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Concentration-dependent effects of tomato straw-derived pyrolysis liquid on growth of tomato seedlings: synergistic regulation of soil properties, photosynthesis, phytohormones, and antioxidant defense

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Abstract: To address issues such as the low utilization rate of tomato straw resources and prominent continuous cropping obstacles in greenhouse tomato seedling cultivation, this study used autogenous tomato straw-derived pyrolysis liquid (TSPL) as the material, with distilled water as a control (CK). Dilution ratios of 250 (TSPL-250), 300 (TSPL-300), and 350 (TSPL-350) times were applied through root irrigation to investigate their effects on tomato seedling growth, root activity, soil physicochemical properties, photosynthetic characteristics, endogenous hormones, and antioxidant systems. The results showed that pyrolyzate at different dilution ratios significantly promoted tomato seedling growth, with the TSPL-300 treatment yielding the most prominent effect, exhibiting a "low-concentration promotion, high-concentration inhibition" dose-response pattern. TSPL-300 significantly increased root activity by 45.93% and improved soil available nutrient content, enhancing soil

fertility and salinity conditions. Regarding photosynthetic parameters, the TSPL-300 treatment increased net photosynthetic rate (Pn), stomatal conductance (Gs), and intercellular CO_2 concentration (Ci) by 526.53%, 236.15%, and 25.36%, respectively. Endogenous hormone analysis showed that the TSPL-300 treatment increased indole-3-acetic acid (IAA), gibberellin (GA_3), and cytokinin (CTK) by 85.71%, 30.78%, and 45.61%, respectively. Physiological and biochemical analyses indicated that all treatments significantly increased antioxidant enzyme activities, but high-concentration treatments also led to increased accumulation of hydrogen peroxide (H_2O_2) and malondialdehyde (MDA), suggesting that moderate oxidative stress is a trigger for activating defense responses. Correlation analysis suggested potential associations among soil properties, photosynthetic traits, endogenous hormones, antioxidant responses, and seedling growth. Low-to-medium concentrations of pyrolyzate promoted growth synergistically through multiple pathways, while high concentrations exacerbated membrane lipid peroxidation damage and inhibited growth. This study clarifies the optimal application concentration and growth-promoting mechanism of tomato straw pyrolyzate, providing a theoretical basis for its application as a potential biostimulant-like material and for the resource utilization of agricultural and forestry waste.

Keywords: Tomato straw, Pyrolysis liquid, Seedling growth, Endogenous hormones, Physiological mechanisms

1. Introduction

The total amount of agricultural and forestry waste generated worldwide each year is enormous, and how to achieve its efficient resource utilization has become an important issue

for the sustainable development of agriculture [1-2]. Tomato (Solanum lycopersicum L.) is one of the food crops with the largest greenhouse cultivation area in the world, and its production generates a large amount of straw waste [3-4]. It is estimated that each hectare of tomato cultivation can produce about 20-30 t of straw residue annually. Traditionally, this straw is often discarded at will or burned in the field, which not only causes a tremendous waste of biomass resources, but also leads to environmental problems such as soil continuous-cropping obstacles, pathogen accumulation, and air pollution [3]. Therefore, exploring efficient and green ways to utilize tomato straw has become a key problem urgently needing resolution in the sustainable development of protected agriculture.

As a widely recognized biomass conversion approach, pyrolysis technology can not only effectively reduce the environmental problems caused by traditional biomass combustion, but its by-product-pyrolysis liquid-has also attracted increasing attention for its resource value [5]. Pyrolysis liquid is an acidic liquid by-product produced during biomass pyrolytic carbonization, rich in various bioactive substances such as organic acids, phenols, ketones, and esters, and shows broad application prospects in agriculture [2,6]. In agricultural production, pyrolysis liquid can be used as a plant growth promoter, soil conditioner, antimicrobial agent, insecticide, repellent, and so on [7], and has become a research hotspot in the field of biomass resource utilization in recent years [8]. Under the current background of green agricultural development, using pyrolysis liquid to replace part of chemical inputs not only helps reduce agriculture's dependence on chemically synthesized substances, but also opens up new avenues for the resource recycling of agricultural and forestry waste. In-depth investigation of the effects of pyrolysis liquid on tomato growth and development is both a

practical need to ensure stable and high tomato yields and a key link in promoting high-quality development of protected and green agriculture.

Pyrolysis liquid is most widely used in agriculture as a plant growth regulator [9]. Existing studies have shown that distilled-water dilutions of pyrolysis liquid significantly promote the growth and development of rice, corn, legumes, chrysanthemum, and many other plants [10-11], by promoting seed germination through foliar spraying and direct soil application, thereby improving the plant vigor index [12]. However, the regulatory effect of pyrolysis liquid on plant growth shows a typical concentration dependence [13]. Studies have found that low-concentration pyrolysis liquid can induce mild stress in plants, whereas high-concentration pyrolysis liquid triggers severe oxidative stress, leading to suppressed antioxidant enzyme activity and disrupted hormonal balance, ultimately inhibiting plant growth [14]. This concentration effect pattern of low promotion and high inhibition has been verified in Arabidopsis, wheat, and many other plants. In terms of soil improvement, pyrolysis liquid can reduce soil electrical conductivity (EC) and pH, increase the content of soil available nutrients, promote the proliferation of beneficial soil microorganisms, and improve the rhizosphere microecological environment [15]. In protected tomato seedling production, the application effect of pyrolysis liquid has been preliminarily confirmed. Root irrigation with different concentrations of pyrolysis liquid is beneficial to root growth and increases tomato yield [16-17]. These studies have laid an initial foundation for the application of pyrolysis liquid in protected tomato seedling production.

However, most of the above studies focused on pyrolysis liquid prepared from wood or forest residues, while research on crop straw, especially self-derived pyrolysis liquid from

tomato straw, has rarely been reported. Tomato straw pyrolysis liquid originates from the tomato plant itself, and its active component composition may differ from that of exogenous pyrolysis liquids; when applied to the same crop, it may have better biocompatibility and specificity. At the same time, preparing pyrolysis liquid from tomato straw and reapplying it to tomato seedling cultivation offers the dual advantages of resource conservation and environmental friendliness. However, what exactly is the regulatory effect of tomato straw pyrolysis liquid on tomato seedling growth? Does the mechanism involving “improvement of soil properties-enhancement of root vigor-promotion of photosynthetic performance-coordination of hormones and antioxidant responses” hold true? What is the optimal application concentration? These questions still lack systematic experimental evidence.

Based on this, this study used tomato seedlings as experimental materials and set up root irrigation treatments with tomato straw pyrolysis liquid at different dilution ratios. Morphological indicators, physiological and biochemical indicators, and physicochemical properties of rhizosphere soil were systematically measured, with the aims of: (1) clarifying the concentration effect of tomato straw pyrolysis liquid on tomato seedling growth; (2) revealing the physiological mechanisms by which pyrolysis liquid promotes tomato seedling growth, including its effects on root vigor, photosynthetic performance, endogenous hormone levels, and antioxidant enzyme activity; and (3) elucidating the synergistic pathway through which pyrolysis liquid indirectly affects seedling growth by improving soil properties. The results will provide a scientific basis for the resource utilization of tomato straw and theoretical support for the application of pyrolysis liquid as a green plant growth promoter in protected tomato seedling production.

2 Materials and Methods

2.1 Materials

The tomato seedlings (Solanum lycopersicum L. cv. Hairy Pink 802) were purchased from Shandong Shouguang Kaijiate Agricultural Science and Technology Co., Ltd. China.The seeds were disinfected with 10% NaClO for 10 min, rinsed three times with ddH_2O, and then soaked for 2 h for germination. Seedlings with uniform germination were placed in Petri dishes lined with sterilized moist filter paper and cultured at 27°C for 48 to 72 h, then transplanted into seedling pots, four plants per pot. Plants grown for 3 weeks were used for the experiment.

Test soil: red soil and fermented sheep manure were mixed at a ratio of 7:3 and sterilized by intermittent autoclaving at 121°C for 3 times. The soil had pH 6.72, soil organic matter(SOM) content 16.93 $g \cdot kg^{-1}$, alkaline hydrolyzable nitrogen(HN) 40.05 $mg \cdot kg^{-1}$, available phosphorus(AP) 20.21 $mg \cdot kg^{-1}$, and available potassium(AK) 73.15 $mg \cdot kg^{-1}$.

The tomato straw-derived pyrolysis liquid (TSPL) used in this study was supplied by Yunnan Kunyv Environmental Development Co., Ltd., China. According to the supplie's technical information, TSPL was obtained as the condensate generated during oxygen-limited pyrolysis of air-dried tomato straw. The pyrolysis temperature is maintained at approximately 500°C, the heating rate is $104K \cdot s^{-1}$, and hot steam circulates rapidly. The output rate (total mass ratio of raw materials): liquid (crude pyrolysis solution) 75%; solid (biochar) 12%; gas (synthesis gas) 13%). Let it stand for 3 months, use the siphon method to absorb the clarified liquid in the middle layer, add 5% activated carbon, oscillate ultrasonic for 10 minutes, let it

stand for 36 hours, and filter it three times to obtain the refined pyrolysis solution. The basic physicochemical properties of the TSPL were as follows: pH 3.55, total nitrogen 0.025 $mg \cdot mL^{-1}$, total phosphorus 0.015 $mg \cdot mL^{-1}$, and total potassium 0.062 $mg \cdot mL^{-1}$.

2.2 Experimental Design

The experiment was conducted from October to December 2024 in pots. Four treatments were established: CK, TSPL-250, TSPL-300, and TSPL-350. CK received distilled water. TSPL-250, TSPL-300, and TSPL-350 represented 250-, 300-, and 350-fold dilutions of tomato straw-derived pyrolysis liquid, respectively. Among the tested treatments, TSPL-250 corresponded to the relatively highest TSPL concentration, TSPL-300 to an intermediate concentration, and TSPL-350 to the relatively lowest concentration. Each treatment included three biological replicates, resulting in 12 experimental pots in total. All treatments involved root irrigation on the 7th, 12th, 17th, 22nd, 27th days after transplanting, and the irrigation amount was 200 mL per pot. All other management techniques were performed according to conventional cultivation practices. Soil samples were collected from around the root system of the plants, air-dried, ground, and sieved through 2 mm, 1 mm, and 0.149 mm sieves, then packaged for later use.

2.3 Analysis and Determination

2.3.1 Determination of Tomato Biological Traits

Plant height(PH) was measured from the root base to the growing point with a meter rule; root length(RL) is the distance from root tip to root base; stem diameter(SD) was

measured with a vernier caliper 1 cm above the cotyledons; leaf area(LA) was determined by selecting the second leaf above the cotyledons, measuring leaf length(L) and maximum width(D) with a ruler, and calculating S=L×D×0.5468; Biomass(B) consists of above-ground parts and underground roots. The fresh weights of above-ground and underground parts are measured with a balance after absorbing moisture with filter paper, and their dry weights are determined by a balance after drying to constant weight.

2.3.2 Determination of Tomato Soil Physicochemical Properties

Soil pH (soil:water ratio 2.5:1) and EC (soil:water ratio 5:1) were measured using an EZ-9909 five-in-one water quality tester and an FE-30 Mettler conductivity meter, respectively, both by potentiometric method. SOM was determined by the $K_2Cr_2O_7H_2SO_4$ and $FeSO_4$ volumetric methods. HN was determined by the alkali diffusion method [18]. AP was determined by sodium bicarbonate extraction-spectrophotometric colorimetry (Yan and Arthur, 2025). AK was determined by ammonium acetate extraction-flame photometry (Yan and Arthur, 2025).

2.3.3 Determination of Endogenous Hormones in Tomato Leaves

The contents of endogenous hormones indole acetic acid (IAA), gibberellin (GA_3), abscisic acid (ABA), and cytokinin (CTK) were determined by enzyme-linked immunosorbent assay (ELISA) [19]. One gram of fresh leaf tissue was ground into a homogenate in 80% methanol extract containing 100 mg polyvinylpyrrolidone (PVP) under ice bath conditions, transferred to a 10 mL centrifuge tube and mixed well, then kept at 4°C for 4 h, centrifuged at 6000 $r \cdot min^{-1}$ for 15 min, and the supernatant was purified twice through a C-18 column and brought to a final volume of 1.5 mL. Endogenous hormone

contents (μg·g^{-1}) were determined by the ELISA method provided by China Agricultural University.

2.3.4 Determination of Photosynthetic Characteristics of Plant Leaves

The LI-6400XT photosynthesis system was used to measure leaf photosynthetic parameters. Each leaf was first activated for 30 min. The 2nd, 3rd, and 4th fully expanded leaves from top to bottom were selected per pot, and each leaf was measured three times. The measured parameters included net photosynthetic rate (Pn, μmol·m^{-2}·s^{-1}), transpiration rate (Tr, mmol·m^{-2}·s^{-1}), intercellular CO_2 concentration (Ci, mmol·mol^{-1}), and stomatal conductance (Gs, μmol·m^{-2}·s^{-1}).

2.3.5 Determination of Physiological and Biochemical Properties of Plant Leaves

Chlorophyll(CHL) content in tomato leaves was measured using a SPAD-502 chlorophyll meter, root activity(RA), leaf malondialdehyde(MDA), hydrogen peroxide(H_2O_2) content, and the activities of catalase(CAT), peroxidase(POD), and superoxide dismutase(SOD) were determined using kits from Suzhou Greise Biotechnology Co., Ltd., combined with spectrophotometric methods. The units for the indicators were as follows: RA, μg·h^{-1}·g^{-1}; MDA content, nmol·g^{-1} FW; H_2O_2 content, μmol·g^{-1}; CAT, POD, and SOD activities, U·g^{-1} FW.

2.4 Data Analysis

Data were organized using Microsoft Excel 2010, statistically analyzed using SPSS v20.0, and plotted using Origin 2021. One-way analysis of variance was used, and Duncan's test was used for significance testing ($P<0.05$). Mantel correlation analysis was performed

206 through the online Graph Cloud platform (http://cloudtutu.com.cn/Mantel).

207 **3 Results**

208 ***3.1 Effects of TSPL on tomato seedling growth***

209 TSPL at different dilution ratios significantly increased PH, SD, and LA at all
210 developmental stages of tomato seedlings (Table 1). At 27 days after transplanting, compared
211 with the CK group, all TSPL treatments at different dilutions significantly increased tomato
212 seedling biomass ($P<0.05$). Respectively, TSPL-300 and TSPL-350 produced greater biomass
213 accumulation than TSPL-250, indicating that excessive relative concentration may reduce the
214 growth-promoting effect, increasing biomass by 127.27% and 131.97%, relative to CK, while
215 TSPL-250 increased biomass by 80.56% (Fig. 1-E). All pyrolysis liquid treatments
216 significantly increased the fresh weight of both the shoot and root systems. Specifically, shoot
217 fresh weight increased by 89.76%, 134.15%, and 128.78% at TSPL-250, TSPL-300, and
218 TSPL-350, respectively, relative to CK (Fig. 1-F), while root fresh weight increased by
219 64.04%, 100.00%, and 108.77%, respectively (Fig. 1-G). In addition, Fig. 1-B shows that
220 after 27 d of growth, all pyrolysis liquid treatments significantly increased RL, with the effect
221 ranked as TSPL-300 > TSPL-350 > TSPL-250 > CK. RL under TSPL-300 and TSPL-350
222 increased by 66.73% and 61.22%, respectively, in comparison to CK, whereas TSPL-250
223 increased RL by 35.31%. Meanwhile, all pyrolysis liquid treatments significantly enhanced
224 RA in tomato seedlings (Fig. 1-C,D), and the enhancement first increased and then decreased
225 with increasing dilution.

226 Overall, all three dilution ratios of pyrolysis liquid promoted tomato seedling growth.
227 Low-concentration TSPL- (TSPL-350) exerted the strongest growth-promoting effect,

whereas the medium-concentration treatment (TSPL-300) was most effective at the later seedling stage.

3.2 Effects of TSPL on soil physicochemical properties

The results in Fig. 2 indicate that pyrolysis liquid at different dilution ratios had distinct effects on the physicochemical properties of tomato rhizosphere soil. Compared with CK, TSPL-350 significantly increased soil pH by 2.81%, whereas TSPL-250 significantly decreased soil pH by 7.31%; TSPL-300 had no significant effect on soil pH ($P > 0.05$). All pyrolysis liquid treatments significantly reduced soil EC ($P<0.05$), with TSPL-250 and TSPL-300 showing the greatest reductions, by 60.58% and 63.50%, respectively, relative to CK. All treatments significantly increased soil HN ($P<0.05$), with the greatest increase observed under TSPL-300, which was 28.28% higher than CK. Only TSPL-300 and TSPL-250 significantly increased soil AK and AP; AK increased by 11.58% and 19.02%, respectively, and AP increased by 27.03% and 41.85%, respectively. In contrast, pyrolysis liquid treatments had no significant effect on SOM ($P> 0.05$).

3.3 Effects of TSPL on tomato photosynthetic traits

As shown in Fig. 3-A, all dilution treatments increased Pn in tomato seedlings ($P<0.05$). On day 7, TSPL-350 showed the strongest promotive effect; on days 12, 17, 22, and 27, TSPL-300 was most effective. These results indicate that at the early stage of seedling growth, the enhancement of Pn by pyrolysis liquid increased as dilution decreased; as seedlings developed, the medium-concentration TSPL-300 treatment produced a significantly stronger increase in Pn than either the low-concentration TSPL-350 or high-concentration

TSPL-250 treatment.

However, the effects of different dilution ratios of pyrolysis liquid on Tr, Ci, and Gs varied across developmental stages (Fig. 3-B,C,D) ($P<0.05$). On day 7, all treatments significantly increased Tr, with the effect ranked as TSPL-250 > TSPL-300 > TSPL-350 > CK, and the enhancement weakened as dilution increased. On day 12, TSPL-300 showed the strongest effect, increasing Tr by 40.00% relative to CK. On day 17, TSPL-250 produced the greatest increase, by 36.36% relative to CK. On day 22, only TSPL-350 significantly increased Tr. On day 27, only TSPL-250 significantly increased Tr. On days 7 and 12, all three treatments significantly increased Ci, with TSPL-250 and TSPL-300 showing the strongest effects. On days 17 and 22, only TSPL-300 significantly increased Ci, by 5.14% and 5.57%, respectively, relative to CK. On day 27, TSPL-300 produced the greatest increase in Ci, reaching 25.36% above CK levels. Overall, the high-concentration TSPL-250 treatment had a stronger effect on Ci at the early seedling stage, but this effect gradually weakened as development proceeded, whereas the effect of medium-concentration TSPL-300 progressively strengthened. On days 7, 12, and 17, TSPL-300 produced the most pronounced increase in Gs, by 104.35%, 270.00%, and 236.15%, respectively, relative to CK. On day 22, no significant differences in Gs were observed among treatments and CK. On day 27, all treatments significantly increased Gs, by 50.82%, 50.82%, and 54.10%, respectively, relative to CK. In addition, the effects of all treatments on Gs remained stable on days 7, 12, 17, and 22, whereas their stimulatory effects on Gs were markedly enhanced on day 27.

3.4 Effects of TSPL on endogenous hormones in tomato

As shown in Fig. 4, pyrolysis liquid at different dilution ratios had substantial effects on endogenous hormones in tomato seedlings. Compared with CK, TSPL-300 and TSPL-350 significantly increased IAA and CTK contents. Specifically, IAA increased by 85.71% and 80.67%, and CTK increased by 45.61% and 107.89%, respectively, relative to CK; the increases in IAA did not differ significantly between these two treatments. In contrast, TSPL-250 caused no significant change in IAA or CTK content. Moreover, TSPL-250, TSPL-300, and TSPL-350 all significantly increased GA_3 and ABA contents in tomato seedlings, with GA_3 increasing by 16.91%, 30.78%, and 10.41%, and ABA increasing by 74.42%, 98.48%, and 86.94%, respectively, relative to CK. The increases in ABA did not differ significantly among the three treatments. Among all treatments, TSPL-300 produced the strongest increases in IAA, GA_3, and ABA. These results indicate that the medium dilution of pyrolysis liquid (1:300) exerted the greatest influence on endogenous hormone levels in tomato seedlings, significantly enhancing IAA, GA_3, ABA and CTK.

3.5 Effects of TSPL on tomato physiological and biochemical traits

During the seedling growth period, TSPL-250 and TSPL-300 significantly increased CHL content in tomato seedlings (Fig. 5), by 7.43% and 5.07%, respectively, relative to CK, whereas TSPL-350 had no significant effect. Compared with CK, all treatments significantly increased H_2O_2 and MDA contents in leaves. For H_2O_2, the effect ranked as TSPL-250 > TSPL-350 > TSPL-300, with significant increases of 65.24%, 54.37%, and 26.38%, respectively, relative to CK, indicating that the 250-fold dilution induced the strongest oxidative response., whereas medium and low concentrations were less effective. For MDA,

294 the effect ranked as TSPL-250 > TSPL-300 > TSPL-350, with significant increases of
295 93.65%, 26.42%, and 16.30%, respectively, relative to CK, suggesting that membrane lipid
296 peroxidation became more pronounced as the relative TSPL concentration increased.
297 In addition, TSPL-250, TSPL-300 and TSPL-350 altered antioxidant enzyme activities in
298 tomato seedlings. Compared with CK, all treatments significantly increased POD, SOD, and
299 CAT activities. TSPL-250 and TSPL-300 showed the strongest enhancement of POD activity,
300 increasing it by 151.79% and 170.32%, respectively, relative to CK, whereas TSPL-350 had a
301 weaker effect, increasing POD by 42.16%. These results indicate that medium and high
302 concentrations of pyrolysis liquid most strongly enhanced POD activity, whereas the effect
303 was weaker at low concentration. For SOD activity, the effect ranked as TSPL-300 > TSPL-
304 350 > TSPL-250, with significant increases of 166.18%, 83.77%, and 22.68%, respectively,
305 relative to CK, indicating that the medium concentration was most effective in enhancing
306 SOD activity, whereas the high concentration had a weaker effect. For CAT activity, the effect
307 ranked as TSPL-250 > TSPL-350 > TSPL-300, with significant increases of 233.79%,
308 187.28%, and 159.75%, respectively, relative to CK, indicating that the high concentration
309 was most effective in enhancing CAT activity, whereas the medium and low concentrations
310 were less effective.
311
312 **3.6 Correlation analysis**
313 ***3.6.1 Relationships among tomato growth, soil physicochemical properties, endogenous***
314 ***hormones, photosynthetic traits, and physiological and biochemical indices***
315 Mantel correlation analysis showed a strong association between soil physicochemical

316 properties and tomato biometric traits. Soil EC was significantly negatively correlated with
317 PH, SD, LA, and RL, and extremely significantly negatively correlated with RA. Soil AK,
318 HN, and AP were significantly positively correlated with RA($P<0.05$) (Fig. 6-A). In addition,
319 endogenous hormones, photosynthetic traits, and physiological and biochemical indices in
320 tomato leaves were strongly associated with tomato biometric traits. Spearman correlation
321 analysis of endogenous hormones and biometric traits showed that IAA was significantly
322 positively correlated with PH, SD, LA, and RL; CTK was significantly positively correlated
323 with B; GA3 was significantly positively correlated with RA; and ABA was significantly
324 positively correlated with PH, SD, LA, and RL($P<0.05$) (Fig. 6-B). Spearman analysis of
325 photosynthetic traits and biometric traits showed that Pn and Gs were significantly positively
326 correlated with PH, SD, LA, and RL, whereas intercellular CO_2 Ci was significantly
327 positively correlated with B (Fig. 6-C). Spearman analysis of physiological and biochemical
328 indices and biometric traits showed that POD was significantly positively correlated with PA,
329 while SOD was significantly positively correlated with PH, SD, LA, and RL ($P<0.05$) (Fig. 6-
330 D).

331 ***3.6.2 Relationships between TSPL concentration and tomato biometric traits,*** **endogenous**
332 ***hormones, photosynthetic traits, and physiological and biochemical indices***

333 Spearman correlation analysis showed that the dilution ratio of TSPL was strongly
334 associated with tomato seedling biometric traits, endogenous hormones, photosynthetic traits,
335 and physiological and biochemical indices (Tables 2 and 3). The dilution ratio of TSPL was
336 significantly positively correlated with tomato seedling B, CTK, and Pn, and significantly
337 negatively correlated with Tr, Ci, MDA, and CHL($P<0.01$). These results indicate that TSPL

concentration affects tomato seedling growth and development by modulating endogenous hormone levels, photosynthetic performance, and leaf antioxidant responses.

4 Discussion

4.1 Promotion of tomato seedling growth by TSPL

This study showed that TSPL diluted 250-, 300-, and 350-fold significantly promoted PH, SD, LA, B, and RL in tomato seedlings, consistent with previous reports [16](Jian et al., 2024). In addition, during the early stage of seedling growth, TSPL-350 had a more pronounced effect on PH; as growth progressed, TSPL-300 exerted the strongest promotive effects on all growth indices. This may be related to differences in nutrient and growth-regulator requirements at different developmental stages. At the initial stage, low-concentration TSPL may better meet the requirements for growth initiation, whereas during rapid growth, medium-concentration TSPL may be better suited to the demand for nutrients and physiological regulation [20]. Compared with TSPL-300 and TSPL-350 treatments, TSPL-250 was less effective in promoting tomato growth and development. This may be due to the composition of pyrolysis liquid and its effects on plant physiology and soil ecology. Pyrolysis liquid is a complex mixture containing multiple trace organic components [21]. Depending on composition, it may exert either stimulatory or inhibitory effects on plant growth [22]. Phenolic compounds in pyrolysis liquid play regulatory roles in plant growth and development; in particular, dihydric and polyhydric phenols can significantly promote plant growth. However, phenolic effects are threshold-dependent: they promote growth only at low concentrations, whereas high concentrations inhibit growth [21]. In addition, acetic acid is the

most abundant component in pyrolysis liquid, but excessive organic acid content can be toxic to crop root growth [23-24].

The acidity of pyrolysis liquid is an important factor affecting plant and soil responses. In the present study, distilled water was used as the control, whereas a pH-matched acidified water control was not included. Therefore, the potential contribution of acidity to the observed effects cannot be completely excluded. Nevertheless, TSPL is a complex mixture containing organic acids, mineral nutrients, phenolic compounds, and other bioactive constituents, and the observed changes in soil nutrients, endogenous hormones, photosynthetic gas exchange, and antioxidant responses are unlikely to be explained solely by acidity. Future studies should include pH-adjusted controls to distinguish the effects of acidity from those of other active components.

4.2 Effects of TSPL on tomato root activity and soil physicochemical properties

RA is a key physiological indicator reflecting plant absorption and metabolic capacity [25-26]. In this study, all dilution levels of TSPL significantly enhanced RA in tomato seedlings, with the 300-fold dilution showing the best performance. Increased RA facilitates water and nutrient uptake, thereby supporting plant growth and development. At the same time, TSPL significantly altered soil physicochemical properties: TSPL-350 increased soil pH, TSPL-250 decreased soil pH, and all treatments reduced soil EC and increased HN, while some treatments also increased soil AK and AP. This is consistent with previous studies showing that pyrolysis liquid can promote nutrient activation and increase available nutrient pools through its acidity and abundance of bioactive organic molecules [27-28]. Although

TSPL contained mineral nutrients, the applied solution was highly diluted, and the amount of soluble ions directly introduced into the soil was limited. The decrease in EC may be associated with enhanced plant nutrient uptake and changes in ion availability in the rhizosphere. Nevertheless, the underlying mechanism requires further investigation. The application of high-concentration pyrolysis liquid causes soil acidification, promotes ion migration among soil colloids, releases previously immobilized nutrients, and increases nutrient availability [24]. In addition, the nitrogen and potassium inherently present in pyrolysis liquid contribute more strongly as application rates increase. Therefore, TSPL can create favorable conditions for plant growth by regulating the soil environment and improving fertility.

4.3 Effects of TSPL on tomato photosynthetic traits

Photosynthesis is fundamental to plant biomass production and growth and development [29]. Studies have shown that TSPL can improve net photosynthetic efficiency by regulating Gs and intercellular Ci, thereby promoting the accumulation of photosynthates and plant growth [30], consistent with previous findings [28]. Pyrolysis liquid can enhance net photosynthesis in eggplant and cotton, mainly because phenolics, organic acids, and trace elements in pyrolysis liquid increase CHL content and Gs, thereby improving the efficiency of light energy conversion in chloroplasts [31]. In addition, TSPL at different dilution ratios exerted different effects on photosynthetic traits at different growth stages of tomato seedlings. At the early seedling stage, the effect of TSPL on Pn increased as dilution decreased. As seedlings developed, the medium-concentration TSPL-300 treatment

consistently produced significantly greater increases in Pn than TSPL-350 and TSPL-250 treatments across multiple growth stages. This suggests that during the middle and later stages of tomato growth, medium-concentration TSPL better meets the regulatory needs of photosynthesis, possibly because its components play a key role in modulating the activity of enzymes involved in the Calvin cycle, thereby promoting CO_2 fixation and photosynthate synthesis. Tr also showed stage-specific differences: on day 7, Tr increased with concentration (TSPL-250 > TSPL-300 > TSPL-350 > CK); on day 12, TSPL-300 was highest; on day 17, TSPL-250 was highest; and in later stages only individual treatments remained significantly stimulatory. On days 22 and 27, only TSPL-350 and TSPL-250, respectively, significantly increased tomato seedling Tr. This indicates that the effect of TSPL on Tr depends not only on concentration but also closely on the developmental stage of tomato. In addition, TSPL-300 significantly increased Gs and Ci during the early and middle growth stages (days 7, 12, and 17), by 104.35%, 270.00%, and 236.15%, respectively, relative to CK. This indicates that pyrolysis liquid treatment improves gas exchange and provides sufficient CO_2 supply for photosynthesis.

4.4 Effects of TSPL on endogenous hormones and physiological and biochemical indices in *tomato*

Endogenous hormones play central regulatory roles in plant growth and development [32](Ha et al., 2026). In this study, TSPL-300 and TSPL-350 significantly increased IAA and CTK contents in tomato seedlings; both hormones are crucial for promoting cell elongation and division and for regulating organ development [33]. These results indicate that low- and

426 medium-concentration TSPL can stimulate the synthesis of IAA and CTK in tomato
427 seedlings, thereby promoting cell division and elongation and supporting morphogenesis and
428 growth. All treatments also significantly increased GA_3 and ABA levels in tomato seedlings.
429 The increase in GA_3 may contribute to stem elongation and plant height increase, whereas the
430 increase in ABA may enhance adaptation to environmental stress, such as drought tolerance
431 [34-35]. ABA is often associated with stress responses and growth inhibition under severe or
432 prolonged stress. However, moderate ABA accumulation can also contribute to stomatal
433 regulation, antioxidant defense, and stress adaptation. In this study, TSPL-300 increased ABA
434 content together with improved photosynthetic gas exchange, antioxidant enzyme activity,
435 and seedling growth, suggesting that ABA may have participated in physiological adjustment
436 rather than directly suppressing growth. However, this interpretation requires further
437 validation through molecular and hormone-signaling analyses.

438 At the physiological and biochemical level, TSPL-300 significantly increased CHL
439 content, enhancing light capture and utilization efficiency and providing a stronger energy and
440 material basis for growth [36-38]. Meanwhile, TSPL activated the antioxidant defense system,
441 significantly increasing POD, SOD, and CAT activities in all treatments. Among them, TSPL-
442 300 most strongly enhanced POD and SOD activities. POD, SOD, and CAT remove excess
443 reactive oxygen species and maintain intracellular redox homeostasis. This suggests that
444 pyrolysis liquid can induce defense responses against oxidative stress in tomato seedlings.
445 The differential effects of TSPL at different concentrations on antioxidant enzyme activities
446 reflect the complex response of plants to external stimuli [39]. H_2O_2 is not only a marker of
447 oxidative stress but also an important signaling molecule at controlled levels. However,

excessive H_2O_2 accumulation may cause oxidative damage, as indicated by increased MDA. In the present study, all TSPL treatments increased H_2O_2 and MDA contents, but TSPL-250 caused the largest increases, suggesting a higher risk of oxidative damage. By contrast, TSPL-300 showed a more favorable balance between growth promotion, antioxidant enzyme activation, and oxidative damage. Therefore, the growth-promoting effect of TSPL should be interpreted as concentration-dependent and limited to an appropriate dilution range [38,40]. Increased MDA content is a clear indicator of enhanced membrane lipid peroxidation [41], suggesting that although high-concentration TSPL activates defense responses, it also suppresses healthy plant growth to some extent.

4.5 phytotoxicity and environmental risks of TSPL

Despite its potential growth-promoting effect, pyrolysis liquid may pose phytotoxic or environmental risks if applied at inappropriate concentrations. Organic acids, phenolic compounds, and other condensable pyrolysis products may inhibit root growth, disturb membrane stability, or alter soil microbial communities when present at excessive levels. In the present study, TSPL-250 induced higher H_2O_2 and MDA accumulation than the other dilutions, indicating that relatively high TSPL concentration may impose oxidative stress. Therefore, practical application should be based on appropriate dilution, and long-term studies are needed to assess phytotoxicity, soil microbial responses, residue dynamics, and environmental safety.

5 Conclusions

This study evaluated the effects of tomato straw-derived pyrolysis liquid on tomato

seedlings under controlled pot-culture conditions. The results showed that 250-, 300-, and 350-fold dilutions of TSPL improved seedling growth to varying degrees by influencing soil nutrient availability, endogenous hormone balance, photosynthetic gas exchange, and antioxidant responses. Among the tested treatments, the 300-fold dilution showed the most balanced overall performance, with favorable effects on growth-related physiological traits, soil hydrolyzable nitrogen, IAA, GA_3, ABA, SOD activity, stomatal conductance, and intercellular CO_2 concentration, while inducing less oxidative damage than the 250-fold dilution. Although TSPL increased H_2O_2 and MDA contents, especially at the 250-fold dilution, these results indicate that the application concentration should be carefully controlled to avoid excessive oxidative stress. Overall, appropriately diluted TSPL may have potential as a biostimulant-like material for protected tomato seedling production and as a pathway for tomato straw resource utilization. However, the present findings are limited to a short-term controlled seedling experiment. Further studies involving pH-matched controls, wider concentration gradients, chemical characterization, long-term greenhouse and field trials, and environmental safety assessments are needed before large-scale application.

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Declaration

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

Clinical trial number

Not applicable.

Abbreviations

Calcium, Ca.

Availability of data and materials

If raw data are needed, please contact the corresponding author (Hongyin Zhou, zhy1605202632@163.com).

Authorship contribution

Xiaoqiao Zhu: Writing – original draft. Yan Shen: Investigation. Xiaoli jin: Data curation. Lei Liu: Resources. Naiming Zhang: Visualization, Writing – review & editing. Hongyin Zhou: Writing – review & editing, Funding acquisition.

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Table caption

Table 1 Effects of TSPL on plant height, stem diameter and leaf area of tomato seedlings

Note: The values in the table are average ±SD (n=3). Different lowercase letters indicate significant difference among treatments at $P<0.05$.

Table 2 Spearman correlation analysis of TSPL dilution times with tomato biological traits and endogenous hormones

Note: The values in the table are average ±SD (n=3). Different lowercase letters indicate significant difference among treatments at $P<0.05$.

Table 3 TSPL dilution ratio and tomato photosynthetic characteristics and physiological and biochemical Spearman correlation analysis

Note: The values in the table are average ± SD (n=3). Different lowercase letters indicate significant difference among treatments at $P<0.05$.

Figure caption

Fig. 1 Picture of the effect of TSPL on the growth of tomato seedlings

(A) Phenotype in pots (B) Phenotype of root length (C) Root length of tomato seedlings (D) root activity of tomato seedlings (E) Aboveground and underground fresh weight; (F) Aboveground fresh weight; (G) Fresh weight of underground part.

Fig.2 Effects of TSPL on physical and chemical properties of rhizosphere soil of tomato seedlings

(A) Soil EC value; (B) Soil pH value; (C) Soil organic matter content; (D) Soil available potassium content; (E) Soil alkaline hydrolyzable nitrogen content; (F) Soil available phosphorus content.

Fig. 3 Effects of TSPL on Photosynthetic Characteristics of Tomato leaves

(A) Effects of TSPL on photosynthetic rate of tomato leaves. (B). Effect of TSPL on transpiration rate of tomato leaves. (C). Effects of TSPL on intercellular CO_2 concentration in tomato leaves. (D).Effect of TSPL on stomatal conductance of tomato leaves

Fig. 4 Effects of TSPL on endogenous hormones in tomato

(A) Indole acetic acid content; (B) Cytokinin; (C) Gibberellin; (D) Abscisic acid.

Fig.5 Effects of TSPL on physiological and biochemical of tomato

Fig. 6 correlation analysis

(A) Mantel tests were used to examine the relationships between endogenous hormones, photosynthesis, physiological/biochemical indices, agronomic traits, and soil factors. Spearman correlation analyses were further conducted between (B) hormones, (C) photosynthesis, (D) physiological/biochemical indices, and both agronomic traits and soil properties. In the Mantel tests, line thickness and color represent the correlation *r* and P-value, respectively; heatmap colors denote Spearman's correlation coefficients. Significance: $P < 0.05$, $*P < 0.01$, $**P < 0.001$.

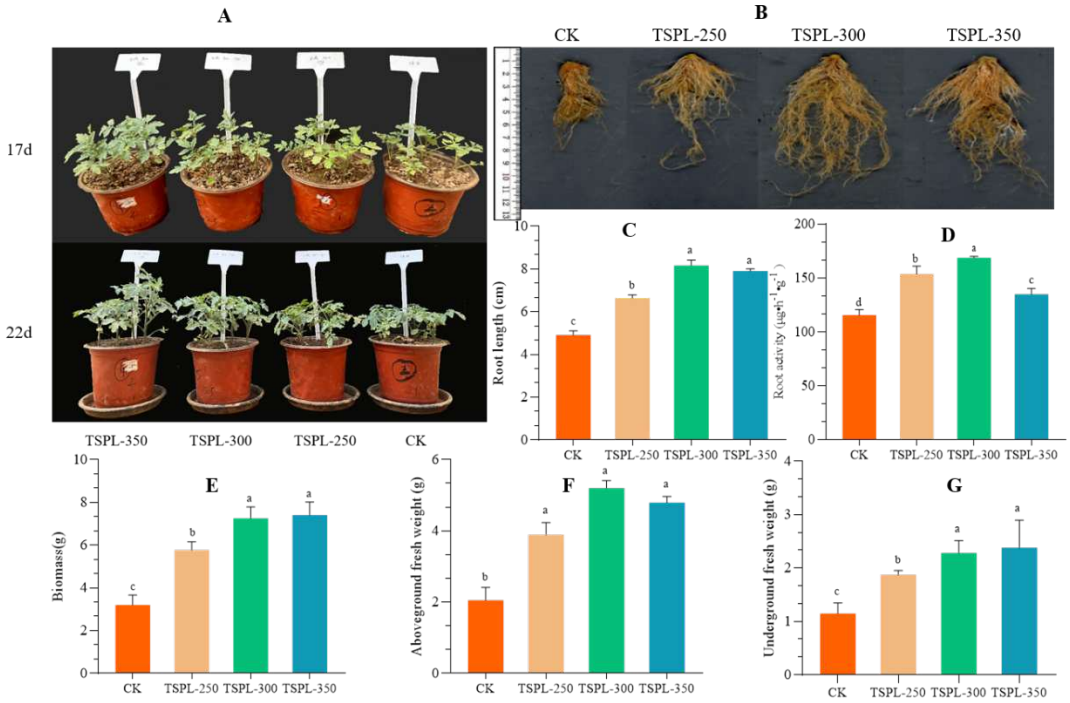

A
B
17d
22d
CK
TSPL-250
TSPL-300
TSPL-350
C
D
Root length (cm)
Root activity (μg·h⁻¹·g⁻¹)
E
F
G
Biomass(g)
Aboveground fresh weight (g)
Underground fresh weight (g)

Fig.1

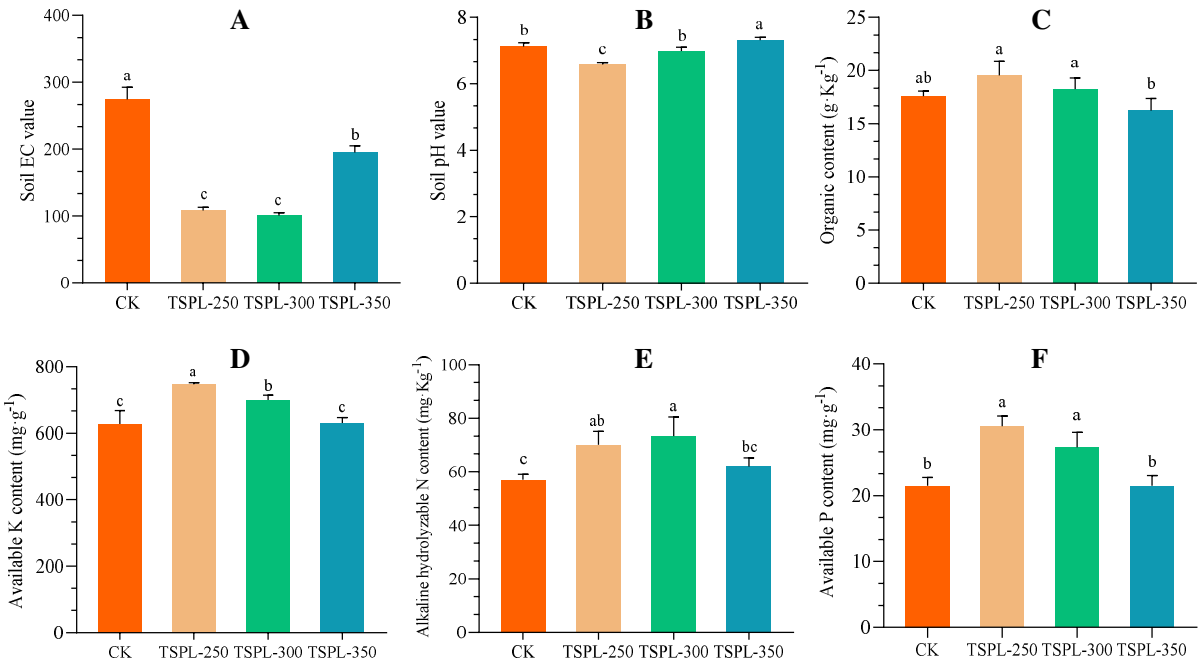

A
Soil EC value
400
300
200
100
0
a
c
c
b
CK
TSPL-250
TSPL-300
TSPL-350
B
Soil pH value
8
6
4
2
0
b
c
b
a
C
Organic content (g·Kg-1)
25
20
15
10
5
0
ab
a
a
b
D
Available K content (mg·g-1)
800
600
400
200
0
c
a
b
c
E
Alkaline hydrolyzable N content (mg·Kg-1)
100
80
60
40
20
0
c
ab
a
bc
F
Available P content (mg·g-1)
40
30
20
10
0
b
a
a
b

Fig. 2

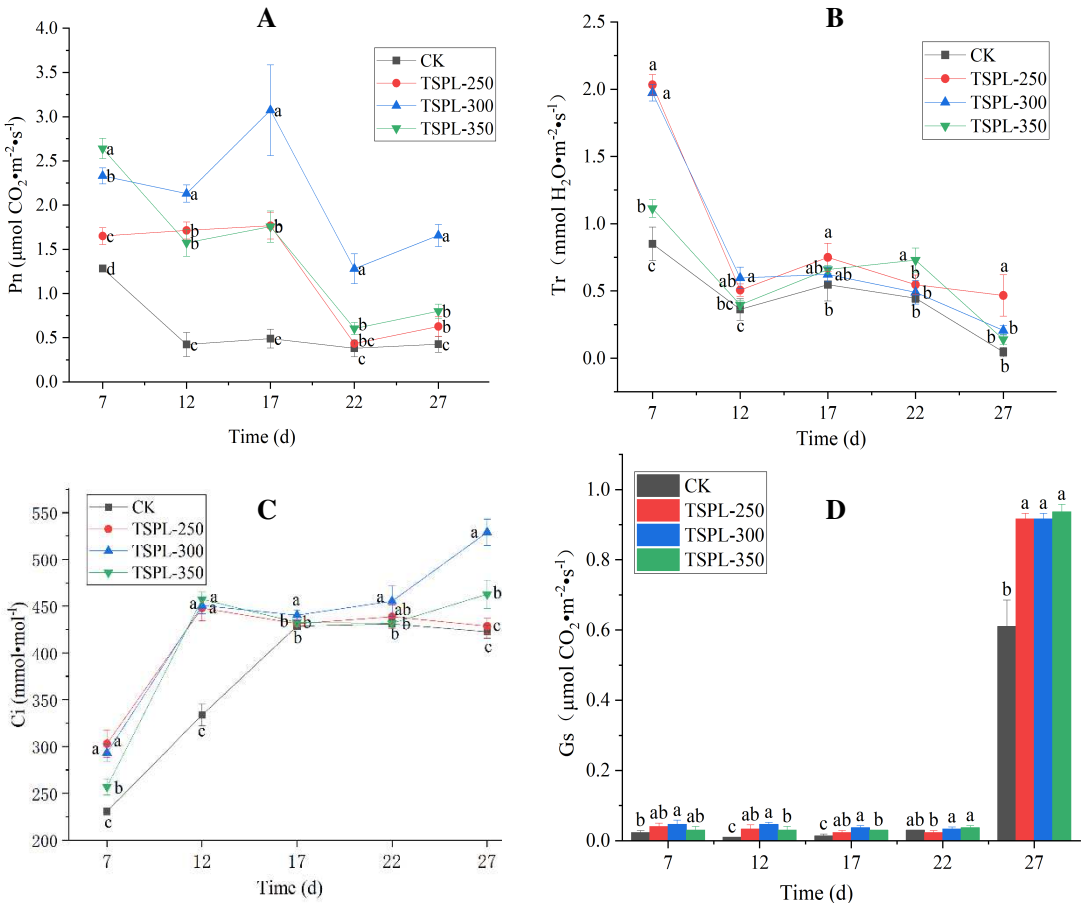

A
B
C
D
CK
TSPL-250
TSPL-300
TSPL-350
Pn (μmol CO2•m-2•s-1)
Tr（mmol H2O•m-2•s-1）
Ci (mmol•mol-1)
Gs（μmol CO2•m-2•s-1）
Time (d)

Fig. 3

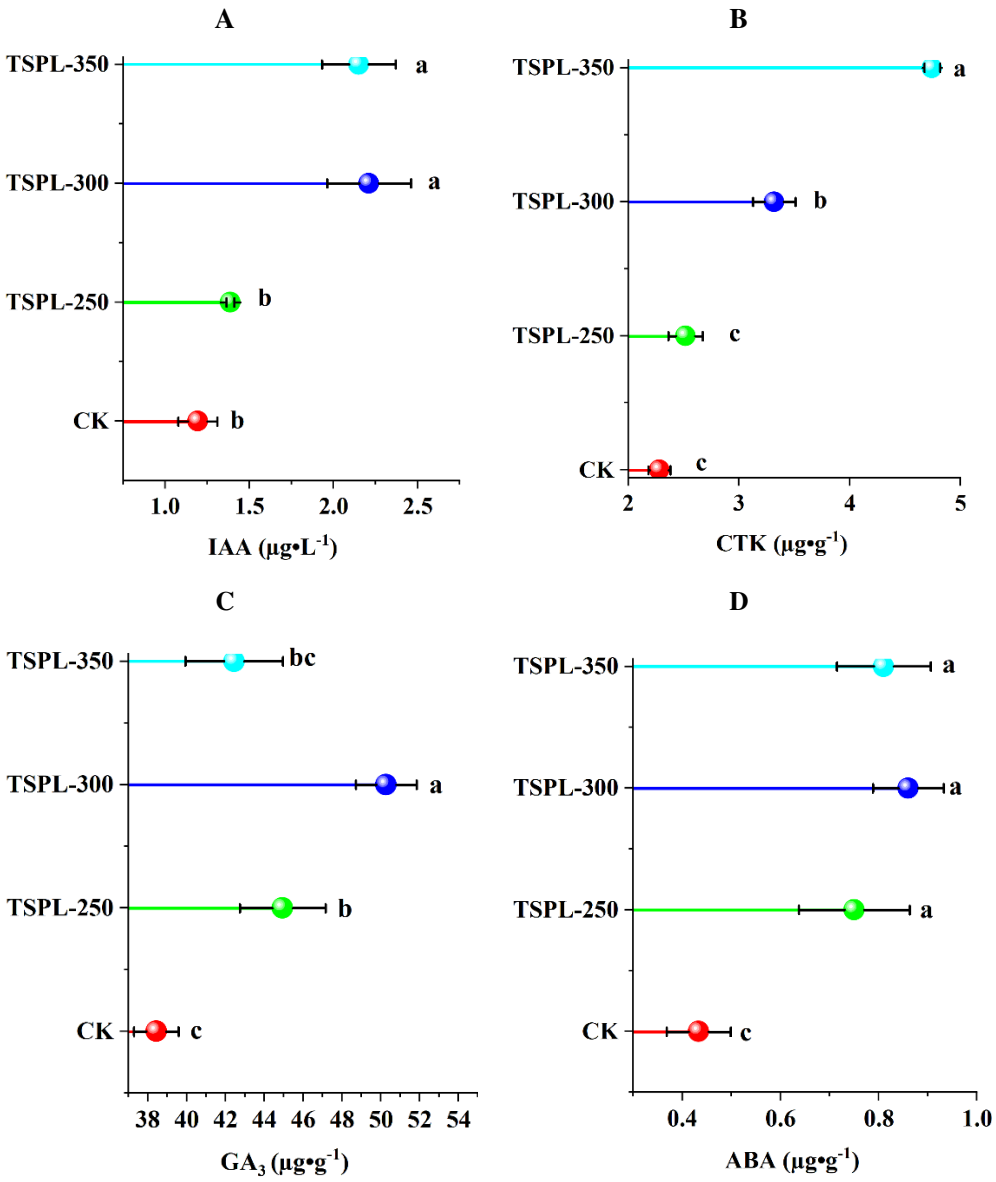

A
TSPL-350
TSPL-300
TSPL-250
CK
a
a
b
b
1.0
1.5
2.0
2.5
IAA (μg•L-1)
B
TSPL-350
TSPL-300
TSPL-250
CK
a
b
c
c
2
3
4
5
CTK (μg•g-1)
C
TSPL-350
TSPL-300
TSPL-250
CK
bc
a
b
c
38
40
42
44
46
48
50
52
54
GA3 (μg•g-1)
D
TSPL-350
TSPL-300
TSPL-250
CK
a
a
a
c
0.4
0.6
0.8
1.0
ABA (μg•g-1)

Fig. 4

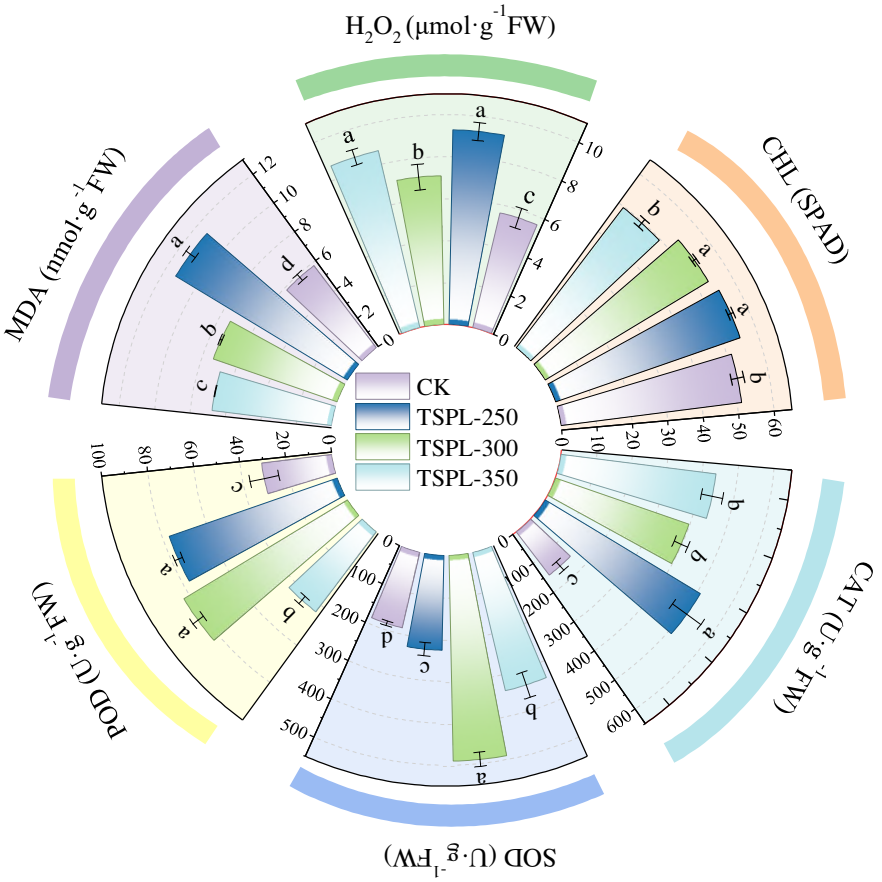

H2O2 (μmol·g-1FW)
CHL (SPAD)
CAT (U·g-1FW)
SOD (U·g-1FW)
POD (U·g-1FW)
MDA (nmol·g-1FW)
CK
TSPL-250
TSPL-300
TSPL-350

Fig. 5

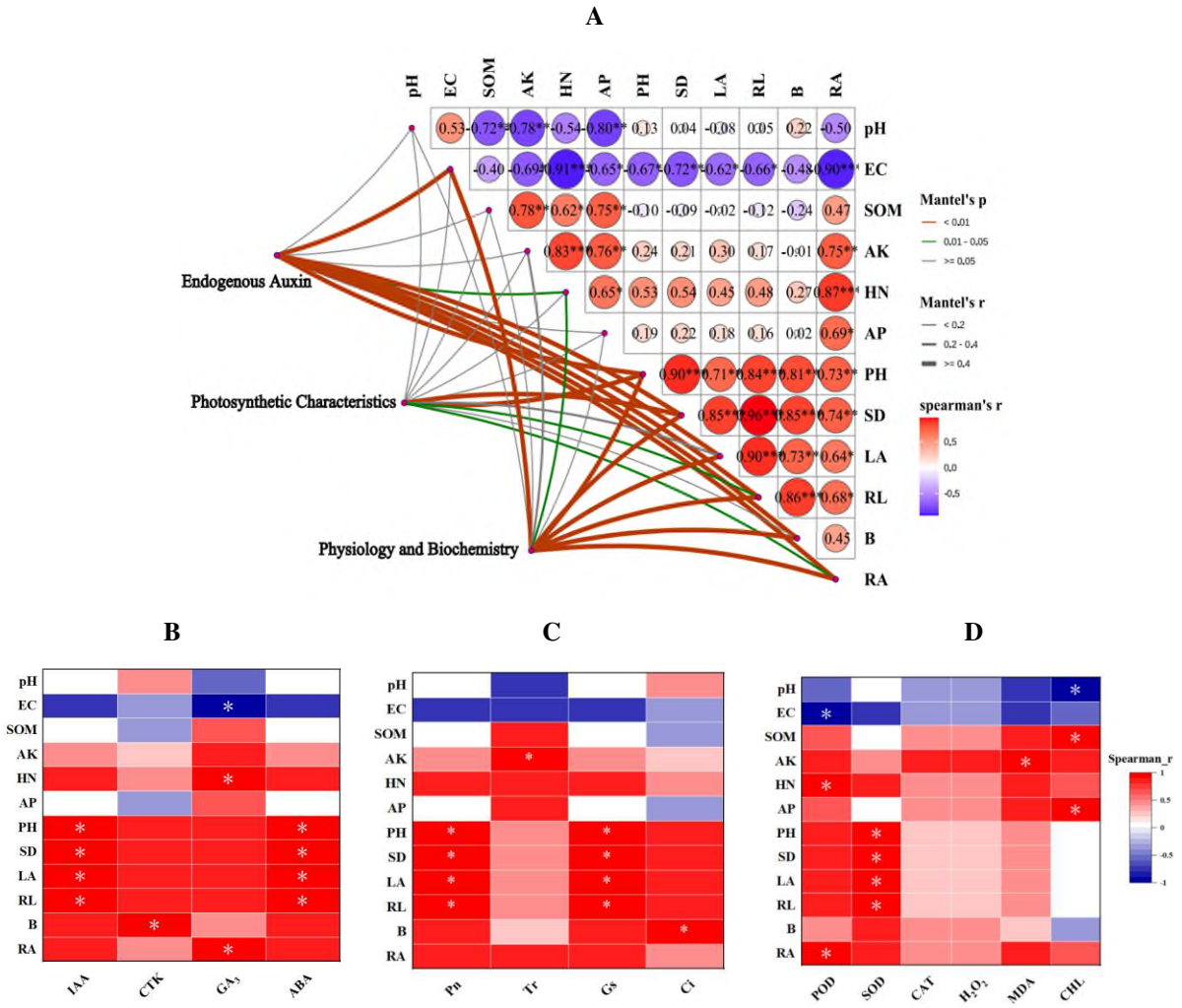

A
pH
EC
SOM
AK
HN
AP
PH
SD
LA
RL
B
RA
Endogenous Auxin
Photosynthetic Characteristics
Physiology and Biochemistry
Mantel's p
< 0.01
0.01 - 0.05
>= 0.05
Mantel's r
< 0.2
0.2 - 0.4
>= 0.4
spearman's r
B
C
D
IAA
CTK
GA3
ABA
Pn
Tr
Gs
Ci
POD
SOD
CAT
H2O2
MDA
CHL
Spearman_r

Fig. 6

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