

Optimizing wood vinegar as an industrial product for sustainable agriculture: A global meta-analysis of its potential for crop production

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ABSTRACT

Wood vinegar (WV), an industrial product derived from biomass pyrolysis, holds significant potential for sustainable crop production. However, a systematic and quantitative assessment of its effects on crop yield across different species, application methods, and environmental conditions has been lacking. Here we present a global meta-analysis based on 94 studies to comprehensively evaluate the impacts of WV on crop seed germination, physiological traits, and yield, and to identify key factors modulating these effects. Our results showed that WV promotes germination in a concentration-dependent manner. At 0.5–1.0%, it increased germination by 31.5% in monocots, while at 0.1–0.5% concentration, it increased germination rate by 25.6% in dicots, without inhibiting subsequent seedling growth. For yield, foliar spray and soil application increased crop yield by 19.4% and 17.8% on average. Application strategies must be optimized by crop type. For foliar spray, monocots require multiple applications at concentrations $\leq 0.5\%$, whereas dicots benefit from fewer applications within the optimal range of 0.1–0.5%. For soil application, limited additions at 0.5–1.0% achieve the best balance between yield benefit and cost for dicots. WV produced at low pyrolysis temperatures ($\leq 500^\circ\text{C}$) is more effective for foliar use, while low-pH (≤ 4) WV is preferable for soil application. Foliar application performed better under high soil nutrient conditions, and soil application was more effective in soils with pH > 7 . Correlation analyses indicate that yield enhancement is closely associated with increased antioxidant enzyme activity in leaves and improved photosynthetic parameters. This study provides global-scale quantitative evidence supporting WV as an industrial biostimulant with strong potential to enhance crop production sustainably, and offers specific parameter thresholds and theoretical guidance for its precise application across diverse crop types and soil conditions.

1. Introduction

Achieving sustainable agricultural production amid growing global population pressures and escalating resource constraints has become a critical challenge for ensuring food security and ecological stability (Pecl et al., 2017; Springmann et al., 2018). However, the heavy dependence

of traditional intensive agriculture on chemical inputs has caused significant environmental damage, such as soil degradation, water eutrophication, and increased greenhouse gas emissions, which endanger biodiversity and human health (Clark and Tilman, 2008; Guo et al., 2010; Yang et al., 2023). In Northeast China, for example, prolonged intensive tillage and excessive fertilizer application have caused

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substantial soil organic carbon depletion, nutrient imbalances, and diminished agroecosystem functionality (Wang et al., 2024). In the quest for sustainable options, wood vinegar (WV), a liquid extracted from the pyrolysis of agricultural and forestry biomass waste, has gained growing attention. As a natural and eco-friendly by-product, it contains an abundance of organic acids, phenolics, and bioactive compounds, offering various environmental benefits, including enhancing plant growth, inhibiting soil-borne pathogens, and improving soil physical and chemical properties (Mathew and Zakaria, 2015). The effects of wood vinegar on crop performance vary widely, and a comprehensive quantitative analysis across different conditions is still missing. Hence, it is crucial to develop effective, ecologically sustainable technologies that work together to improve crop yields, addressing an urgent scientific and practical need (Lambin and Meyfroidt, 2011).

Accumulating evidence suggests that WV holds considerable untapped potential for improving crop productivity. For example, seed soaking with optimal WV concentrations improved germination in basil, lettuce, and chickpea (Maresca et al., 2024), increased germination rates and seedling biomass in rice (Zhang et al., 2022), and enhanced photosynthetic efficiency and grain yield through foliar application (Hur et al., 2025). Similarly, both foliar and soil applications promoted tomato growth and fruit yield (Mungkunkamchao et al., 2013). While WV is presented as beneficial for germination and crop yield, the potential for negative or phytotoxic effects is omitted, as illustrated by reports of suppressed rapeseed germination (Deng et al., 2024) and reduced strawberry growth and yield (Iacomino et al., 2024). This inconsistency likely stems from complex interactions among WV characteristics, application protocols, crop species, and environmental factors. Species-specific responses have been documented, with lentil showing significant yield increases under foliar WV application, whereas chickpea and bean exhibited no response (Carril et al., 2023). Dosage-dependent effects are evident, as varying WV concentrations differentially impacted tomato growth and yield (Ofuo et al., 2024). Feedstock source and pyrolysis temperature play crucial roles in determining the chemical composition of WV and its subsequent agronomic effectiveness (Zhou et al., 2022). For example, Ebrahimi et al. (2022), (2025) showed that even within the same date palm cultivar, the compositions of the raw material and its pyrolysis products differed markedly depending on the climatic zone and the plant part, and the concentrations of acetic acid, phenol, and furfural in the aqueous and organic phases of the wood vinegar also varied significantly. Furthermore, soil-mediated effects vary with edaphic conditions, as WV differentially alters soil enzyme activity, pH, and microbial communities across soil types, thereby modulating crop growth and yield (Kenday et al., 2022). Despite numerous individual studies examining these factors, high heterogeneity in experimental designs and conditions has precluded the development of a systematic quantitative framework for evaluating how these variables collectively regulate WV efficacy and the underlying mechanisms. This variability introduces substantial uncertainty regarding WV's practical efficacy and constrains its adoption as a reliable agronomic practice, necessitating systematic integration and quantitative synthesis of existing evidence to clarify its true effects under varying conditions.

To address this knowledge gap, we conducted a comprehensive global meta-analysis of 94 published studies was conducted to systematically evaluate WV effects on crop production. Our specific objectives were to: (i) quantify WV impacts on seed germination, plant growth, and yield; (ii) analyze how key moderating factors, including crop species, application strategy (dosage and method), WV feedstock and pyrolysis conditions, and soil properties, influence these effects; and (iii) elucidate the physiological mechanisms underlying WV-enhanced crop yield. This study provides a robust theoretical foundation to inform precision application strategies for maximizing WV efficacy in sustainable agriculture.

2. Materials and methods

2.1. Data collection

A comprehensive literature search was conducted to identify peer-reviewed studies published till December 2025 from Web of Science (All Databases, <https://apps.webofknowledge.com>) and China National Knowledge Infrastructure (<http://www.cnki.net>). To ensure comprehensive retrieval while accounting for studies that specify crop species rather than general "crop" terminology, we used the following search terms: "wood vinegar" OR "wood distillate" OR "pyroligneous acid", and after the search each retrieved record was manually screened one by one, to ensure that all relevant studies were included without omission. Study selection followed rigorous inclusion criteria to minimize bias: (i) reporting of at least one response variable related to seed germination and seedling growth (germination rate, seedling height, root length), crop growth and yield (plant height, biomass, yield), or physiological indicators [superoxide dismutase (SOD), peroxidase (POD), catalase (CAT), malondialdehyde (MDA), net photosynthetic rate (Pn), transpiration rate (Tr), intercellular CO₂ concentration (Ci), stomatal conductance (Gs), and total chlorophyll]; (ii) paired control and WV treatments without confounding factors such as stress conditions or additional exogenous substances; and (iii) minimum of three replicates per experimental group. These indicators collectively span seed germination, seedling establishment, vegetative growth, yield formation, and physiological performance, providing a robust framework for comprehensive evaluation of WV effects on crop production.

Following systematic screening, 94 articles met the inclusion criteria (Figure S1). We extracted means, standard deviations (SD), and sample sizes for all response variables from tables, text, figures, or supplementary materials using GetData Graph Digitizer software (<http://www.getdata-graph-digitizer.com>). Geographical coordinates were obtained from original articles or determined via Google Earth (<https://earth.google.com>). The global distribution of study sites encompassed Africa, Europe, the Americas, and Asia (Fig. 1A). Publication temporal analysis revealed that 57% of studies (n = 54) were published between 2021 and 2025. Experimental settings comprised 70% laboratory or greenhouse studies (n = 66) and 30% field trials (n = 28) (Fig. 1B).

When a single experiment reported multiple WV concentrations or application methods, each treatment group was extracted as a separate observation and paired with its corresponding control group (Gurevitch et al., 2018). To standardize comparisons across studies, WV concentrations expressed as dilution ratios, or mL/L, were converted to percentage (v/v) units. Crop species were categorized as monocots (e.g., rice, wheat, Chinese chive) or dicots (e.g., soybean, tomato, pepper, tobacco, rapeseed), reflecting fundamental differences in germination patterns, leaf morphology, and root architecture that influence optimal WV response concentrations. Application methods were classified as seed treatment, foliar spray, or soil application. optimal concentrations and application frequencies for each crop category under different application methods were subsequently analyzed. Notably, soil application studies predominantly involved dicot crops, with insufficient representation of monocots to enable valid subgroup comparisons. Therefore, crop-type-specific analyses were restricted to seed treatment and foliar spray.

WV production characteristics were categorized as follows: feedstock type (wood, straw, agricultural waste), pyrolysis temperature (≤ 500 °C or > 500 °C), and raw pH (≤ 4 or > 4). Additionally, we examined crop yield responses in relation to soil properties [pH, total nitrogen (TN), available phosphorus (AP), available potassium (AK), and soil organic matter (SOM)] under both foliar spray and soil application methods.

2.2. Meta-analysis

The natural logarithm of the response ratio (LnRR) was employed to

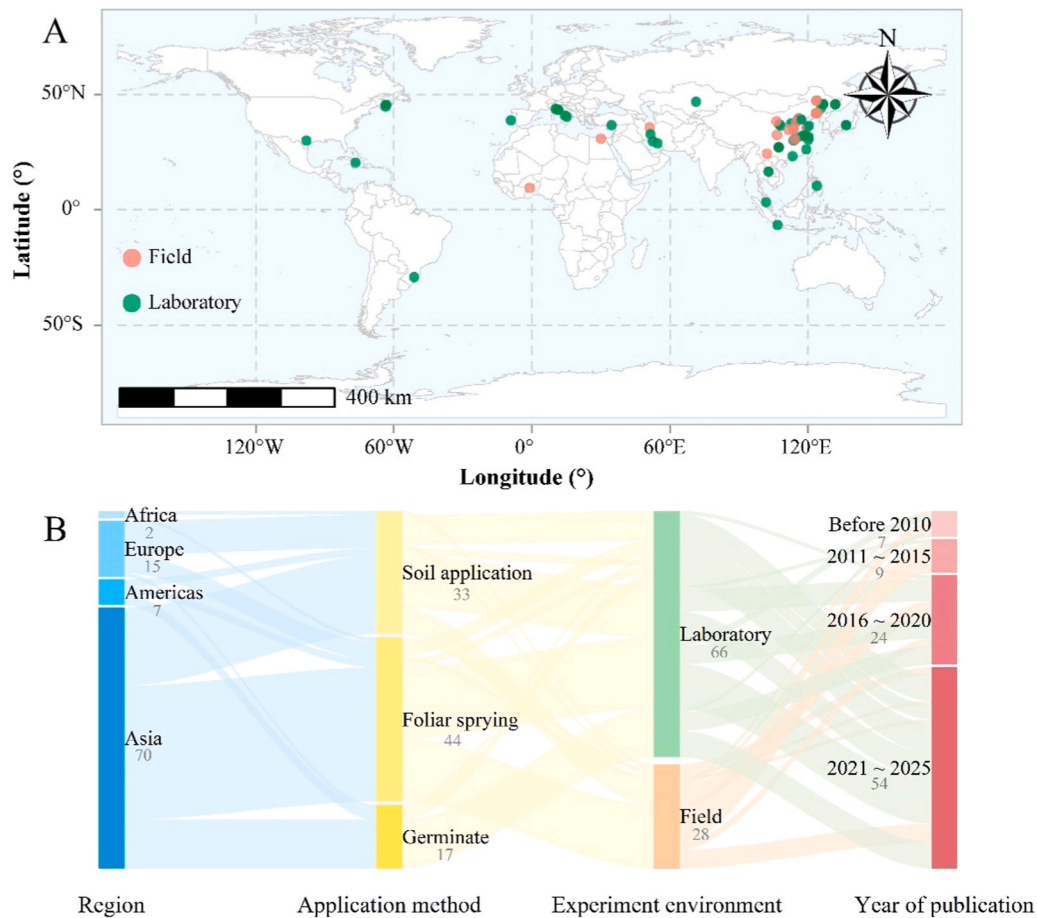


Fig. 1. Global distribution of included studies (A) and the number of studies in this meta-analysis by geographic region, application method, experimental condition, and publication year (B).

quantify the effects of WV application on crop seed germination, seedling growth, plant growth, and yield. The calculation equation is:

$$\ln RR = \ln \left(\frac{X_t}{X_c} \right) = \ln X_t - \ln X_c \quad (1)$$

In the formula, X_t and X_c denote the means of the treatment and control groups, respectively. The $\ln RR$ value > 0 indicates a positive impact, while a $\ln RR$ value < 0 indicates a negative effect. The corresponding error variance (V) of $\ln RR$ is calculated as follows:

$$V(\ln RR) = \frac{SD_t^2}{N_t X_t^2} + \frac{SD_c^2}{N_c X_c^2} \quad (2)$$

In the formula, SD_t and SD_c represent the SD of the treatment and control groups, respectively; N_t and N_c represent the sample sizes of the treatment and control groups, respectively. When the papers presented the standard error (SE) instead of the SD, we used the following equation to convert it:

$$SD = SE \times \sqrt{n} \quad (3)$$

The $\ln RR$ values for each variable were converted to the percentage change caused by WV using the following equation:

$$\text{Changes (\%)} = (e^{\ln RR} - 1) \times 100 \quad (4)$$

The statistical analyses were conducted in Origin 2021 (Analytical Software Northampton, Hampton, MA, USA) (<https://www.originlab.com.cn/>) software and R (version 4.3.1) (Lucent Technologies, Durham, NC, USA) (<https://www.r-project.org/>) software using “metafor” packages (Viechtbauer, 2010; Lajeunesse, 2016). The missing SD was filled using the coefficient of variation from all studies with complete information (Abdellah et al., 2022a; Deng et al., 2025a; Abdellah et al., 2026). The overall effect of WV was estimated using a mixed-effects model in the `rma.mv` function. Both linear and nonlinear fitting models were used to examine the correlation between the effect value and both concentration and frequency. As for the relationships among plant height, biomass, and yield, we performed polynomial and linear fits and selected the model with the lower AIC (Akaike Information Criterion) value. To test for publication bias, the fail-safe number method was applied. The fail-safe number greater than $5n + 10$ is considered robust to publication bias (n is the original number of studies) (Rosenberg, 2005; Abdellah et al., 2022b). In this meta-analysis, the data showed no evidence of publication bias, indicating that the results are robust and reliable (Table S1).

3. Result

3.1. Overall effect of WV application

On average, crop germination rates were not significantly affected by seed treatment with WV compared to controls ($p > 0.05$), but the effect exhibits significant concentration dependency, with optimal concentrations significantly improving germination (see 3.4). However, it significantly inhibited early seedling development, reducing seedling

height and root length by 17.5% and 28.4%, respectively ($p < 0.001$) (Fig. 2A). These inhibitory effects on germination and seedling growth were consistent across monocot and dicot crops ($p > 0.05$) (Figures 2D and S2A). Foliar spray significantly enhanced vegetative growth and productivity, increasing plant height, biomass, and yield by 7.7%, 25.9%, and 19.4%, respectively ($p < 0.001$) (Fig. 2B). These beneficial effects were comparable between monocots and dicots ($p > 0.05$) (Figure 2E and S2B). Soil application significantly improved plant height and yield by 4.6% and 17.8%, respectively ($p < 0.001$), but did not significantly affect biomass accumulation ($p > 0.05$) (Fig. 2C). Yield enhancement through soil application was similar across crop types ($p > 0.05$) (Fig. 2F). Comparative analysis of application methods revealed that foliar spraying produced significantly greater biomass enhancement than soil application ($p < 0.001$). However, effects on plant height and yield did not differ significantly between methods ($p > 0.05$) (Figure S3).

3.2. Effects of feedstock, pyrolysis temperature, and raw WV pH on crop seed germination and yield

Feedstock type, pyrolysis temperature, and raw WV pH did not significantly modulate seed germination responses ($p > 0.05$) (Fig. 3A). For foliar spray, pyrolysis temperature critically influenced WV efficacy ($p < 0.001$). Low-temperature ($\leq 500^\circ\text{C}$) WV significantly increased yield by 72.7% compared to controls, whereas high-temperature ($>500^\circ\text{C}$) WV significantly reduced yield by 30.4% (Fig. 3B). For soil application, raw WV pH significantly affected yield responses ($p < 0.05$). Low-pH (≤ 4) WV significantly enhanced yield by 25.4% ($p < 0.001$), whereas high-pH (>4) formulations produced no significant yield effects

($p > 0.05$) (Fig. 3C).

3.3. Influence of soil properties on crop yield response to WV

The yield response to foliar WV application was notably affected by soil nutrient status. In high-nutrient conditions, defined as total nitrogen (TN) $> 2\text{ g/kg}$, available phosphorus (AP) $> 50\text{ mg/kg}$, available potassium (AK) $> 100\text{ mg/kg}$, or soil organic matter (SOM) $> 12\text{ g/kg}$, foliar spraying increased yields by 18.6–30.0% ($p < 0.001$). These increases were significantly greater than those in soils with lower nutrient levels ($p < 0.05$). Soil pH, however, did not significantly influence the effectiveness of foliar spray ($p > 0.05$) (Fig. 4A). Conversely, soil pH played a critical role in soil application results. When soil pH was above 7, soil application increased yields by 25.1% ($p < 0.001$), a significantly higher effect than in neutral or acidic soils ($\text{pH} \leq 7$) ($p < 0.05$). Nutrient levels in the soil did not significantly affect the yield response to soil application ($p > 0.05$) (Fig. 4B).

3.4. Effects of WV concentration and application frequency on crop seed germination, growth, and yield

The effects of WV on seed germination and seedling growth varied with concentration. For monocots, germination responses showed no significant logarithmic relationship with concentration ($p = 0.56$) (Fig. 5A); however, concentrations of 0.5–1.0% significantly increased germination by 31.5% ($p < 0.001$), whereas other concentrations produced no significant effects ($p > 0.05$) (Fig. 5C). Neither seedling height nor root length was significantly affected at any concentration ($p > 0.05$) (Figure S4A). For dicots, concentration effects followed a

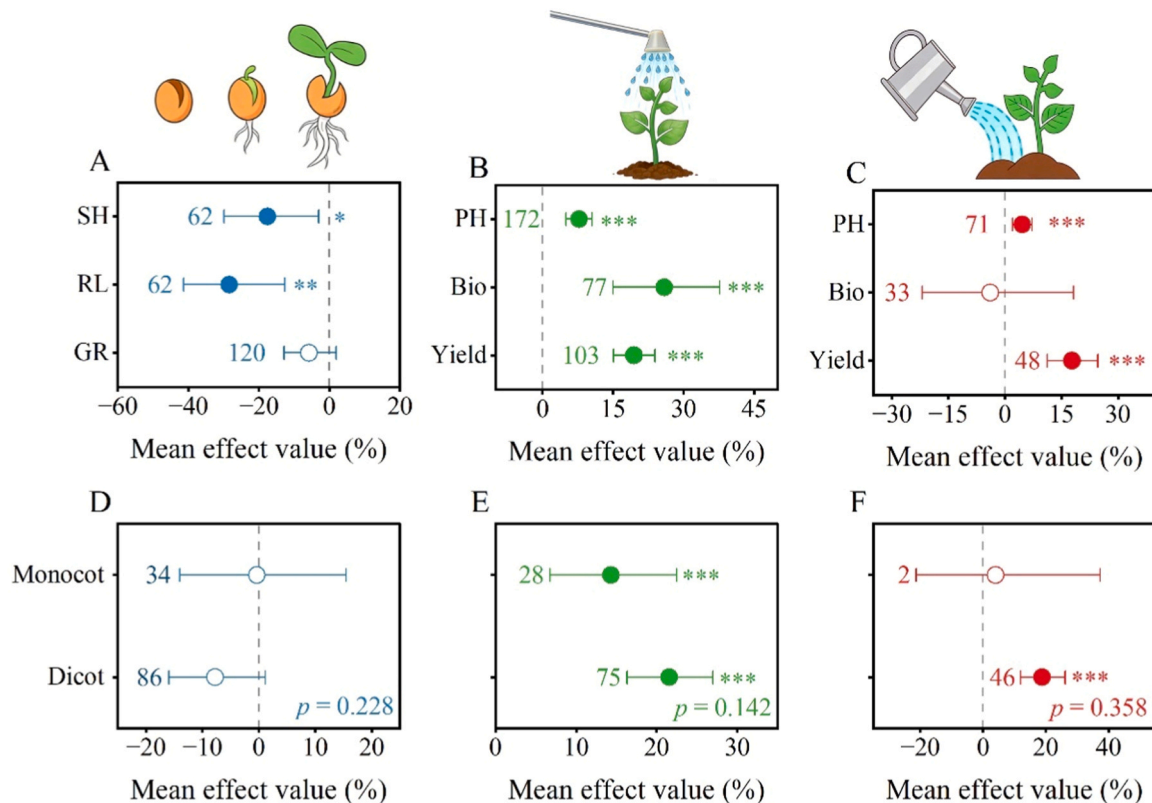


Fig. 2. Effects of wood vinegar seed soaking on crop germination and growth and differences between crop types (A and D); effects of wood vinegar foliar spray on crop growth and yield and differences between crop types (B and E); effects of wood vinegar soil application on crop growth and yield and differences between crop types (C and F). Solid dots in the figure indicate significant effects, while hollow dots indicate non-significant effects. Values are mean relative changes and error bars show the 95% CI. The number of observations for each indicator is presented on the left. Non-significant change is indicated by confidence intervals overlapping the reference line ($p \geq 0.05$). * indicated $p < 0.05$, ** indicated $p < 0.01$, *** indicated $p < 0.001$. SH, seedling height; RL, root length; GR, germination rate; PH, plant height; Bio, biomass.

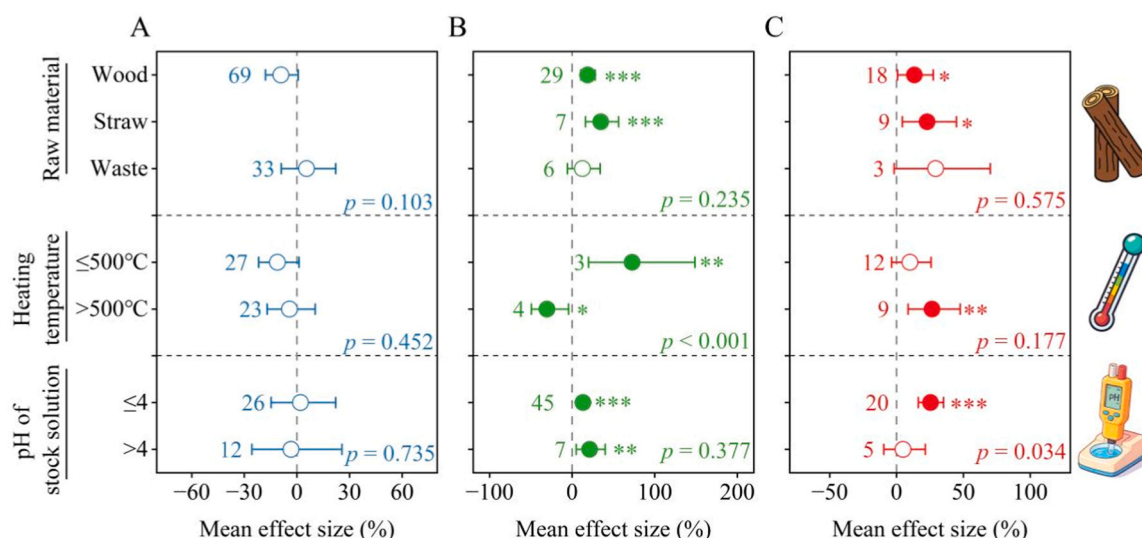


Fig. 3. Effects of feedstock type, pyrolysis temperature, and raw WV pH on the crop seed germination effect value via wood vinegar soaking (A), and the crop yield effect value via foliar spraying and soil application of wood vinegar (B). Solid dots in the figure indicate significant effects, while hollow dots indicate non-significant effects. Values are mean relative changes and error bars show the 95% CI. The number of observations for each category is presented on the left. Non-significant change is indicated by confidence intervals overlapping the reference line ($p \geq 0.05$). * indicated $p < 0.05$, ** indicated $p < 0.01$, *** indicated $p < 0.001$.

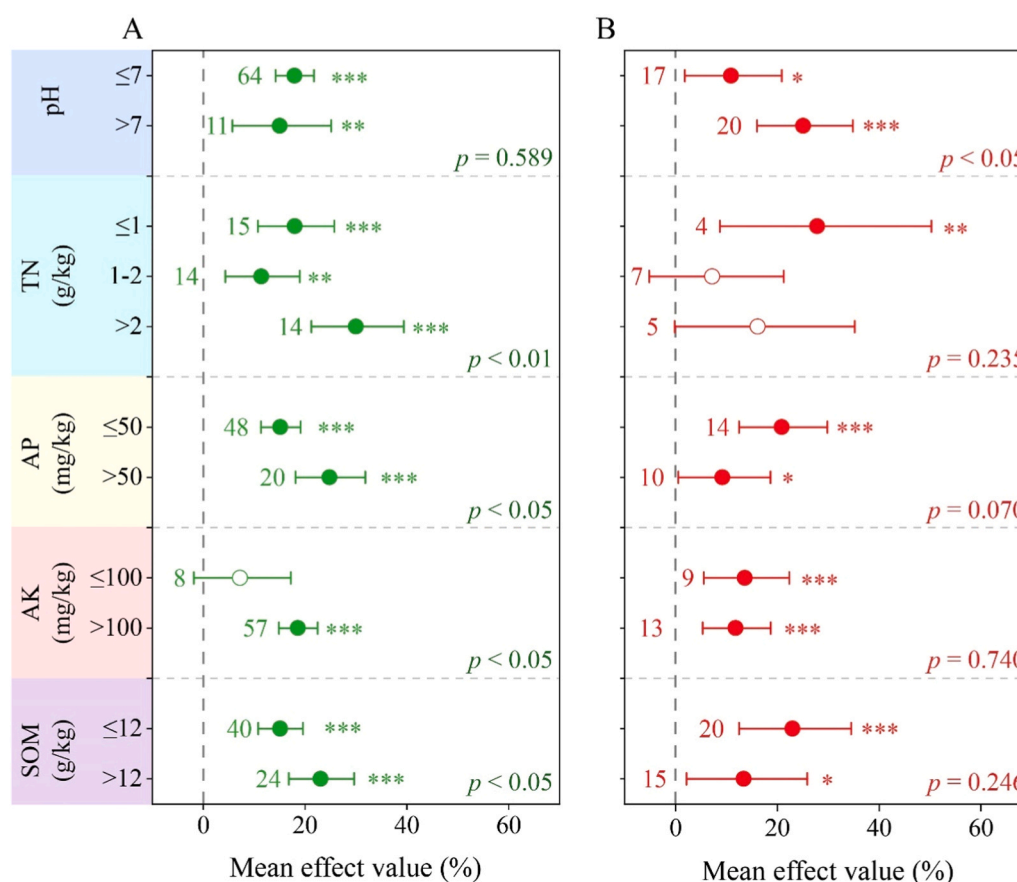


Fig. 4. Effects of soil properties on the crop yield effect value of wood vinegar through foliar application (A) and soil application (B). Solid dots in the figure indicate significant effects, while hollow dots indicate non-significant effects. Values are mean relative changes and error bars show the 95% CI. The number of observations for each category is presented on the left. Non-significant change is indicated by confidence intervals overlapping the reference line ($p \geq 0.05$). * indicated $p < 0.05$, ** indicated $p < 0.01$, *** indicated $p < 0.001$. TN: soil total nitrogen; AP: soil available phosphorus; AK: soil available potassium; SOM: soil organic matter.

significant quadratic relationship ($p < 0.05$) (Fig. 5B). Concentrations of 0.1–0.5% significantly enhanced germination by 25.6% ($p < 0.01$), whereas concentrations $>1.0\%$ significantly inhibited germination ($p <$

0.05) (Fig. 5D). While seedling height remained unaffected ($p > 0.05$), root elongation was significantly suppressed at concentrations $>1.0\%$ ($p < 0.01$) (Figure S4B).

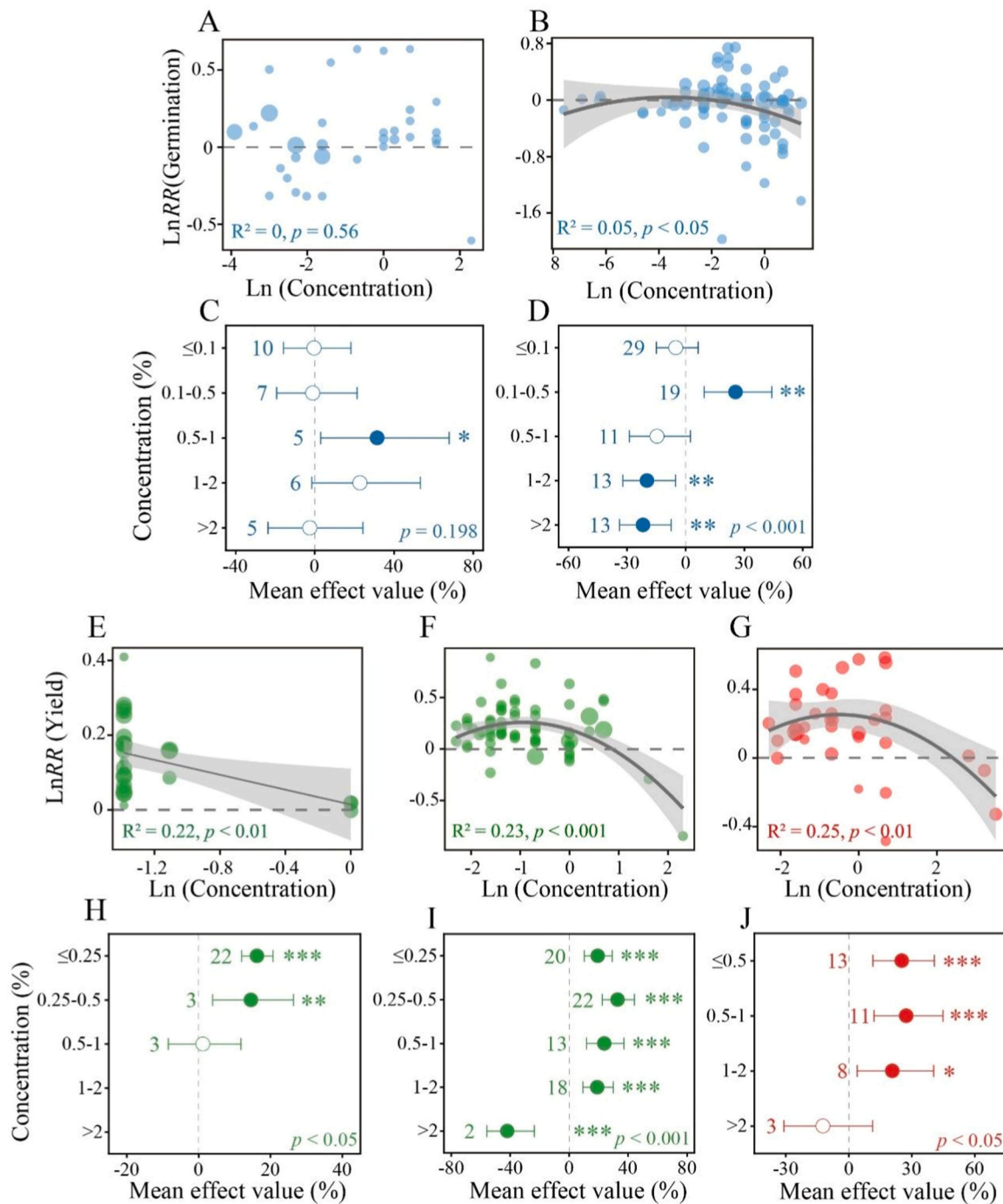


Fig. 5. Effects of wood vinegar concentration on the seed germination effect value of monocots (A and C) and dicots (B and D) crops via seed soaking, the yield effect value of monocots (E and H) and dicots (F and I) crops through foliar spraying, and the yield effect value of dicots (G and J) crops through soil application. Solid dots in the figure indicate significant effects, while hollow dots indicate non-significant effects. Values are mean relative changes and error bars show the 95% CI. The number of observations for each category is presented on the left. Non-significant change is indicated by confidence intervals overlapping the reference line ($p \geq 0.05$). * indicated $p < 0.05$, ** indicated $p < 0.01$, *** indicated $p < 0.001$. Significance in the regression model was indicated by $p < 0.05$.

The effects of foliar spray on yield were modulated by concentration. For monocots, yield response was significantly negatively correlated with the natural logarithm of concentration ($p < 0.01$) (Fig. 5E). Concentrations $\leq 0.5\%$ significantly increased yield by 16.3% ($p < 0.001$), an effect superior to higher concentrations ($p < 0.05$) (Fig. 5H). Neither plant height nor biomass was significantly affected ($p = 0.555$ and $p = 0.545$, respectively) (Figure S4C and S4D). For dicots, yield response followed a significant parabolic relationship with concentration ($p < 0.001$) (Fig. 5F). The optimal range of 0.25–0.5% significantly increased

yield by 32.9% ($p < 0.001$), whereas concentrations $> 2.0\%$ significantly reduced yield by 42.0% ($p < 0.001$) (Fig. 5I). Plant height was significantly affected ($p < 0.05$), with 0.5–1.0% producing optimal enhancement (21.3% increase, $p < 0.05$), whereas biomass remained unaffected ($p = 0.058$) (Figure S4C and S4D). Soil application in dicots also exhibited parabolic concentration effects ($p < 0.01$) (Fig. 5G). Concentrations of 0.5–1.0% produced maximal yield enhancement (27.4% increase), whereas concentrations $> 2.0\%$ eliminated significant yield benefits ($p > 0.05$) (Fig. 5J). While plant height was unaffected ($p =$

0.183), biomass accumulation was significantly suppressed at concentrations $>1.0\%$ (53.0% reduction, $p < 0.01$) (Figure S4E and S4F).

Foliar spray frequency exhibited opposing relationships with yield between crop types: a significant positive correlation for monocots ($p < 0.01$) versus a significant negative correlation for dicots ($p < 0.001$) (Fig. 6A, B). Soil application frequency did not significantly affect yield in either crop category ($p > 0.05$) (Fig. 6C).

3.5. Effects of WV application on crop physiological indicators and their correlations

WV treatment significantly modulated crop physiological indicators, with effects varying by application method. Foliar spray significantly enhanced antioxidant capacity and photosynthetic efficiency, increasing SOD and CAT activities by 14.2% and 48.2%, respectively, while reducing MDA content by 18.0% ($p < 0.05$) (Fig. 7A). Furthermore, foliar WV application increased total chlorophyll content, Pn, Tr, Ci, and Gs by 12.6%, 8.3%, 12.0%, 11.5%, and 14.3%, respectively ($p < 0.05$) (Fig. 7C). In comparison, soil application significantly increased SOD activity, total chlorophyll content, and Pn by 17.6%, 17.3%, and 56.3%, respectively ($p < 0.05$) (Fig. 7B and D), without significantly affecting other antioxidant or gas exchange parameters ($p > 0.05$).

Correlation analyses revealed significant positive associations between physiological improvements and growth parameters. Plant height was significantly correlated with Gs and Tr ($p < 0.05$). Biomass accumulation showed significant positive correlations with SOD, CAT, Pn, Ci, and Tr ($p < 0.05$). Most critically, yield enhancement was significantly associated with improvements in Pn, Gs, and Tr ($p < 0.05$) (Fig. 8A). Furthermore, yield responses were significantly positively correlated with both plant height ($R^2 = 0.40$, $p < 0.001$) and biomass ($R^2 = 0.88$, $p < 0.001$) effect sizes (Fig. 8B and C).

4. Discussion

4.1. Overall effects of WV on crop growth and yield

This meta-analysis represents the first quantitative synthesis of WV effects on crop performance across diverse agricultural systems. Both foliar spray and soil application significantly enhanced yield (Fig. 2B and C). These yield gains may be driven by macromolecular organic compounds in WV. Organic acids, phenols, and carbonyls can elicit hormetic responses analogous to plant hormones (Zhou et al., 2025). The two application methods produced divergent effects on biomass accumulation. Foliar spray increased biomass by 25.9%. Soil application produced no significant effect (Figure S3). This contrast points to distinct modes of physiological action. Foliar spray delivers WV directly to photosynthetic organs, enabling rapid modulation of stomatal conductance and chlorophyll efficiency, thereby accelerating carbon assimilation and biomass accumulation (Mungkumkamchao et al.,

2013). Soil application, conversely, primarily modifies rhizosphere biogeochemistry, potentially redirecting assimilate allocation toward root system expansion or reproductive organs (Yu et al., 2024; Zhao et al., 2024a). Despite differences in germination physiology and leaf structure, we found no significant differences in WV responses between monocots and dicots in germination, growth, or yield (Figures 2D–F and S2). This convergence hints at common underlying mechanisms of WV action. The mildly acidic environment generated by WV application could enhance ethylene biosynthesis, thereby reducing seed dormancy (Ribeiro et al., 2018). Simultaneously, WV-induced enhancement of α -amylase activity accelerates endosperm starch hydrolysis, ensuring adequate energy provision for germination and early seedling establishment (Zhu et al., 2026). Overall, the yield-promoting effect of WV and the absence of systematic differences between monocots and dicots in the pooled response are among the most consistently supported findings, whereas the magnitude and even direction of effects on biomass accumulation, germination, and physiological parameters are strongly conditional on application method, concentration, and crop type.

4.2. Optimizing concentration and application frequency is key to enhancing the promotional effects of WV on crop germination, growth, and yield

We found that the effect of WV on germination and early growth is not universal. It depends heavily on concentration. Our study shows that, on average, under non-optimized concentration conditions, WV seed soaking has no significant promoting effect on seed germination rate (Fig. 2A); however, this average effect masks a significant concentration dependence: an appropriate concentration of WV significantly promotes seed germination, while an excessively high concentration inhibits this process (Fig. 5). For seedling growth, WV had no significant effect on shoot and root length in monocots, but high concentrations exhibited significant inhibitory effects in dicots (Figure S4A and S4B). The biphasic response likely reflects dual mechanisms of WV action. Beneficial concentrations create a mildly acidic environment conducive to ethylene-mediated dormancy alleviation and α -amylase activation, thereby accelerating starch hydrolysis and energy provision (Ribeiro et al., 2018; Zhu et al., 2026). Conversely, excessive acidity at high concentrations disrupts cellular pH homeostasis and metabolic equilibrium (Liu et al., 2011). Seedlings undergoing rapid cellular differentiation exhibit heightened metabolic activity and sensitive regulatory systems, rendering them more responsive yet vulnerable to external chemical signals (Ochoa-Lopez et al., 2020). Additionally, phenolic compounds, abundant in WV, can generate oxidative stress at elevated concentrations, compromising membrane integrity and impairing germination and early growth (Kumar et al., 2025). These phytotoxic effects necessitate rigorous concentration optimization for seed soaking applications. The present meta-analysis reveals taxon-specific optima:

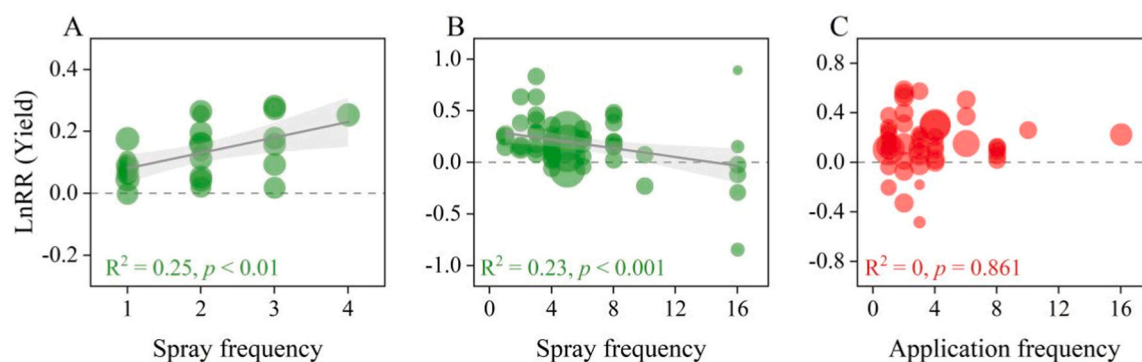


Fig. 6. Effects of foliar spraying frequency of wood vinegar on the yield effect value of monocots (A) and dicots (B) crops; effects of soil application frequency of wood vinegar on the yield effect value of dicots (C) crops. Significance in the regression model was indicated by $p < 0.05$.

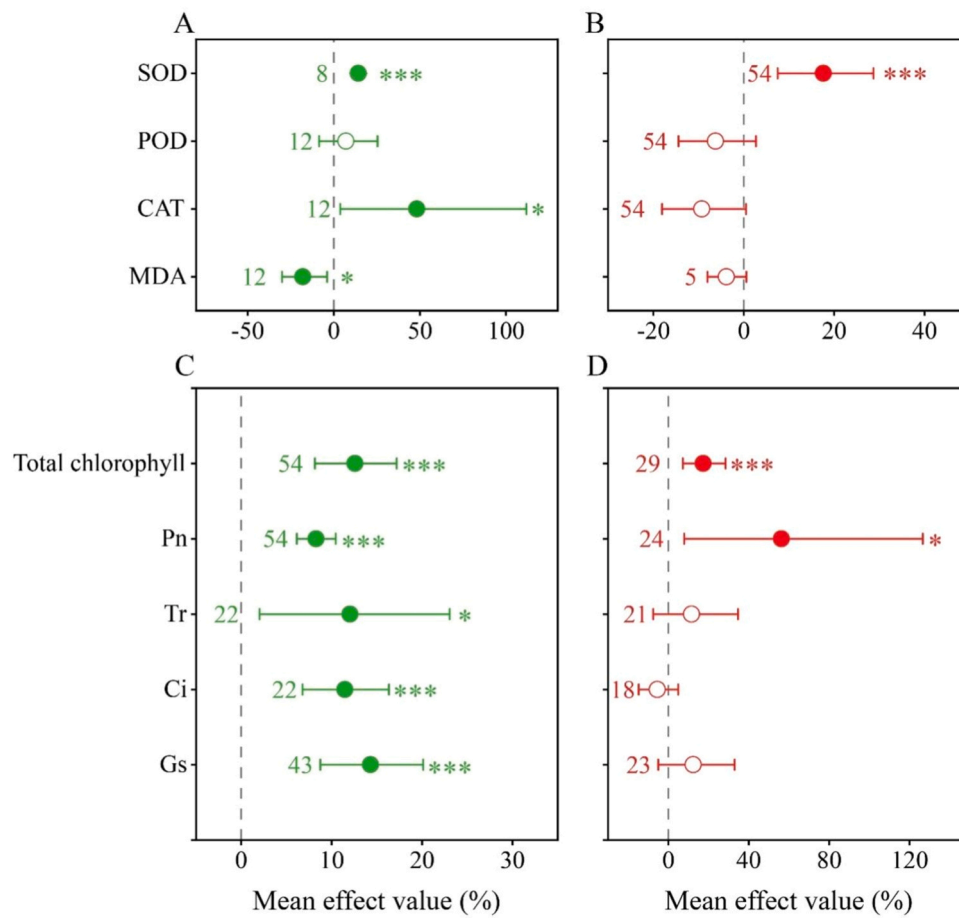


Fig. 7. Effects of foliar spraying (A and C) and soil application (B and D) of wood vinegar on the antioxidant and photosynthetic systems of crops. Solid dots in the figure indicate significant effects, while hollow dots indicate non-significant effects. Values are mean relative changes and error bars show the 95% CI. The number of observations for each indicator is presented on the left. Non-significant change is indicated by confidence intervals overlapping the reference line ($p \geq 0.05$). * indicated $p < 0.05$, ** indicated $p < 0.01$, *** indicated $p < 0.001$. SOD, superoxide dismutase; POD, peroxidase; CAT, catalase; MDA, malondialdehyde; Pn, net photosynthetic rate; Tr, transpiration rate; Ci, intercellular CO_2 concentration; Gs, stomatal conductance.

monocots require higher concentrations (0.5–1.0%) than dicots (0.1–0.5%) (Fig. 5). This divergence aligns with established patterns of hormonal tolerance, as monocots generally exhibit greater resilience to elevated concentrations of growth-regulating substances than dicots (Torra et al., 2024). Therefore, it's recommended to use seed-soaking concentrations of 0.5–1.0% for monocots and 0.1–0.5% for dicots to maximize germination without compromising subsequent seedling vigor. These results confirm that no single concentration works best for all crops. The germination-promoting effect of WV is entirely conditional on choosing the right dose for each plant type.

Concentration is also a core factor determining WV's impact on crop growth, development, and final yield (Ma et al., 2022a). Foliar WV application enhances crop productivity, but exclusively within defined concentration windows; exceeding these thresholds nullifies benefits or induces yield penalties (Fig. 5). Optimal concentrations improve photosynthetic efficiency, soluble carbohydrate accumulation, and nutrient acquisition, processes fundamental to biomass production and yield formation (He et al., 2025; Hur et al., 2025). Conversely, foliar spray of excessively high concentrations risks yield loss. Excessive acidic substances can directly damage leaf cell membranes, reduce chlorophyll content, induce stomatal closure, cause oxidative stress, and inhibit photosynthesis, leading to lower yields (Luo et al., 2019; Maliang et al., 2025). Similar concentration effects were observed with soil application (Fig. 5). Adding WV at an optimal concentration can improve soil structure and microbial community composition, enhancing nutrient availability (Seo et al., 2015; Yuan et al., 2022). These improvements

support boosting the yield (Zhou et al., 2021). Conversely, over-application acidifies soil, disrupts microbial equilibrium, and compromises root function.

Application frequency is a crucial yet often overlooked factor influencing the effectiveness of foliar WV, with optimal levels varying across crop types. Yield response correlated positively with application frequency in monocots but negatively in dicots (Fig. 6). This divergence reflects fundamental leaf architectural differences: monocot leaves are typically narrow, upright, and steeply inclined, promoting droplet runoff and reducing retention time. The upright leaf architecture of monocot significantly lowers spray retention compared with dicot, as the narrow, erect morphology minimizes vertical interception area and steep inclination frequently exceeds the critical retention angle, causing gravitational shedding shortly after impactation (Ferguson et al., 2015). Compounding this morphological limitation, monocot leaf surfaces are typically covered with epicuticular wax crystals that render them superhydrophobic, with contact angles exceeding 150° , thereby promoting droplet bouncing and fragmentation upon impact rather than stable adhesion (Muhammad et al., 2020). In contrast, dicot leaves are broad, horizontally oriented, and possess superior liquid-holding capacity, enabling efficient single-application absorption. Their horizontal presentation maximizes droplet interception probability, and the relatively lower contact angles facilitate droplet spreading and prolonged surface retention, thereby extending the window for cuticular penetration (Ma et al., 2022b). Consequently, the inherently limited retention efficiency and shortened contact time of monocot leaves necessitate

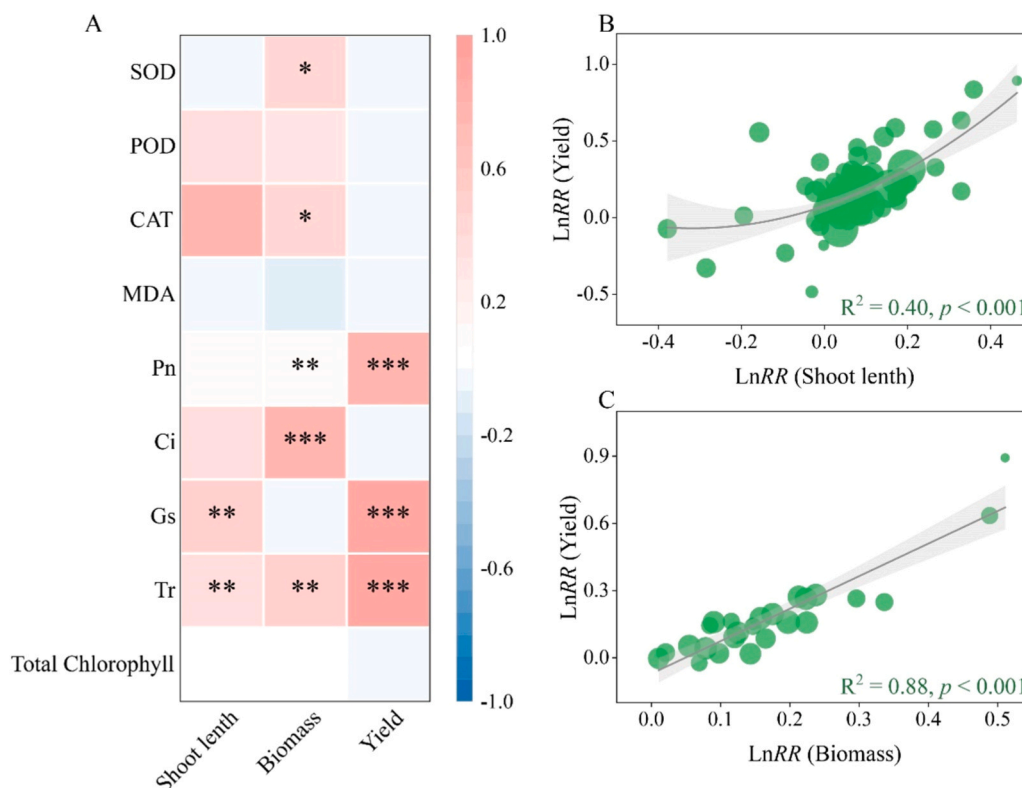


Fig. 8. Relationships between crop growth, yield, and physiological indicators (A); Correlation analysis among effect values of plant height, biomass, and yield (B and C). * indicated $p < 0.05$, ** indicated $p < 0.01$, *** indicated $p < 0.001$. Significance in the regression model was indicated by $p < 0.05$. SOD, superoxide dismutase; POD, peroxidase; CAT, catalase; MDA, malondialdehyde; Pn, net photosynthetic rate; Tr, transpiration rate; Ci, intercellular CO_2 concentration; Gs, stomatal conductance.

multiple applications to achieve cumulative deposition equivalent to a single effective application on dicot foliage. Excessive frequency in dicots risks cumulative phytotoxicity and tissue damage (Maliang et al., 2025). In summary, precision agriculture approaches must integrate crop-specific concentration and frequency parameters. For monocots, we recommend low-concentration ($< 0.5\%$), high-frequency foliar spray, potentially supplemented with surfactants to enhance retention. For dicots, moderate concentrations ($0.1\text{--}0.5\%$) with minimal applications are optimal. Soil application should employ limited additions ($0.5\text{--}1.0\%$) to balance agronomic benefits with economic and environmental sustainability. When comparing the relative importance of these modulating factors, concentration emerged as the most pervasive driver. It determined whether the effect on germination, growth, and yield was positive, negative, or absent. Application method was equally critical for determining biomass allocation and the specific physiological pathway that was activated. Crop type further modulated the optimal concentration and frequency window but was less influential on its own. This comparison suggests that application protocols should first optimize concentration and then select the appropriate method based on the target crop and growth stage.

4.3. Feedstock type, pyrolysis temperature, raw WV properties, and soil characteristics modulate the yield-enhancing efficiency of WV

The agronomic effectiveness of WV depends on interactions among feedstock type, pyrolysis conditions, WV chemical characteristics, and soil environment. Our analysis reveals that feedstock type, pyrolysis temperature, and raw WV pH do not significantly influence seed germination responses (Fig. 3A). However, for foliar spray, pyrolysis temperature emerges as a critical quality determinant. Low-temperature ($\leq 500^\circ\text{C}$) WV significantly enhanced yield, whereas high-temperature ($> 500^\circ\text{C}$) products significantly reduced productivity (Fig. 3B). This

dichotomy reflects temperature-dependent compositional shifts. Low-temperature pyrolysis preserves bioactive small-molecule constituents, including organic acids, ketones, and phenolic compounds, that exhibit plant hormone-like activity, stimulating stomatal opening, enhancing chlorophyll biosynthesis, and improving photosynthetic efficiency (Wu et al., 2015; Kumar et al., 2025). Elevated pyrolysis temperatures, conversely, concentrate phenolic compounds to phytotoxic levels, inducing oxidative stress and cellular damage that compromise yield formation (Wu et al., 2015; Lu et al., 2019).

For soil applications, raw liquid pH is the primary predictor of efficacy. Low-pH (≤ 4) formulations significantly outperformed higher-pH alternatives (Fig. 3C), as pH inversely correlates with organic acid content, the predominant bioactive fraction in WV (Zhao et al., 2024a). These organic acids exert dual beneficial effects: they acidify the rhizosphere, mobilizing sparingly soluble mineral nutrients through chelation and protonation reactions, and serve as readily metabolizable carbon substrates that stimulate beneficial rhizosphere microbiota and promote growth-enhancing metabolite production (Yan et al., 2025). These findings establish clear selection criteria: low-temperature-derived WV should be prioritized for foliar spray, whereas low-pH formulations are optimal for soil incorporation.

Soil characteristics differentially modulate the performance of foliar versus soil application, revealing context-specific optimization opportunities. Foliar spray efficacy exhibited pronounced dependence on soil nutrient status, with superior performance in high-fertility soils ($\text{TN} > 2\text{ g/kg}$, $\text{AP} > 50\text{ mg/kg}$, $\text{AK} > 100\text{ mg/kg}$, $\text{SOM} > 12\text{ g/kg}$), but remained insensitive to initial soil pH (Fig. 4A). This nutrient dependency reflects the physiological mechanism of foliar WV: enhanced transpiration rates and root metabolic activity increase nutrient acquisition capacity (Afsharipour et al., 2025; Hur et al., 2025), but the realization of yield benefits requires adequate nutrient availability to support accelerated growth (Fujioka et al., 2019).

Conversely, the effectiveness of soil application did not depend on available nutrient levels but was closely linked to soil pH, with the greatest benefits observed in neutral-to-alkaline soils ($\text{pH} > 7$) (Fig. 4B). The acidic properties of WV help raise pH in alkaline soils, improving chemical conditions for root growth and nutrient access (Zhang et al., 2023). Simultaneously, WV-derived organic matter improves soil structural stability and microbial community composition, enhancing nutrient cycling and retention (Seo et al., 2015). We suggest using foliar spray in soils with higher nutrient levels to enhance crop nutrient uptake. In alkaline environments, soil application is recommended to amend the soil and provide a better growing environment for crops. In summary, the agronomic benefit of WV depends on the match between its own properties and the soil environment. The success of foliar-applied WV is highly conditional on pyrolysis temperature and soil nutrient status. The success of soil application depends on both the pH of the WV product and the soil pH.

4.4. WV promotes crop growth and yield by activating antioxidant enzymes and enhancing photosynthesis

WV application triggers coordinated physiological responses that support growth and yield. Our data highlight differences between general and conditional effects. The activation of antioxidant enzymes such as SOD and CAT is a common pathway for boosting yields, observed consistently across both application methods. However, WV's enhancement of photosynthesis varies with the application method, indicating a context-specific mechanism. Our findings show that foliar spray notably increases SOD and CAT activities while reducing MDA content (Fig. 7A). Soil application mainly elevates SOD activity (Fig. 7B). Multiple studies confirm that exogenously applied acetic acid can serve as a signaling molecule, influencing proline metabolism and strengthening antioxidant defenses to promote crop growth (Rahman et al., 2021; Mahmud et al., 2023). Additionally, WV-derived phenolic compounds possess a potent reducing capacity, enabling direct chemical scavenging of ROS and mitigating oxidative damage (Dykes et al., 2005; Lizcano et al., 2010). For photosynthetic parameters, the two methods produced distinct response profiles. Foliar spray significantly increased total leaf chlorophyll content, Pn, Tr, Gs, and Ci (Fig. 7C). Soil application increased chlorophyll content but primarily enhanced Pn (Fig. 7D). These improvements arise from coordinated effects on ROS homeostasis and stomatal regulation. Foliar WV likely mitigates chlorophyll degradation by enhancing antioxidant-mediated ROS scavenging, thereby preserving the integrity of photosynthetic pigments (Ma et al., 2022a). The bioactive small molecules in WV, including organic acids and phenolics, may function as hormone analogs, stimulating stomatal opening and enhancing CO₂ diffusion and fixation efficiency (Kim et al., 2012). In contrast, soil application likely improves the rhizosphere environment by modulating soil pH and optimizing microbial community structure, thereby promoting root growth (Seo et al., 2015; Zhao et al., 2024a). A robust root system secretes more cytokinins, which are transported via the xylem transpiration stream to the above-ground leaves, upregulating the expression and activity of key photosynthetic enzymes, enhancing carbon fixation capacity, and ultimately increasing the net photosynthetic rate (Gujjar et al., 2020; Zhao et al., 2024a; Zhao et al., 2024b).

Correlation analysis further clarified the physiological mechanisms underlying WV's yield enhancement. Crop growth indicators were significantly positively correlated with antioxidant enzyme activities and photosynthetic parameters, but not significantly with chlorophyll content (Fig. 8A). Increased antioxidant enzyme activity helps scavenge ROS within the crop, creating favorable conditions for growth (Deng et al., 2025b). In the absence of environmental stress, chlorophyll content may have already reached the saturation point for light capture and is no longer the limiting factor for photosynthetic rate (Salesse-Smith et al., 2025). In this scenario, WV-mediated optimization of electron transport efficiency in the light reactions and of the activity of

carbon-fixing enzymes in the dark reactions becomes the core driver of net photosynthetic rate and biomass accumulation. Thus, WV likely promotes growth by activating the antioxidant system to maintain a healthy state, while simultaneously enhancing stomatal conductance and carbon fixation efficiency, thereby synergistically boosting photosynthetic productivity and increasing biomass accumulation.

Furthermore, crop yield was significantly positively correlated with net photosynthetic rate, transpiration rate, stomatal conductance, plant height, and biomass (Fig. 8). An efficient photosynthetic system provides ample photosynthates, while sufficient biomass stores more dry matter, laying the material foundation for yield formation (Zhu et al., 2025). This synergistic optimization of "source" and "sink," coupled with efficient photosynthate translocation mediated by transpiration rate, ultimately enhances crop yield (Fig. 9) (Kunrath et al., 2020; Pan et al., 2022).

4.5. Challenges and future perspectives

This meta-analysis, combining data from 94 separate studies, identifies evidence-based strategies for applying WV across various agricultural settings and affirms its significant potential as a sustainable biostimulant, especially for industrial crops. These results offer practical guidance for farmers establishing precision WV use protocols. However, certain methodological and knowledge gaps need to be addressed, guiding future research efforts to unlock WV's full potential in crop production.

First, soil application effects of WV on monocots require systematic investigation. Current studies are insufficient to determine optimal concentrations and application frequencies for cereal crops. Future research should employ metabolomics, transcriptomics, and rhizosphere microbiome analysis to clarify how WV affects root development, nutrient uptake, and microbial community structure in monocot systems. These mechanistic insights are essential for developing evidence-based application protocols for cereal production.

Secondly, assessing the long-term agronomic impacts of WV requires multi-year, multi-site field trials. While our meta-analysis covers yield studies, most rely on foliar sprays or soil applications. Conversely, seed treatment research seldom monitors beyond the seedling stage to assess final yields. This gap hampers our ability to connect early germination benefits with harvest results. Plants may compensate later, or increased vegetative growth might divert resources from reproductive parts, lowering harvest index. We suggest longitudinal studies that track the same plants from seed treatment through maturity, examining yield components, harvest index, and product quality in high-value crops like tobacco, rapeseed, and cotton. Such data are essential to confirm if early-stage advantages translate into meaningful yield improvements.

Third, standardizing the chemical composition of WV formulations is essential for reliable research and industry use. Many studies mention application rates but do not measure bioactive components such as organic acids, phenolics, and carbonyl compounds. Future efforts should utilize standardized analytical techniques like gas chromatography-mass spectrometry (GC-MS) and high-performance liquid chromatography (HPLC) to identify links between chemical makeup and agronomic results. This will improve quality control, ensure batch consistency, and support the development of formulations tailored to specific crops.

Fourth, exploring how WV interacts with other agricultural inputs like biochar, microbial inoculants, and mineral fertilizers is a crucial research area. While WV is often studied alone, its combined effects with these inputs are not well understood. It is uncertain whether such combinations result in additive, synergistic, or antagonistic impacts on crop growth and yield across various field conditions. Future studies should aim to identify the specific conditions that enhance or hinder WV's performance when used with these inputs and examine the mechanisms involved. Conducting field research in different soil types and cropping systems is essential to confirm laboratory findings and

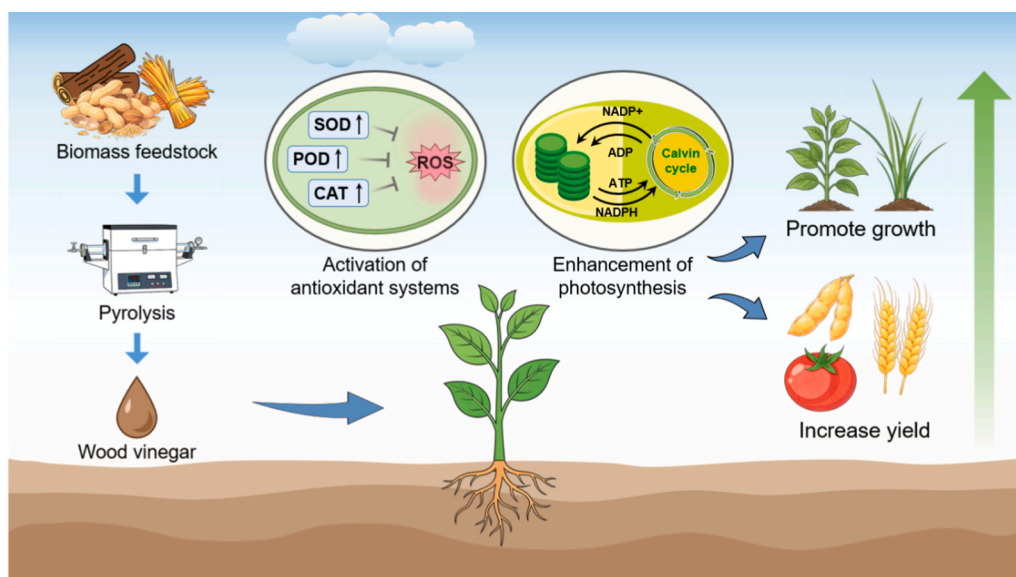


Fig. 9. Wood vinegar promotes crop growth and increases yield by activating antioxidant systems and enhancing photosynthesis. SOD, superoxide dismutase; POD, peroxidase; CAT, catalase; ROS, reactive oxygen species.

develop practical guidelines for combined application. Understanding these interactions is vital for effectively integrating WV into current agricultural practices and optimizing its benefits.

Fifth, understanding the mechanisms by which WV can reduce abiotic stresses under climate change is crucial. Drought, salinity, and high temperatures increasingly threaten crop yields. Future research should explore the physiological and molecular basis of WV's stress tolerance, such as reactive oxygen species scavenging, osmolyte buildup, heat-shock protein production, and stomatal control. Particular focus should be on industrial crops grown in marginal lands, where WV-driven stress management could offer significant agronomic advantages.

Sixth, scaling up WV for industrial use requires comprehensive life-cycle assessments and techno-economic analyses of the entire production process, from biomass pyrolysis to its agricultural application. Future efforts must measure the carbon footprint, energy efficiency, and costs under various feedstocks and pyrolysis settings. Combining environmental and economic data with agronomic effectiveness will help determine WV's cost-effectiveness, market viability, and policy framework needed to position WV as a sustainable industrial product within a circular bioeconomy.

Ultimately, future research should systematically investigate how genotype, environment, and management practices interact to create the conditional effects we observed. This effort is crucial for developing predictive guidelines and enhancing the practical utility of WV applications.

In conclusion, transforming WV from an experimental amendment into a standard agricultural input depends on coordinated, interdisciplinary research across material science, soil biology, crop physiology, environmental economics, and industrial ecology. Making WV an effective, economically viable, and environmentally sustainable tool is crucial for building climate-resilient agricultural systems and securing crop production amidst environmental uncertainties.

5. Conclusion

This study offers a quantitative assessment of WV as a biostimulant affecting seed germination, physiological processes, and crop yield, synthesizing global data comprehensively. Our findings indicate that WV enhances germination in a concentration-dependent manner. Optimal soaking concentrations were 0.5–1.0% for monocots and 0.1–0.5% for dicots, boosting germination rates by 31.5% and 25.6%

respectively, without hindering seedling growth. Regarding yield, foliar sprays and soil applications increased crop productivity by an average of 19.4% and 17.8%, with effects influenced by application method, crop type, and environmental factors. Monocots responded best to multiple foliar sprays at concentrations $\leq 0.5\%$, while dicots preferred fewer applications within the 0.25–0.5% range. For soil treatments, small doses at 0.5–1.0% yielded optimal results balancing cost and gains. WV produced at low pyrolysis temperatures ($\leq 500^\circ\text{C}$) was more effective as a foliar treatment, while low-pH (≤ 4) WV was better suited to soil application. Foliar spraying performed better in high-nutrient soils, whereas soil application was more effective in soils with pH > 7 . Correlation analyses show WV boosts crop growth by activating leaf antioxidant enzymes and improving photosynthesis. Overall, this research demonstrates WV, derived from biomass, has significant unexploited potential to sustainably boost crop production, providing global data and practical parameters for precise application strategies across various crops and soil conditions.

CRediT authorship contribution statement

Qin-Fen Li: Writing – review & editing, Methodology, Funding acquisition. **Yousif Abdelrahman Yousif Abdellah:** Writing – review & editing, Methodology. **Rui-Long Wang:** Writing – review & editing, Project administration, Methodology, Funding acquisition. **Hao-Yu Wang:** Visualization, Methodology, Investigation. **Shi-Wen Deng:** Writing – original draft, Software, Methodology, Data curation.

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Declaration of Competing Interest

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.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.indcrop.2026.123931](https://doi.org/10.1016/j.indcrop.2026.123931).

Data availability

Data will be made available on request.

References

- Abdellah, Y.A., Gao, J., Shi, Z., Shi, X., Liu, W., Yang, C., Keiblinger, K.M., Zhao, X., Elsheikh, E.A., Iqbal, S., Sun, S., Liu, D., Yu, F., 2026. Synthesis of air pollution patterns and nutrient composition during organic fertilizer production: a meta-analytical study. *Environ. Biogeochem. Process.* 2, e005. <https://doi.org/10.48130/ebp-0025-0022>.
- Abdellah, Y.A.Y., Shi, Z., Luo, Y., Hou, W., Yang, X., Wang, R., 2022a. Effects of different additives and aerobic composting factors on heavy metal bioavailability reduction and compost parameters: a meta-analysis. *Environ. Pollut.* 307, 119549. <https://doi.org/10.1016/j.envpol.2022.119549>.
- Abdellah, Y.A.Y., Shi, Z., Sun, S., Luo, Y., Yang, X., Hou, W., Wang, R., 2022b. An assessment of composting conditions, humic matters formation and product maturity in response to different additives: a meta-analysis. *J. Clean. Prod.* 366, 132953. <https://doi.org/10.1016/j.jclepro.2022.132953>.
- Afsharipour, S., Seyedi, A., Dastjerdi, A.M., 2025. Salinity tolerance in *Cucumis sativus* seedlings: the role of pistachio wood vinegar on the improvement of biochemical parameters and seedlings vigor. *Bmc Plant. Biol.* 25, 224. <https://doi.org/10.1186/s12870-025-06237-y>.
- Carril, P., Bianchi, E., Cicchi, C., Coppi, A., Dainelli, M., Gonnelli, C., Loppi, S., Pazzagli, L., Colzi, I., 2023. Effects of wood distillate (pyroligneous acid) on the yield parameters and mineral composition of three leguminous crops. *Environments* 10 (7), 126. <https://doi.org/10.3390/ENVIRONMENTS10070126>.
- Clark, C.M., Tilman, D., 2008. Loss of plant species after chronic low-level nitrogen deposition to prairie grasslands. *Nature* 451, 712–715. <https://doi.org/10.1038/nature06503>.
- Deng, H., Zhang, Y., Liu, K., Mao, Q., Agathokleous, E., 2024. Allelopathic effects of eucalyptus extract and wood vinegar on germination and sprouting of rapeseed (*Brassica rapa* L.). *Environ. Sci. Pollut. Res.* 31 (3), 4280–4289. <https://doi.org/10.1007/s11356-023-31481-w>.
- Deng, S., Abdellah, Y.A.Y., Chen, H., Gao, P., Abdallah, M.M., Rana, M.S., Yu, F., Dai, Q., Wang, R., 2025a. Optimizing agricultural management practices to promote ratoon rice yield during ratoon crop: a comprehensive global meta-analysis. *Field Crop. Res.* 328, 109943. <https://doi.org/10.1016/j.fcr.2025.109943>.
- Deng, S., Liang, W., Chen, H., Abdallah, M.M., Wang, R., 2025b. The effect of microplastic pollution on rice growth, paddy soil properties and greenhouse gas emissions: a global meta-analysis. *Environ. Res.* 285, 122484. <https://doi.org/10.1016/j.envres.2025.122484>.
- Dykes, L., Rooney, L.W., Waniska, R.D., Rooney, W.L., 2005. Phenolic compounds and antioxidant activity of sorghum grains of varying genotypes. *J. Agric. Food Chem.* 53 (17), 6813–6818. <https://doi.org/10.1021/jf050419e>.
- Ebrahimi, G., Shakeri, A., Ahmadi, P., Dalvand, M., Shafie, M., Hosseinabadi, H.Z., 2022. Chemical constituents of palm wastes slow pyrolysis derived vinegar. *Maderas* 24 (47), 1–8. <https://doi.org/10.4067/s0718-221x2022000100447>.
- Ebrahimi, G., Ahmadi, P., Dalvand, M., 2025. Constituent elements, pH and electrical conductivity values of feedstock, ash and slow pyrolysis derived biochar of date palm wastes. *Drv. Ind.* 76 (2), 177–188. <https://doi.org/10.5552/drvid.2025.0223>.
- Ferguson, J.C., O'Donnell, C.C., Chauhan, B.S., Adkins, S.W., Kruger, G.R., Wang, R., Ferreira, P.H.U., Hewitt, A.J., 2015. Determining the uniformity and consistency of droplet size across spray drift reducing nozzles in a wind tunnel. *Crop. Prot.* 76, 1–6. <https://doi.org/10.1016/j.cropro.2015.06.008>.
- Fujioka, H., Samejima, H., Suzuki, H., Mizutani, M., Okamoto, M., Sugimoto, Y., 2019. Aberrant protein phosphatase 2c leads to abscisic acid insensitivity and high transpiration in parasitic striga. *Nat. Plants* 5 (3), 258–262. <https://doi.org/10.1038/s41477-019-0362-7>.
- Gujjar, R.S., Banyen, P., Chuekong, W., Worakan, P., Roytrakul, S., Supaibulwatana, K., 2020. A synthetic cytokinin improves photosynthesis in rice under drought stress by modulating the abundance of proteins related to stomatal conductance, chlorophyll contents, and rubisco activity. *Plants-Basel* 9 (9), 1106. <https://doi.org/10.3390/plants9091106>.
- Guo, J.H., Liu, X.J., Zhang, Y., Shen, J.L., Han, W.X., Zhang, W.F., Christie, P., Goulding, K.W.T., Vitousek, P.M., Zhang, F.S., 2010. Significant acidification in major Chinese croplands. *Science* 327, 1008–1010. <https://doi.org/10.1126/science.1182570>.
- Gurevitch, J., Koricheva, J., Nakagawa, S., Stewart, G., 2018. Meta-analysis and the science of research synthesis. *Nature* 555, 175–182. <https://doi.org/10.1038/nature25753>.
- He, L., Geng, K., Li, B., Li, S., Gustave, W., Wang, J., Jeyakumar, P., Zhang, X., Wang, H., 2025. Enhancement of nutrient use efficiency with biochar and wood vinegar: a promising strategy for improving soil productivity. *J. Sci. Food Agric.* 105 (1), 465–472. <https://doi.org/10.1002/jsfa.13844>.
- Hur, G., Ashraf, M., Nadeem, M.Y., Rehman, R.S., Thwin, H.M., Shakoor, K., Seleiman, M.F., Alotaibi, M., Yuan, B., 2025. Exogenous application of wood vinegar improves rice yield and quality by elevating photosynthetic efficiency and enhancing the accumulation of total soluble sugars. *Plant. Physiol. Biochem.* 218, 109306. <https://doi.org/10.1016/j.plaphy.2024.109306>.
- Iacomino, G., Idbella, M., Staropoli, A., Nanni, B., Bertoli, T., Vinale, F., Bonanomi, G., 2024. Understanding the potential of wood vinegar: chemical composition and biological effects on crops and pests. *Agron.-Basel* 14 (1), 114. <https://doi.org/10.3390/agronomy14010114>.
- Kenday, S.A., Logeshwaran, P., Kannappan, M., Mallavarapu, M., 2022. Effect of pyroligneous acid on the microbial community composition and plant growth-promoting bacteria (PGBP) in soils. *Soil. Syst.* 6 (1), 10. <https://doi.org/10.3390/soilsystems6010010>.
- Kim, T., Michniewicz, M., Bergmann, D.C., Wang, Z., 2012. Brassinosteroid regulates stomatal development by GSK3-mediated inhibition of a MAPK pathway. *Nature* 482, 419–422. <https://doi.org/10.1038/nature10794>.
- Kumar, S., Rahman, M., Bouket, A.C., Ahadi, R., Meena, M., Bhupenchandra, I., Singh, U. B., Arutselvan, R., Kumar, R., Singh, S.P., Kashyap, A.S., Tripathi, R., Gupta, S., Dutta, P., Harish, Singh, R., Swapnil, P., 2025. Unravelling the multifarious role of wood vinegar made from waste biomass in plant growth promotion, biotic stress tolerance, and sustainable agriculture. *J. Anal. Appl. Pyrolysis* 185, 106851. <https://doi.org/10.1016/j.jaap.2024.106851>.
- Kunrath, T.R., Lemaire, G., Teixeira, E., Brown, H.E., Ciampitti, I.A., Sadras, V.O., 2020. Allometric relationships between nitrogen uptake and transpiration to untangle interactions between nitrogen supply and drought in maize and sorghum. *Eur. J. Agron.* 120, 126145. <https://doi.org/10.1016/j.eja.2020.126145>.
- Lajeunesse, M.J., 2016. Facilitating systematic reviews, data extraction and meta-analysis with the metagear package for r. *Methods Ecol. Evol.* 3, 323–330. <https://doi.org/10.1111/2041-210X.12472>.
- Lambin, E.F., Meyfroidt, P., 2011. Global land use change, economic globalization, and the looming land scarcity. *Proc. Natl. Acad. Sci. U. S. A.* 9 (108), 3465–3472. <https://doi.org/10.1073/pnas.1100480108>.
- Liu, T.T., Wu, P., Wang, L.H., Zhou, Q., 2011. Response of soybean seed germination to cadmium and acid rain. *Biol. Trace Elem. Res.* 144, 1186–1196. <https://doi.org/10.1007/s12011-011-9053-6>.
- Lizcano, L.J., Bakkali, F., Ruiz-Larrea, M.B., Ruiz-Sanz, J.I., 2010. Antioxidant activity and polyphenol content of aqueous extracts from colombian amazonian plants with medicinal use. *Food Chem.* 4 (119), 1566–1570. <https://doi.org/10.1016/j.foodchem.2009.09.043>.
- Lu, X., Jiang, J., He, J., Sun, K., Sun, Y., 2019. Effect of pyrolysis temperature on the characteristics of wood vinegar derived from Chinese fir waste: a comprehensive study on its growth regulation performance and mechanism. *ACS Omega* 4 (21), 19054–19062. <https://doi.org/10.1021/acsomega.9b02240>.
- Luo, X., Wang, Z., Mekki, K., Wang, X., Liu, B., Zheng, H., You, X., Li, F., 2019. Effect of co-application of wood vinegar and biochar on seed germination and seedling growth. *J. Soils Sediment.* 19 (12), 3934–3944. <https://doi.org/10.1007/s11368-019-02365-9>.
- Ma, J., Islam, F., Ayyaz, A., Fang, R., Hannan, F., Farooq, M.A., Ali, B., Huang, Q., Sun, R., Zhou, W., 2022a. Wood vinegar induces salinity tolerance by alleviating oxidative damages and protecting photosystem ii in rapeseed cultivars. *Ind. Crop. Prod.* 189, 115763. <https://doi.org/10.1016/j.indcrop.2022.115763>.
- Ma, J., Liu, K., Dong, X., Chen, C., Qiu, B., Zhang, S., 2022b. Effects of leaf surface roughness and contact angle on in vivo measurement of droplet retention. *Agronomy* 12 (9), 2228. <https://doi.org/10.3390/agronomy12092228>.
- Mahmud, S., Kamruzzaman, M., Bhattacharyya, S., Alharbi, K., Moneim, D.A.E., Mostafa, M.G., 2023. Acetic acid positively modulates proline metabolism for mitigating PEG-mediated drought stress in maize and arabidopsis. *Front. Plant. Sci.* 14, 1167238. <https://doi.org/10.3389/fpls.2023.1167238>.
- Maliang, H.D., Li, X.X., Wang, Y.F., Ma, J.Y., 2025. Nature's chemical warfare: deconstructing bamboo tar's phytotoxic signature for targeted weed biocontrol. *Ind. Crop. Prod.* 234, 121586. <https://doi.org/10.1016/j.indcrop.2025.121586>.
- Maresca, V., Fedeli, R., Vannini, A., Munzi, S., Correa, A., Cruz, C., Loppi, S., 2024. Wood distillate enhances seed germination of chickpea, lettuce, and basil. *Appl. Sci.-Basel* 14 (2), 631. <https://doi.org/10.3390/app14020631>.
- Mathew, S., Zakaria, Z.A., 2015. Pyroligneous acid - the smoky acidic liquid from plant biomass. *Appl. Microbiol. Biotechnol.* 99 (2), 611–622. <https://doi.org/10.1007/s00253-014-6242-1>.
- Muhammad, S., Wuyts, K., Nuyts, G., De Wael, K., Samson, R., 2020. Characterization of epicuticular wax structures on leaves of urban plant species and its association with leaf wettability. *Urban. For. Urban. Green.* 47, 126557. <https://doi.org/10.1016/j.ufug.2019.126557>.
- Mungkunkamchao, T., Kesmla, T., Pimratch, S., Toomsan, B., Jothityangkoon, D., 2013. Wood vinegar and fermented bioextracts: natural products to enhance growth and yield of tomato (*Solanum lycopersicum* L.). *Sci. Hortic.* 154, 66–72. <https://doi.org/10.1016/j.scienta.2013.02.020>.
- Ochoa-Lopez, S., Damian, X., Rebollo, R., Fornoni, J., Dominguez, C.A., Boege, K., 2020. Ontogenetic changes in the targets of natural selection in three plant defenses. *New Phytol.* 226 (5), 1480–1491. <https://doi.org/10.1111/nph.16422>.
- Ofoe, R., Mousavi, S.M.N., Thomas, R.H., Abbey, L., 2024. Foliar application of pyroligneous acid acts synergistically with fertilizer to improve the productivity and phytochemical properties of greenhouse-grown tomato. *Sci. Rep.* 14, 1934. <https://doi.org/10.1038/s41598-024-52026-2>.
- Pan, Y.H., Guo, J.J., Fan, L.Y., Ji, Y., Liu, Z., Wang, F., Pu, Z.X., Ling, N., Shen, Q.R., Guo, S.W., 2022. The source-sink balance during the grain filling period facilitates rice production under organic fertilizer substitution. *Eur. J. Agron.* 134, 126468. <https://doi.org/10.1016/j.eja.2022.126468>.
- Pecl, G.T., Araujo, M.B., Bell, J.D., Blanchard, J., Bonebrake, T.C., Chen, I., Clark, T.D., Colwell, R.K., Danielsen, F., Evengard, B., Falconi, L., Ferrier, S., Frusher, S., Garcia, R.A., Griffiths, R.B., Hobday, A.J., Janion-Scheepers, C., Jarzyna, M.A.,

- Jennings, S., Lenoir, J., Linnetved, H.I., Martin, V.Y., McCormack, P.C., McDonald, J., Mitchell, N.J., Mustonen, T., Pandolfi, J.M., Pettorelli, N., Popova, E., Robinson, S.A., Scheffers, B.R., Shaw, J.D., Sorte, C.J.B., Strugnell, J.M., Sunday, J. M., Tuanmu, M., Verges, A., Villanueva, C., Wernberg, T., Wapstra, E., Williams, S. E., 2017. Biodiversity redistribution under climate change: impacts on ecosystems and human well-being. *Science* 355, eaai9214. <https://doi.org/10.1126/science.aai9214>.
- Rahman, M., Mostofa, M.G., Keya, S.S., Rahman, A., Das, A.K., Islam, R., Abdelrahman, M., Bhuiyan, S.U., Naznin, T., Ansary, M.U., Tran, L.P., 2021. Acetic acid improves drought acclimation in soybean: an integrative response of photosynthesis, osmoregulation, mineral uptake and antioxidant defense. *Physiol. Plant.* 172, 334–350. <https://doi.org/10.1111/ppl.13191>.
- Ribeiro, R.P., Costa, L.C., Medina, E.F., Araujo, W.L., Zsogon, A., Ribeiro, D.M., 2018. Ethylene coordinates seed germination behavior in response to low soil pH in *Stylosanthes humilis*. *Plant. Soil.* 425, 87–100. <https://doi.org/10.1007/s11104-018-3572-2>.
- Rosenberg, M.S., 2005. The file-drawer problem revisited: a general weighted method for calculating fail-safe numbers in meta-analysis. *Evolution* 59, 464–468. <http://doi.org/10.1111/j.0014-3820.2005.tb01004>.
- Salesse-Smith, C.E., Wang, Y., Long, S.P., 2025. Increasing rubisco as a simple means to enhance photosynthesis and productivity now without lowering nitrogen use efficiency. *New. Phytol.* 245 (3), 951–965. <https://doi.org/10.1111/nph.20298>.
- Seo, P.D., Ultra, V.U., Rubenecia, M.R.U., Lee, S.C., 2015. Influence of herbicides-pyroligneous acids mixtures on some soil properties, growth and grain quality of paddy rice. *Int. J. Agric. Biol.* 17 (3), 499–506. <https://doi.org/10.17957/IJAB/17.3.14.349>.
- Springmann, M., Clark, M., Mason-D'Croz, D., Wiebe, K., Bodirsky, B.L., Lassaletta, L., de Vries, W., Vermeulen, S.J., Herrero, M., Carlson, K.M., Jonell, M., Troell, M., DeClerck, F., Gordon, L.J., Zurayk, R., Scarborough, P., Rayner, M., Loken, B., Fanzo, J., Godfray, H.C.J., Tilman, D., Rockstrom, J., Willett, W., 2018. Options for keeping the food system within environmental limits. *Nature* 562, 519–525. <https://doi.org/10.1038/s41586-018-0594-0>.
- Torra, J., la Cruz, R.A., de Figueiredo, M.R.A., Gaines, T.A., Jugulam, M., Jr, A.M., Palma-Bautista, C., Rojano-Delgado, A.M., Riechers, D.E., 2024. Metabolism of 2,4-d in plants: comparative analysis of metabolic detoxification pathways in tolerant crops and resistant weeds. *Pest. Manag. Sci.* 80 (12), 6041–6052. <https://doi.org/10.1002/ps.8373>.
- Viechtbauer, W., 2010. Conducting meta-analyses in R with the metafor package. *J. Stat. Softw.* 3 (36), 1–48. <http://doi.org/10.18637/jss.v036.i03>.
- Wang, Y., Yu, H.J., Wang, S.J., Li, H.Q., Wang, Y.T., 2024. Unveiling trends and environmental impacts of global black soil crop production: a comprehensive assessment. *Resour. Conserv. Recycl.* 208, 107717. <https://doi.org/10.1016/j.resconrec.2024.107717>.
- Wu, Q., Zhang, S., Hou, B., Zheng, H., Deng, W., Liu, D., Tang, W., 2015. Study on the preparation of wood vinegar from biomass residues by carbonization process. *Bioresour. Technol.* 179, 98–103. <https://doi.org/10.1016/j.biortech.2014.12.026>.
- Yan, X.Q., Wang, Z.J., Bao, J., Zhao, M.Q., Wang, M.J., Sun, P.B., Jia, Y.S., Gengtu, 2025. Integrated microbiological and metabolomic analysis reveals the mechanisms by which biochar and wood vinegar enhance the cold tolerance of alfalfa. *Ind. Crop. Prod.* 238, 122388. <https://doi.org/10.1016/j.indcrop.2025.122388>.
- Yang, Q.F., Ma, J.H., Yang, F., Zheng, H., Lu, Z.B., Qiao, F., Zhang, K.N., Gong, H.R., Men, X.Y., Li, J., Ouyang, F., Ge, F., 2023. The hidden indirect environmental effect undercuts the contribution of crop nitrogen fertilizer application to the net ecosystem economic benefit. *J. Clean. Prod.* 426, 139204. <https://doi.org/10.1016/j.jclepro.2023.139204>.
- Yu, Z., Wang, H., Zhu, Y., Zhao, H., Xin, M., Sun, Y., 2024. Biochar and wood vinegar amendments influence the potential nitrification rate and nitrifier communities in high pH sodic saline soils. *Eur. J. Soil. Biol.* 122, 103658. <https://doi.org/10.1016/j.ejsobi.2024.103658>.
- Yuan, Y., Kong, Q., Zheng, Y., Zheng, H., Liu, Y., Cheng, Y., Zhang, X., Li, Z., You, X., Li, Y., 2022. Co-application of biochar and pyroligneous acid improved peanut production and nutritional quality in a coastal soil. *Environ. Technol. Innov.* 28, 102886. <https://doi.org/10.1016/j.eti.2022.102886>.
- Zhang, K., Khan, Z., Liu, J., Luo, T., Zhu, K., Hu, L., Bi, J., Luo, L., 2022. Germination and growth performance of water-saving and drought-resistant rice enhanced by seed treatment with wood vinegar and biochar under dry direct-seeded system. *Agron.-Basel* 12 (5), 1223. <https://doi.org/10.3390/agronomy12051223>.
- Zhang, S.W., Zhu, Q.C., de Vries, W., Ros, G.H., Chen, X.H., Muneer, M.A., Zhang, F.S., Wu, L.Q., 2023. Effects of soil amendments on soil acidity and crop yields in acidic soils: a world-wide meta-analysis. *J. Environ. Manag.* 345, 118531. <https://doi.org/10.1016/j.jenvman.2023.118531>.
- Zhao, J.Z., Wang, J.Q., Liu, J., Zhang, P.H., Kudoyarova, G., Liu, C.J., Zhang, K.W., 2024a. Spatially distributed cytokinins: metabolism signaling, and transport. *Plant. Commun.* 5 (7), 100936. <https://doi.org/10.1016/j.xplc.2024.100936>.
- Zhao, W., Zhao, H., Sun, X., Wang, H., Sun, Y., Liang, Y., Wang, D., 2024b. Biochar and wood vinegar altered the composition of inorganic phosphorus bacteria community in saline-alkali soils and promoted the bioavailability of phosphorus. *J. Environ. Manag.* 370, 122501. <https://doi.org/10.1016/j.jenvman.2024.122501>.
- Zhou, H., Zhang, N., Mu, L., Gao, L., Bao, L., Tang, C., 2025. New enlightenment on the regulatory effects of acids and phenolic compounds in wood vinegar, a by-product of biomass pyrolysis, on tomato production. *Front. Microbiol.* 16, 1538998. <https://doi.org/10.3389/fmicb.2025.1538998>.
- Zhou, J.Y., Yu, J.B., Diao, C.Q., Qin, Q.Q., Wang, X., 2022. Effects of wood vinegar on the photosynthetic properties and root growth of flue-cured tobacco under drought stress. *Hubei Agric. Sci.* 61 (4), 85–88. <https://doi.org/10.14088/j.cnki.issn0439-8114.2022.04.016>.
- Zhou, R.R., Wang, Y., Tian, M.M., Jahan, M.S., Shu, S., Sun, J., Li, P.P., Ahammed, G.J., Guo, S.R., 2021. Mixing of biochar, vinegar and mushroom residues regulates soil microbial community and increases cucumber yield under continuous cropping regime. *Appl. Soil. Ecol.* 161, 103883. <https://doi.org/10.1016/j.apsoil.2021.103883>.
- Zhu, J., Zheng, G., Tao, Y., Liao, W., Ye, C., Xu, Y., Xiao, D., Chu, G., Xu, C., Wang, D., 2026. Wood vinegar enhances seedling rate of rice seeds under flooding stress by mitigating oxidative damage and maintaining energy homeostasis. *Rice Sci.* 33 (1), 129–140. <https://doi.org/10.1016/j.rsci.2025.08.006>.
- Zhu, K.Y., Tao, W.L., Jiang, Y., Zhang, W.Y., Wang, Z., Gu, J.F., Zhang, J.H., Yang, J.C., 2025. Changes in lysine content in rice caryopses during grain filling and in response to mid-season nitrogen management. *Field Crop. Res.* 333, 110062. <https://doi.org/10.1016/j.fcr.2025.110062>.