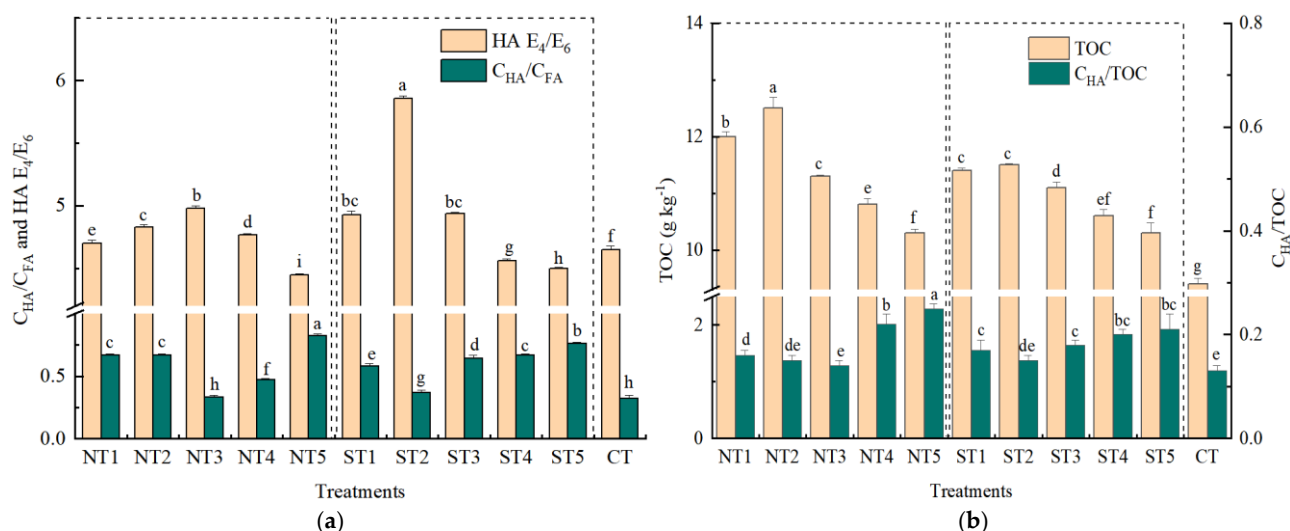


Figure 3. Effects of different tillage practices combined with integrated management strategies on (a) C_{HA}/C_{FA} ratio and HA E_4/E_6 ratio, and (b) TOC content and C_{HA}/TOC ratio. Note: Data are expressed as mean values of three independent field biological replicates ($n = 3$, randomized complete blocks). Each replicate corresponds to one independent experimental plot, and composite soil samples collected via the five-point sampling method within each plot were used for all determinations. Technical replicates of chemical measurement were averaged prior to statistical analysis to avoid pseudo-replication. Statistical comparisons were performed using one-way ANOVA followed by Duncan's multiple range test ($p < 0.05$). Different lowercase letters above bars indicate statistically significant differences among the 11 treatments at the $p < 0.05$ level.

Relative to CT, NT and ST significantly increased TOC content (Figure 3b). In the NT series, TOC showed a unimodal trend, peaking at 12.5 g kg^{-1} (NT2) and dropping to 10.3 g kg^{-1} (NT5, the lowest). The ST series exhibited a similar pattern, with the highest TOC at ST2 (11.5 g kg^{-1}). TOC in NT1–NT4 was significantly higher than in ST1–ST4, with no significant difference between NT5 and ST5; CT had the lowest TOC overall. The C_{HA}/TOC ratio (indicator of stable HA contribution to SOC) was higher in NT and ST than in CT. In NT, it increased from 0.14–0.16 (NT1–NT3) to 0.22 (NT4) and 0.25 (NT5). In ST, it rose from 0.15–0.17 (ST1–ST3) to 0.20 (ST4) and 0.21 (ST5). NT5 and ST5 had the highest C_{HA}/TOC ratios in their respective systems, while CT had the lowest.

For all molecular structure analyses (FTIR, DT–TGA, and ^{13}C -CPMAS-NMR), quantitative parameters were calculated independently across the three biological replicates and subjected to one-way ANOVA. Statistical results confirmed that tillage systems and integrated agronomic practices exerted significant effects on core HA structural indices ($p < 0.05$), indicating that observed inter-treatment differences in HA molecular properties exceeded random variability arising from soil spatial heterogeneity, sample preparation, HA extraction and instrumental analysis. Representative spectra and curves are presented in Figures 4–6 to clearly visualize overall spectral patterns, while all quantitative comparisons and significance tests are based on the full dataset of three biological replicates.

Table 4 illustrates HA elemental molar ratios under NT, ST, and CT. The H/C ratio reflects molecular aromaticity, with lower values indicating higher aromaticity [22]. Both NT and ST exhibited an up-then-down trend, peaking at NT3 and ST3 and falling to the lowest at NT5 and ST5. Overall, ST had markedly higher H/C ratios than NT and CT. In the NT treatment, the C/N ratio followed a U-shaped temporal trend, reaching its minimum value at NT3. Compared with NT1, the C/N ratio at NT5 was significantly lower. In contrast, under the ST treatment, the C/N ratio increased monotonically from ST1 to ST5; the O/C ratio (reflecting O-containing functional group abundance; higher values mean

greater oxidation/polarity [23]) showed a unimodal trend in NT (increasing to NT4, then decreasing) and a V-shaped trend in ST (decreasing to ST3, then increasing).

Table 4. Effects of different tillage practices combined with integrated management strategies on the elemental molar ratios of HA

Tillage System	Treatments	H/C Ratio	C/N Ratio	O/C Ratio
No-tillage (NT) system	NT1	1.09 ± 0.04 i	15.1 ± 1.5 f	0.58 ± 0.03 g
	NT2	1.72 ± 0.12 f	11.6 ± 1.1 h	1.00 ± 0.07 c
	NT3	1.98 ± 0.16 e	8.2 ± 0.9 i	1.11 ± 0.09 bc
	NT4	1.30 ± 0.09 h	11.7 ± 1.1 h	1.40 ± 0.04 a
	NT5	0.99 ± 0.06 j	12.1 ± 1.4 g	0.96 ± 0.08 d
Strip-tillage (ST) system	ST1	3.45 ± 0.21 cd	13.7 ± 1.3 e	1.17 ± 0.11 b
	ST2	3.49 ± 0.24 c	19.5 ± 1.7 d	0.55 ± 0.04 gh
	ST3	4.17 ± 0.32 a	21.0 ± 1.9 c	0.40 ± 0.02 h
	ST4	3.77 ± 0.17 b	23.3 ± 2.1 b	0.81 ± 0.09 e
	ST5	2.71 ± 0.09 d	29.8 ± 2.3 a	1.15 ± 0.13 b
Conventional tillage (CT, control)	CT	1.36 ± 0.09 g	13.9 ± 1.4 e	0.67 ± 0.08 f

Note: Treatments are grouped by tillage system to facilitate pattern comparison. Data are calculated from three independent field biological replicates. Abbreviations: HA = humic acid; H/C = hydrogen-to-carbon molar ratio; C/N = carbon-to-nitrogen molar ratio; O/C = oxygen-to-carbon molar ratio. Different lowercase letters within the same column indicate significant differences across all 11 treatments, tested by one-way ANOVA followed by Duncan's multiple range test ($p < 0.05$).

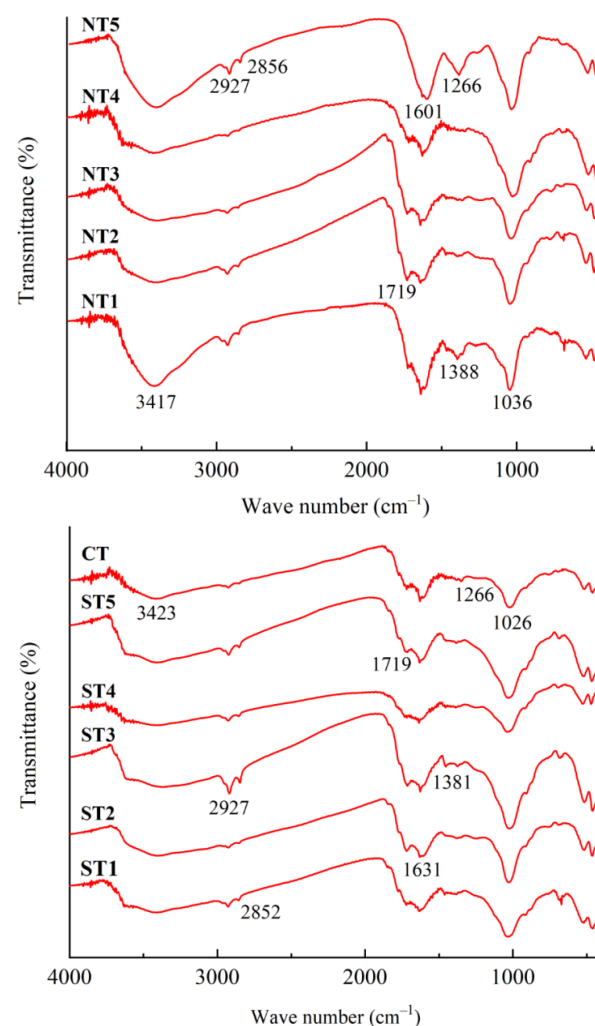


Figure 4. Representative FTIR spectra of HA under different tillage practices combined with integrated management strategies. All samples were analyzed independently for each of the three field biological replicates, with 2–3 technical replicates averaged per sample to reduce analytical error. Quantitative peak intensity ratios derived from the full replicate dataset were statistically tested via one-way ANOVA followed by Duncan’s multiple range test ($p < 0.05$), confirming that inter-treatment spectral differences were statistically significant relative to biological and analytical variability.

As shown in Figure 4 and Table S1, alcoholic and phenolic O–H stretching vibrations ($3384\text{--}3428\text{ cm}^{-1}$) were most intense in NT1 and least in NT4. In ST treatments, intensities ranged from 39.6% to 49.2%, with ST4 the highest. CT had moderate intensity, higher than all ST subgroups. Aliphatic C–H stretching vibrations ($2924\text{--}2934\text{ cm}^{-1}$ and $2853\text{--}2856\text{ cm}^{-1}$) showed consistent trends: ST3 had the highest intensity at both bands, while NT4 had the lowest. C=O stretching vibrations of carboxyl groups ($1720\text{--}1723\text{ cm}^{-1}$) peaked in NT2 and NT3, followed by ST2. NT5 and ST5 had the lowest intensities in their respective series, with CT intensity significantly lower than the ST series. Aromatic C=C stretching vibrations were most intense in NT5 and ST5. C–O stretching vibrations in polysaccharides ($1023\text{--}1037\text{ cm}^{-1}$) peaked in NT4 and ST3, were the lowest in NT1, and CT was lower than all ST treatments. The aliphatic C/carboxyl C ratio (I_{2920}/I_{1720}) was highest in NT1/NT5 and lowest in NT3. In ST, ST3 had the highest ratio (exceeding CT) and ST2 the lowest. The aliphatic C/aromatic C ratio (I_{2920}/I_{1630}) in NT ranged from 0.06 to 0.16, except for NT2 (0.36, exceeding CT’s 0.17), with NT5 the lowest. ST1–ST4 treatments had higher ratios than CT, with ST3 achieving the maximum ratio of 0.81.

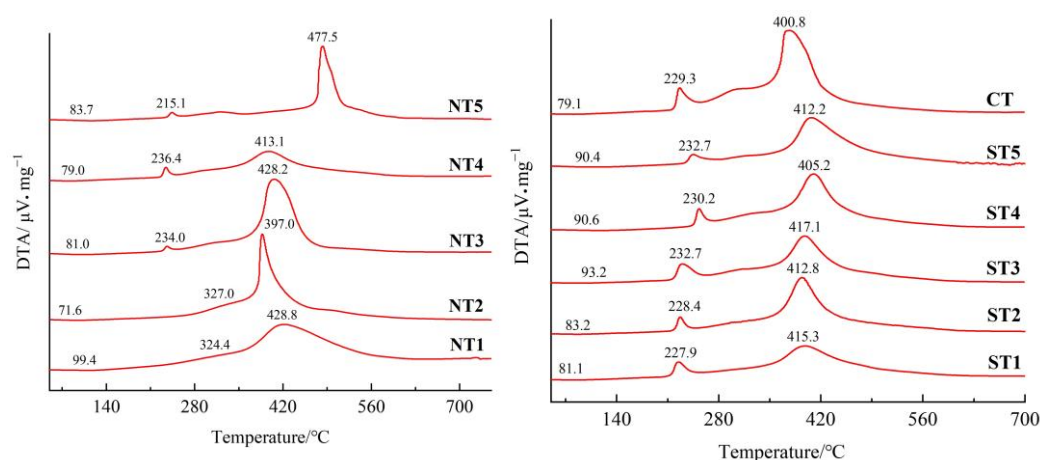


Figure 5. Representative DT–TGA curves of HA under different tillage practices combined with integrated management strategies. Thermal analysis was performed independently for each of the three field biological replicates. Derived thermal parameters (medium- and high-temperature exothermic heat, H/M exothermic ratio, H/M mass loss ratio) were calculated per replicate and subjected to ANOVA and Duncan’s test ($p < 0.05$), verifying that treatment effects exceeded variability from sample preparation and instrumental measurement.

As shown in Figure 5 and Table S2, low-temperature endothermic peaks (71.6–99.4 °C) were derived from bound water desorption and the decomposition of labile HA fractions (simple carbohydrates, aliphatics) [24]. In the medium-temperature range (215.1–324.4 °C), the exothermic heat of the NT series decreased steadily from NT1 to NT5. The ST series increased sharply from ST1 to ST2, followed by a gradual decline to ST5. The CT had a higher medium-temperature exothermic value than all NT treatments and most ST treatments except ST2. NT5 and ST5 represented the lowest medium-temperature exothermic levels in their respective groups. High-temperature exothermic performance

(397.0–428.8 °C) varied greatly across tillage systems [24]. For NT, exothermic heat declined from NT1 to NT3 and then rose to NT5. In the ST series, ST2–ST4 yielded higher exothermic values than ST1, while ST5 was slightly lower than ST1. Overall, HA under NT exhibited consistently higher high-temperature exothermicity than CT; only ST2–ST4 exceeded CT, and both ST1 and ST5 were lower than CT.

The high/medium-temperature (H/M) exothermic ratio presented an inverted U-shaped trend in both NT and ST treatments. The H/M of NT decreased from NT1 to NT2 and then surged to NT5. For ST, it fell from ST1 to ST2 before increasing to ST5. The maximum H/M values appeared in NT5 and ST5. NT had a wider H/M variation range (12.8–55.4) than ST (8.9–22.8), and both were superior to CT. Conversely, the H/M mass loss ratio showed a unimodal distribution: it increased from NT1 to the peak at NT3 and then decreased to NT5; in the ST group, it rose from ST1 to the peak at ST4 and declined to ST5. NT1 and ST1 had lower mass loss ratios than CT, whereas all treatments of NT2–NT5 and ST2–ST5 were higher than CT.

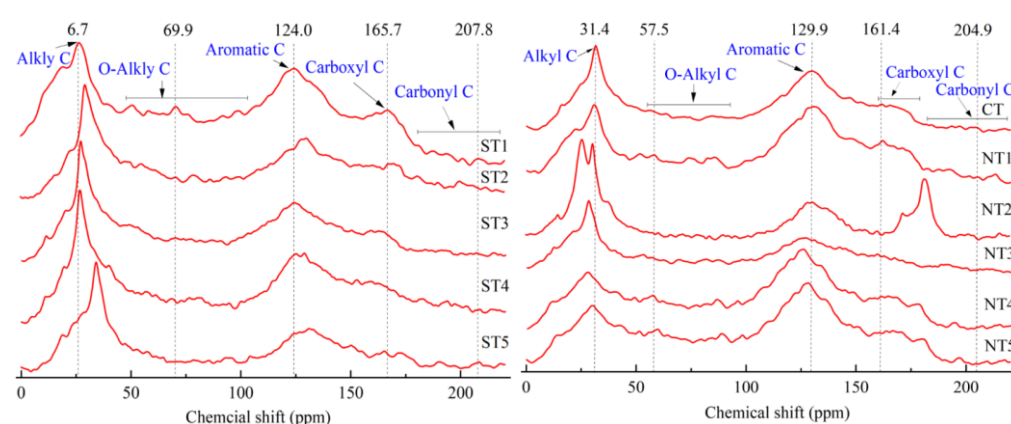


Figure 6. Representative solid-state ^{13}C -CPMAS-NMR spectra of HA under different tillage practices combined with integrated management strategies. Spectral acquisition and functional group integration were conducted independently for each of the three biological replicates. Relative abundances of C functional groups and derived structural ratios (aliphatic C/aromatic C, hydrophobic C/hydrophilic C) were calculated per replicate and statistically analyzed, with significant inter-treatment differences confirmed at the $p < 0.05$ level.

^{13}C -CPMAS-NMR spectroscopy quantified the relative distribution of C functional groups in HA under CT, NT, and ST treatments. Chemical shift regions were assigned as follows: alkyl C (0–45 ppm), O-alkyl C (45–110 ppm, labile C), aromatic C (110–163 ppm, stable C), carboxyl C (163–180 ppm), and carbonyl C (180–220 ppm). Two diagnostic ratios were calculated: aliphatic C/aromatic C ([alkyl C + O-alkyl C]/aromatic C, reflecting humification degree) and hydrophobic C/hydrophilic C ([alkyl C + aromatic C]/[O-alkyl C + carbonyl C], indicating structural stability).

As shown in Figure 6 and Table S3, among NT sub-treatments, NT1 had the highest aromatic C and lowest aliphatic C/aromatic C ratio, whereas NT2 had the highest alkyl, carboxyl, and carbonyl C but the lowest O-alkyl and aromatic C. Relative to NT3, high-density planting (NT4, NT5) decreased alkyl C, but increased O-alkyl, aromatic, and carbonyl C. In ST sub-treatments, ST1 had the highest O-alkyl C (across all treatments), lowest aromatic and carbonyl C, highest aliphatic C/aromatic C ratio, and lowest hydrophobic C/hydrophilic C ratio, while ST2 had the highest carboxyl C. Compared with ST3, ST4–ST5 had lower O-alkyl C, but higher carboxyl and carbonyl C, with ST4 having the highest aromatic C in ST treatments. CT had lower alkyl C and aliphatic C/aromatic C ratios than ST, but higher aromatic C. The ST series yielded significantly higher aliphatic C/aromatic C ratios compared to the corresponding NT conditions. In contrast, the CT series exhibited

a ratio of 1.19—lower than the NT average and substantially lower than the ST average. In NT, the hydrophobic C/hydrophilic C ratio increased from NT1 to a peak at NT2, then decreased to NT3–NT5. In ST, it increased progressively from ST1 to ST5.

3.5. PCA

PCA was performed to evaluate the integrated effects of tillage and agronomic practices on soil HS composition, HA molecular structure, and maize yield (Figure 7). Seven principal components with eigenvalues >1 were extracted, explaining 93.186% of the total variance and adequately representing the original dataset (Table S4). PC1 (32.397% variance) was positively loaded on C_{DOM} , C_{HE} , C_{WSS} , C_{HA}/C_{FA} , C_{HA}/TOC , BIX, and HIX, closely related to microbial SOM decomposition, humification, and stable C sequestration (Table S5). PC2 (18.792%) reflected HA structural complexity and soil C–N balance via high loadings of H/C, C/N, C_{Hu} and I2920/I1630. PC3 and PC4 mainly indicated HA thermal stability and C sequestration capacity, while PC5–PC7 further captured variations in secondary HA structural parameters. Linear coefficients showed C_{DOM} , C_{HE} and C_{HA}/TOC dominated PC1, and H/C ratio and C_{Hu} governed PC2 (Table S6). Comprehensive evaluation scores ranked ST5 highest, followed by ST4, NT5, and NT4, with CT the lowest (Table S7). Visually, all ST treatments with optimized management (ST3–ST5) clustered on the right side of the plot (high PC1), indicating stronger overall humification and C sequestration capacity. NT high-density treatments (NT4, NT5) also performed well, but lagged behind corresponding ST treatments. CT was located on the far left, with the lowest comprehensive score. Overall, ST3–ST5 outperformed corresponding NT treatments and CT, demonstrating optimized ST practices that better improved soil fertility and HA quality.

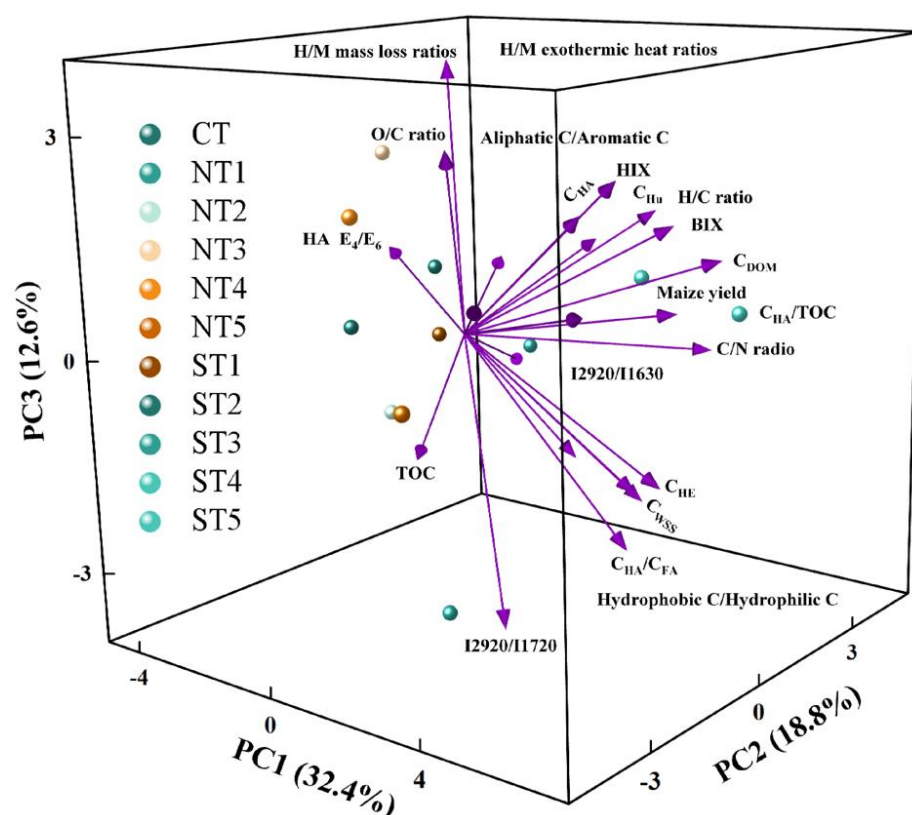


Figure 7. PCA of soil HS properties, HA molecular structure indices, and maize yield under different tillage practices combined with integrated management strategies. Note: Dots represent individual treatments. Arrows indicate the loading direction and magnitude of each indicator. Treatments located in the direction of an arrow have higher values for that corresponding indicator. Ab-

abbreviations: C_{DOM} = C content of dissolved organic matter; HIX = humification index; BIX = autochthonous contribution; C_{HA} = C content of humic acid; C_{HE} = C content of humic-extracted acid; C_{Hu} = C content of humin; TOC = total organic C; C_{HA}/C_{FA} = ratio of humic acid C to fulvic acid C; C_{HA}/TOC = ratio of humic acid C to total organic C; HA = humic acid; $HA\ E_4/E_6$ = absorbance ratio of humic acid at 465 nm and 665 nm; H/C = hydrogen-to-carbon molar ratio; C/N = carbon-to-nitrogen molar ratio; O/C = oxygen-to-carbon molar ratio; I2920/I1630 = ratio of FTIR absorbance at 2920 cm^{-1} to 1630 cm^{-1} (aliphatic C/aromatic C); I2920/I1720 = ratio of FTIR absorbance at 2920 cm^{-1} to 1720 cm^{-1} (aliphatic C/carboxyl C); H/M exothermic heat ratios = ratio of high-temperature to medium-temperature exothermic heat from DT-TGA; H/M mass loss ratios = ratio of high-temperature to medium-temperature mass loss from DT-TGA.

Table S8 shows the variances of 22 variables divided into between-group variance (attributed to differences between different groups or treatments) and within-group variance (attributed to random errors or individual differences within the groups). The core statistical indicators were summarized as follows.

Degrees of freedom (df) and sample size: The between-group degrees of freedom were always 10, indicating that the experiment compared 11 different groups ($k - 1 = 10$, that is, $k = 11$). The within-group degrees of freedom were 22, indicating that the total sample size was 33 ($N - k = 22$, that is, $N = 33$). From this, it could be inferred that each of the 11 groups contains three replicate samples. F value and p value: From C_{DOM} to corn yield, the p values of all analyzed variables were less than 0.001. This means that the observed between-group differences were highly unlikely to be caused by random factors (less than 0.1%), and thus the null hypothesis of equal group means could be fully rejected. High F values further confirmed the significant differences in group means. Regardless of what treatments, conditions, or regions these 11 groups represent, they all had a highly statistically significant and substantive impact on all measured parameters and the final corn yield ($p < 0.001$). The experimental conditions not only significantly changed the ratios of basic elements and the spectral characteristics of humus, but also directly affected the final crop yield. Each treatment had the most intense impact on the C/N and thermal stability parameters. In contrast, its impact on biological indicators and total C content was slightly milder, but still reached the significant statistical standard.

4. Discussion

4.1. Maize Yield and Its Constituent Factors Under Different Tillage Practices

The five sub-treatments under each tillage system are sequential cumulative combinations of multiple agronomic measures, not independently varied single factors. The primary purpose of this gradient design is to screen the optimal integrated tillage–cultivation mode, not to quantify the independent effect of any individual measure. Correspondingly, the two-step statistical strategy was adopted to balance the design rationality and research objectives: the one-way ANOVA across all treatments directly supports integrated mode screening, while the split-plot ANOVA of baseline treatments verifies the fundamental effect of tillage practices. Given the cumulative additive property of sub-treatments, this strategy is more applicable than a full factorial split-plot analysis for technology optimization and on-farm extension. The overall yield advantages conferred by NT and ST systems under conventional management practices were achieved in conjunction with continuous full straw return. ST treatments achieved 6.78% higher average yields than NT treatments, which was plausibly associated with their unique soil disturbance pattern: unlike NT, which retained surface straw and avoided soil disturbance [13], ST only disturbed the narrow planting strip while leaving inter-row soil undisturbed. This optimized rhizosphere soil aeration, water infiltration, and nutrient distribution [25,26], reduced root mechanical impedance [27], and enhanced root nutrient/water uptake capacity [28]. In

contrast, NT suffered from limited nutrient mobility and root penetration due to long-term compaction [5]. Among NT treatments, NT2 had the lowest yield, which might be partly explained by the combined shift in fertilization regime (reduced chemical fertilizer plus microbial agents and ZnSO_4) under compacted soil conditions: the altered nutrient supply profile without improved soil structure may have led to insufficient nutrient availability [29], and microbial agents and ZnSO_4 could not offset yield loss due to restricted nutrient diffusion and microbial activity in compacted soil [30]. In ST systems, the improved rhizosphere environment enhanced microbial colonization and activity [25], promoting nutrient transformation and Zn absorption, thus enabling ST2 to maintain high yield [31].

Along the integrated management gradient, increasing planting density by 5% and 10% significantly boosted ST4 and ST5 yields [32], but slightly impaired NT treatments [33], a pattern that could be driven by differing resource supply capacities between the two tillage systems. ST's strip-disturbed structure optimized light, water, and nutrient distribution [34,35], allowing higher density to fully utilize resources and improve group productivity [36]. In contrast, NT's compaction and nutrient stratification [37] intensified inter-plant competition and reduced resource use efficiency [38]. ST5 achieved the highest yield, likely through the combined effects of strip tillage, straw decomposition promotion [39], and optimized density, maximizing nutrient supply, resource accessibility, and light utilization [40,41].

NT1 had the highest spike row number, attributed to stable root and inflorescence development under NT [42]. ST1 had the maximum grains per row, as conventional fertilization ensured balanced nutrients during floret differentiation [39]. Both NT1 and ST5 had the highest kernel number per spike: NT1 benefited from undisturbed soil nutrient accumulation, while ST5 was associated with optimized density and straw-derived nutrients [40]. ST1 and NT1 had the lowest dented grain rates due to balanced nutrient availability [43]. All NT sub-treatments had higher damage than CT, which might be related to compaction and nutrient stratification restricting grain filling [44]. CT had the highest hundred-grain weight, as low kernel number and planting density offset this advantage [32]. ST5 and NT4 had relatively high hundred-grain weight due to improved soil water retention and nutrient availability [45], while ST3 and NT3 had the lowest, possibly associated with temporary nutrient immobilization during straw decomposition [26].

4.2. C Content and Fluorescence Indices of DOM Under Different Tillage Practices

C_{DOM} content followed the order $\text{ST} > \text{NT} > \text{CT}$, a pattern that might be primarily driven by the combined effects of differential straw C input and reduced soil disturbance intensity, with straw decomposition efficiency further modulating the release of soluble organic fractions [46]. CT exhibited the lowest C_{DOM} : the combination of straw burning (eliminating exogenous straw C input) and frequent tillage disrupted aggregates, enhanced aeration, and accelerated labile organic C mineralization, restricting C_{DOM} production [47]. In contrast, NT and ST reduced disturbance, protecting SOM from oxidative decomposition and preserving microbial habitats to promote C_{DOM} accumulation [48]. In NT, C_{DOM} increased progressively from NT1 to NT5 along the management gradient, which could be linked to the stepwise addition of microbial inputs, straw decomposition regulation, and higher planting density: the integrated upgrades from NT2 to NT3 (fertilizer adjustment plus straw decomposition promotion) boosted microbial activity and SOM breakdown into soluble C_{DOM} [49], while higher planting density (NT4–NT5) might have also increased root exudation and crop residue inputs as supplementary C sources [32]. ST showed a more pronounced C_{DOM} increase (ST1–ST5) owing to its hybrid design: partial planting strip disturbance improved straw–microbe–mineral contact, accelerating straw decomposition more efficiently than NT [50], and higher planting density (ST3–ST5)

was hypothesized to have further enhanced root exudation to support microbial activity and soluble organic compound mobilization [51].

FI values consistently exceeding 1.9 across all treatments confirmed that soil microorganisms were the dominant regulators of DOM composition in this study system, with autochthonous biogenic processes governing DOM source characteristics [48]. Given the narrow variation range of FI and the potential contribution of instrumental noise to minor numerical fluctuations, we did not attempt to interpret the detailed FI differences between individual sub-treatments as ecologically meaningful mechanistic signals. Rising BIX in NT and ST reflected increased fresh autochthonous DOM input [52], which was plausibly driven by integrated agronomic practices [53]. Increased root exudation under higher planting density, as documented in prior studies [54], might have contributed to this pattern, but was not directly measured here. Lower CT BIX reflected intensive tillage's disruption of microbial communities. Rising HIX along the integrated management gradient coupled with synchronous C_{DOM} accumulation indicated genuine enhancement of DOM humification driven by straw transformation and microbial anabolism [55]: lignocellulose-degrading microbes introduced at the NT3/ST3 gradient accelerated straw conversion into HS [56], and higher planting density (NT4–NT5, ST4–ST5) further increased root exudates and crop residue inputs, promoting the accumulation of aromatic DOM structures. ST5 achieved the highest HIX alongside the highest C_{DOM} content, as ST balanced partial disturbance (promoting straw decomposition and HS synthesis) and undisturbed inter-row protection (reducing DOM leaching and mineralization) [13]. For CT, the relatively high HIX value in the context of the lowest C_{DOM} content represented a residual enrichment artifact rather than advanced humification. Intensive conventional tillage disrupted soil aggregates and exposed organic matter to oxidative decomposition, rapidly depleting labile protein-like and carbohydrate-like DOM fractions. The small remaining DOM pool was therefore dominated by recalcitrant humic-like components that resisted mineralization, resulting in an elevated HIX [56]. However, this pattern reflected severe depletion of the overall DOM pool rather than active HS formation.

4.3. HS Composition Under Different Tillage Practices

C_{WSS} was higher in NT and ST than CT, indicating that conservation tillage systems with continuous straw C input better preserved labile organic C relative to CT with complete straw removal via burning. Intensive inversion and straw burning in CT destroyed soil aggregates, accelerated mineralization of labile C, and cut straw C input, lowering C_{WSS} [15]. Among NT treatments, NT4 had the peak C_{WSS} , which could be partly associated with moderate planting density increasing root-derived C input and straw decomposition releasing soluble residue C. The root exudation component of this inference was supported by prior work [56] rather than direct quantification in this study. Low nutrient supply and the absence of microbial inoculants limited C_{WSS} accumulation in NT1 and NT2. For ST, ST1 showed the highest C_{WSS} due to moderate soil disturbance promoting diffusion of soluble organic C from surface straw [57]. Reduced fertilization and exogenous microbial assimilation of labile C led to the minimum C_{WSS} in ST3 [58]. NT5 had the highest C_{HE} in NT, associated with the highest level of integrated management (10% higher planting density plus full straw return and decomposition promotion) and reduced soil disturbance preserving new HS [59]. The lowest C_{HE} in NT1 likely favored straw mineralization over C_{HE} synthesis [60]. In ST, ST1's highest C_{HE} benefited from hybrid strip tillage (tilled rows enhancing nutrient availability, untilled inter-rows retaining moisture/OM) [61]. ST3's lower C_{HE} might be related to exogenous microbes + reduced fertilizer impeding straw decomposition: high straw C vs. limited N induced microbial N immobilization, constraining humification [62]; NT4 had the highest C_{HA} , followed by NT5, a pat-

tern that could be linked to the combined effects of straw decomposition technology (accelerating lignin/cellulose degradation into aromatic monomers for HA polymerization) and a 5% or 10% density increase, which might have enhanced root exudation to fuel microbial humification. This proposed pathway was based on previous findings [49]. Similar to the CT, the C_{HA} in the NT3 was comparatively low, suggesting that the integrated management at this gradient failed to convert straw C into stable C_{HA} , possibly due to low microbial C-use efficiency [63]. In ST, C_{HA} increased from ST1 to ST5, reflecting the integrated promotion effects of the progressively upgraded agronomic practices on HA accumulation [16]. ST5 had the highest C_{HA} , plausibly driven by ST (improving aeration/nutrient distribution for microbial ligninolytic activity) and 10% density increase (enhancing residue input for HA precursors) [25]. Under NT, C_{Hu} rose from NT1 to NT4 owing to less soil disturbance that protected aggregates and physically encapsulated Hu [16], while a slight C_{Hu} decline in NT5 might have been caused by overly high planting density, which intensified water and nutrient competition and inhibited mineral-bound Hu formation [64]. Under ST, ST3 achieved the maximum C_{Hu} , as strip plowing combined with partial straw incorporation promoted interactions between straw-derived organics and soil minerals to form stable Hu–mineral complexes [65]. By contrast, lower C_{Hu} in ST4 and ST5 relative to CT could be attributed to high-density-induced soil disturbance, which destroyed existing complexes and restrained new complex formation [66].

NT and ST outperformed CT in TOC accumulation. This difference stems from the dual effects of continuous straw C supplementation and reduced tillage disturbance, as CT's intensive inversion coupled with straw burning disrupted soil aggregates, exposing organic C to microbial decomposition and accelerating C mineralization. In contrast, NT and ST minimized soil disturbance, preserved crop residues, and promoted large-aggregate formation, which occluded organic C and reduced microbial accessibility [43]. Peak TOC at NT2 and ST2 was attributed to reduced fertilizer input (suppressing microbial decomposition) and $ZnSO_4$ -promoted straw humification [12]. TOC decline from NT2/ST2 to NT5/ST5 was mainly related to a 10% higher planting density, which intensified intra-specific resource competition, reducing root biomass and belowground C inputs [43]. Higher density might also stimulate microbial activity via increased labile C exudation, accelerating SOC decomposition and offsetting conservation tillage benefits. NT outperformed ST in TOC due to near-zero disturbance [16], but this difference was masked by severe competitive stress at the highest density.

The C_{HA}/TOC ratio highlighted SOC stability, with CT's lowest ratio confirming that intensive tillage impaired humification. Increased C_{HA}/TOC ratios from NT1–NT3/ST1–ST3 to NT4–NT5/ST4–ST5 suggested that higher levels of integrated management enhanced stable C_{HA} accumulation, likely via altered root exudate composition [67] and accelerated DOM transformation into stable HS, reinforced by aggregate protection [16]. Thus, NT5 and ST5 had the lowest TOC, but a more stable SOC pool.

4.4. Molecular Structure of HA and HS Quality Under Different Tillage Practices

In NT systems, the E_4/E_6 ratio peaked at NT3 and then declined. The peak might be associated with the addition of straw decomposition measures at this gradient, which accelerated the conversion of straw-derived C into low-molecular-weight aliphatic precursors for HA formation, lowering HA structural complexity and raising the E_4/E_6 ratio [68]. All structural modifications of HA under conservation tillage are fundamentally dependent on the continuous supply of straw organic substrates, and tillage disturbance intensity regulates the transformation pathway and rate of these straw-derived precursors. Higher planting density in NT4–NT5 aggravated water and nutrient competition, suppressed decomposer microbial activity, slowed SOM degradation, and enriched recalcitrant aromatic components in HA, thereby reducing the E_4/E_6 ratio [32]. The ST system showed a similar

“increase-then-decrease” E_4/E_6 trend, with a more pronounced peak at ST2, likely due to its hybrid tillage design that improved soil aeration and water permeability, favoring heterotrophic microbial proliferation [69]. Increased planting density in ST4–ST5 reduced the ratio, respectively, mirroring resource limitation-induced microbial suppression in NT systems [70]. Compared with CT, higher E_4/E_6 ratios in NT1–NT4 and ST1–ST3 confirmed that conservation tillage with straw incorporation simplified the HA structure. Lower ratios in NT5, ST4, and ST5 indicated that higher-density integrated management modified this effect [32,71].

The U-shaped C_{HA}/C_{FA} trends in NT and ST (minima at NT3/ST2, maxima at NT5/ST5) reflected the dynamic balance between HA decomposition and synthesis regulated by the stepwise integrated tillage–cultivation systems. In NT, the initial ratio decline (NT1–NT3) was associated with short-term HA degradation into labile fractions (e.g., FA), consistent with NT3’s high E_4/E_6 ratio [72]. Subsequent increases (NT4–NT5) might be partly explained by enhanced root biomass and exudation, which could provide C and energy for HS-synthesizing microorganisms that polymerized FA into stable HA [13,73]; with NT5 achieving the highest ratio. In ST, the ratio decline (ST1–ST2) was attributed to rapid SOM decomposition leading to incomplete humification (FA production outpacing conversion to HA) [74]. Subsequent increases (ST3–ST5) stemmed from the sequential addition of straw management and planting density upgrades, which enhanced microbial-mediated HA synthesis while balancing soil aeration for microbial activity and SOM preservation [75]. CT’s lowest C_{HA}/C_{FA} ratio reflected adverse effects of intensive tillage on HA stability and HS synthesis.

The “increase-then-decrease” trends in NT and ST reflected integrated responses of HA structure to integrated straw decomposition regulation and planting density adjustments [20]. NT3’s peak H/C ratio resulted from microbial degradation of straw cellulose/hemicellulose into aliphatic compounds incorporated into HA [21,62]. Subsequent increases in planting density (NT4–NT5) inhibited microbial activity, promoting aromatic monomer accumulation and reducing the H/C ratio [44,76]. ST had consistently higher H/C ratios than NT and CT, due to hybrid tillage enhancing soil aeration and straw–soil contact [54], which accelerated aliphatic fraction release [36] and sustained microbial activity even at high planting density [77]; the C/N ratio indicated microbial C–N availability (lower values = sufficient N, active decomposition) [54]. NT3’s minimum C/N ratio might be associated with synchronized C mineralization and N release under the fertilizer-reduced, straw-decomposition-promoted regime [78]. Higher planting density (NT4–NT5) increased the C/N ratio by intensifying N uptake and constraining microbial C mineralization [32]. In ST, the monotonic C/N increase stemmed from limited straw–soil mixing constraining microbial decomposition and C accumulation [79]. Higher planting density exacerbated N limitation, further increasing the C/N ratio [32]. NT’s unimodal trend resulted from minimal disturbance [1], enhanced microbial oxidation (peak O/C in NT4), and soil compaction (decline in NT5) [80]. ST’s V-shaped O/C trend was driven by balanced aeration [81], reduced aeration from deep straw incorporation (lowest O/C in ST3), and plant residue input (recovery in ST4–ST5) [82].

NT1 exhibited the highest O–H stretching intensity, attributed to minimal soil disturbance preserving aggregates and microbial habitats, thus inhibiting degradation of hydroxyl-rich substrates [83]. NT4 had the lowest intensity due to intense inter-plant competition at high planting density (68,250 plants ha^{−1}), stimulating microbial decomposition of hydroxyl-containing compounds [64]. In ST treatments, ST4 had the highest O–H intensity: strip tillage optimized soil conditions for microbial activity, and a 5% density increase enhanced root exudation of hydroxyl-rich substances incorporated into HA [25]. CT’s moderate O–H intensity (exceeding ST) reflected dual effects of soil inversion and straw burning [84]. ST3’s highest aliphatic C–H intensity highlighted the combined effects

of ST and straw decomposition promotion, which promoted the release of aliphatic compounds incorporated into HA [36]. NT4's low intensity resulted from altered microbial communities favoring aliphatic C decomposition under high planting density [85]. High carboxyl intensity in NT2/NT3 (followed by ST2) might be linked to the combined shift in fertilization and microbial inoculation: microbes secreted oxidases generating $-\text{COOH}$, with Zn^{2+} enhancing enzymatic activity [40]. Low intensities in NT5/ST5 were due to high planting density increasing crop nutrient uptake, limiting substrates for microbial oxidation [85]. NT5/ST5's high aromatic C=C intensity (exceeding CT) was linked to the highest-density integrated management (71,500 plants ha^{-1}) increasing aromatic-rich crop residues, with minimal disturbance preserving these recalcitrant fractions [64,86]. The maximal C=O intensity in NT4/ST3 (minimum in NT1) confirmed the efficacy of straw decomposition promotion in the integrated package: microbes secreted cellulases/hemicellulases releasing polysaccharides from straw [87], with NT4's 5% density increase enhancing root exudation of polysaccharide-rich mucilage [88]. NT1's low intensity reflected limited polysaccharide input (no decomposition technology + low density). CT's lower intensity than ST resulted from tillage-induced polysaccharide mineralization [89]. High I2920/I1720 in NT1/NT5 reflected reduced microbial oxidation (minimal disturbance for NT1; high density for NT5) limiting carboxyl formation [22,90]. ST3's highest ratio resulted from enhanced aliphatic input and moderate oxidative carboxylation. CT had lower ratios due to tillage-induced carboxyl formation [25]. Lowest ratios in NT3/ST2 aligned with high carboxyl intensity, driven by microbial oxidation [40]. ST3's highest I2920/I1630 reflected efficient incorporation of straw-derived aliphatic precursors [61]. NT5's lowest ratio resulted from aromatic C accumulation and aliphatic C depletion [91]. Lower ratios in CT than ST1–ST4 suggested CT favored aromatic accumulation, while ST1–ST4 balanced aliphatic/aromatic fractions [92]. ST5's ratio below CT confirmed enhanced aromaticity, consistent with its high aromatic C=C intensity.

The continuous decline in medium-temperature exothermic heat across the NT series was related to intensified soil compaction and nutrient stratification under NT with increasing planting density, inhibiting microbial degradation of moderately stable HA components and thus decreasing exothermic energy release during medium-temperature decomposition [20]. The sharp increase in medium-temperature exothermic heat from ST1 to ST2 and the subsequent gradual decline indicated that appropriate agronomic intensification promoted decomposition of moderately stable HA fractions under ST, while further intensification (from ST3 to ST5) reduced the abundance of labile medium-temperature components. Higher medium-temperature exothermic heat in CT resulted from intensive tillage disturbance, which exposed moderately stable HA components to oxidative mineralization and accelerated heat release during medium-temperature decomposition [5]. Differences in high-temperature exothermic patterns between NT and ST reflected divergent accumulation characteristics of recalcitrant HA structures. The initial decrease then increase in NT high-temperature exothermic heat indicated that recalcitrant HA fractions were significantly accumulated at high planting density under minimal soil disturbance, which protected recalcitrant fractions from oxidative degradation [24]. Elevated high-temperature exothermic heat in ST2–ST4 demonstrated optimized formation of recalcitrant HA under appropriate ST intensity. Notably, ST5 showed the highest H/M exothermic ratio (indicating enhanced relative thermal stability), but its absolute high-temperature exothermic heat was slightly lower than that of ST1. This pattern did not contradict the improved HA stability at ST5, but reflected a fundamental shift in HA molecular composition driven by the integrated management gradient.

At ST1, HA was a mixture of native soil HS (moderate aromaticity) and partially transformed straw-derived aliphatic components. The high H/C ratio of aliphatic fractions

contributed to higher unit combustion heat release in the high-temperature range, resulting in a moderate absolute exothermic value. From ST2 to ST3, enhanced microbial activity under straw decomposition promotion rapidly converted straw into abundant aliphatic intermediates and aromatic precursors, raising both medium- and high-temperature exothermic heat with a faster increase in labile fractions, thus lowering the H/M ratio. From ST4 to ST5, the combined effects of 5–10% higher planting density and N limitation (reduced fertilization + intensified crop N uptake) drove two key changes: (i) labile aliphatic components were further mineralized by microorganisms, leading to continuous decline in medium-temperature exothermic heat; and (ii) HA molecular structure shifted toward aromatic condensation and hydrophobic stabilization, as confirmed by the decreasing H/C ratio, enhanced aromatic C=C intensity in FTIR, and rising hydrophobic C/hydrophilic C ratio in ^{13}C -NMR. Since aromatic-condensed structures had a lower H/C ratio and thus lower unit mass combustion heat than aliphatic-rich components, the absolute high-temperature exothermic heat decreased slightly despite the increased proportion of recalcitrant fractions. Moderate high-temperature exothermic heat of CT was due to intensive tillage, which accelerated the degradation of recalcitrant HA fractions.

The inverted U-shaped H/M exothermic ratio in NT and ST indicated that HA structure stability gradually improved with increasing agronomic intensification. The highest H/M ratios at NT5 and ST5 reflected the dominant enrichment of recalcitrant high-temperature fractions relative to labile medium-temperature components [51]. The narrower H/M range of ST confirmed that ST balanced HA labile and recalcitrant distribution and moderated HA stability evolution. The lowest H/M ratio of CT verified that intensive tillage failed to improve HA stability. The unimodal H/M mass loss ratio was closely associated with straw conversion efficiency to HA fractions. Peak ratios at NT3 and ST4 reflected optimal conversion of straw to moderately stable and recalcitrant HA under appropriate planting density and ST conditions [93]. Relatively low H/M mass loss ratio of CT resulted from intensive organic mineralization and weak differentiation between high and medium temperature mass loss [94].

NT1's high aromatic C and low aliphatic C/aromatic C ratio highlighted unmodified NT's superior ability to promote HA humification and aromaticity, attributed to minimal soil disturbance that preserves aggregates and reducing O_2 diffusion [95]. Anaerobic microsites favored fungal-mediated lignin decomposition and aromatic polymerization [96], while surface residue retention supplied lignin-derived aromatic precursors [83]. NT2's high alkyl, carboxyl, and carbonyl C (and low O-alkyl, aromatic C) reflected the combined effects of reduced fertilization and microbial agent addition. The microbial consortium decomposed labile O-alkyl C into aliphatic compounds incorporated into HA [97], while oxidative enzymes generated carboxyl and carbonyl groups [40], outweighing aromatic polymerization. NT4 and NT5's shifted C functional groups (reduced alkyl C, increased O-alkyl/aromatic/carbonyl C) relative to NT3 were partly driven by high planting density, which had been reported to enhanced root exudation (supplying O-alkyl C-rich substrates) [88] and residue input (providing aromatic precursors) [13]. Reduced alkyl C likely resulted from intensified microbial decomposition to meet crop nutrient demand [32].

ST1's high O-alkyl C and low aromatic/carbonyl C/hydrophobic C/hydrophilic C ratio reflected ST's hybrid design. Partial disturbance enhanced aeration, promoting aerobic microbial decomposition of aromatic C while retaining labile O-alkyl C in inter-rows [98], disrupting aggregate protection of aromatic structures and reducing stability [99]. ST5's highest Hydrophobic C/Hydrophilic C ratio (enhanced HA hydrophobicity/stability) might have resulted from ST's balanced aeration/residue preservation [13] and high planting density augmenting root exudates and crop residues; Aliphatic compounds enriched alkyl C, while lignin decomposition supplied aromatic precursors [14], with reduced O-alkyl C reflecting intensified microbial decomposition. ST4's high aromatic/carbonyl C

among ST treatments was attributed to moderate planting density optimizing resources, shifting microbial communities to ligninolytic fungi [13] that decomposed lignin into polymerizable aromatic monomers and generated carbonyl groups [65]. CT's relatively low aliphatic C/aromatic C ratio did not represent more advanced humification, but rather reflected the selective preservation of recalcitrant aromatic residues after intensive tillage-driven mineralization of labile aliphatic fractions. Intensive inversion tillage disrupted soil aggregates and exposed aliphatic C to rapid oxidative decomposition by aerobic microorganisms [5], which preferentially removed labile aliphatic components from the HA pool and left behind recalcitrant aromatic moieties as residual fractions [100]. This passive enrichment of aromatic structures was fundamentally different from active humification driven by microbial anabolism and precursor polymerization under conservation tillage. The lower mean aliphatic C/aromatic C ratio in NT than ST confirmed NT's promotion of HA aromaticity via minimal disturbance [101]. The hydrophobic C/hydrophilic C ratio showed a unimodal trend in NT (peaking at NT2) and a progressive increase in ST (peaking at ST5). NT2's high ratio resulted from microbial agent-mediated aliphatic accumulation/oxidation, while ST5's was driven by balanced disturbance and dense residue input.

4.5. Comprehensive Evaluation

PCA elucidated the ecological processes and driving factors regulated by tillage systems coupled with straw C input and incremental agronomic practices. PC1 was governed by microbial activity and humification, controlling soil C dynamics. With straw C as the primary substrate and reduced soil disturbance preserving intact microbial habitats, NT and ST promoted DOM accumulation and humification and facilitated stable HA formation for long-term soil carbon sequestration [17,101]. By comparison, CT suffered low PC1 scores because intensive tillage and straw burning disrupted microbial communities and organic substrate supply, restraining humification [17]. PC2 represented HA structural complexity and soil C–N balance. ST (especially ST3 and ST4) favored aliphatic-enriched HA with higher bioavailability and balanced C–N availability. Elevated crop N uptake slightly increased the C/N ratio under high-density ST5 [32,102]. Moderate PC2 scores of NT4 and NT5 were attributed to soil compaction that restricted nutrient diffusion and microbial activity [5].

Comprehensive PCA scores were highest in ST5 and ST4. The superior performance of ST5 derived from the integrated effects of the complete strip-tillage cultivation package: it was reasonably inferred that ST improved soil aeration and straw–soil contact to accelerate SOM decomposition mediated by soil microorganisms, while higher density increased crop residue inputs to support HA synthesis, thereby concurrently enhancing maize yield and soil fertility via optimized HA structure and humus composition [14,103]. It should be noted that this microbial regulatory pathway was deduced from indirect proxy indicators such as DOM fluorescence and HS fraction characteristics, and direct microbiological data are still needed to verify the exact mechanism in follow-up studies. NT4 and NT5 had lower PC1 and PC2 scores than corresponding ST treatments, due to nutrient stratification and low straw decomposition efficiency under undisturbed NT [18]. Nevertheless, high-density NT5 still outperformed CT, which could mitigate soil compaction limitations and improve soil carbon sequestration [57]. Clear treatment differentiation in PCA space verified that tillage intensity and agronomic measures dominated soil HS dynamics and HA structure. Overall, ST coupled with proper planting density and straw decomposition regulation was the optimal management practice for improving soil fertility, HA stability, and maize yield in sloping Albic farmland of the black soil region in humid Jilin, China. Notably, although the detailed HS composition and HA structural data were derived from the second year of the experiment, the two-year continuous implementation of tillage and management practices allowed sufficient time for treatment

effects to accumulate in the relatively stable SOM pool. This study duration effectively reduced the bias caused by extremely short-term observations and provided more credible evidence for tillage regulation of soil HS properties in sloping black soil farmlands. We acknowledge that a two-year field trial was relatively short for capturing the long-term steady-state evolution of soil HS structure. However, the tested Albic soil had a low initial SOC content and high sensitivity to anthropogenic management. Coupled with continuous full straw return and targeted straw decomposition regulation, fresh straw-derived organic matter was rapidly transformed into HA precursors, leading to detectable changes in HA functional groups, thermal stability, and C skeleton composition within a short period. These statistically significant differences across biological replicates confirmed that the observed structural responses were directional early adaptations to tillage and agronomic practices, rather than random noise from sample handling or instrumental error. Nevertheless, long-term multiyear positioning monitoring is still necessary to reveal the long-term evolutionary trajectory of HA molecular structure under conservation tillage systems.

5. Conclusions

This study employed a cumulative additive experimental design rather than a full factorial design, which is a widely adopted strategy in applied agronomic research targeting technology optimization and on-farm extension. This design prioritized the identification of the best-performing integrated production mode for local sloping farmlands, and could intuitively reflect the yield and soil benefits of stepwise technology upgrading. The two-year continuous field experiment provided sufficient cumulative treatment duration for soil HS responses, enhancing the reliability of the results compared with a single-year trial. A key limitation of this experimental approach, however, is its inability to fully disentangle the independent contributions of individual agronomic factors to the overall observed effects. Furthermore, the two-year trial duration mainly captured the early response of HA molecular properties to management practices, and long-term multiyear monitoring is still required to elucidate the temporal dynamics of HS structural evolution under long-term conservation tillage. Additionally, root exudation quantity and composition were not directly measured in this study. The proposed roles of root-derived C in regulating DOM dynamics, HS fractionation, and HA molecular transformation were all inferred from published evidence rather than validated by *in situ* determinations. Under the tested conditions of sloping Albic soil in the northeast China black soil region, both NT and ST, supported by continuous full straw C input, effectively alleviated SOC loss, promoted DOM accumulation and humification, and optimized the proportional distribution of HS fractions, which strengthened soil C sequestration capacity and nutrient supply capability. ST outperformed NT in both maize yield and soil quality improvement, and ST5 (ST with full straw return integrated with straw decomposition promotion and a 10% planting density increase) was identified as the optimal treatment. It was inferred that this regime significantly enhanced HA aromaticity, thermal stability, and hydrophobicity mainly through the combined action of reduced strip disturbance and optimized straw C transformation, modulating soil microbial activity and straw transformation efficiency, thereby stabilizing the soil C pool and improving soil fertility. Notably, this mechanistic explanation was based on indirect proxy indices rather than direct microbiological measurements, and its exact driving pathway remains to be validated through targeted microbial assays. PCA confirmed the superior comprehensive effect of ST5 over all other treatments. The cumulative additive subplot design adopted in this work superimposed multiple agronomic parameters step by step without independent single-factor controls, so this study could not quantitatively distinguish the independent contribution of fertilizer reduction, straw decomposition promotion, or increased planting density to yield

and soil HS properties. Our experimental layout was purposefully designed for integrated technical scheme screening rather than single agronomic factor mechanism dissection. Targeted independent single-factor trials will be carried out in follow-up research to separate individual agronomic effects.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/agriculture16141553/s1>, Figure S1: Schematic diagram of the cumulative additive split-plot experimental layout.; Table S1: Effects of different tillage practices combined with integrated management strategies on the relative intensity of main absorption peaks in the FTIR spectra of HA.; Table S2: Comparative analysis of exothermic heat and mass loss of HA under different tillage practices combined with integrated management strategies., Table S3: Relative C distribution (%) of HA in solid state ¹³C-CPMAS-NMR spectra under different tillage practices combined with integrated management strategies., Table S4: Eigenvalues, contribution rates, and cumulative contribution rates of the first seven principal components., Table S5: Loading coefficient of each principal component., Table S6: Linear combination coefficient matrix of each principal component., Table S7 Average score and total score of main components., Table S8: One-way ANOVA performed across all 11 treatments with treatment as the fixed factor and block as the random factor., Table S9: Full plot-level dataset.

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