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**Wanqiong Shi**
**Yongfeng Liao**
2727555930qqc.om

Gansu Forestry Voctech University
**Yaxiong Zhang**
**Hongjie Li**
**Hai Wang**

**Research Article**

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# Effects of biochar on plant growth and physiological responses under drought stress: a meta-analysis

**Wanqiong Shi[1]; Yongfeng Liao[1,3,*]; Yaxiong Zhang[1,3]; Hongjie Li[1,3]; Hai Wang[2,4]**

1 School of Forestry Engineering, Gansu Forestry Voctech University, Tianshui 741020, Gansu Province, PR China

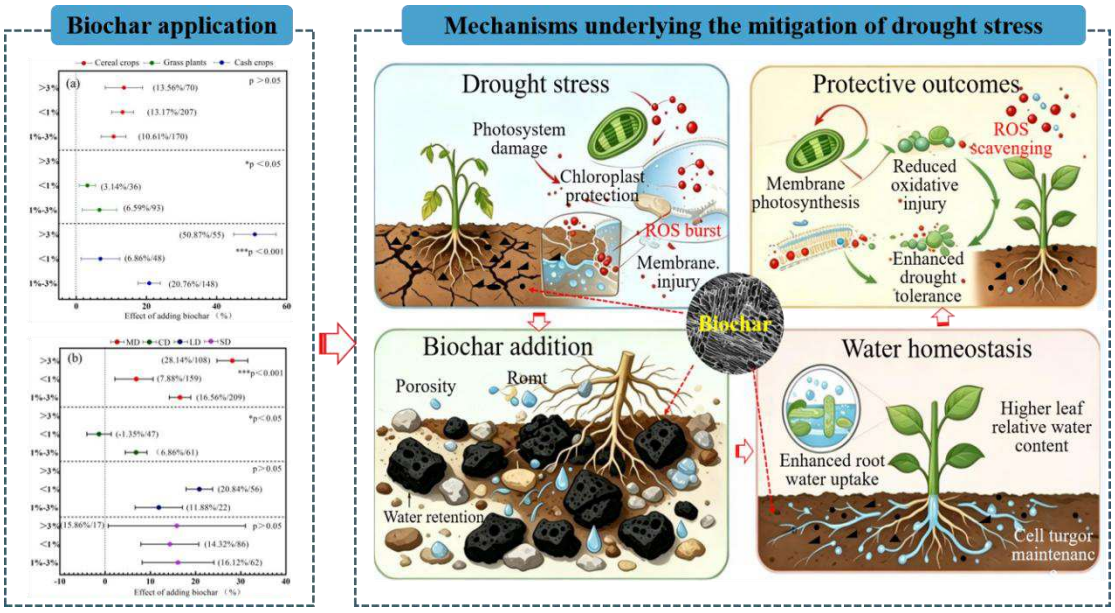
2 School of Environmental Engineering, Gansu Forestry Voctech University, Tianshui 741020, Gansu Province, PR China

3 College of Forestry, Gansu Agricultural University, Lanzhou 730070, Gansu Province, PR China

4 College of Resources and Environmental Sciences, Gansu Agricultural University, Lanzhou 730070, Gansu Province, PR China

* Corresponding author. E-mail: 272755593@qq.com

## Graphical Abstract




## Abstract

***Background and Aims*** Global climate anomalies have intensified agricultural drought stress, severely inhibiting plant growth and threatening food security. Biochar

can effectively alleviate drought stress in plants; however, its drought-mitigating effects vary considerably among different conditions and have not yet been quantitatively characterized.

***Methods*** In this study, a meta-analysis was conducted to investigate the effects of biochar on plant growth and physiological responses under drought stress.

***Results*** The results showed that, under drought stress, biochar produced the greatest increase in plant growth in cash crops (23.05%), followed by cereal crops (12.29%) and grass plants (3.78%). After biochar application, plant growth increased by 15.12%, 16.13%, 18.59%, and 3.19% under severe drought (SD), moderate drought (MD), mild drought (LD), and normal water supply (CD) conditions, respectively, indicating that biochar effectively alleviated drought-induced damage. Application rates of 1%–3% improved plant physiological status and alleviated oxidative damage, whereas higher application rates enhanced the supply of soil mineral nutrients. Compared with wood-derived biochar, straw-derived biochar exhibited broader applicability and stronger drought-mitigating effects. The underlying mechanisms are that biochar alleviates crop water stress by improving soil properties, enhancing water and nutrient supply, activating the plant antioxidant system, and maintaining photosynthetic stability.

***Conclusion*** In summary, biochar application promoted plant growth and significantly alleviated drought stress, providing a theoretical basis for the scientific application of biochar in arid and semi-arid regions.

**Key words:** Drought stress; Water use efficiency; Biochar; Meta-analysis; Plant

growth

# Introduction

Owing to global climate anomalies and ecological degradation, the frequency, duration, and intensity of agricultural drought have increased markedly, and soil water deficits have become a major abiotic constraint on agricultural productivity and food security (Yang et al., 2021; Wen et al., 2026). Drought not only reduces plant biomass and causes extensive plant mortality but also severely disrupts ecosystem functioning, ultimately leading to biodiversity loss Drought stress disturbs plant water balance, accelerates leaf senescence, and reduces photosynthetic rates (Liang et al., 2019); it also induces the excessive accumulation of reactive oxygen species (ROS) (Vijayaraghavareddy et al., 2022), triggers membrane lipid peroxidation (Soliman et al., 2026), and interferes with nutrient uptake and transport (Tang et al., 2023), ultimately leading to substantial declines in crop biomass and yield. Therefore, developing low-cost and environmentally friendly soil amendment strategies to enhance plant drought tolerance is crucial for sustainable agricultural development in arid and semi-arid regions.

Biochar, a carbon-rich amendment produced by pyrolysis, is characterized by high porosity and favorable surface chemical properties (Oktaviana et al., 2025). It can improve soil physical structure, enhance soil water retention capacity, immobilize mineral nutrients, and regulate the rhizosphere microenvironment, thereby showing great potential for alleviating drought stress in plants (Ullah et al., 2021; Malik et al., 2024; Zhang et al., 2026a). The effectiveness of biochar in maintaining soil moisture

varies with biochar properties, application rates, and environmental conditions (Langeroodi et al., 2019; Jin et al., 2019; Wu et al., 2022). Faloye et al. (2019) reported that applying cattle manure biochar at 15 and 20 t/ha under sandy soil conditions increased plant water use efficiency by 139% and 91%, respectively, while maize straw residue biochar also improved crop water use efficiency by 9.8%–20.5%. In addition, numerous studies have confirmed that biochar can increase leaf chlorophyll content and improve gas exchange parameters under drought conditions (Obadi et al., 2023). Biochar can also activate the antioxidant defense system, alleviate oxidative damage, improve osmotic adjustment, and thereby mitigate drought stress and promote plant growth (Mishra et al., 2026; Lee et al., 2025; Khan et al., 2021; Obadi et al., 2023). However, the drought-mitigating effects of biochar are influenced by multiple factors, including feedstock type, application rate, drought intensity, background soil properties, and crop species (Saleem, 2026; Bashir et al., 2025; Obia et al., 2016). Although biochar can significantly improve crop drought resistance, Zhu et al. (2023) reported that high-dose biochar application significantly reduced rice panicle number and seed-setting rate and adversely affected the diversity and stability of soil bacterial and archaeal communities. Similarly, Rodríguez-Vila et al. (2022) reported that the addition of corncob biochar reduced plant growth and total micronutrient uptake in neutral soils. Therefore, individual studies, which are constrained by specific experimental conditions and plant types, are insufficient to quantitatively estimate the overall effects of biochar on plant growth and physiological responses under drought stress, and the moderating effects of these

71 factors remain to be quantitatively characterized.

72 Although numerous field and pot experiments have investigated the effects of
73 biochar on plant physiological responses under drought stress, the results remain
74 inconsistent (Zhang et al., 2023; Duan et al., 2024). Moreover, differences in drought
75 treatment methods, crop types, and biochar application rates have made it difficult to
76 quantitatively compare the effects of biochar on plant growth, photosynthetic
77 performance, and antioxidant responses under drought stress (Bashir et al., 2025).
78 Therefore, in this study, we conducted a meta-analysis to quantitatively evaluate the
79 effects of biochar application on plant growth and physiological responses under
80 drought stress.

81 Therefore, this study conducted a meta-analysis to quantitatively evaluate the
82 overall effects of biochar on plant growth and physiological responses under drought
83 stress. Specifically, we aimed to: (i) quantify the overall effects of biochar on plant
84 growth under drought stress; (ii) evaluate the effects of biochar on plant physiological
85 and antioxidant responses; and (iii) elucidate the potential mechanisms underlying the
86 drought-mitigating effects of biochar, with particular emphasis on the moderating
87 effects of key factors such as drought intensity and crop type. The findings provide
88 quantitative evidence and a theoretical basis for the scientific application of biochar in
89 arid and semi-arid agricultural regions.

## 90 Materials and Methods

### 91 *Data sources and grouping*

92 Data were collected from publications indexed in the Web of Science

(https://apps.webofknowledge.com/) and the China National Knowledge Infrastructure (CNKI, http://www.cnki.net/) before June 2026, using the following search keywords: “biochar”, “drought stress”, “drought”, “deficit irrigation”, “plant growth”, “yield”, “antioxidant”, and “photosynthesis”. To meet the requirements of meta-analysis, the selected studies followed the criteria below: (i) the control and treatment groups were conducted under the same experimental conditions with identical management measures, with the no-biochar treatment serving as the control and the biochar-amended treatment as the treatment group; (ii) the crop species, drought levels, and experimental environments were identical between the treatment and control groups; (iii) each treatment had a fixed number of replicates; (iv) the mean, standard deviation (SD), or standard error (SE) were reported in the article or its supplementary materials; (v) soil physicochemical and plant physiological indicators were explicitly measured, with consistent measurement methods for the same indicator across different treatments; and (vi) evaluation-type articles, review articles, and dissertations were excluded. The screening process is shown in Fig. S1.

Based on the above criteria, a total of 30 valid publications and 876 sets of valid data were screened out.

$$SD=SE\times\sqrt{n} \quad (1)$$

where $n$ is the number of replicates.

## *Data classification*

In this study, the influencing variables were grouped as follows: plants were classified into three categories, namely cereal crops, cash crops, and grass plants;

biochar was categorized into two types according to feedstock, namely straw-derived and wood-derived biochar; drought intensity was divided into four levels, i.e., severe drought (SD), moderate drought (MD), mild drought (LD), and normal water supply (CD); and the experimental types comprised pot experiments and field experiments. In addition, the following evaluation indicators were extracted: chlorophyll traits (Chl), plant growth traits (G), antioxidant and osmotic adjustment traits (AO), photosynthetic traits (PS), gas exchange traits (GE), biomass and yield traits (BY), ion exchange traits (IQ), mineral nutrition traits (MN), and soil physicochemical traits (SPC).

*Data analysis*

Using the means, numbers of replicates, and standard deviations of the control and treatment groups in each study, the natural logarithm of the response ratio (ln*RR*), a commonly used effect size in ecology, was adopted as the effect size. The variance of ln*RR* ($v_i$) was calculated according to Eqs. (2) and (3), respectively:

$$lnRR=ln\frac{X_t}{X_C} \quad (2)$$

$$v_i=\frac{S_t^2}{n_t X_t^2}+\frac{S_c^2}{n_c X_c^2} \quad (3)$$

Where, $X_t$ and $X_c$ are the means of the treatment and control groups, respectively; $S_t$ and $S_c$ are the standard deviations of the treatment and control groups, respectively; and $n_t$ and $n_c$ are the numbers of replicates of the treatment and control groups, respectively.

In the meta-analysis, a random-effects model was employed to estimate the mean cumulative effect size and its 95% confidence interval (CI) (Sun et al., 2020). If the

95% CI overlapped with zero, the effect of biochar on the corresponding variable (drought intensity, crop type, or evaluation indicator) was considered not significant; if the 95% CI did not include zero, biochar application exerted a positive (>0) or negative (<0) effect on the corresponding variable (Ren et al., 2022; Liu et al., 2023).

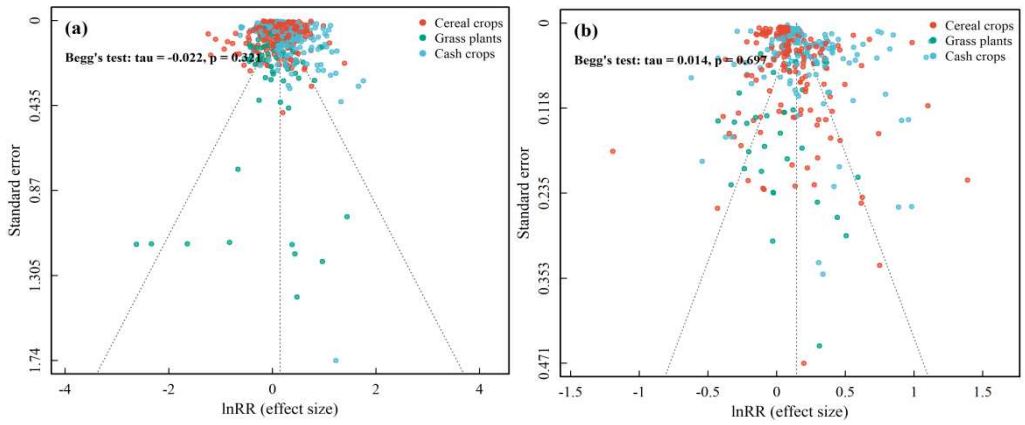
To facilitate the interpretation of the effects of biochar application on crop types, physicochemical properties, and drought stress, ln*RR* and its 95% CI were converted into percentage changes (Liu et al., 2023).

$$Percentage=\left(e^{\ln RR}-1\right)\times 100\% \quad (4)$$

*Publication bias test*

A funnel plot was used to visually assess the presence of publication bias. In the absence of publication bias, the funnel plot resembles an inverted, symmetrical funnel; otherwise, it is asymmetric (Wang et al., 2019a). The $Q$ statistic and $I^2$ index were used to evaluate between-study heterogeneity, with larger $I^2$ values indicating higher heterogeneity. Studies have shown that biochar application indeed exerts significant effects on drought indicators and plant physicochemical indicators, and all indicators exhibited high heterogeneity, with biochar application effectively alleviating the effects of drought stress on plants (Bai et al., 2026). Table S1 presents the bias tests for the effects of biochar on crop types and drought stress; the fail-safe numbers ($N_{fs}$) were all greater than $5n + 10$. Fig. 1 shows the funnel plots of the publication bias tests for biochar application. Begg's rank correlation test yielded tau values of −0.022 and 0.04 for the overall biochar effect and the 1%–3% application rate subgroup, respectively, with $p$ values of 0.321 and 0.697 (both $p > 0.05$), indicating no

159 significant publication bias. Sensitivity analysis further confirmed the robustness and
160 reliability of the pooled effect sizes.




161

162 **Fig. 1**. Funnel plots of the publication bias test [(a) overall biochar application; (b) biochar
163 application at 1%–3% in the subgroup].

164 *Data processing*

165 Excel 2019 was used to create and manage the dataset, MetaWin 2.1 was used to
166 perform the meta-analysis, GraphPad Prism 9 was used to generate forest plots, and R
167 software was used to conduct Begg's bias test and to generate funnel plots and
168 correlation heatmaps.

169 # Results

170 *Overall effects of biochar application on plant growth under drought*
171 *stress*

172 Subgroup analysis showed that exogenous biochar application significantly
173 increased plant biomass, with pronounced species-specific responses among cash
174 crops, grass plants, and cereal crops. Compared with the control, biochar application

increased the biomass of cash crops, grass plants, and cereal crops by 23.05% ($p$ < 0.0001), 3.78% ($p$ > 0.05), and 12.29% ($p$ < 0.05), with 95% CIs of 20.57%–25.53%, 1.72%–5.85%, and 10.17%–14.42%, respectively (Fig. S2a). Fig. 2 shows the overall effects of different biochar application rates on crop types and drought stress. In Fig. 2a, subgroup analysis was performed according to crop type and biochar application rate. At application rates >3%, biochar exerted the greatest effects on the indicators of cash crops and cereal crops, with effect sizes of 13.56% and 50.87%, respectively. At application rates <1%, the variation in effect sizes was relatively small, and cereal crops exhibited higher tolerance to changes in the biochar application rate, with stable improvement achievable at low application rates. Between-group heterogeneity tests showed that the biochar application rate significantly altered the effect levels for cash crops ($p$ < 0.001), whereas it did not significantly alter the effect levels for cereal crops ($p$ > 0.05).

After biochar application, the overall effect sizes for plant growth increased by 15.12% ($p$ > 0.05), 16.13% ($p$ < 0.0001), 18.59% ($p$ > 0.05), and 3.19% ($p$ < 0.01) under SD, MD, LD, and CD conditions, with 95% CIs of 10.46%–19.79%, 14.45%–17.40%, 16.07%–21.11%, and 1.41%–4.96%, respectively (Fig. S2b). As shown in Fig. 2b, among the subgroups, the effect of the biochar application rate was most sensitive under MD stress ($p$ < 0.001), with the effect size increasing from 7.88% to 28.14% as the application rate increased. Between-group heterogeneity was not significant under LD and SD stress ($p$ > 0.05); all biochar application rates exerted

positive effects, and further increasing the application rate contributed little to additional drought alleviation.

Overall, biochar application promoted plant growth and alleviated drought stress. The fail-safe numbers and Begg's test confirmed the reliability of the results. The overall CIs did not overlap with zero, indicating that biochar at different application rates exerted statistically significant promoting effects on the physicochemical indicators of the three crop types and alleviated the effects of drought.

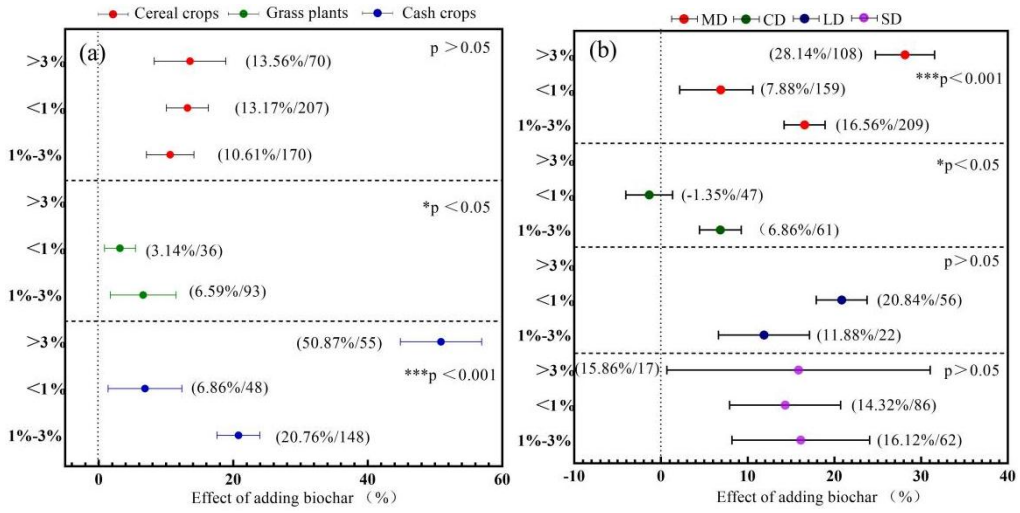



**Fig. 2**. Effect sizes of biochar at different application rates on plants (a) and drought stress (b).

## *Effects of biochar application rate on plant physiological growth and the antioxidant system*

Fig. 3 shows the effects of biochar application rate on crop physiological growth. When the biochar application rates were <1%, 1%–3%, and >3%, between-group heterogeneity was highly significant for all rates ($p$ < 0.001), indicating that the

application rate significantly regulated the response of various plant indicators. In Fig. 3a, the moderate application rate (1%–3%) was most effective in alleviating oxidative damage, with AO traits decreasing by 18.37% (95% CI: −23.61% to −13.12%); except for PS traits, which showed no significant change, all other indicators were significantly increased, with MN traits increasing by 47.92% (95% CI: 43.29%–52.55%). At the low application rate (<1%), only AO traits significantly decreased by 4.54% (95% CI: −7.95% to −1.14%), indicating a decline in antioxidant capacity, whereas most other indicators showed slight positive responses. Notably, the 95% CIs of IQ traits and GE traits both crossed zero, indicating that biochar application at <1% could not significantly improve leaf gas exchange efficiency or ion uptake capacity (Fig. 3b). At the high application rate (>3%), the increase in MN traits rose to 51.11% (95% CI: 45.65%–56.57%), the highest across all application gradients (Fig. 3c).

In terms of plant species, under the combined effects of drought and biochar, the Chl traits of cereal crops increased by 10.18% (95% CI: 5.37%–16.75%), whereas cash crops and grass plants showed no significant changes, indicating that the physiological regulation of biochar on cereal crops was significantly greater than that on cash crops and grass plants ( Figs. S3).

In summary, MN traits were the most sensitive to changes in the biochar dosage, with the promoting effects continuously strengthening as the application rate increased. Both <1% and 1%–3% application rates alleviated crop oxidative stress, and the 1%–3% rate exerted balanced effects on crop physiological regulation and soil properties, whereas high rates mainly substantially enhanced crop nutrient uptake.

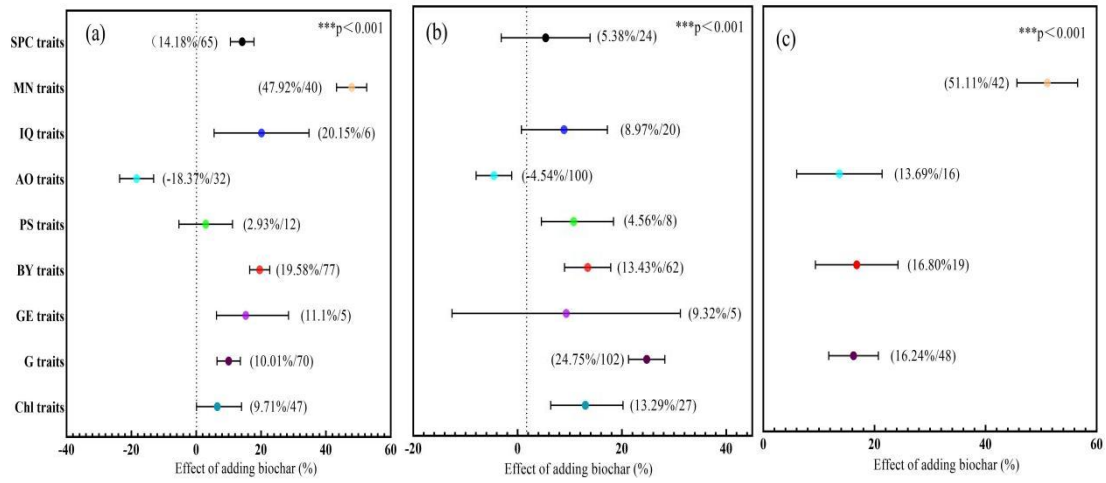



**Fig. 3**. Effect sizes of biochar application rate on plant physiological regulation and soil physicochemical properties [(a) 1%–3%; (b) <1%; (c) >3%].

## *Effects of soil water conditions on plant physiological growth*

Fig. 4 presents the subgroup analysis of the effects of water conditions on plant physiological regulation and soil physicochemical properties. As shown in Fig. 4, between-group heterogeneity was highly significant for MD, SD, and CD ($p < 0.001$), whereas no significant difference was detected for LD ($p > 0.05$), indicating that water stress intensity significantly regulated the responses of various plant indicators.

The results showed that under severe drought, MN traits increased by 27.22% (95% CI: 17.74%–35.70%), and various plant growth and photosynthetic indicators were significantly upregulated, along with improved soil physicochemical properties, with SPC traits increasing by 13.03% (95% CI: 5.47%–20.59%). Under moderate drought, the increase in mineral nutrition (MN) traits was the highest (53.80%, 95% CI: 49.86%–57.75%), accompanied by a significant decrease in AO traits of 9.81%

(95% CI: −13.29% to −6.34%), conferring the dual advantages of promoting nutrient accumulation and alleviating oxidative stress. Under mild drought, the regulation of all indicators was weak, with no obvious differentiation among indicators. Under normal water conditions, the overall improvement effect was the weakest, with only a slight reduction in oxidative damage. Overall, mineral nutrition indicators were the most sensitive to drought stress, and the promoting effects exhibited a trend of first increasing and then decreasing with increasing stress intensity, with moderate drought being the optimal water regime for biochar improvement.

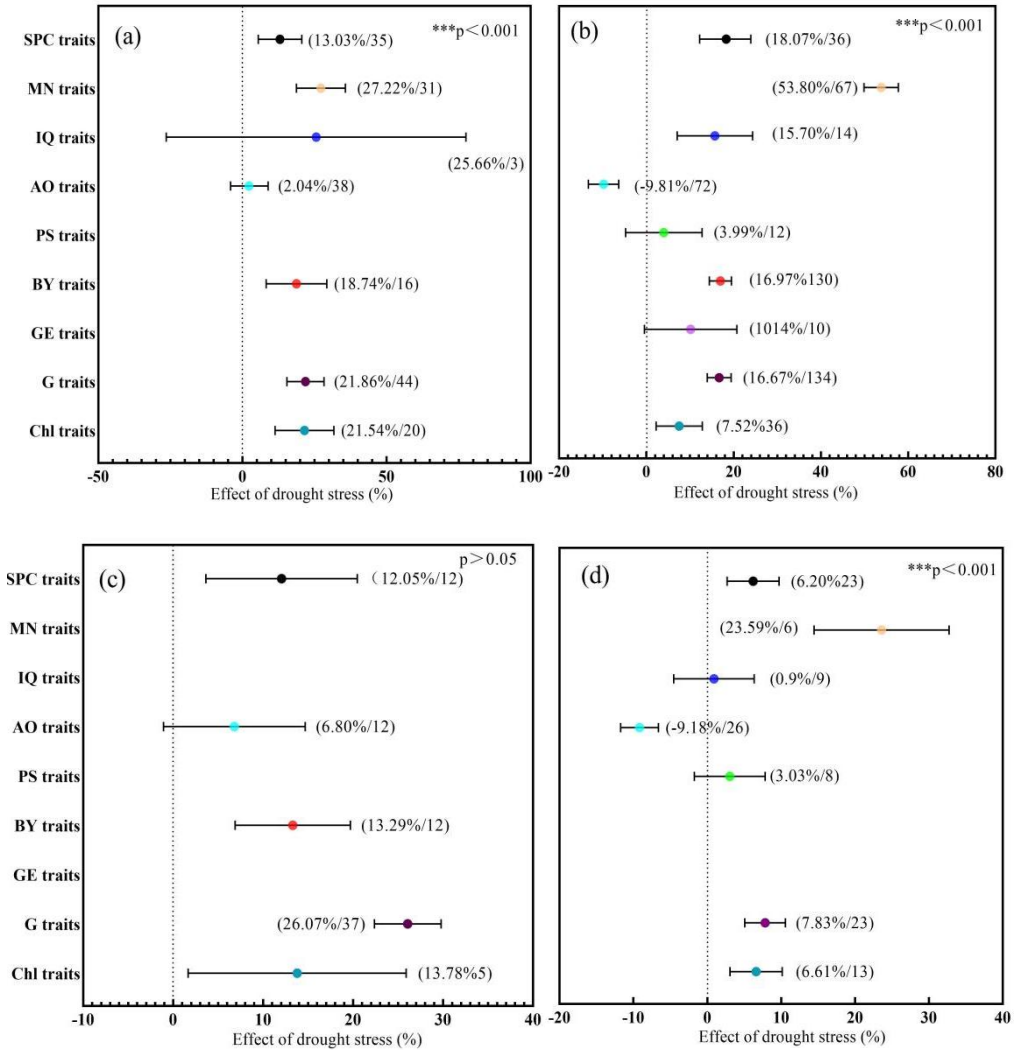


**Fig. 4**. Effect sizes of drought stress on plant physiological regulation and soil physicochemical properties [(a) SD; (b) MD; (c) LD; (d) CD].

## *Differences in biochar effects under different moderating variables*

Fig. 5 compares the ameliorative effects of straw-derived and wood-derived biochar. Subgroup analysis showed that, for straw biochar, between-group differences were highly significant ($p < 0.001$) at both the soil and plant physiological regulation levels, whereas for wood biochar, only two soil categories were available and no significant between-group differences were found ($p > 0.05$). Straw biochar exerted positive effects under all four water stress regimes, with the greatest effect size increase of 20.14% (95% CI: 14.58%–25.71%) under LD drought (Fig. 5a). It also exerted significant positive effects on all three plant types, with the highest increase in cash crops (23.94%, 95% CI: 21.60%–26.68%); owing to insufficient data, no valid effect size was obtained for wood biochar (Fig. 5b). Analyses of plant and soil physicochemical indicators showed that straw biochar significantly increased MN traits by 46.97% (95% CI: 43.16%–50.78%) while alleviating antioxidant stress, with AO traits decreasing by 5.71% (95% CI: −8.64% to −2.77%); wood biochar had only limited soil data with a relatively low degree of improvement (Fig. 5c1 and 5c2).

Subgroup analysis was also conducted by experimental type (pot vs. field). Both cash crops and cereal crops showed greater improvement in field experiments than in pot experiments: cash crops increased by 13.70% and 6.56% in field and pot experiments, respectively, while cereal crops increased by 20.45% and 12.16%,

281 respectively. The 95% CI for grass plants overlapped with zero, indicating that the
282 experimental type had no significant effect (Fig. S4a). Regarding water regimes, the
283 effects of experimental type differed highly significantly under MD and SD ($p < 0.01$),
284 with field experiments consistently outperforming pot experiments. Under MD, the
285 increases in field and pot experiments were 15.26% and 9.76%, respectively; under
286 SD, the increases were 19.41% and 12.36%, respectively, indicating that the
287 superiority of field over pot experiments became more pronounced with increasing
288 stress intensity (Fig. S4b).

289 In summary, straw biochar exhibited broader applicability and stronger
290 comprehensive improvement effects, with the most obvious advantages for cash crops
291 and cereal crops under MD stress. All stratified subgroup effects were significantly
292 positive. Field soil environments were more conducive to realizing the improvement
293 potential of biochar, whereas short-term pot experiments tended to underestimate its
294 yield- and quality-enhancing effects; grass plants were the least affected by
295 experimental conditions.

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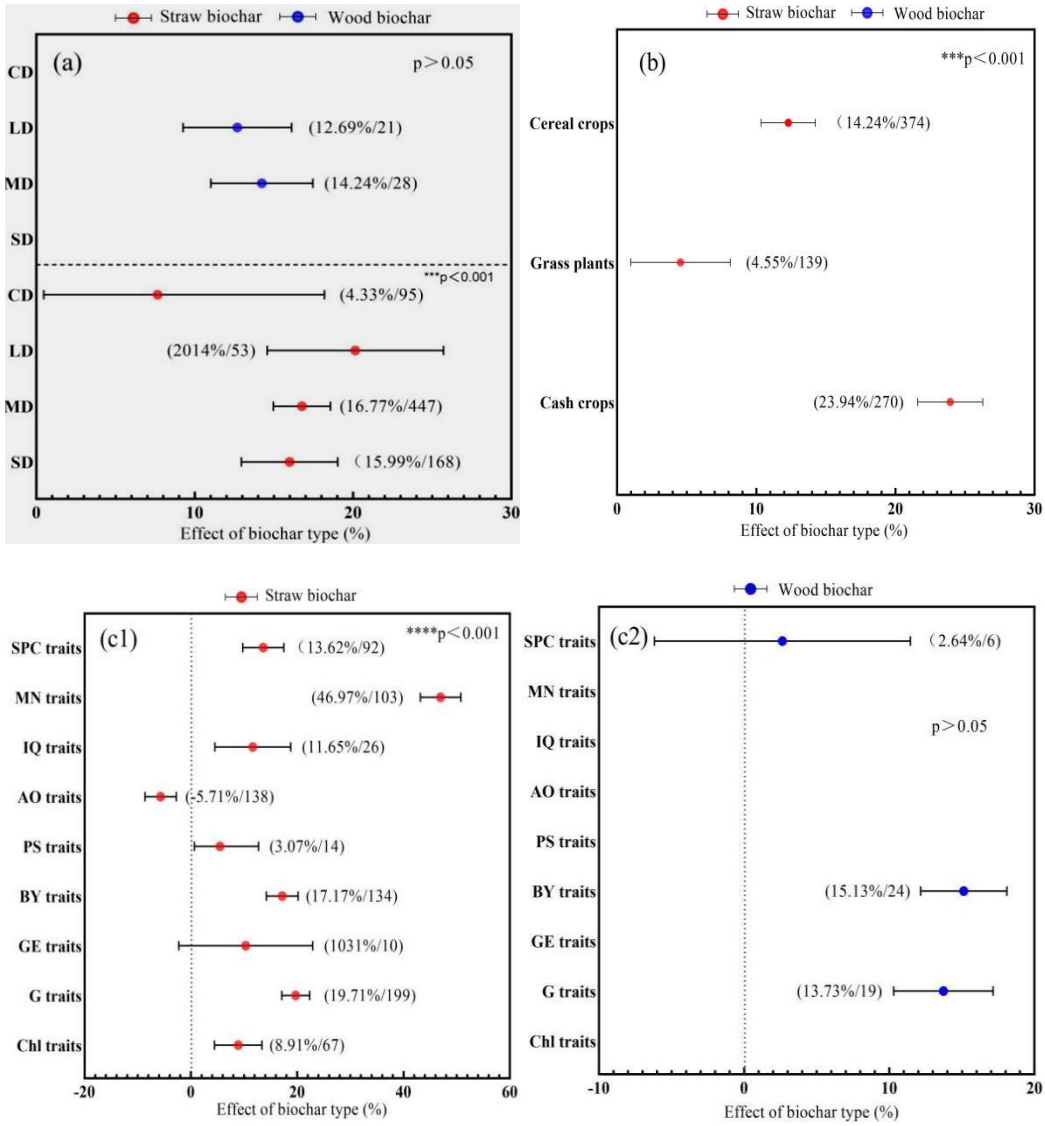



**Fig. 5**. Effects of biochar type [(a) effects on drought stress; (b) effects of straw biochar on plant types; (c1) effects of straw biochar on plant and soil physicochemical properties; (d) effects of wood biochar on plant and soil physicochemical properties].

# Discussion

## *General patterns of biochar alleviating plant drought stress*

Water is essential for plant growth and development and plays a critical role in physiological processes. Drought stress disrupts plant physiological processes,

306 impairs nutrient uptake, and inhibits growth and development, ultimately leading to
307 reduced biomass and, in severe cases, plant death. Ali et al. (2017) reported that
308 biochar application increased plant growth rate, biomass, and yield under drought
309 stress, while also improving photosynthetic efficiency and nutrient uptake and altering
310 gas exchange characteristics. Yu et al. (2022) reported that biochar application
311 increased soil moisture content in the 0–100 cm soil layer by 14.8% and 17.3%,
312 respectively, compared with the control (CK). Zanutel et al. (2024) showed that fresh
313 biochar application reduced soil bulk density by 16.8% and increased saturated water
314 content by 16.0%. These effects may be attributed to the high porosity and large
315 specific surface area of biochar, which enable greater water retention and thereby
316 enhance soil water retention; moreover, increases in soil porosity and moisture
317 content became more pronounced with increasing biochar application rates (Liu et al.,
318 2017).

319 The meta-analysis results showed that biochar application at different rates
320 generally alleviated drought stress and promoted plant growth, with the underlying
321 mechanisms involving multiple interconnected physiological and soil processes. At
322 low-to-moderate application rates (≤3%), biochar improved soil pore structure,
323 enhanced soil water retention and nutrient availability, and improved the rhizosphere
324 environment, thereby maintaining leaf photosynthetic performance, increasing
325 antioxidant enzyme activities and the contents of osmotic adjustment substances,
326 alleviating drought-induced reductions in plant height and biomass, and ultimately
327 promoting plant growth and enhancing drought tolerance (Wu et al., 2023). Ali et al.

(2021) reported that 3% biochar application increased maize plant height and root length under drought stress and increased leaf relative water content while reducing electrolyte leakage compared with the control. However, when the application rate exceeds an appropriate threshold, biochar may reduce soil water availability, thereby aggravating drought-induced damage and suppressing plant growth and drought tolerance (Ahmed et al., 2017).

In summary, appropriate biochar application rates can improve soil water status, increase field capacity and available water content, and prolong soil water availability under drought stress, thereby alleviating drought stress, sustaining root water uptake, and promoting plant growth.

### *Soil nutrient regulation mechanisms underlying biochar-promoted plant growth*

In summary, biochar improves the soil ecological environment by enhancing soil quality and regulating nutrient availability (Azeem et al., 2023) and alleviates drought stress through multiple soil environmental regulation pathways, thereby promoting plant growth and enhancing plant drought tolerance (Rahman et al., 2025). The meta-analysis results showed that biochar application significantly increased MN traits, with a 27.22% increase under SD treatment, indicating enhanced soil mineral nutrient availability. Biochar has a high water-retention capacity that can increase soil field capacity and improve plant drought tolerance, with stronger effects in sandy soils (Wang et al., 2021; Ajayi, 2016). The microporous structure and interparticle gaps of biochar facilitate water storage, whereas mesopores increase plant-available

water in soil (Zhou et al., 2026). Water stored within biochar pores can be gradually released into the surrounding soil, thereby enhancing soil water retention (Wang et al., 2019b). In addition, biochar particles can fill soil macropores and alter water flow and storage, thereby increasing soil field capacity and available water content.

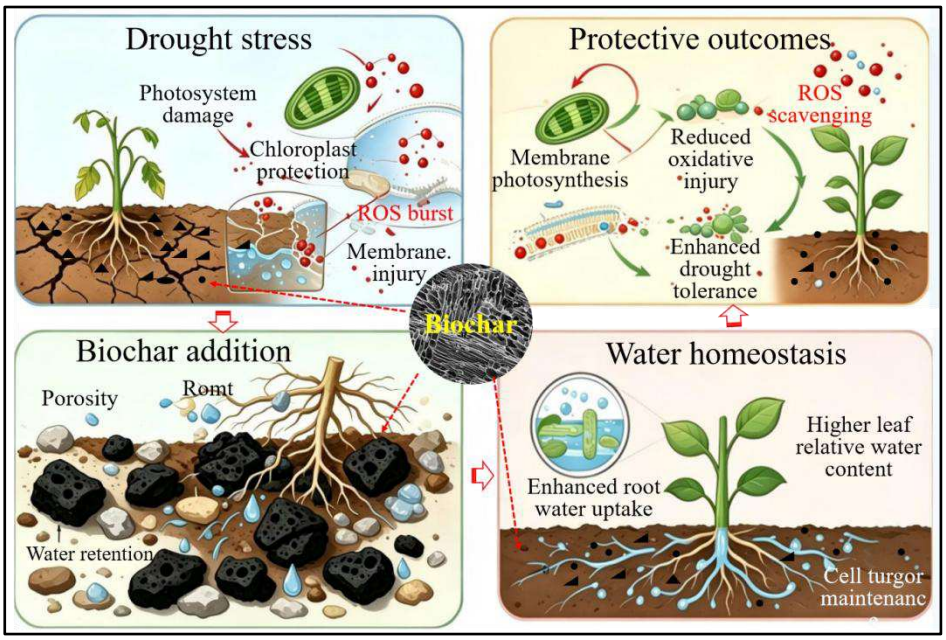
Biochar can synergistically improve the soil water–fertilizer environment by enhancing soil nutrient retention and availability (Wu et al., 2023). Owing to its high cation exchange capacity (CEC), biochar can adsorb and immobilize mineral nutrients, reduce nutrient leaching under drought, increase the availability of soil nitrogen, phosphorus, and potassium, and thereby sustain plant nutrient supply under water deficit conditions (Edeh, 2022). Biochar application can also enhance soil water retention and reduce the leaching of soil nutrients and organic matter. For example, sawdust-derived biochar reduced the leaching losses of ammonium nitrogen ($NH_4^+$–N) and potassium by 30% and phosphorus by 68%, respectively (Kuo et al., 2020), whereas coconut shell biochar reduced total nitrogen (TN) leaching by up to 36.7% (Benites et al., 2026). These effects may be attributed to the negatively charged oxygen-containing functional groups on the biochar surface, including carboxyl (−COOH), carbonyl (C=O), and hydroxyl (−OH) groups, together with its high CEC, which facilitate the adsorption and immobilization of mineral cations such as $NH_4^+$ and $K^+$ through electrostatic interactions and cation exchange (Rana et al., 2025). Under water deficit, the diffusion of soil nutrient ions decreases substantially; however, nutrients adsorbed by biochar can be gradually released through ion exchange, increasing the pools of soil available nitrogen, phosphorus, and potassium

and maintaining nutrient availability in the rhizosphere, thereby sustaining plant nutrient supply under drought stress. In addition, surface functional groups of biochar can promote the accumulation of proteins, soluble sugars, and amino acids, thereby enhancing osmotic adjustment and helping maintain plant water status under drought stress (Pandya et al., 2023; Zhang et al., 2019).

### *Mechanisms by which biochar enhances plant physiological drought tolerance*

Drought stress can damage the plant photosynthetic system, disrupt cellular water balance, and induce oxidative damage (Mijani, 2026). Biochar can regulate plant physiological metabolism through multiple pathways to enhance plant drought tolerance. The meta-analysis showed that biochar significantly increased plant biomass and chlorophyll content and alleviated oxidative damage in plants.

Fig. 6 presents a schematic diagram of the mechanisms by which biochar enhances plant drought tolerance. At the photosynthetic level, biochar application helped maintain chloroplast integrity, reduce chlorophyll degradation, and support cell expansion (Zhang et al., 2024). Compared with the drought-stressed control, the contents of chlorophyll a, chlorophyll b, and total chlorophyll increased by 18.97%, 49.02%, and 26.67%, respectively (Hareem et al., 2024). Therefore, biochar has been shown to alleviate drought-induced chlorophyll degradation, improve photosynthetic efficiency, enhance stomatal conductance and net photosynthetic rates, reduce the inhibition of carbon assimilation caused by water deficit, and improve water use efficiency (Bashir et al., 2025; Tanure et al., 2019).




394

395 **Fig. 6**. Mechanisms underlying biochar-mediated alleviation of plant drought stress.

396

397 Adequate cellular water maintains cell turgor and supports physiological
398 processes such as photosynthesis and nutrient transport, providing a prerequisite for
399 plant drought tolerance. Biochar can increase the relative content of unsaturated fatty
400 acids in cell membranes, thereby improving membrane fluidity and maintaining
401 membrane structural integrity under drought stress (Parastesh et al., 2025). Biochar
402 promotes the expression of aquaporin-related genes, thereby enhancing root water
403 uptake and transport, maintaining leaf relative water content and cell turgor, and
404 reducing the risk of drought-induced cellular dehydration and wilting (Malik et al.,
405 2024; Pandya et al., 2023). In addition, biochar can activate the plant antioxidant
406 defense system by increasing the activities of antioxidant enzymes, including
407 superoxide dismutase (SOD), catalase (CAT), peroxidase (POD), and glutathione
408 reductase (GR), thereby enhancing ROS-scavenging capacity (Shabbir et al., 2026;

Rahman et al., 2025). This antioxidant defense reduces the accumulation of hydrogen peroxide and superoxide anions, inhibits membrane lipid peroxidation, decreases malondialdehyde (MDA) accumulation, and preserves membrane integrity. Together with genetic regulation, these mechanisms alleviate drought-induced membrane damage.

### *Key factors influencing the differences in biochar effects*

The alleviating effects of biochar on drought stress exhibited pronounced between-study heterogeneity, and the meta-analysis results showed that they were jointly regulated by plant type, biochar properties, application rate, drought intensity, and soil conditions. Biochar mainly improved soil water and nitrogen supply and alleviated photosynthetic system damage, thereby reducing drought-induced yield losses and increasing the yield of cereal crops such as maize (Rahman et al., 2025; Chen et al., 2023). Cash crops (e.g., cotton and tomato) are relatively sensitive to changes in soil nutrients and the rhizosphere environment; biochar can optimize root architecture, enhance plant water retention capacity, and improve fruit nutritional quality (Usman et al., 2023; Nawaz et al., 2023; Zhang et al., 2026b). Compared with grass plants, for which aboveground biomass serves as the core indicator, biochar effectively reduced nutrient loss and increased soil organic matter content, thereby improving the forage yield and reproductive capacity of alfalfa (Wang et al., 2022; Ma et al., 2025). In summary, under drought stress, the differential responses of plant species to biochar may arise from differences in root architecture, nutrient

requirements, physiological metabolism, and biomass allocation, with cereal crops and cash crops responding more strongly to biochar than grass plants.

The feedstock type of biochar strongly influences its water retention and nutrient-related properties and contributes to its effectiveness as a soil amendment. Compared with wood-derived biochar, straw-derived biochar more effectively improved leaf water status and increased K and P availability, stomatal density, abscisic acid concentration, and maximum stomatal conductance (Hou et al., 2023; Wan et al., 2025). By contrast, wood-derived biochar application reduced dry matter content and yield index (Wan et al., 2025). This may be because straw-derived biochar has a higher cation exchange capacity (CEC), abundant mesopores, and a greater abundance of functional groups such as C=C and −OH, thereby enhancing soil water retention and nutrient availability and producing stronger drought-mitigating effects (Demir, 2026; Ayman, 2026). Wood-derived biochar generally contains fewer mineral nutrients, has a higher carbon content, and is characterized by predominantly microporous structures (Li et al., 2023; El-Naggar et al., 2019), thereby providing limited improvements in soil water availability and rhizosphere nutrient availability. Consequently, its drought-mitigating effects are weaker than those of straw-derived biochar. In addition, biochar application rate exhibits a significant threshold effect. Obia et al. (2016) reported that low biochar application rates (1%–2% w/w) and larger particle sizes (e.g., 1–5 mm) enhanced water retention in light-textured soils. Ndede et al. (2022) recommended an application rate of 5% (v/v), which significantly increased soil water content in sandy soils, thereby mitigating drought stress in plants. In

452 contrast, at a high biochar application rate of 40 mg/hm², the abundance and diversity
453 of bacterial and fungal communities changed significantly, while the abundances of
454 *Actinobacteria*, *Gammaproteobacteria*, *Firmicutes*, and *Alternaria* (*Ascomycota*)
455 decreased significantly at higher biochar application rates (do Nascimento et al.,
456 2023). Therefore, low biochar application rates can improve plant nutritional status,
457 whereas excessive application may disrupt soil pH, microbial community composition,
458 and carbon cycling, thereby resulting in neutral or even negative effects on plant
459 performance (Kocsis et al., 2020; Li et al., 2020).

460 *Research limitations and prospects*

461 This meta-analysis of the effects of biochar on plant growth and physiological
462 responses under drought stress has several limitations. Most of the available data were
463 derived from pot and short-term greenhouse experiments, with relatively few
464 long-term field studies; thus, extrapolating results from controlled experiments to
465 field conditions remains uncertain. Information on biochar feedstock types, drought
466 intensity, and background soil properties varied considerably among studies, and
467 some subgroups had relatively small sample sizes, potentially reducing the precision
468 of subgroup analyses. In addition, most studies focused on plant phenotypic and
469 physiological indicators, whereas data on root–soil–microbe interactions and
470 molecular regulatory mechanisms remain scarce, limiting our ability to elucidate the
471 multilevel mechanisms underlying biochar-mediated drought mitigation. Future
472 studies should systematically investigate the interactive effects of biochar feedstock,
473 pyrolysis temperature, application rate, and drought intensity; integrate root

morphology, microbiome, and transcriptome data to elucidate the mechanisms underlying biochar-mediated plant drought tolerance; and establish application thresholds tailored to specific biochar feedstocks, soil conditions, and crop types. These efforts will provide a stronger theoretical basis for the practical application of biochar in arid and semi-arid agricultural regions.

# Conclusions

The meta-analysis results of this study showed that biochar application under drought stress effectively improved the soil environment and regulated plant physiological growth, with significant treatment-dependent and feedstock-specific effects. After biochar application, the overall effect sizes for plant growth increased by 15.12% ($p > 0.05$), 16.13% ($p < 0.0001$), 18.59% ($p > 0.05$), and 3.19% ($p < 0.01$) under SD, MD, LD, and CD conditions, respectively, indicating that biochar effectively alleviated drought stress and promoted plant growth. In terms of crop types, biochar increased the biomass of cash crops, grass plants, and cereal crops by 23.05%, 3.78%, and 12.29%, respectively. Furthermore, compared with wood-derived biochar, straw-derived biochar exhibited superior improvement of plant leaf water status, effectively prolonging the duration of soil water supply and improving plant nutrient accumulation. The main mechanisms are that biochar application improves soil properties, enhances soil water retention capacity and nutrient supply, effectively alleviates plant oxidative stress and chlorophyll degradation, improves photosynthetic efficiency, and activates the plant antioxidant defense system. In summary, the rational application of biochar under drought stress can significantly relieve water

stress and enhance plant drought tolerance, representing an effective regulation strategy for improving the quality and efficiency of agricultural ecosystems in arid regions.

## Author Contribution

Wanqiong Shi: Writing – original draft, Methodology, Data curation, Investigation, Software. Yongfeng Liao: Writing – review & editing, Project administration, Methodology, Conceptualization. Yaxiong Zhang: Methodology, Validation, Project administration. Hongjie Li: Supervision, Resources, Visualization. Hai Wang: Investigation.

## Competing interests

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

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