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Effects of *Stropharia rugosoannulata*–Tomato Rotation Coupled with Spent Mushroom Substrate Incorporation on Soil Fertility, Yield and Fruit Quality of Tomato

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Abstract

Continuous monocropping of tomato causes soil degradation, secondary salinization, and yield decline. Mushroom–vegetable rotation coupled with spent mushroom substrate (SMS) incorporation offers a recycling strategy to mitigate these obstacles. Here, a five-stage progressive field experiment (2023–2025, Yantai, Shandong, China) was conducted to screen the optimal local configuration of *Stropharia rugosoannulata*–tomato rotation and reveal its soil improvement mechanisms. The combination of variety Nieyang and an apple woodchip-based substrate achieved the highest mushroom yield, with the substrate formula ($F = 11.64$, $p = 0.0006$) dominating productivity. Deep incorporation of SMS into the 0–20 cm plow layer (M treatment) avoided the seedling stress and mortality caused by surface mulching and increased the marketable yield of the large-fruited tomato R35 by 28.0% ($79,560 \text{ kg} \cdot \text{ha}^{-1}$, $p < 0.05$) without altering fruit soluble solids ($p = 0.611$). Two consecutive rotation years increased soil organic carbon by 17.6% (from 3.29 to $3.87 \text{ g} \cdot \text{kg}^{-1}$) and total nitrogen by 243% (from 0.79 to $2.71 \text{ g} \cdot \text{kg}^{-1}$) and raised soil desalination efficiency from 33.5% to 56.2%, while soil EC and pH remained within the optimal range for tomato growth. Cross-regional verification showed universal regulation of soil pH and EC but background-dependent nutrient accumulation. The system improves soil fertility through mycelium-mediated biological desalination, progressive SMS-derived carbon pool accumulation, and complementary acid–base homeostasis, generating a net annual economic benefit of approximately $255,000 \text{ CNY} \cdot \text{ha}^{-1}$ ($\approx 38,060 \text{ USD} \cdot \text{ha}^{-1}$). This recyclable rotation pattern is suitable for popularization in Jiaodong facility-grown tomato production.

Keywords: *Stropharia rugosoannulata*; tomato; continuous cropping obstacle; substrate formula; mycelium-mediated desalination; soil carbon pool; acid–base homeostasis; circular agriculture



Received: 5 August 2026

Revised: 4 September 2026

Accepted: 7 September 2026

Published: 9 September 2026

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1. Introduction

Tomato (*Solanum lycopersicum* L.) is one of the most economically important facility-grown vegetables in northern China. Long-term continuous monocropping has induced severe continuous cropping obstacles, including soil acidification, secondary salinization, nutrient imbalance, and disrupted microbial community structure, resulting in reduced productivity and deteriorated fruit quality [1,2]. The Jiaodong region of Shandong Province is a core facility-grown tomato production base, where intensive monocropping has aggravated soil degradation [3], urgently requiring eco-friendly and recyclable improvement strategies to replace traditional chemical remediation.

Reasonable crop rotation is a fundamental agronomic measure to alleviate continuous cropping obstacles and restore degraded soil, regulating soil physicochemical properties, optimizing nutrient cycling, and improving rhizosphere microenvironments through the functional complementarity of different crops [4,5]. As a high-efficiency edible mushroom recommended by the Food and Agriculture Organization (FAO), *Stropharia rugosoannulata* can utilize various agricultural wastes—such as rice husks, corn cobs, and fruit tree woodchips—as cultivation substrates, exhibiting wide adaptability and high resource utilization efficiency [6]. Spent mushroom substrate (SMS), the byproduct after mushroom harvesting, is a high-quality organic soil amendment rich in organic carbon and fungal mycelial protein; its return effectively supplements soil organic carbon and nutrients and improves soil humus content [7–9].

Previous studies have verified the positive soil improvement effects of mushroom–vegetable rotation systems. Rice–*S. rugosoannulata* rotation realizes annual circular production and increases soil organic matter via in situ return of SMS [10]. *S. rugosoannulata*–strawberry rotation significantly improves soil nutrient status and the soil microenvironment [11], and diversified mushroom–vegetable rotations can alleviate continuous cropping soil degradation and promote subsequent vegetable yields [12,13]. However, systematic research on *S. rugosoannulata*–plastic-covered tunnel tomato rotation is still insufficient: localized mushroom variety and substrate screening, scientific SMS return modes, long-term soil fertility accumulation, cross-regional adaptability, and yield–quality regulation mechanisms remain unclear, restricting the large-scale promotion of this green rotation model.

To fill these gaps, this study established an annual *S. rugosoannulata*–tomato rotation in a plastic-covered tunnel system, comprising five progressive experimental stages. We hypothesized that (i) substrate formula, rather than mushroom variety, dominates mushroom yield under local conditions; (ii) deep incorporation of SMS into the plow layer avoids seedling stress caused by surface mulching and improves tomato yield without quality deterioration; and (iii) consecutive rotation years progressively improve soil fertility through biological desalination, carbon pool accumulation, and acid–base homeostasis, while salinity and pH regulation are universal across regions but nutrient accumulation is background-dependent. Accordingly, the objectives were to (1) screen the optimal local mushroom cultivation configuration and SMS incorporation method; (2) clarify the dynamic changes in soil fertility, salinity, and pH during two consecutive rotation years; (3) verify the cross-regional adaptability of the rotation model; (4) evaluate tomato yield, fruit quality, and economic benefits; and (5) reveal the core soil improvement mechanisms. This study provides theoretical support and technical guidance for obstacle mitigation and agricultural waste recycling in Jiaodong facility-grown tomato production.

2. Materials and Methods

2.1. Experimental Site Conditions

All experiments were conducted in simple plastic tunnels (Figure S1) at two typical tomato production bases in Yantai City (Fushan District and Longkou City), Shandong Province, China, from September 2023 to August 2025. The tunnels were 2 m high at the shoulders, with insect-proof nets installed on both sides for ventilation and pest prevention (Figure S1). In summer, the temperature inside the plastic tunnel is kept below 30 °C for tomato growth by using external shading nets and side ventilation. In winter, the temperature is maintained above 4 °C for *Stropharia rugosoannulata* cultivation by adding internal small arch tunnels and closing both sides. These measures ensure the normal growth of both crops throughout the year.

The core experiment was conducted at Jingyue Farm (Xisongzhou Village, Fushan District) on a cinnamon soil (Eutric Cambisol; WRB, 2022 [14]) that had been under continuous

tomato monocropping for three years; the cross-regional verification experiment was performed at Maoyuan Agricultural Co., Ltd. (Guanqian Yujia Village, Huangshangguan Town, Longkou City, China) on a brown soil (Haplic Luvisol; WRB, 2022 [14]). The locations of the two experimental sites are shown in Figure S2. The initial 0–20 cm soil physicochemical properties of both sites are summarized in Table 1.

Table 1. Initial soil physicochemical properties (0–20 cm) of the two experimental sites.

Parameter	Fushan (Cinnamon Soil)	Longkou (Brown Soil)
pH	6.74	7.09
EC (dS·m ^{−1})	0.44	0.23
Soil organic carbon (g·kg ^{−1})	3.29	4.95
Total nitrogen (g·kg ^{−1})	0.79	3.05
Total phosphorus (g·kg ^{−1})	1.35	1.54
Available potassium (mg·kg ^{−1})	171.02	163.92

Note: Values refer to the 0–20 cm soil layer at T1 (before rotation). EC = electrical conductivity (1:5 soil-to-water extract). Soil texture: sandy loam (Fushan) and loam (Longkou).

No chemical fertilizers or commercial organic fertilizers were applied throughout the experimental period. Soil nutrient supplementation solely depended on in situ SMS returning. Field management including irrigation, weeding, and pest control was uniformly implemented to ensure consistent experimental conditions.

2.2. Experimental Design

A five-stage progressive experimental design was adopted to systematically optimize and verify the rotation system, covering cultivation configuration screening, returning mode optimization, soil vertical nutrient distribution analysis, long-term positioning monitoring, and cross-regional adaptability evaluation.

2.2.1. Screening of Mushroom Varieties and Cultivation Substrates

The three *S. rugosoannulata* varieties tested were commercial cultivars widely cultivated in Shandong Province: Juxian (A), characterized by a brown pileus and medium-sized fruiting bodies; Nieyang (B), a locally selected cultivar with high adaptability and good yield stability; and Nanfang (C), a southern-type cultivar. The three tomato inbred lines (R35 large-fruited, pink cherry, and red cherry) were developed by our research group and differ mainly in fruit size and color.

A 3 × 3 two-factor completely randomized experimental design was applied, including three *S. rugosoannulata* varieties (A: Juxian, B: Nieyang, C: Nanfang) and three cultivation substrates: Substrate I: 38% rice husk + 30% corn cob + 30% non-apple woodchip + 2% lime; Substrate II: 38% rice husk + 30% corn cob + 30% apple woodchip + 2% lime; Substrate III: 38% rice husk + 30% corn cob + 30% cotton residue + 2% lime. All percentages are on a dry-weight basis (w/w). A total of nine treatments with three replicates each were set up. The optimal variety–substrate combination was selected based on fresh mushroom yield.

2.2.2. Optimization of SMS Returning Methods and Tomato Variety Adaptation

Based on the optimal mushroom cultivation combination, three SMS returning treatments were established: D (direct surface mulching of SMS without soil mixing), M (mixing the mushroom residue with the 0–20 cm plow layer soil), and O (original soil control, no SMS returning). For the D and M treatments, SMS was applied at approximately 30 t·ha^{−1} (fresh weight), either retained on the soil surface or mixed into the 0–20 cm plow layer, respectively. That is, after harvesting *Stropharia rugosoannulata*, the spent mushroom substrate (SMS) can either be left on the surface without tillage or be fully

incorporated into the 0–20 cm soil layer by deep turning with a spade. Three tomato inbred lines bred by our research group (R35, a large-fruited line; pink cherry tomato; red cherry tomato) were matched with each returning mode, forming nine treatment combinations with three replicates. The optimal field configuration was screened via yield and quality evaluation.

2.2.3. Vertical Distribution Characteristics of Soil Organic Carbon

After completion of the first rotation cycle (T3, August 2024), soil samples were collected from three layers (0–5 cm, 5–10 cm, 10–20 cm) under D, M, and O treatments. Soil organic carbon content was determined to clarify the vertical distribution differences in soil nutrients under different SMS returning modes.

2.2.4. Two-Year Consecutive Positioning Monitoring Experiment

The optimal configuration (variety B + Substrate II + M treatment) was used for continuous two-year rotation monitoring. The annual cropping arrangement was as follows: *S. rugosoannulata* sowing in early September, mushroom harvesting in mid-April of the next year, tomato transplanting in late April, and tomato harvesting in late August. Five key sampling stages were set: T1 (September 2023, before the first mushroom sowing, initial background), T2 (April 2024, after the first mushroom harvest), T3 (August 2024, after the first tomato harvest), T4 (April 2025, after the second mushroom harvest), and T5 (August 2025, after the second tomato harvest).

2.2.5. Cross-Regional Adaptability Verification

Consistent rotation management was carried out at the Fushan (2023–2024) and Longkou (2024–2025) experimental sites with unified optimal cultivation parameters. Soil samples were collected at T1 (pre-rotation), T2 (post-mushroom), and T3 (post-tomato) in each site. The difference method (Δ = measured value – initial value) was used to eliminate soil background differences and compare regional improvement effects.

2.3. Measurement Indicators and Methods

The fresh mushroom yield of each plot (12.0 m²) was independently measured and converted into unit-area yield (kg·ha^{−1}). Tomato yield (marketable fruit only; culls such as cracked and malformed fruits were excluded) was determined by randomly selecting three uniform, representative plants per plot, excluding border plants to avoid edge effects; three plants per replicate were selected as a compromise between sampling representativeness and labor intensity, consistent with common practice in plot-scale vegetable trials. The plot yield was converted into per-hectare yield (kg·ha^{−1}) based on the planting density. Fruit soluble solid content was measured using an ATAGO PAL-1 handheld refractometer. Each tomato plot was 12.0 m². Plants were ridge-cultivated on 70 cm-wide ridges with 40 cm furrows and double-row planted at a 50 cm within-row spacing, corresponding to a density of 37,500 plants·ha^{−1} (2500 plants per mu, about 45 plants per plot).

Soil organic carbon was determined by the potassium dichromate oxidation-ferrous sulfate titration method. Soil pH and EC were measured via the electrode method (soil:water = 1:5); EC is expressed in dS·m^{−1} (1 dS·m^{−1} = 1000 μS·cm^{−1}). Total nitrogen was determined by the Kjeldahl method. Total phosphorus was measured by sulfuric-perchloric acid digestion and the molybdenum–antimony colorimetric method. Available potassium was determined by ammonium acetate extraction-flame photometry. Soil desalination efficiency was calculated as (EC at T1 – EC at the sampling stage)/EC at T1 × 100%.

2.4. Data Analysis

Data sorting and basic calculation were performed using Excel 2019. Two-way ANOVA and significance analysis were conducted via SPSS 25.0, with Tukey HSD multiple comparison at $p < 0.05$. All data were expressed as mean $\pm$ standard deviation (SD). Figures were plotted using Origin 2024.

3. Results

Both mushroom variety and cultivation substrate significantly affected fresh mushroom yield, with no significant interactive effect ($F = 1.64$, $p = 0.207$; Figure 1). The substrate effect ($F = 11.64$, $p = 0.0006$) was significantly stronger than the variety effect ($F = 7.11$, $p = 0.0053$), indicating that substrate formula was the dominant factor regulating local mushroom productivity. Among the three varieties, variety B (Nieyang) achieved the numerically highest average yield of 29.35 kg per plot, although pairwise differences among varieties were not statistically significant (Tukey HSD: B vs. A, $p = 0.052$; B vs. C, $p = 0.927$). Substrate II containing apple woodchips exhibited the optimal yield of 32.41 kg per plot, significantly higher than Substrate I (17.55 kg per plot, $p = 0.0025$), whereas the difference from Substrate III was not significant ($p = 0.222$). The combination of variety B and Substrate II obtained the maximum plot yield of 34.50 kg, which was confirmed as the optimal localized cultivation configuration for subsequent experiments.

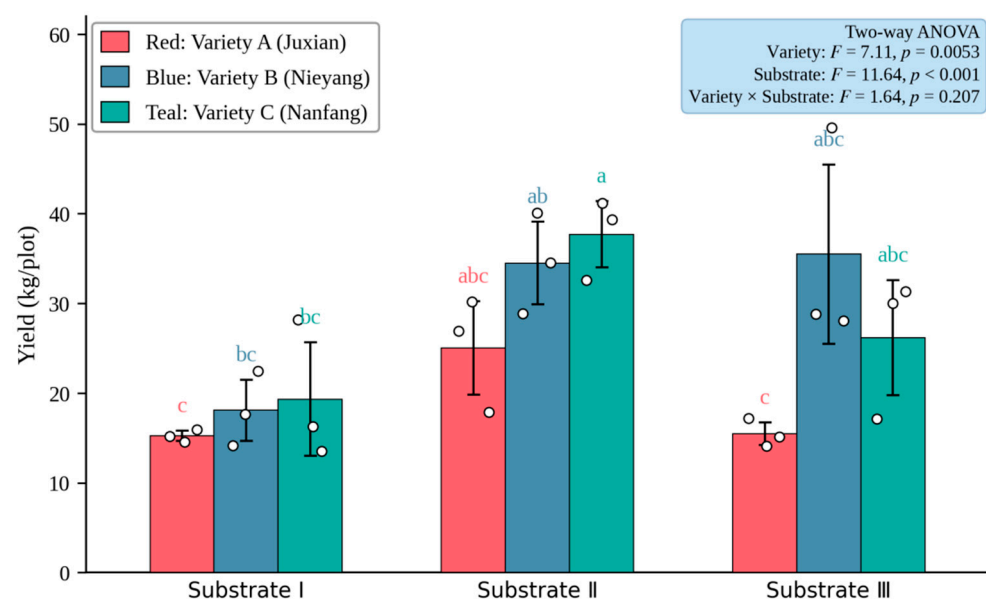


Figure 1. Effects of variety and substrate on fresh mushroom yield of *S. rugosoannulata*. Note: Bars represent mean $\pm$ SD ($n = 3$). Lowercase letters above bars indicate Tukey HSD compact letter display ($\alpha = 0.05$); the same letter denotes no significant difference between treatments. White dots represent individual replicate values. Error bars indicate SD. A = Juxian *S. rugosoannulata*, B = Nieyang *S. rugosoannulata*, C = Nanfang *S. rugosoannulata*.

3.1. Effects of SMS Returning Modes on Tomato Yield and Quality

SMS returning modes significantly affected tomato yield ($F = 50.9$, $p < 0.001$), with a clear variety-dependent response (interaction: $F = 0.90$, $p = 0.483$; Figure 2). The large-fruited inbred line R35 under the M treatment achieved the highest marketable yield of 79,560 kg·ha⁻¹, which was 28.0% higher than the blank control (O treatment, $p < 0.05$). Notably, the D treatment (direct surface mulching of SMS) caused a 33.3% tomato seedling mortality rate, and its measured yield was adjusted for the dead-plant rate; the underlying mechanisms are interpreted in Section 4.2.

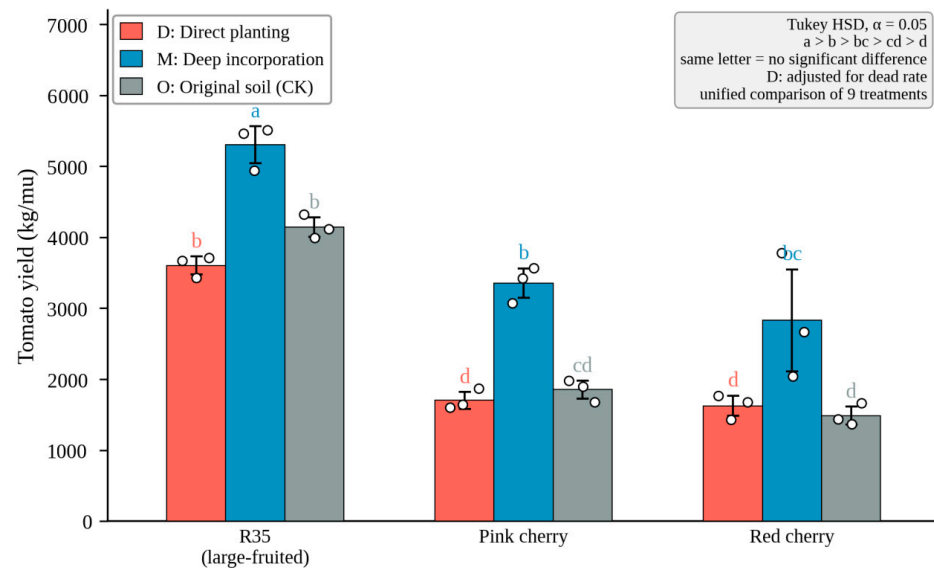


Figure 2. Effects of spent mushroom substrate (SMS) utilization methods on tomato yield across three varieties. Note: Bars represent mean $\pm$ SD ($n = 3$). Lowercase letters above bars indicate Tukey HSD compact letter display ($\alpha = 0.05$); the same letter denotes no significant difference between treatments. White dots represent individual replicate values. D = direct surface mulching of SMS without soil mixing (yield adjusted for dead plant rate), M = mixing the mushroom residue with the 0–20 cm plow layer soil, O = original soil control (no SMS). R35 = large-fruited tomato inbred line. Significant differences were determined by unified comparison across all nine treatment combinations.

Fruit soluble solid content was predominantly determined by tomato genetic characteristics ($F = 99.89$, $p < 0.001$). SMS returning mode ($F = 0.51$, $p = 0.611$) and the interaction effect ($F = 1.70$, $p = 0.194$) had no significant influence on fruit soluble solids (Figure 3). Within the same tomato variety, no significant difference was observed between the M treatment and the control. Unlike most organic amendment modes, which often cause quality decline through nutrient dilution [15], this rotation system achieved a yield increase without quality deterioration, demonstrating the superior balanced nutrient supply capacity of SMS [16].

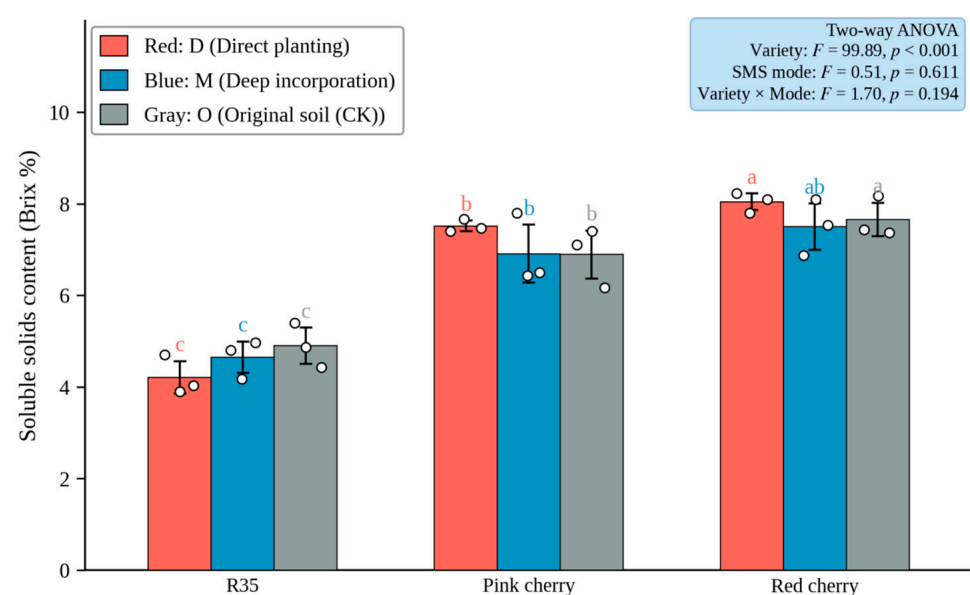


Figure 3. Effects of SMS utilization methods on tomato soluble solids content across three varieties. Note: Bars represent mean $\pm$ SD ($n = 3$). Lowercase letters indicate Tukey HSD compact letter display

($\alpha = 0.05$); the same letter denotes no significant difference. White dots represent individual replicate values. D = direct surface mulching of SMS without soil mixing, M = mixing the mushroom residue with the 0–20 cm plow layer soil, O = original soil control (no SMS). Unified comparison across all nine treatment combinations.

3.2. Vertical Distribution of Soil Organic Carbon Under Different SMS Returning Modes

A significant interactive effect was observed between SMS returning mode and soil depth on soil organic carbon content at the end of the first rotation cycle ($F = 26.64$, $p < 0.001$; Figure 4). The D treatment showed the highest organic carbon content ($4.228 \text{ g}\cdot\text{kg}^{-1}$) in the 10–20 cm layer, whereas the M treatment realized uniform SMS distribution in the 0–20 cm plow layer, with the highest organic carbon content ($4.145 \text{ g}\cdot\text{kg}^{-1}$) in the 5–10 cm root-concentrated layer, which precisely matched tomato root distribution and provided a stable nutrient foundation for high yield. The control treatment showed a continuous decline of soil organic carbon, confirming that continuous tomato monocropping caused net soil organic carbon consumption without exogenous organic input. (The mechanistic interpretation of the vertical carbon distribution is provided in Section 4.2.)

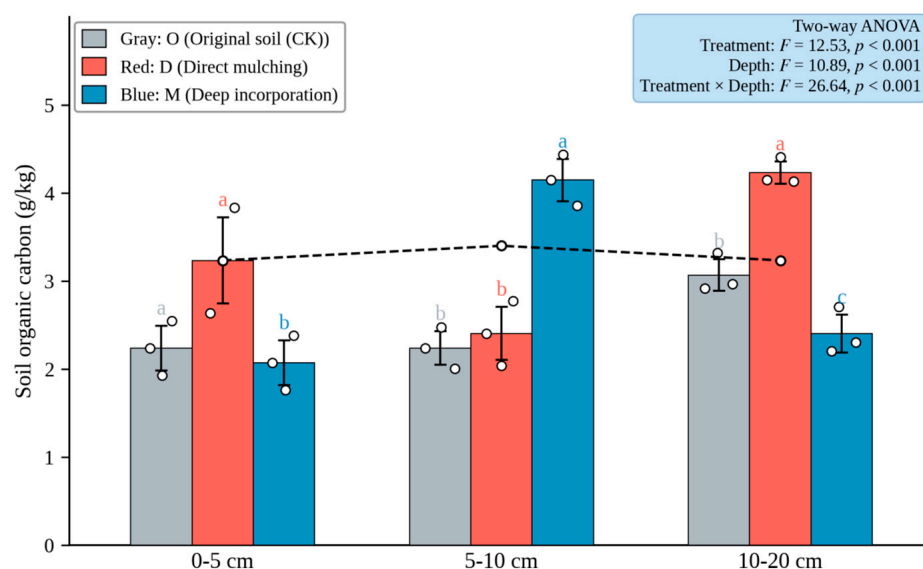


Figure 4. Effects of SMS utilization methods on soil organic carbon at different depths at T3 (after the completion of the first mushroom–tomato rotation cycle). Note: Bars represent mean $\pm$ SD ($n = 3$). Lowercase letters indicate Tukey HSD compact letter display ($\alpha = 0.05$); the same letter denotes no significant difference. Dashed lines indicate the T1 baseline. Treatment $\times$ depth interaction: $p < 0.001$.

3.3. Cumulative Improvement Effects of Two-Year Consecutive Rotation on Soil Fertility

The two-year positioning monitoring demonstrated that the *S. rugosoannulata*–tomato rotation system effectively reversed soil degradation and transformed soil nutrient status from consumption to accumulation (Figure 5). Soil organic carbon fluctuated but showed a net upward trend over two years: it slightly increased to $3.46 \text{ g}\cdot\text{kg}^{-1}$ at T2 due to exogenous SMS carbon input, then decreased to $2.87 \text{ g}\cdot\text{kg}^{-1}$ at T3 (temporarily below the initial level) owing to tomato nutrient consumption, and finally increased to $3.87 \text{ g}\cdot\text{kg}^{-1}$ at T5, representing a net increase of 17.6% compared with the initial value. The second rotation cycle exhibited a higher carbon accumulation rate, reflecting the long-term improvement advantage of progressive SMS carbon decomposition.

Soil total nitrogen showed the most pronounced increase, rising from $0.79 \text{ g}\cdot\text{kg}^{-1}$ to $2.71 \text{ g}\cdot\text{kg}^{-1}$ with an increment of 243%. Without additional chemical nitrogen input, the substantial nitrogen accumulation was mainly derived from SMS organic nitrogen mineral-

ization and soil recalcitrant nitrogen activation by mushroom mycelia, which promoted microbial nitrogen enrichment and retention [7]. Total phosphorus presented a dynamic trend of initial decrease and final balance. The cinnamon soil in Fushan exhibited strong phosphorus fixation, leading to reduced total phosphorus after mushroom cultivation. However, mycelial organic acid secretion and tomato root exudates activated occluded soil phosphorus, realizing phosphorus balance ($1.37 \text{ g} \cdot \text{kg}^{-1}$ at T5 vs. initial $1.35 \text{ g} \cdot \text{kg}^{-1}$).

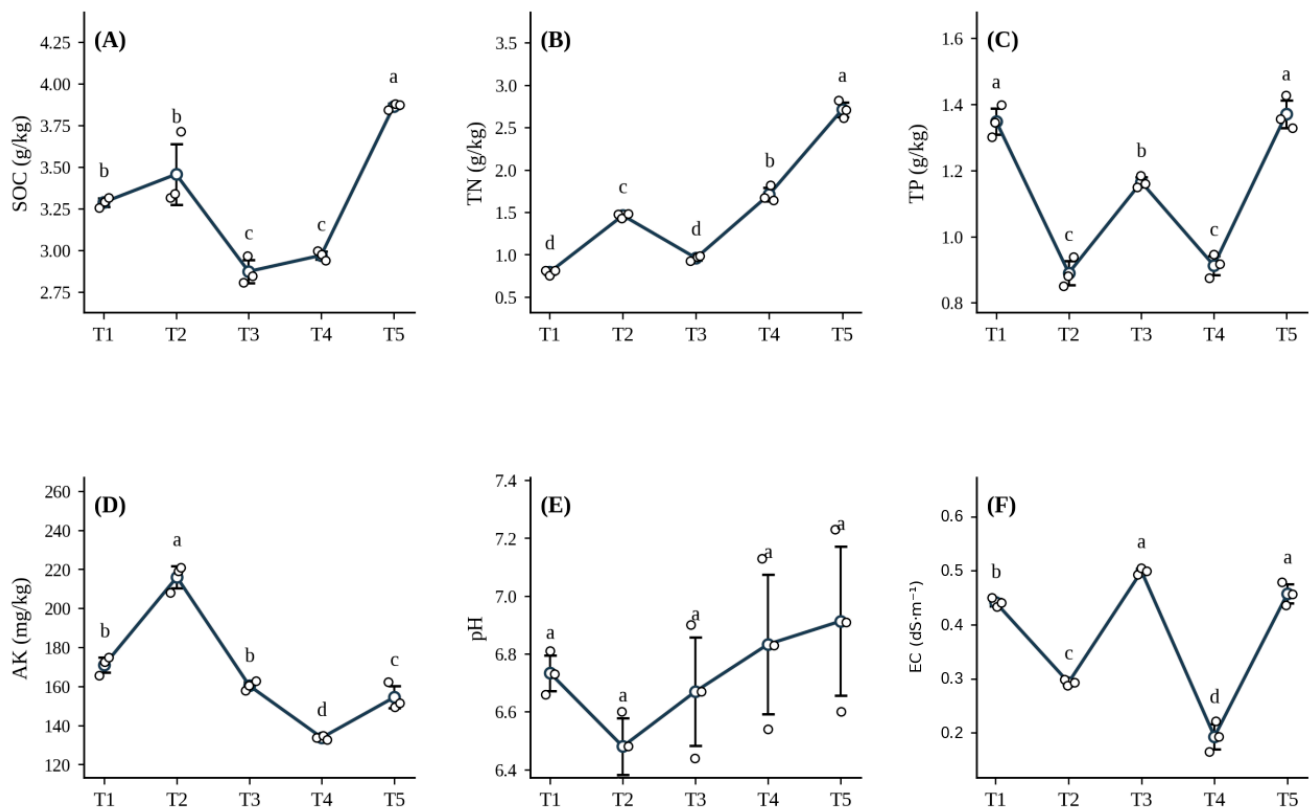


Figure 5. Cumulative effects of two-year consecutive rotation on soil physicochemical properties. (A) soil organic carbon content; (B) total nitrogen content; (C) total phosphorus content; (D) available potassium content; (E) soil pH; (F) soil electrical conductivity. Note: Lines represent mean $\pm$ SD ($n = 3$). T1 = before rotation, T2 = after the first mushroom harvest, T3 = after the first tomato harvest, T4 = after the second mushroom harvest, T5 = after the second tomato harvest. White dots represent individual values. Lowercase letters indicate Tukey HSD compact letter display ($\alpha = 0.05$) among time points; the same letter denotes no significant difference.

Soil available potassium decreased continuously from $171.0 \text{ mg} \cdot \text{kg}^{-1}$ to $154.5 \text{ mg} \cdot \text{kg}^{-1}$. The high potassium demand of tomato, rapid mineralization of SMS potassium, and increased leaching loss jointly caused potassium deficit, indicating that regular potassium supplementation ($150\text{--}225 \text{ kg} \cdot \text{ha}^{-1}$ every 2–3 rotation seasons) is required to maintain nutrient balance [17]. The rotation system exhibited excellent biological desalination and acid–base stabilization capacity. Soil desalination efficiency increased from 33.5% (after the first rotation cycle) to 56.2% (after the second rotation cycle). Mycelial networks adsorbed and transported soluble soil salts, and soil EC (1:5 soil-to-water extract) was always maintained below $0.50 \text{ dS} \cdot \text{m}^{-1}$, corresponding to an estimated saturated-paste EC (ECe) below the tomato salinity threshold of $2.5 \text{ dS} \cdot \text{m}^{-1}$ [18]. Soil pH was stably maintained at 6.5–7.0, forming a self-buffering system via the complementary effects of mushroom mycelial organic acid secretion and tomato root physiological regulation.

3.4. Cross-Regional Adaptability of the Rotation System

Cross-site verification revealed consistent regulatory effects on soil pH and EC between Fushan cinnamon soil and Longkou brown soil, indicating universal adaptability of the rotation system in terms of salinity and acid–base regulation (Figure 6). In contrast, soil nutrient accumulation exhibited significant background dependence: low-fertility Fushan soil showed net organic carbon consumption in the first rotation season, whereas high-fertility Longkou soil achieved net carbon accumulation, and nitrogen, phosphorus, and potassium dynamics differed between the two soils. (The theoretical interpretation of this background dependence is provided in Section 4.5).

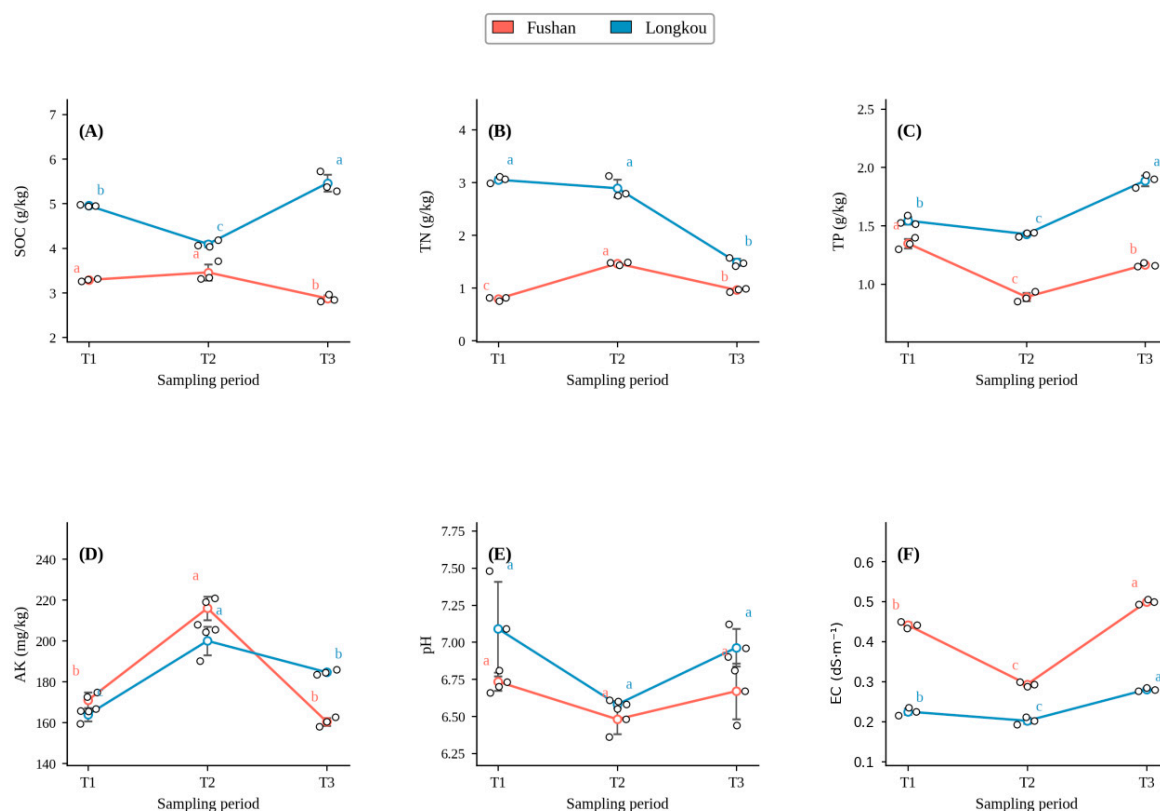


Figure 6. Effects of the *S. rugosoannulata*–tomato rotation on soil pH, EC and nutrient contents in Fushan and Longkou. (A) soil organic carbon content; (B) total nitrogen content; (C) total phosphorus content; (D) available potassium content; (E) soil pH; (F) soil electrical conductivity. Note: Lines represent mean $\pm$ SD ($n = 3$). T1 = before rotation, T2 = after mushroom harvest, T3 = after tomato harvest. White dots represent individual values. Lowercase letters indicate Tukey HSD compact letter display ($\alpha = 0.05$) among time points within the same region; the same letter denotes no significant difference. Fushan = red, Longkou = blue.

3.5. Economic Benefit Evaluation

Based on the optimal configuration, the rotation system was estimated to generate a total annual gross revenue of approximately 483,900 CNY·ha^{−1} ($\approx 72,223$ USD·ha^{−1}; mushroom 285,000 CNY·ha^{−1} $\approx 42,537$ USD·ha^{−1}, based on the estimated marketable mushroom yield of 28,500 kg·ha^{−1} excluding open-cap and damaged fruiting bodies; tomato 198,900 CNY·ha^{−1} $\approx 29,686$ USD·ha^{−1}, based on marketable fruit yield) against total production costs of approximately 228,900 CNY·ha^{−1} ($\approx 34,164$ USD·ha^{−1}), yielding a net economic benefit of approximately 255,000 CNY·ha^{−1} ($\approx 38,060$ USD·ha^{−1}; Table 2; exchange rate ≈ 6.7 CNY per USD). The mushroom–tomato dual cropping mode realized high-efficiency utilization of agricultural wastes, soil ecological restoration, and crop yield improvement, achieving significant economic and ecological benefits.

Table 2. Annual economic benefit accounting of the *S. rugosoannulata*–tomato rotation system (CNY·ha^{−1} and USD·ha^{−1}).

Item	Value (CNY·ha ^{−1})	Value (USD·ha ^{−1})
Gross revenue		
Mushroom (28,500 kg·ha ^{−1} × 10 CNY·kg ^{−1})	285,000	≈42,537
Tomato (79,560 kg·ha ^{−1} × 2.5 CNY·kg ^{−1})	198,900	≈29,686
Total gross revenue	483,900	≈72,223
Production costs		
Cultivation substrate (30 t·ha ^{−1})	24,000	≈3582
Spawn	12,000	≈1791
Agricultural materials (film, drip tape, trellis, pesticides)	18,000	≈2687
Water and electricity	6000	≈896
Labor	168,900	≈25,209
Total production costs	228,900	≈34,164
Net economic benefit	255,000	≈38,060

Note: Values are estimated based on the optimal configuration (variety B × Substrate II × M treatment), marketable yields (mushroom: estimated marketable yield of 28,500 kg·ha^{−1}, excluding open-cap and damaged fruiting bodies; tomato: marketable fruit yield), and local wholesale market surveys in Yantai during 2024–2025 (mushroom 10 CNY·kg^{−1}; tomato 2.5 CNY·kg^{−1}). Labor was estimated at approximately 676 work-days·ha^{−1}·yr^{−1} at 250 CNY work-day^{−1}. Fixed costs (plastic tunnel depreciation and land rent) are not included.

4. Discussion

4.1. Localization Value of Mushroom Variety and Substrate Screening

This study confirmed that the cultivation substrate exerted a stronger effect on *S. rugosoannulata* yield than the variety ($F = 11.64$ vs. $F = 7.11$), consistent with previous studies [19,20]. The apple woodchip-based substrate showed optimal adaptability due to its superior physical porosity and water retention capacity [21], well-matched lignocellulosic components with mushroom-degrading enzyme systems [22], and convenient local material availability. The utilization of regional fruit tree waste enables low-cost and sustainable mushroom cultivation and agricultural waste recycling, providing a localized substrate formula for green *S. rugosoannulata* production in northern China.

4.2. Advantages of Deep SMS Incorporation for Soil Improvement

Deep SMS incorporation into the 0–20 cm plow layer (M treatment) was significantly superior to surface mulching (D treatment) and was identified as the optimal returning method for tomato cultivation. The 33.3% seedling mortality observed under the D treatment can be attributed to the excessive porosity and poor water retention of fresh SMS, which caused rapid soil water loss and seedling drought stress, together with microbial nitrogen immobilization induced by the high C/N ratio of fresh SMS, resulting in severe seedling nitrogen starvation [23]. In addition, restricted root growth of the surviving plants and limited vertical migration of surface-decomposed SMS carbon jointly explain why the D treatment accumulated the highest organic carbon in the deep 10–20 cm layer rather than in the root zone (Section 3.3). Physically, deep incorporation realizes uniform mixing of SMS with the plow layer soil, optimizing soil aggregate structure and water-holding capacity. Chemically, it weakens the short-term nitrogen immobilization effect and enables stable and sustained nutrient release. Biologically, SMS carries abundant active mycelia and functional microorganisms; it is a high-quality organic amendment, with an organic matter content of 60–75% (dry-weight base) and a mycelial crude protein content of 8–12% [7,9]. Deep incorporation achieves uniform microbial inoculation across the entire plow layer, activates soil biological activity in the root zone, and improves the rhizosphere microenvironment, thereby laying a solid foundation for high tomato yield [23]. SMS-based amendments have

also been successfully applied to remediate contaminated agricultural soils [24], further supporting the multi-functional value of SMS recycling.

4.3. Progressive Carbon Pool Mechanism for Long-Term Soil Fertility Accumulation

Based on the observed soil organic carbon dynamics, we propose that the rotation system improved soil fertility through a progressive decomposition mechanism involving three functional carbon pools: labile carbon, recalcitrant carbon, and microbial residual carbon [25,26]. In the first rotation season, rapid mineralization of labile carbon provided nutrients for crop growth but caused temporary organic carbon fluctuation due to crop nutrient consumption. In the second rotation cycle, continuous degradation of recalcitrant carbon and stable accumulation of microbial residual carbon significantly improved soil carbon sequestration efficiency, realizing net soil organic carbon accumulation, which is consistent with the recent view that mineral-associated organic matter stabilization is driven by both litter quality and the carbon saturation deficit [27,28]. This three-pool progressive mechanism reveals the core process underlying long-term soil fertility improvement in mushroom–vegetable rotation systems and explains the year-by-year fertility promotion effect.

4.4. Biological Desalination and Acid–Base Homeostasis Mechanisms

The *S. rugosoannulata*–tomato rotation system exhibited a self-regulating ecological mechanism to mitigate soil secondary salinization and acidification in facility-grown tomato production. Basidiomycete mycelia actively adsorbed and transported soluble soil salts and removed salts from the soil via sporophyte harvesting, achieving biological desalination [29]. The continuous expansion of fungal mycelial networks improves soil aggregate structure and permeability, leading to progressively enhanced soil desalination over successive cropping cycles [29,30]. Meanwhile, the complementary acid–base regulation between mushroom and tomato crops maintained soil pH within the optimal range, effectively avoiding continuous cropping-induced soil acidification. This green ecological improvement method is more sustainable than traditional physical leaching and chemical amendment strategies.

4.5. Theoretical Interpretation of Regional Adaptability

The dual improvement characteristics of the rotation system were clearly clarified: soil environmental indicators (pH and EC) were universally regulated independent of soil background, due to the inherent ecological functions of mushroom lignocellulose degradation [31] and tomato rhizosphere regulation. In contrast, nutrient accumulation was strictly constrained by the soil carbon saturation theory [25,27]: low-fertility soil with a large saturation deficit but low carbon sequestration efficiency requires continuous multi-season organic input to realize stable nutrient accumulation, whereas high-fertility soil reached nutrient balance rapidly. This study provides a theoretical basis for targeted soil improvement and differentiated field management according to initial soil fertility.

4.6. System Deficiencies and Optimized Regulation Strategies

A notable potassium deficit was identified in this rotation system, which restricted long-term stable yield. The high potassium consumption of tomato and rapid leaching of SMS-derived potassium jointly caused gradual soil potassium decline. Supplementary potassium fertilizer application of 150–225 kg·ha^{−1} every 2–3 rotation seasons [17] can effectively balance soil potassium and maintain system productivity. Additionally, this study focused on soil physicochemical properties and crop performance; future research should explore soil microbial community structure, enzyme activity, and rhizosphere metabolic mechanisms to further improve the theoretical system of mushroom–vegetable rotation soil remediation.

5. Conclusions

The optimal localized *S. rugosoannulata* cultivation configuration for Jiaodong facility-grown tomato production was the Nieyang variety cultivated with apple woodchip compound substrate, with substrate properties dominating mushroom yield performance. Deep incorporation of SMS into the 0–20 cm plow layer eliminated seedling stress induced by fresh SMS surface mulching, realizing a 28.0% increase in marketable yield for R35 large-fruited tomato without fruit quality deterioration.

Two consecutive years of *S. rugosoannulata*–tomato rotation effectively reversed continuous cropping soil degradation via three core mechanisms: progressive SMS carbon pool accumulation, mycelium-mediated biological desalination, and complementary acid–base homeostasis. Soil organic carbon and total nitrogen increased by 17.6% and 243%, respectively, and soil desalination efficiency reached 56.2%, maintaining stable and suitable soil microenvironment conditions. Regular potassium supplementation is required to alleviate the system potassium deficit and sustain nutrient balance.

The rotation model exhibits universal soil salinity and pH regulation effects and background-dependent nutrient accumulation characteristics, supporting site-specific field management. With an annual net economic benefit of approximately 255,000 CNY·ha^{−1} (≈38,060 USD·ha^{−1}), this green and recyclable rotation system effectively mitigates continuous cropping obstacles in facility-grown tomato production, achieving agricultural waste recycling, soil restoration, and yield improvement, and has broad prospects for popularization and application in the Jiaodong facility-grown tomato production region. Future research should evaluate the long-term stability of the system over additional rotation cycles, elucidate the succession of soil microbial communities and enzyme activities, optimize potassium supplementation regimes, and demonstrate the model in other facility-grown vegetable production regions of northern China.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/agronomy16181767/s1>, Figure S1: Schematic diagram of the simple plastic tunnel used in the field experiments; Figure S2: Location of the two experimental sites in Yantai City, Shandong Province, China.

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

Funding: This research was funded by the Shandong Provincial Natural Science Foundation (ZR2022MC138); the Yantai Municipal Science and Technology Plant Program (2022XDRH028); and the Ludong University High-level Talent Fund (LDRC246385).

Data Availability Statement: The data presented in this study are available on request from the corresponding authors.

Conflicts of Interest: The authors declare no conflicts of interest.

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