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New insights into the impact of wood vinegar on the growth and rhizosphere microorganisms of Cherry Radish (*Raphanus Sativus*)

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Understanding the impact of wood vinegar on the growth of cherry radish is indispensable for its use in crop cultivation and evaluating its biosafety. Our study explored the regulation of rhizosphere microbial abundance and activity by wood vinegar, as well as the relationship between microbial community and growth factors in-depth and systematically. Bacterial communities at the phylum and genus levels were significantly changed after wood vinegar treatment. The abundance of *Actinobacteriota* and *Firmicutes* increased, while Proteobacteria was promoted in high carbon soil by wood vinegar application. Fungi positively responded to radish root traits and were correlated with aboveground biomass and fruit production. The fungi that correlated with photosynthesis included *Albifimbria*, *Allomyces*, *Calcarisporiella*, *Clonostachys*, *Fusarium*, *Fusicolla*, *Knufia*, *Nigrospora*, *Paraconiothyrium*, *Preussia*, *Talaromyces*, and *Mortierellomycota*. Wood vinegar treatment significantly affected the composition and abundance of soil bacterial and fungal communities in radish rhizosphere. The promotion of radish growth by wood vinegar may be attributed to the stimulation of soil microorganisms that degraded aromatic compounds and drove nitrogen cycling. This study provided novel insights into the significant promotion of radish growth by wood vinegar and identified potential microbial targets for agricultural applications.

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ABSTRACT

Understanding the impact of wood vinegar on the growth of cherry radish is indispensable for its use in crop cultivation and evaluating its biosafety. Our study explored the regulation of rhizosphere microbial abundance and activity by wood vinegar, as well as the relationship between microbial community and growth factors in-depth and systematically. Bacterial communities at the phylum and genus levels were significantly changed after wood vinegar treatment. The abundance of *Actinobacteriota* and *Firmicutes* increased, while Proteobacteria was promoted in high carbon soil by wood vinegar application. Fungi positively responded to radish root traits and were correlated with aboveground biomass and fruit production. The fungi that correlated with photosynthesis included *Albifimbria*, *Allomyces*, *Calcarisporiella*, *Clonostachys*, *Fusarium*, *Fusicolla*, *Knufia*, *Nigrospora*, *Paraconiothyrium*, *Preussia*, *Talaromyces*, and *Mortierellomycota*. Wood vinegar treatment significantly affected the composition and abundance of soil bacterial and fungal communities in radish rhizosphere. The promotion of radish growth by wood vinegar may be attributed to the stimulation of soil microorganisms that degraded aromatic compounds and drove nitrogen cycling. This study provided novel insights into the significant promotion of radish growth by wood vinegar and identified potential microbial targets for agricultural applications.

Key words: Wood vinegar; cherry radish; yield; photosynthesis; microorganism.

1. Introduction

Agricultural and forestry waste, which is approximately 2 billion tons generated annually in China (Fan et al. 2020), is an important biomass resource as a byproduct generated during the production and processing of agroforestry (Ozturk et al. 2017). Wood vinegar (WV) obtained *via* condensing and separating the flue gas generated from biomass pyrolysis (Hagner et al. 2013), which has a wide range of applications in agriculture, environmental protection, and healthcare (Mahmud et al. 2018; Grewal et al. 2018; Hu and Gholizadeh, 2020; Sarchami et al. 2021). Mmojieje et al. (2015) reported that WV from mixed wood biomass exhibited up to 90% mortality for red spider mite and green peach aphid. Gao et al. (2020) reported that wheat straw vinegar containing phenols, acetic acid, and cations significantly decreased the wheat fusarium head blight infection rate and deoxynivalenol content by 66% and 69%, respectively. Recently, research on the application of WVs has mainly focused on their antibacterial properties and insecticidal effects in agriculture. Nevertheless, the sawdust vinegar from low temperature (< 400 °C) can be used as liquid fertilizer to promote wheat seeds germination (Shang et al. 2021). These results almost focused on the biological response of WV to the target substance (plants, pests, pathogens), but the rhizosphere microbial behavior of WV was largely overlooked.

WV, as soil remediation agents, consisted of alcohols, esters, amines, pyridines, as well as trace elements such as K, P, Ca, Mn and Fe (Hou et al. 2018; Lu et al. 2020). As reported by many previous studies, WV could increase soil fertility by increasing nutrient elements (e.g., nitrogen (N), phosphorus (P), and potassium (K)) (Polthanee et al. 2015; Sun et al. 2018), reducing NH_3 volatilization (Win et al. 2009), and dissolved organic molecules (Lashari et al. 2013; Lashari et al. 2015), resulting in improved production of crop. WV gotten from biomass pyrolysis at low temperature (< 150 °C) are mainly composed of acid compounds, which promote the length of wheat main roots to nearly 1.2 times (Lu et al. 2019). Lashari et al. (2013) reported that biochar poultry manure compost-WV amendment significantly increased wheat yield through the effect of WV on leaching soluble salts and enhancing the effectiveness of P and K. Moreover, the dose of 3.0% mL hazelnut shell WV had positive effects on the number of bacteria and β-glucosidase enzyme activity in soil (Koc et al. 2019). To our best knowledge, most of the previous study focused on the effect of WV on soil microorganisms and plant growth singly (Jeong et al. 2015), and no reports was conducted to evaluate the regulation of rhizosphere microorganisms through WV leading to crop growth. Therefore, the effects of WV composition on the response of soil microorganisms and the promotion of cherry radish (*Raphanus Sativus*) growth were studied, and its applications were further determined.

In this study, rice straw as the raw material and were successfully extracted WV through pyrolysis. We deeply explored the influence of WV on the rhizosphere microbial community of cherry radish through soil culture experiments. In addition, the effects WV concentrations on the growth indicators, photosynthetic efficiency, and chlorophyll content of radish were also explored. Exploring whether WV has the effect of activating rhizosphere microorganisms, and thus stimulating the absorption of nutrients by crops in the rhizosphere. These results could provide new insights into the resource utilization of agricultural waste, and important support for green agricultural development.

2. Materials and methods

2.1 Materials

The cultivated brown soil has a pH value of 6.5, 32.38 g/kg of organic matter, 15.12 g/kg of total nitrogen, 15.26 mg/kg of available phosphorus and 56.58 mg/kg available potassium. The "Red Angel" cherry radish used as the experiment crop and was purchased from Beijing Dongsheng Seed Industry Co., Ltd. When rice straw is heated to a temperature of 450℃, a condensed liquid known as wood vinegar is collected. Once standing, the clarified wood vinegar in the middle is taken.

2.2 Experimental design

Cherry radish seeds in a 5% (v/v) NaClO for 10 minutes for disinfection, and rinsed with clean water several times to remove residual disinfectants (Gu et al. 2021). Firstly, five seeded seeds were sown directly at a depth of 1 cm on the surface of bowl soil (3 kg). After 7 days of seedling growth, excess plants were removed, leaving one plant with good and consistent growth in each pot. After 45 days of growth, the cherry radish was harvested and related indicators were measured in the soil. Each group of treatments was set with 5 replicates, and a total of 5 treatments were set in the experiment: the untreated wood vinegar was set as the control (CK), and the wood vinegar was diluted 400 (W400), 300 (W300), 200 (W200), 100 (W100), and 50 (W50) times, respectively. During the experiment, 500 mL of wood vinegar with different dilution ratios were poured into pots and bowls, and the same volume of water was poured into CK.

2.3 Characterization of Soil and WV

The soil pH is measured using the potential method (soil-water ratio 2.5:1). The organic matter of the soil was determined using potassium dichromate-sulfuric acid ($K_2Cr_2O_7$-H_2SO_4) for oxidation and ferrous sulfate ($FeSO_4$) titration (Peng et al. 2016). The soil sample is digested using copper sulfate ($CuSO_4$) and potassium sulfate (K_2SO_4), and then titrated with hydrochloric acid (HCl) to obtain total nitrogen (Lenaerts et al. 2018). The available phosphorus and potassium were determined by modified kelowna methods (Qian et al. 1994).

The molecular composition of WV samples measured using an electrospray ionization (ESI) Fourier transform ion cyclotron resonance mass spectrometry (FT-ICR MS) (Bruker SolariX, Bruker, Germany) equipped with a 9.4 T superconducting magnet. Sample solutions were injected into the electrospray source at 180 μL/h with a syringe. The operating conditions for negative-ion formation be applied with a 4.0 kV spray shield voltage, 4.5 kV capillary column introduced voltage, and 320 V capillary column end voltage. The mass range was configured with 200–800 Mass to charge ratio (m/z). The samples were performed 128 FT-ICR MS scans to improve signal-to-noise ratio and dynamic range. The detailed determinations of H/C, O/C, and double bond equivalents (DBE) of molecular compositions are presented in Text S1 (Hua et al. 2019).

2.4 Measurements of Plant Growth

Cherry radish fruit was harvested after ripening, and the diameter of the fruit is measured using a ruler (centimeters) and the yield is calculated. After harvest, the root morphology of cherry radish treated with different doses of WV was analyzed using the WinRhizo system v.4.0b (Instruments Regent LA2400, Japan). The photosynthetic index was measured on a sunny morning (9:00-11:00), and the second leaf at the top of the plant was selected as the measured leaf. (Gu et al., 2021) The net photosynthetic rate (Pn), transpiration rate (Tr), stomatal conductance (Gs), and intracellular CO_2 concentrations (Ci) of cherry radish were analyzed by the CIRAS-3 portable gas exchange system (PP-Systems, USA) (Liu et al. 2020). The supernatant was separated and the absorbance was recorded at 662 nm for Chlorophyll a and 646 nm for Chlorophyll b using the Shimadzu UV-1800 spectrophotometer (Shimadzu, Kyoto, Japan) (Şükran et al. 1998).

2.5 Microbial diversity and community

The DNA of soil bacteria was extracted from 0.5 g of frozen soil using the FastDNA SPIN Kit (MP Biomedicals, CA, USA). The 16S rRNA gene was amplified through thermocycler polymerase chain reaction (PCR) system (GeneAmp 9700, ABI, USA) using 16S rRNA amplicon (338F, 5′-ACTCCTACGGGAGGCAGCAG-3′)/806R, 5′-GGAC TACHVGGGTWTCTAAT-3′). Then, the quality and concentration of the extracted DNA were determined using a NanoDrop ND-1000 UV–Vis spectrophotometer (Thermo Fisher, Waltham, MA, USA) and a Quanti Fluor dsDNA system (Promega, Madison, WI, USA). Majorbio Bio-Pharm Technology Co. Ltd. (Shanghai, China) used the Illumina MiSeq platform (Illumina, San Diego, USA) to analyze the bacterial diversity according to the standard protocols. The online Majorbio Cloud Platform (http://www.majorbio.com) was used to perform data analysis, which included Venn diagram analysis, collinearity analysis, alpha diversity analysis, beta diversity analysis, and heatmap analysis.

2.6 Statistical Analysis

One-way ANOVA, correlation analysis, and Duncan's multiple range-test were obtained from SPSS version 25.0 (IBM, Armonk, NY, USA). All the experiments were carried out in triplicate and a significant difference was considered at $p < 0.05$. Unless otherwise indicated, all other experiments were conducted in triplicate, and significant differences between the experiments were taken into account ($p < 0.05$).

3. Results and discussions

3.1 Composition analysis of wood vinegar

The molecular composition of WV from biomass pyrolysis through FT-ICR MS analysis are depicted in Fig. 1. Compared to CHON, CHONS, and CHOS chemicals, CHO compounds contain higher carbon number, oxygen number, and double bond equivalent (DBE value) due to high-temperature pyrolysis (Shang et al. 2021). The high number of carbon, oxygen, and DBE of WV were mainly attributed to biomass deoxygenation and bond breaking reaction (Mettler et al. 2012). All detected substances are divided into seven groups, which were shown as follows: (Lian et al. 2023) (lipid (H/C: 1.5–2.0; O/C: 0–0.3), protein (H/C: 1.5–2.2; O/C: 0.3–0.67), carbohydrate (H/C: 1.5–2.2; O/C: 0.67–1.2), unsaturated hydrocarbon (H/C: 0.7–1.5; O/C: 0–0.1), lignin (H/C: 0.7–1.5; O/C: 0.1–0.67), tannin (H/C: 0–1.5; O/C: 0. 67–1.2), and condensed aromatic-like components (H/C: 0.2–0.7; O/C: 0–0.67)), and the results shown in the Van Krevelen diagram clearly illustrated the differences in molecular composition of WV. The main distribution of WV compounds H/C= 0.2-0.7 and H/C= 0.5-1.5, indicating rich aromatic structure and lignin, with 45.51% and 22.70% contents, respectively (Fig. 2c-2d). Lignin decomposed at high temperatures to form more lignin/CRAM like structures and aromatic WVs (Qu et al. 2011), which was also supported by previous studies (Qu et al. 2011; Shang et al. 2021).

3.2 Wood vinegar promotes the yield of *cherry radish*

The effects of WV at different concentrations on the yield indicators of cherry radish were different and were shown in Fig. 2. Within a certain concentration range (W50-W200), the yield of cherry radish gradually increased with the increased concentration of wood vinegar. When the added concentration of WV reached W200, the diameter and yield of radish reached the largest values, increasing by 42.43% and 44.91% respectively. The application of WV increased soil organic matter, enhanced nutrient uptake by plants, and stimulated populations of beneficial microorganisms (Cardelli et al. 2020; Wang et al. 2022). Soil treatment with a 500-fold diluted WV resulted in a significant (P<0.05) 73.39% increase in bacterial population (e.g., Gram-negative bacteria, anaerobic bacteria, and aerobic bacteria) and enhanced soil ecological activity (Rui et al. 2014). Simultaneously, WV could also promote the shoot biomass of radish (Fig. S1). After treated by 200-fold diluted WV (W200), the growth rate and biomass accumulation of radish increased by 34.08% compared with CK, which may be related to the regulation of WV on soil microbial activity, and possible by promoting radish nutrient absorption. Overall, the use of WV can improve the growing environment of radish, thereby promoting aboveground growth and development of radish (Mhamdi et al. 2023).

3.3. Effect of wood vinegar on Photosynthesis of *cherry radish*

The effect of WV treatment on the photosynthesis of cherry radish are shown in Fig. 3. Compared with CK, there was a significant difference in the net photosynthetic rate of cherry radish treated with different concentrations of WV (p<0.05). After applying 200 times WV, the maximum net photosynthetic rate reached 25.53 μm $CO_2/(m^2\cdot s)$, which was 80.45% and 19.97-101.84% higher than the CK and other WV treatment groups, respectively. The net photosynthesis also verified that the W200 treatment group had the strongest ability to accumulate fruit and biomass in cherry radish (Fig. 2). WV enhanced net photosynthesis by regulating soil microbial activity and enhancing the ability of crop roots to absorb nutrients (Chen et al. 2016; Rui et al. 2014). Similarly, 200 times WV treatment had a positive impact on the transpiration rate of cherries (up to 15.88 mmol $H_2O/(m^2 \cdot s)$), accelerating water absorption and transportation (Fig. 3b). The transpiration rate of cherries was related with root growth (Kulkarni et al. 2017), and the changed trend of root index in W200 treated cherries further confirmed the enhanced transpiration rates (Fig. S2). For example, after W200 treatment, the contents of root tips, length, and surface area were 35.50, 16.70 cm, and 36.33 cm^2, respectively, with an increase of 59.19%, 74.14%, and 26.72% compared to CK. The stomatal conductance fluctuations were significant, with a significant level (p<0.05) observed in the WV treatment compared to the control, particularly with W200 showing a 92.57% increase (Fig. 3c). As the concentration of WV increased, the stomatal conductance of cherry radishes firstly decreased and then increased, which was consistent with the changes in net photosynthetic rates and transpiration rates. Except for the W50 treatment, the intercellular CO_2 concentration in cherry radish leaves of all other treatment groups was lower than that of the CK group, with a decrease range of 13.83%-28.56% (Fig. 3d). The lower the intercellular CO_2 concentration, the more CO_2 was utilized by the leaves for photosynthesis (Gu et al. 2021). The trend of intercellular CO_2 content in different treatment groups were basically the opposite of net photosynthetic rate, which was consistent with the laws of plant photosynthesis. In addition, the trends in cherry leaf chlorophyll content and chlorophyll a/b ratio (Fig. S3) were in line with the patterns of changed net photosynthetic rates.

3.4 Effects of WV on the Abundance and Diversity of Bacteria and Fungi

The coverage of the WV treatment group (W200 and W400) and the CK were all above 0.99, indicating that the sequencing results well reflected the actual situation of the bacteria and fungi of the samples (Fig. 4a-4b). The Shannon index of the treatment group with 200-fold diluted WV showed the highest value, indicating that the treatment with 200-fold diluted WV was beneficial to the increase of rhizosphere bacteria diversity, as shown in Fig. 4a-4b. Simpson's index also showed that the bacterial community of the treatment group with 200-fold diluted WV had the lowest Simpson index, which further supports the results of the Shannon index. The results showed that W200 had no significant difference in fungal diversity index (p>0.05), but had extremely significant differences in bacterial Shannon (p<0.001), Simpson (p<0.001), and OUT number (p<0.001), indicating that W200 can promote bacterial diversity and richness. Venn diagram could be used to represent the similarity and overlap of soil microorganisms (Fig. S4). The operational taxonomic unit (OTU) number of bacteria and fungi in the soil samples after treated differently were 2047 and 290, respectively. The independent bacteria and fungi OTU numbers in the 200-fold diluted (W200) WV treatment were 148 and 164, accounting for 5.63% and 24.33% of the OTUs, respectively. Results from the data indicated that WV treatment increased the composition of dominant bacterial and fungal genera in the rhizosphere soil and formed a more diverse microbial environment in the bacterial community structure, thereby benefiting the growth of cherry radishes.

After WV treatment, there were significant differences in the relative abundance of bacterial communities at both the phylum and genus levels (Fig. 5). After 200-fold diluted WV treatment, the proportion of *Actinobacteriota* and *Firmicutes* in soil samples increased, with respective increases of 40.88% and 126.67% compared to the CK group. *Actinobacteriota* can promote the decomposition of soil organic matter and nutrient transformation, thereby contributing to the improvement of soil fertility (Lan et al. 2022; Ren et al. 2018). The WV compounds contained 68.21% organic matter, which stimulated the activity of actinomyces and thereby increased its abundance. In addition, *Actinobacteriota* also had a certain bioprotective effect, thus inhibiting the growth of pathogenic bacteria and promoting the healthy growth of cherry radish. Meanwhile, the abundance of *Proteobacteria* (up to 25.82%) in high carbon soil was promoted by W200 application (Fierer et al. 2007), and it was considered as an important soil symbiont together with Firmicutes (Anderson et al. 2018; Zhalnina et al. 2015). Moreover, the bacterial genera with relative abundance greater than 1% in soil treated with WV at different dilution concentrations and CK were *Arthrobacter*, *Sphingomonas*, *Vicinamibacterales*, *Vicinamibacteraceae*, *Massilia*, *g__RB41*, *norank_f__norank_o__norank_c__KD4-96*, and *norank_f__Roseiflexaceae* (Fig. 5b). More importantly, the abundance of *Arthrobacter*, *Sphingomonas*, and *norank_f__ norank_o__Cyanobacteriales* genera in WV at a concentration of 200 times was significantly higher (over 10%) than other treatments, indicating a significant change in the proportion of dominant bacterial genera in the rhizosphere soil of radish. Especially for *norank_f__ norank_o__Cyanobacteriales*, which were between 15.34 and 230.05 times higher than CK and W400. Notably, WV additives stimulate radish to absorb rhizosphere elements, degrade variety aromatic compounds (the main component of WV), and drive nitrogen cycling by increasing the abundance of dominant soil microorganisms, such as *Arthrobacter* (Schwabe et al. 2021), *Sphingomonas* (Gong et al. 2016; Liu et al. 2017), and *norank_f__ norank_o__Cyanobacteriales* (Wang et al. 2023).

Additionally, compared to CK and W400 treatments, the fungi in the W200 treatment group showed a significant increase (0.98-25.06 fold higher) in the main phylum, specifically *Basidiomycota*, *unclassified_k__Fungi*, and *Blastocladiomycota*, with the main fungal genera being *unclassified_f__Stachybotryaceae*. *Basidiomycota*, as a crucial decomposer, generates enzymes (peroxide) that enzymatically break down plant components such as cellulose and lignin, thereby augmenting the overall carbon pool of the soil (Ahmed et al. 2020). Moreover, *unclassified_k__Fungi*, as a dominant genus in rhizosphere soil, stimulates fungi that generate total nitrogen (Yang et al. 2022). The organic matter (W200) in the rhizosphere promotes the abundance of *Blastocladiomycota* (Zhang et al. 2021), which is beneficial for crop growth. Similarly, *Stachybotryaceae* also showed a positive response to nitrogen in the rhizosphere soil (Kumar et al. 2022). These results also indicated that fungal communities displayed a vital role in the utilization and absorption of soil nutrients by crops.

3.5 The Relationship between Radish Growth Factors and Microbial Communities

The correlation plot generated in Fig. 6 and S5 could dentify the microbial communities and growth factors mediating the promotion of radish growth by WV. The root growth indicators (length, tip, surface area, and diameter) showed significant correlation ($p<0.05$) with the genera of *Arthrobacter*, *norank_f__norank_o__Cyanobacteriales*, and *Agromyces* (Fig. S5). Among them, the *Arthrobacter* and *norank_f__norank_o__Cyanobacteriales* in the W200 treatment group were 1.85-297.85 times higher than those in the CK and W400 treatment groups. It has been reported that *Arthrobacter* (Schwabe et al. 2021) and *norank_f__ norank_o__Cyanobacteriales* (Wang et al. 2023) degrade aromatic compounds (WV) to drive the cycling of nitrogen nutrients in the rhizosphere. Meanwhile, *norank_f__norank_o__Cyanobacteriales*, *Ellin6067*, and *Agronomyces* exhibit a significant relationship ($p<0.05$) with photosynthesis. In the soil treated with W200, it was found that *norank_f__norank_o__Cyanobacteriales*(Wang et al. 2023) and *Agronomyces* (Wang et al. 2020) were involved in nitrogen and carbon cycling, respectively, thereby promoting radish growth and significantly improving physiological indicators.

For fungal communities, *Allomyces*, *Clonostachys*, *Fusarium*, *Fusicolla*, *Knufia*, *Nigrospora*, *Paraconiothyrium*, *Preussia*, *Talaromyces*, *Trichocladium*, *unclassified_f__Didymellaceae*, *unclassified_f__Stachybotryaceae*, *unclassified_Mortierellomycota* showed a positive response ($p<0.05$) to root length, root number, and root surface area of radish, while also showed a positive correlation ($p<0.05$) with aboveground biomass and fruit (Fig. 6). The fungi that positively correlated ($p<0.05$) with the photosynthesis (except for Ci) of radish include *Albifimbria*, *Allomyces*, *Calcarisporiella*, *Clonostachys*, *Fusarium*, *Fusicolla*, *Knufia*, *Nigrospora*, *Paraconiothyrium*, *Preussia*, *Talaromyces*, *unclassified_c__Sordariomycetes*, *unclassified_Chytridiomycota*, *unclassified_f__Didymellaceae*, *unclassified_f__Stachybotryaceae*, *unclassified_Mortierellomycota*. Particularly, *Allomyces*, *Fusarium*, *Fusicolla*, *Trichocladium*, and *unclassified_f__Didymellaceae*, showed a very significant correlation with radish growth and physiological indicators (p<0.01). The common bacterial species (such as, *Cladorrhinum* (Barrera et al. 2019), *Fusarium* (Yuan et al. 2020), *Allomyces* (Zhang et al. 2013), *Clonostachys* (Fournier et al. 2020)) in the soil could decompose the organic matter (WV), or WV could activate these bacteria to enhance the absorption of nutrients by radish, thus promoting the development of its root system and ultimately boosting crop photosynthesis and yield. Studies have already verified that Fusarium and Fusarium were the main rhizosphere populations that promoted rapeseed growth and resulted in a higher yield (Lay et al. et al. 2018). Data showed that WV stimulated the dominant microorganisms in the radish rhizosphere, thus increasing nutrient absorption and boosting yield.

4. Conclusions

In this study, the effects of wood vinegar on physiological indicators and rhizosphere microbial community of cherry radish were studied through soil culture experiments. The experimental results indicated that within a certain concentration range (W50-W200), cherry radish yield gradually increased with the increasing wood vinegar concentration. When the concentration of added wood vinegar reached W200, the diameter, biomass, and yield of radish increased by 42.43%, 34.08%, and 44.91%, respectively. After applying wood vinegar (W200), the maximum net photosynthetic rate of the leafy cherry radish reached 25.53 μm $CO_2/(m^2 \cdot s)$, which showed the same growth trend as other photosynthetic indicators. The application of wood vinegar is beneficial for the growth and reproduction of microbial communities, and the microorganisms (e.g., *Allomyces*, *Fusarium*, and *Fusicolla*) have a very significant impact (p<0.01) on promoting the growth of cherry radish. The promoting effect may be related to the enhanced soil microbial activity by wood vinegar, or through promoting the absorption of nutrients. Considering the types of biomasses and pyrolysis temperature varied largely, further information about the wood vinegar on the growth and yield of cherry radish, even many other plants, needed further conducted.

Conflicts of interest

The authors declare no conflicts of interest.

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Author Contributions

Shiguo Gu, Wei Zhu, Xiaokang Li, and Yongkang Niu: writing–original draft, formal analysis, conceptualization, and methodology. Liying Ren and Qingshan He: conceptualization and resources. Yuying Ren: resources and investigation. Shiguo Gu: project administration. Shiguo

Gu, Binbin Sun and Qingshan He: funding acquisition, supervision, and writing–review & editing.

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Figure 1

Fig. 1. Plots of carbon (CHO, CHON, CHONS, and CHOS chemicals)

(a) and oxygen (CHO, CHON, CHONS, and CHOS chemicals) (b) number versus DBE of WV. (c) Van Krevelen diagrams of CHO, CHON, CHONS, and CHOS chemicals for biomass pyrolysis derived-WV, and (d) Bar diagrams for the contribution of the major classes for biomass pyrolysis-derived WV.

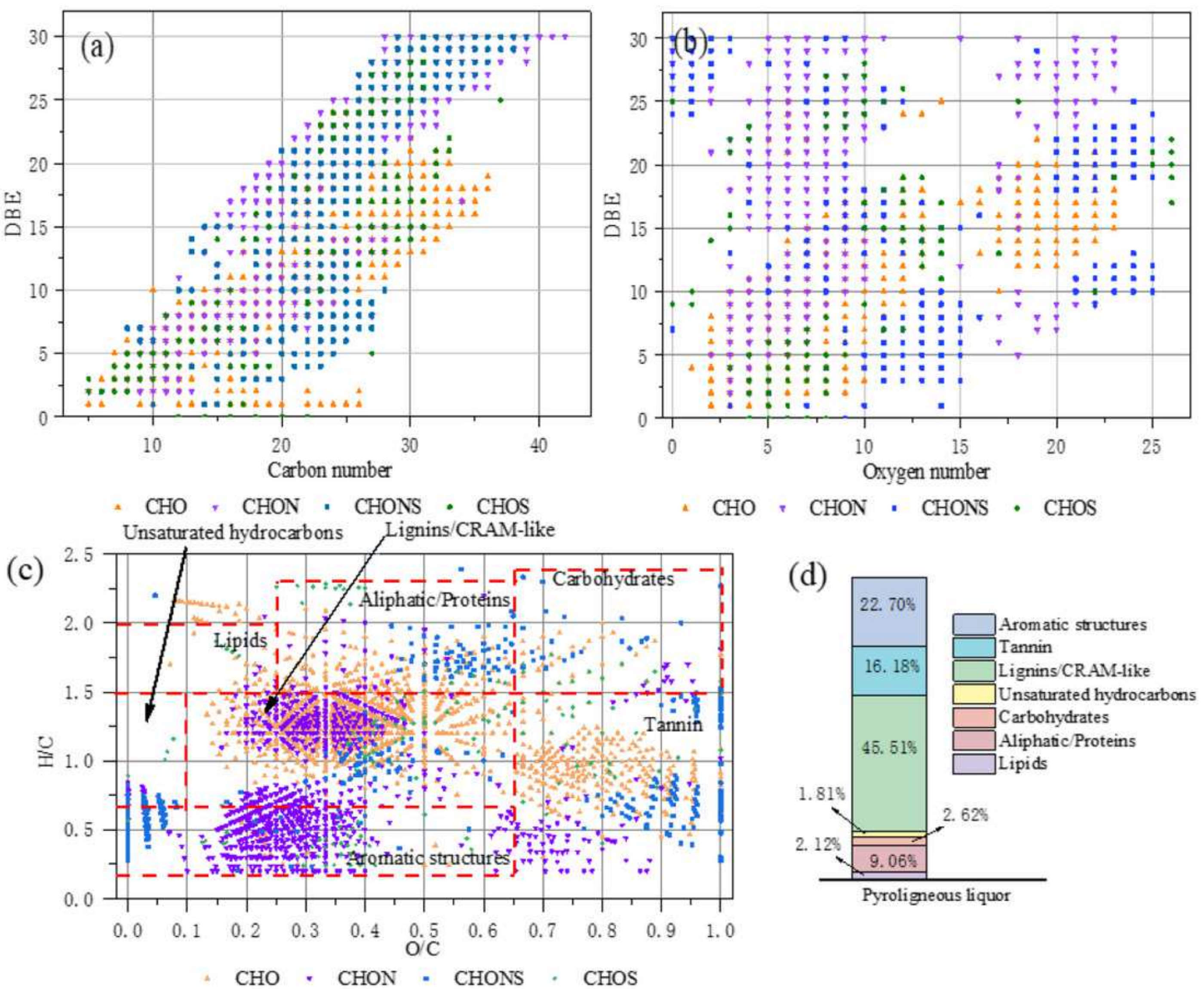


Figure 2

Fig. 2 Effect of wood vinegar treatment on the diameter (a) and weight (b) of cherry radish fruit. Data with different letters are significantly different ($p < 0.05$).

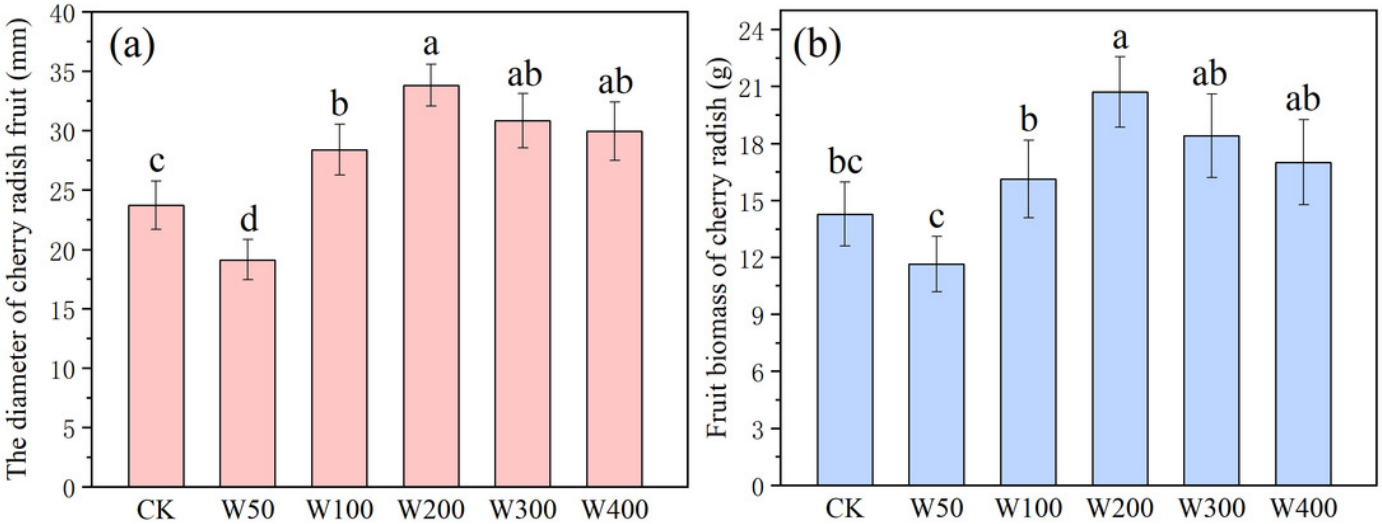


Figure 3

Fig. 3 The gas exchange parameters: (a) net photosynthetic rate (Pn), (b) transpiration rate (Tr), (c) stomatal conductance (Gs), and (d) intercellular CO_2 concentration (Ci) of *cherry radish*.

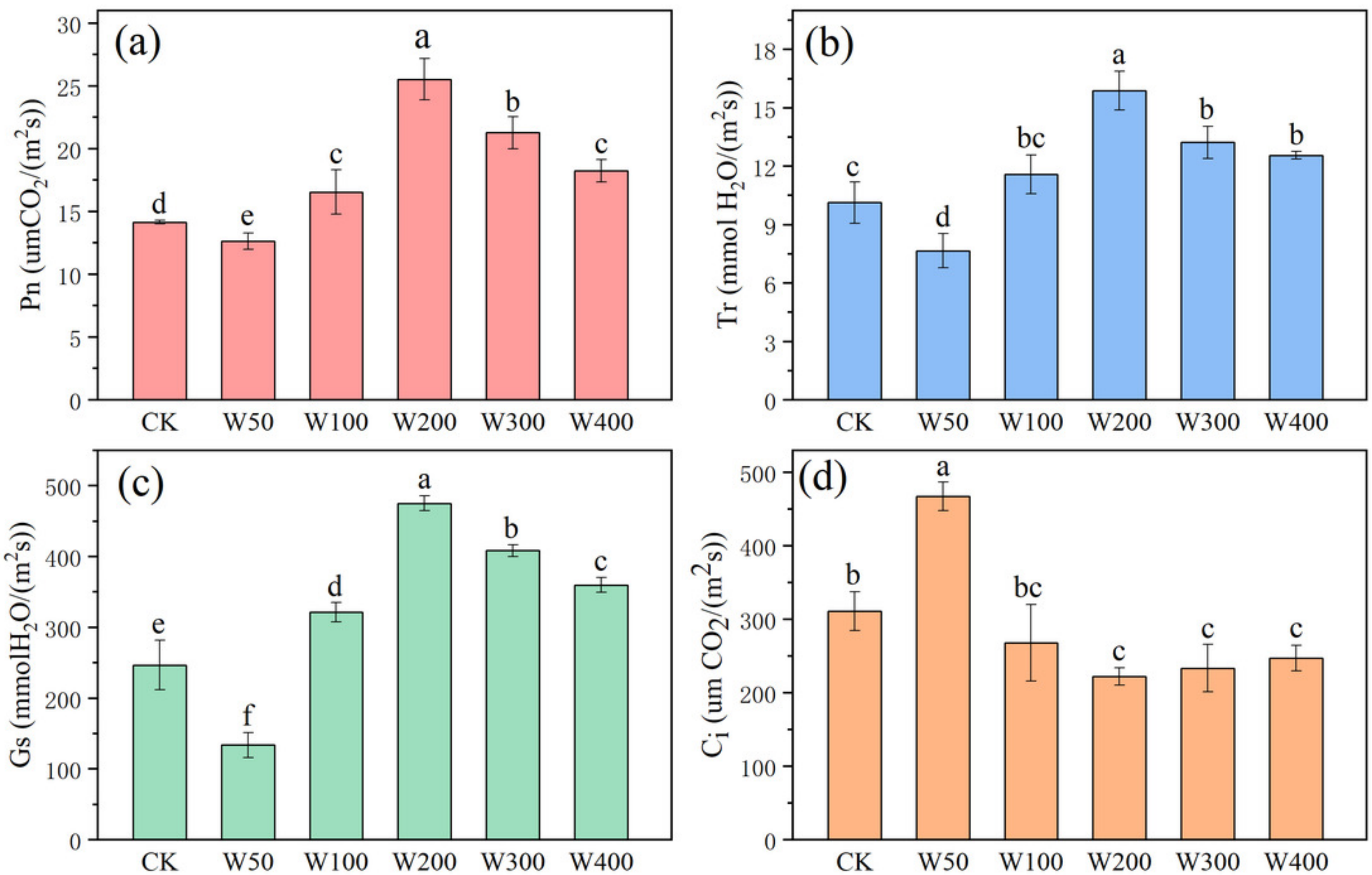


Figure 4

Fig. 4 Effects of Wood Vinegar on the Abundance and Diversity of Bacteria (a) and Fungi (b) in Rhizosphere Soil

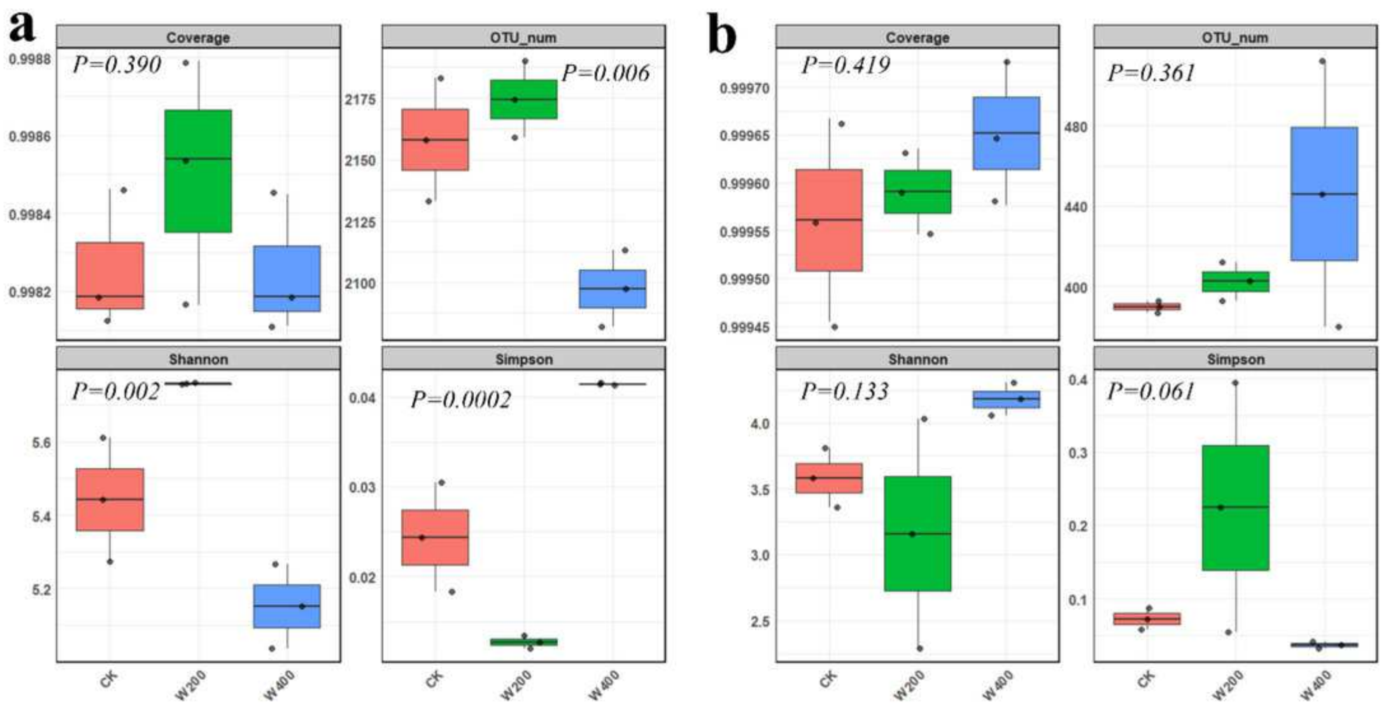


Figure 5

Fig. 5 The relative abundance of soil bacteria (phylum (a) and genus (b)) and fungi (phylum (c) and genus (d))

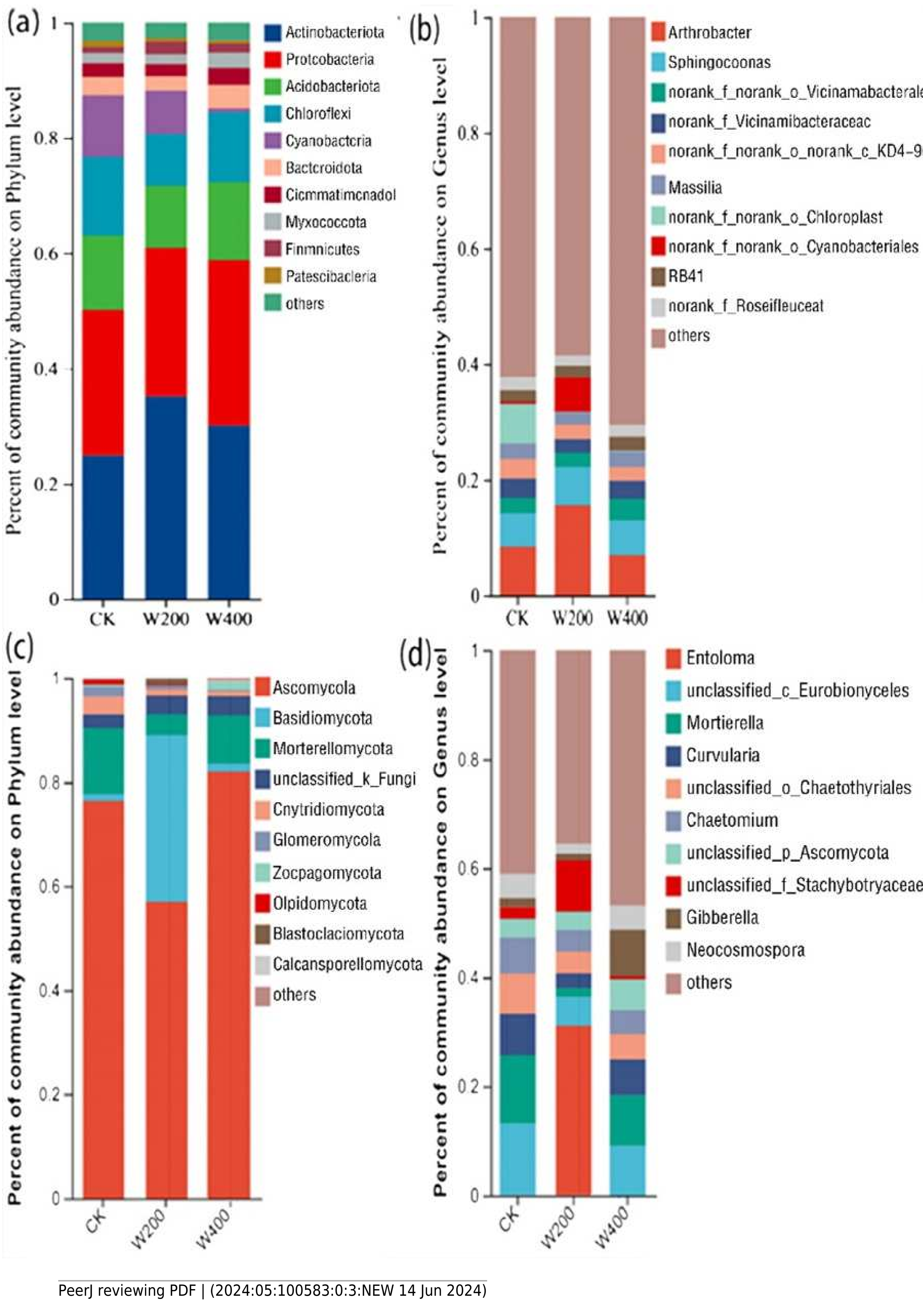
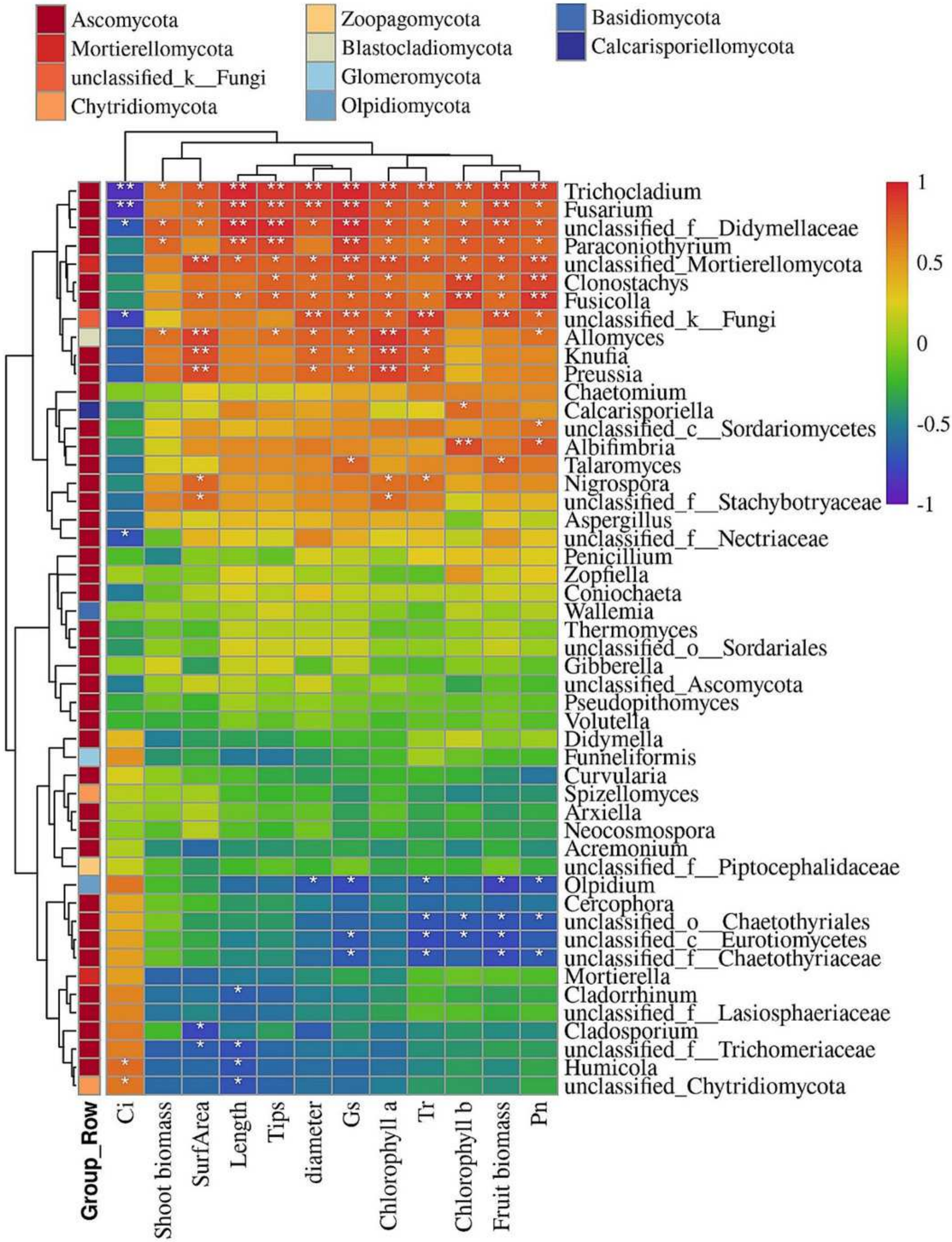

(a)
Percent of community abundance on Phylum level
0
0.2
0.4
0.6
0.8
1
CK
W200
W400
Actinobacteriota
Protcobacteria
Acidobacteriota
Chloroflexi
Cyanobactcria
Bactcroidota
Cicmmatimcnadol
Myxococcota
Finmnicutes
Patescibacleria
others
(b)
Percent of community abundance on Genus level
Arthrobacter
Sphingocoonas
norank_f_norank_o_Vicinamabacterales
norank_f_Vicinamibacteraceac
norank_f_norank_o_norank_c_KD4-96
Massilia
norank_f_norank_o_Chloroplast
norank_f_norank_o_Cyanobacteriales
RB41
norank_f_Roseifleuceat
others
(c)
Percent of community abundance on Phylum level
Ascomycola
Basidiomycota
Morterellomycota
unclassified_k_Fungi
Cnytridiomycota
Glomeromycola
Zocpagomycota
Olpidomycota
Blastoclaciomycota
Calcansporellomycota
others
(d)
Percent of community abundance on Genus level
Entoloma
unclassified_c_Eurobionyceles
Mortierella
Curvularia
unclassified_o_Chaetothyriales
Chaetomium
unclassified_p_Ascomycota
unclassified_f_Stachybotryaceae
Gibberella
Neocosmospora
others

Figure 6

Fig. 6 Thermogram analysis of the correlation between fungi community and growth factors. Note: * Significant correlation at 0.05 level, * * Very significant correlation at 0.01 level.



Ascomycota
Mortierellomycota
unclassified_k__Fungi
Chytridiomycota
Zoopagomycota
Blastocladiomycota
Glomeromycota
Olpidiomycota
Basidiomycota
Calcarisporiellomycota
Trichocladium
Fusarium
unclassified_f__Didymellaceae
Paraconiothyrium
unclassified_Mortierellomycota
Clonostachys
Fusicolla
unclassified_k__Fungi
Allomyces
Knufia
Preussia
Chaetomium
Calcarisporiella
unclassified_c__Sordariomycetes
Albifimbria
Talaromyces
Nigrospora
unclassified_f__Stachybotryaceae
Aspergillus
unclassified_f__Nectriaceae
Penicillium
Zopfiella
Coniochaeta
Wallemia
Thermomyces
unclassified_o__Sordariales
Gibberella
unclassified_Ascomycota
Pseudopithomyces
Volutella
Didymella
Funneliformis
Curvularia
Spizellomyces
Arxiella
Neocosmospora
Acremonium
unclassified_f__Piptocephalidaceae
Olpidium
Cercophora
unclassified_o__Chaetothyriales
unclassified_c__Eurotiomycetes
unclassified_f__Chaetothyriaceae
Mortierella
Cladorrhinum
unclassified_f__Lasiosphaeriaceae
Cladosporium
unclassified_f__Trichomeriaceae
Humicola
unclassified_Chytridiomycota
1
0.5
0
-0.5
-1
Group_Row
Ci
Shoot biomass
SurfArea
Length
Tips
diameter
Gs
Chlorophyll a
Tr
Chlorophyll b
Fruit biomass
Pn