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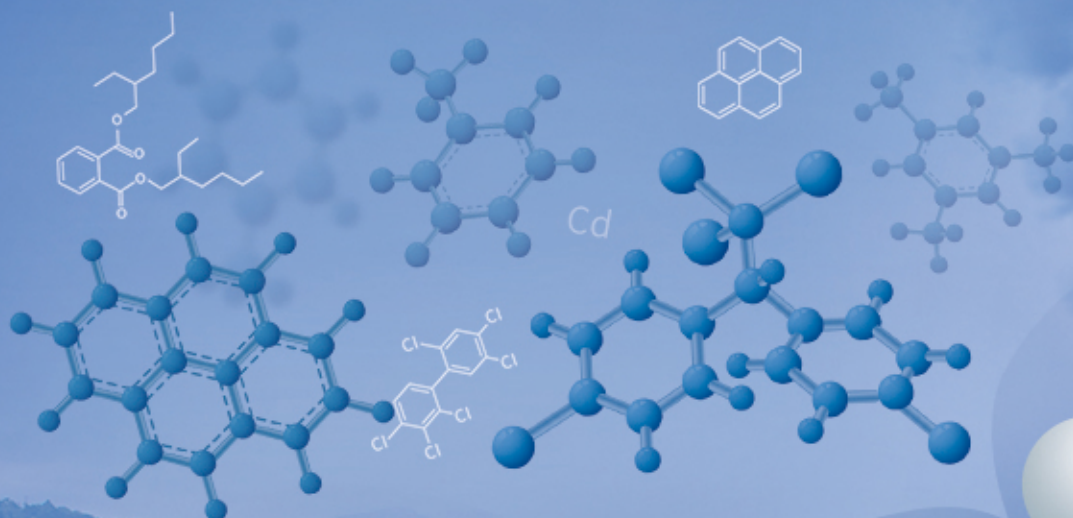
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升金湖水体优先污染物筛选与风险评价

龚雄虎, 丁琪琪, 金苗, 薛滨, 张路, 姚书春, 王兆德, 卢少勇, 赵中华



PAHs

VOCs

HMs

PCBs

PAEs

OCPs

ANTs

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炭化苹果枝通过减少土壤 DTPA-Cd 降低苹果砧木镉积累和镉伤害

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摘要: 为探究炭化苹果枝对苹果砧木镉积累和镉伤害的影响, 以盆栽苹果砧木(平邑甜茶)实生苗为试材, 在施有 0.5% 和 1% (质量分数) 的炭化苹果枝的盆土中灌入含镉(CdSO_4) 营养液, 分析盆土中二乙三胺五乙酸(diethylenetriamine pentaacetic acid, DTPA)所提取镉(DTPA-Cd)及根茎叶镉含量, 检测根系和叶片抗氧化酶活性和根系细胞死亡情况以及叶片光合速率。结果表明, 施用炭化苹果枝的盆土 DTPA-Cd 含量显著低于未施用炭化苹果枝的, 其中施用 0.5% 和 1% 的炭化苹果枝使盆土 DTPA-Cd 含量在处理第 12 d 分别比未施的降低 17.50% 和 25.55%; 施入炭化苹果枝明显降低苹果砧木根茎叶镉积累量, 提高根系和叶片超氧化物歧化酶(SOD)、过氧化物酶(POD)和过氧化氢酶(CAT)活性, 降低根系和叶片 $\cdot\text{O}_2^-$ 生成速率、 H_2O_2 和 MDA 含量, 还降低根系细胞死亡比率, 提高叶片光合速率, 其中施用(ω)0.5% 和 1% 的炭化苹果枝使根系镉含量在处理第 12 d 分别比未施的降低 29.49% 和 37.18%, 使根细胞死亡比率分别比未施的降低 22.73% 和 29.09%。这些说明施用炭化苹果枝可通过降低土壤 DTPA-Cd 含量, 减少苹果砧木对镉的吸收和积累, 减轻根系细胞以及叶片光合性能所受到的伤害, 施用 1% 的比施用 0.5% 的效果更显著。

关键词: 炭化苹果枝; 苹果砧木; DTPA-Cd; 镉积累; 细胞死亡; 光合性能

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Carbonized Apple Branches Decrease the Accumulation and Damage of Cadmium on Apple Rootstock by Reducing DTPA-Cd in Soil

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Abstract: To explore the effects of carbonized apple branches on cadmium (Cd) accumulation and its damage to apple rootstock, the rootstocks of apple (*Malus hupehensis* Rehd.) in pots containing soil together with 0.5% and 1% (ω) carbonized apple branches were irrigated by a nutrient solution containing CdSO_4 . The content of DTPA-Cd (cadmium extracted by diethylenetriamine pentaacetic acid) in the potting soil, and the accumulation of Cd in the roots, stems, and leaves of apple rootstocks, were subsequently monitored. The activities of antioxidant enzymes in roots and leaves, root cell death, and the net photosynthesis rate were further analyzed. The results showed that the concentration of DTPA-Cd in the potting soil with carbonized apple branches was significantly lower than that without carbonized apple branches (Cd-only). Compared with the Cd-only treatment, the concentration of DTPA-Cd in the potting soil decreased by 17.50% and 25.55% in the treatment with 0.5% and 1% (ω) carbonized apple branches for 12 days. The Cd accumulation in roots, stems, and leaves; the accumulations of superoxide anions ($\cdot\text{O}_2^-$), hydrogen peroxide (H_2O_2), and malondialdehyde (MDA) in roots and leaves; and the amount of cell death in the roots of apple rootstock treated by carbonized apple branches were significantly lower compared to the Cd-only treatment. However, the activities of superoxide dismutase (SOD), peroxidase (POD), and catalase (CAT) in the roots and leaves, and the net photosynthesis rate of apple rootstock treated by carbonized apple branches, were significantly higher than under the Cd-only treatment. Compared with the Cd-only treatment, Cd accumulation in roots decreased by 29.49% and 37.18% in the treatment with 0.5% and 1% (ω) carbonized apple branches for 12 days, and the amount of cell death decreased by 22.73% and 29.09%, respectively. Our results show that carbonized apple branches reduce the uptake and accumulation of Cd in apple rootstock by reducing the content of DTPA-Cd in the soil, thereby alleviating the damaging effect of Cd on cells and photosynthesis. Moreover, the use of 1% (ω) carbonized apple branches was more effective than 0.5% (ω).

Key words: carbonized apple branches; apple rootstock; DTPA-Cd; the accumulation of Cd; cell death; photosynthesis

镉(Cd)是污染普遍、毒性很强的重金属。土壤中的镉除来源于含镉矿石风化外,主要来自金属冶炼、化石燃料的使用、垃圾焚烧和废水不当使用、电池和电镀废料以及含镉肥料的施用等^[1-3]。在含镉土壤中,植物会通过根系吸收和积累镉,这些被根系吸收的镉与能够被二乙三胺五乙酸(diethylenetriamine pentaacetic acid, DTPA)所浸提的镉(DTPA-Cd)密切相关,施用豌豆和玉米秸秆烧制的生物炭能够降低土壤 DTPA-Cd 含量,也能够降低菠菜和水稻体内的镉含量^[4,5]。

镉在根系积累会使根系褐变,生长萎缩,吸收能力下降,损伤细胞等^[6-8];根系中的镉还可通过木质部运向地上部,降低叶绿素含量和叶片 CO_2 同化能力,影响叶片光合作用和呼吸作用^[7,9,10];植物体内镉积累还会引起 H_2O_2 等活性氧(ROS)升高而产生氧

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化胁迫,导致细胞甚至植株死亡^[7, 11, 12]. 据报道,活性炭能够通过减少细胞死亡而缓解镉对小麦根系的伤害^[13]; 外施生物炭能够提高番茄叶片光合色素含量,促进植株生长,缓解镉毒害^[14],还能够降低小麦和玉米根、茎和籽粒镉含量,提高镉污染土壤中水稻和小麦的光合速率,促进植株生长等^[15~17].

近年来,一些果园土壤已出现镉超标问题,严重威胁果树正常生长和果品质量安全^[18~20]. 比如,浙江省浦江县有些果园的土壤镉含量超出国家安全标准限量 48% 以上,柑橘、葡萄、梨和李子果实中的镉含量均超过了安全标准^[18]; 辽东半岛苹果园土壤镉污染指数虽然小于 1,但仍有 6.34% 的果皮样品镉超标^[19]; 陕西省猕猴桃园有 10.0% 的土壤样品受到镉污染,12.5% 的果实样品镉含量超过国家最高限量^[20]. 减少植株对镉的吸收和积累是减轻镉毒害的根本途径,这主要取决于土壤镉的含量与状态以及根系的性能. 炭化苹果枝是以废弃苹果枝条为原料制备的生物炭, Ali 等^[21] 的研究表明,苹果枝生物炭明显降低了土壤镉的酸溶性和可还原性组分,同时也降低了植株根系和地上部镉含量. 我国是世界苹果生产大国,栽培苹果依靠砧木立足土壤,苹果接穗和果实镉积累情况明显受砧木影响^[22]. 平邑甜茶是我国栽培苹果常用砧木之一,本研究主要探讨炭化苹果枝对土壤 DTPA-Cd 含量和平邑甜茶抗氧化酶活性、细胞死亡和光合速率的影响,以期为果树废枝利用及缓解果树镉毒害提供参考.

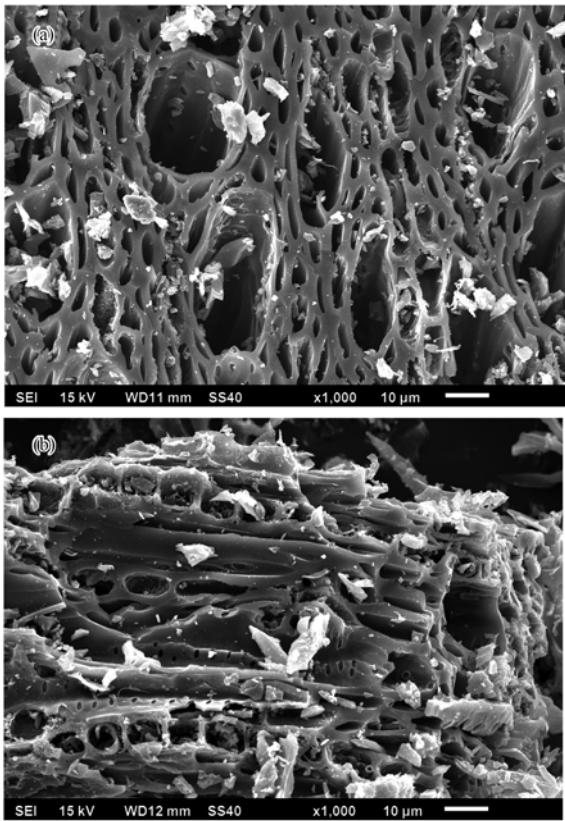
1 材料与方法

1.1 试验材料 with 处理

本研究在山东农业大学果树生物学重点实验室进行,试验材料为生长在光照培养箱内的一年生苹果砧木 (平邑甜茶, *Malus hupehensis* Rehd. var.

pingyiensis Jiang) 实生幼苗; 箱内培养条件: 25℃, 光照 14 h; 22℃, 黑暗 10 h, 相对湿度 70%~80%, 光量子强度 170 mol·(m²·s)⁻¹. 在幼苗长至 6~8 片真叶时,选取长势一致的移栽处理.

炭化苹果枝是将冬季修剪下的苹果枝条洗净、风干、粉碎后填满于密闭坩埚中,放入高温炉中在缺氧、700℃ 条件下热解 2 h 制得,其在 JSM-5610LV 型扫描电镜的超微结构如图 1,化学特性见表 1.



(a) 纵径, (b) 横径

图 1 炭化苹果枝电镜扫描图像

Fig. 1 Scanning electron microscope (SEM) figure of carbonized apple branches

表 1 炭化苹果枝的化学特性^[23]

Table 1 Chemical characteristics of carbonized apple branches												
项目	热解温度 /℃	产率 /%	元素组成及原子比/%							pH 值	灰分 /%	
			C	H	N	S	O	H/C	O/C			(N + O)/C
参数	700	32.6	74.21	3.68	1.29	0.04	15.72	60	16	17	10.0	8.9

处理前将具 6~8 片真叶的平邑甜茶实生苗移至塑料花盆中,盆高 11 cm、直径 14 cm,盆土按照曹辉等^[23]的方法用果园壤土、河沙和腐熟兔粪以 3:1:1 的体积比均匀混合而成,盆土中: pH 7.1、容重 1.45 g·cm⁻³、有机质 12.41 g·kg⁻¹、速效磷 32.9 mg·kg⁻¹、碱解氮 26.6 mg·kg⁻¹ 和速效钾 102.5 mg·kg⁻¹. 每盆定植 3 株,培养 1 周后,用 1/2 Hoagland 营养液配制 CdSO₄ 浓度为 100 μmol·L⁻¹ 的镉溶液,对各盆进行以下处理: ①直接将 200 mL

镉溶液均匀灌入盆土,盆土镉含量为 9.82 mg·kg⁻¹,此为 CdSO₄ 处理,记做 Cd; ②在离主根 3~5 cm、深度 3~4 cm 的位置,按照盆土质量的 0.5% (质量分数,下同) 施入炭化苹果枝,然后将 200 mL 镉溶液均匀灌入盆土,此为 CdSO₄ + 0.5% BC 处理,记作 Cd + 0.5% BC; ③按上述同样方式施入 1% 炭化苹果枝后灌入镉溶液,记作 Cd + 1% BC. 上述 3 种处理的盆土含水量维持在田间持水量 60%,每 3 盆为一小区,各处理至少重复 3 次. 定期取样测定·O₂⁻ 生成

速率、 H_2O_2 、MDA 及镉含量、抗氧化酶活性、细胞死亡数量和盆土 DTPA-Cd 含量等。

1.2 测定项目与方法

1.2.1 土壤 DTPA-Cd 含量的测定

土壤 DTPA-Cd 含量的测定参考农云军等^[24]试验方法:取烘干过 20 目土壤样品 5 g 加入至 10 mL DTPA 提取液($0.005 \text{ mol} \cdot \text{L}^{-1}$ DTPA + $0.01 \text{ mol} \cdot \text{L}^{-1}$ CaCl_2 + $0.1 \text{ mol} \cdot \text{L}^{-1}$ TEA, pH 7.3)超声提取 25 min, $3000 \text{ r} \cdot \text{min}^{-1}$ 离心 5 min, 过滤, 利用电感耦合等离子体质谱仪 (ICP-MS NexION 300X, 美国 PerkinElmer 公司) 进行镉含量测定。

1.2.2 根茎叶镉含量的测定

用去离子水将平邑甜茶冲洗干净后, 将根茎叶分开烘干, 研磨成粉末状, 称样在 CEM Mars6 高通量密闭微波消解系统(美国 CEM 公司)中消解, 再利用电感耦合等离子体质谱仪 (ICP-MS NexION 300X, 美国 PerkinElmer 公司) 测定样品镉含量。

1.2.3 根系、叶片 $\cdot O_2^-$ 生成速率、 H_2O_2 和 MDA 含量的测定

$\cdot O_2^-$ 生成速率和 H_2O_2 含量的测定分别参照邹琦^[25]和 Zhang 等^[26]的方法。MDA 含量的测定参照赵世杰等^[27]的方法。

1.2.4 根系和叶片中 SOD、POD 和 CAT 活性的测定

取 0.5 g 根系(叶片)鲜样, 加入适量磷酸缓冲液, 冰浴研磨, 然后倒入离心管, 低温($0 \sim 4^\circ\text{C}$)离心后, 取上清液冷藏保存。SOD 活性[四唑氮蓝法(nitro blue tetrazolium, NBT)]、POD 活性(愈创木酚法)和 CAT 活性测定参照赵世杰等^[27]的方法。

1.2.5 根系细胞死亡情况的测定

细胞死亡测定参照 Steffens 等^[28]的方法, 取适量处理后平邑甜茶根系擦净浸泡在 0.25% (ω) 的伊文思蓝溶液中染色; 取出根系冲洗干净, 放入 5 mL 50% 甲醇/1% SDS, 50°C 水浴提取 30 min, 利用分光光度计在 600 nm 下测定提取液吸光度, 利用单位质量根样品的吸光度(以 $A_{600 \text{ nm}} \cdot \text{g}^{-1}$ 表示)反映细胞死亡情况。

1.2.6 叶片光合速率和叶绿素相对含量的测定

利用 CI-RAS-2 便携式光合荧光仪、SPAD-502PLUS 叶绿素测定仪, 在天气晴朗的 09:30 ~ 11:00 测试平邑甜茶功能叶片的光合速率和叶绿素相对含量。

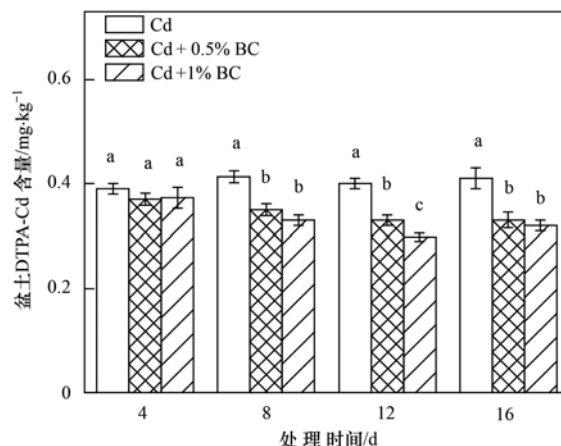
1.3 数据分析

采用 SPSS 16.0 统计软件进行数据分析, 差异性显著采用 Turkey 多重比较法($P < 0.05$)分析, 采用 Origin 8.0 软件作图。

2 结果与分析

2.1 炭化苹果枝对盆土 DTPA-Cd 含量的影响

在处理第 8 ~ 16 d, 施用(ω)0.5% 和 1% 的炭化苹果枝均显著降低了盆土 DTPA-Cd 含量(图 2); 与单纯灌入镉溶液(盆土未施用炭化苹果枝)的相比, 施用 0.5% 和 1% 的炭化苹果枝在处理 12 d 使盆土 DTPA-Cd 含量分别下降 17.50% 和 25.55%, 炭化苹果枝用量 1% 的效果显著好于用量 0.5% 的($P < 0.05$)。



BC 为炭化苹果枝, 不同小写字母表示差异显著 ($P < 0.05$), 下同

图 2 炭化苹果枝对盆土 DTPA-Cd 含量的影响

Fig. 2 Effect of BC on the DTPA-Cd content of potting soil

2.2 炭化苹果枝对平邑甜茶根茎叶镉含量的影响

由图 3 可见, 在单纯灌入镉溶液的条件下, 平邑甜茶根茎叶镉含量随处理时间的延长而升高, 在盆土施入 0.5% 和 1% 的炭化苹果枝后再灌入镉溶液, 多数平邑甜茶根茎叶镉含量比未施用炭化苹果枝的

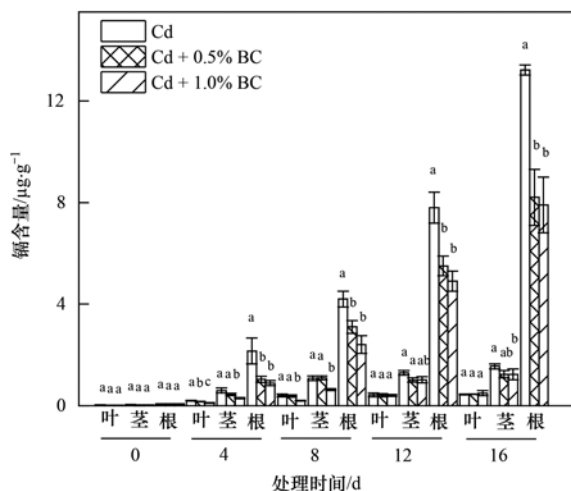


图 3 Cd、Cd + 0.5% BC 和 Cd + 1% BC 处理对平邑甜茶根茎叶镉含量的影响

Fig. 3 Effects of Cd, Cd + 0.5% BC, and Cd + 1% BC on Cd accumulation in the leaves, stems, and roots of *Malus hupehensis*

显著降低. 与未施用炭化苹果枝的相比, 施用 0.5% 的炭化苹果枝使根、茎、叶镉含量在处理第 4 d 分别下降 52.09%、26.67% 和 20.1%, 处理第 12 d 分别下降 29.49%、22.31% 和 4.75%; 施用 1% 的炭化苹果枝使根、茎、叶镉含量在处理第 4 d 分别下降 58.06%、50.01% 和 44.98%, 处理第 12 d 分别下降 37.18%、21.54% 和 6.98%.

2.3 炭化苹果枝对平邑甜茶根系和叶片抗氧化性能的影响

H_2O_2 是一种 ROS, 会引起膜脂过氧化损伤, MDA 是膜脂过氧化的产物. 图 4 显示, 在单纯灌入镉溶液的条件下, 平邑甜茶根系 $\cdot O_2^-$ 生成速率、 H_2O_2 和 MDA 含量随处理时间的延长而呈现出先增加后降低的变化趋势, 在盆土中施入 0.5% 和 1% 的炭化苹果枝后再灌入镉溶液, 平邑甜茶根系 $\cdot O_2^-$ 生成速率、MDA 和 H_2O_2 含量比未施用炭化苹果枝的

显著降低, 而抗氧化酶 (SOD、POD 和 CAT) 活性显著提高. 与未施用炭化苹果枝的相比, 施用 0.5% 和 1% 的炭化苹果枝使根系 $\cdot O_2^-$ 生成速率处理第 4 d 分别下降 29.51% 和 32.79%, 处理 12 d 分别下降 37.17% 和 51.33%; 使 H_2O_2 含量在处理第 4 d 分别下降 24.13% 和 28.97%, 处理 12 d 分别下降 34.00% 和 35.99%; 使 MDA 含量在处理第 4 d 分别下降 30.23% 和 31.25%, 处理 12 d 分别下降 26.09% 和 38.26%; 使 SOD 活性在处理第 4 d 分别提高 28.89% 和 33.33%, 处理 12 d 分别提高 37.50% 和 45.00%; 使 POD 活性在处理第 4 d 分别提高 44.44% 和 55.56%, 处理 12 d 分别提高 78.95% 和 73.68%; 使 CAT 活性在处理第 4 d 分别提高 12.35% 和 40.74%, 处理第 12 d 分别提高 41.18% 和 68.24%. 总体来说, 炭化苹果枝用量 1% 的效果好于用量 0.5% 的.

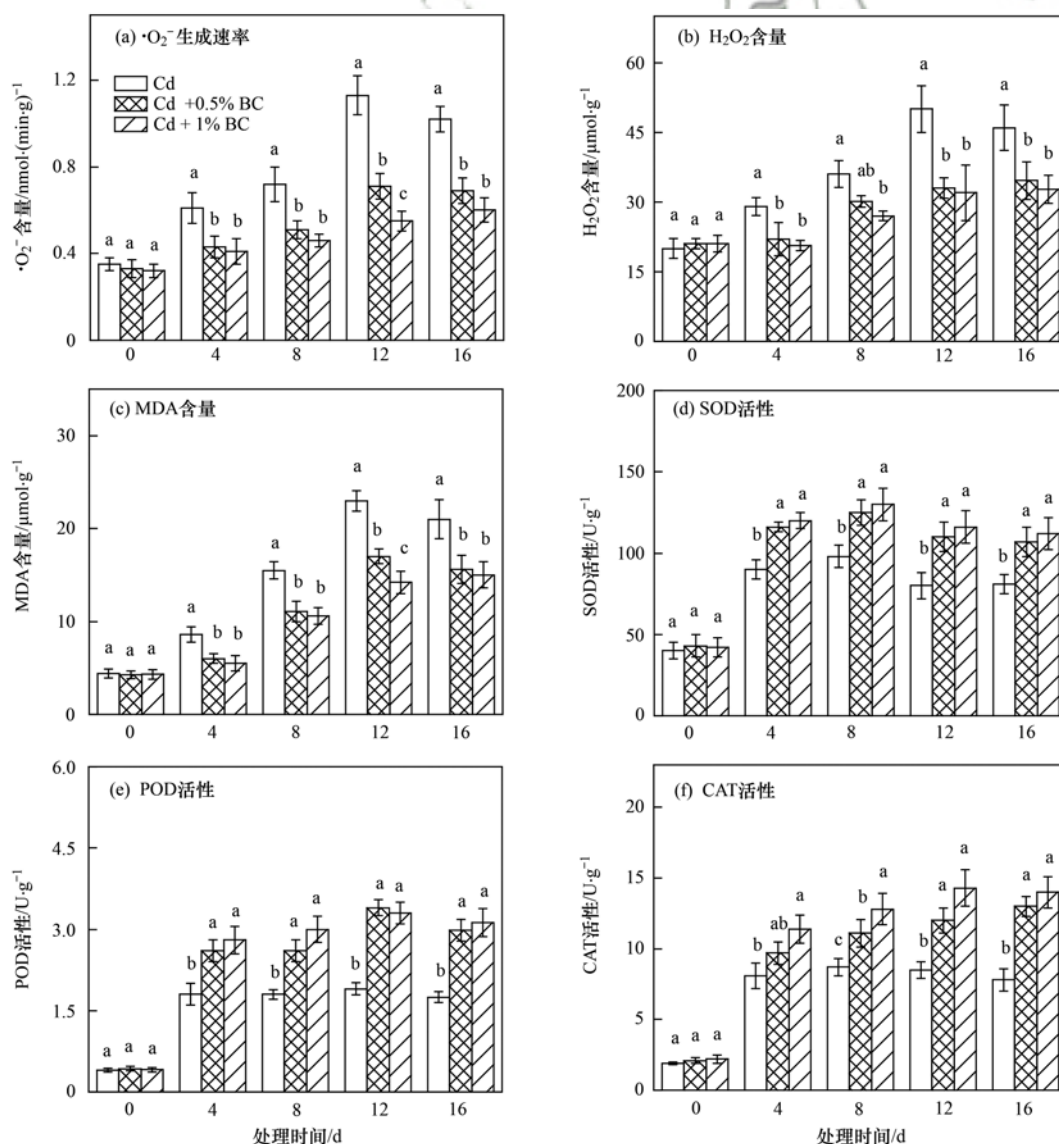


图 4 Cd、Cd + 0.5% BC 和 Cd + 1% BC 处理对平邑甜茶根系抗氧化性能的影响

Fig. 4 Effects of Cd, Cd + 0.5% BC, and Cd + 1% BC on the oxidation resistance of roots of *Malus hupehensis*

在单纯灌入镉溶液的条件下,平邑甜茶叶片 $\cdot\text{O}_2^-$ 生成速率、 H_2O_2 和MDA含量随处理时间延长(0~12 d)不断增加,而后(12~16 d)下降[图5(a)~5(c)];在盆土中施入0.5%和1%的炭化苹果枝后再灌入镉溶液,平邑甜茶叶片 $\cdot\text{O}_2^-$ 生成速率、 H_2O_2 和MDA含量比未施用炭化苹果枝的显著降低[图5(a)~5(c)],而抗氧化酶(SOD、POD和CAT)活性显著提高[图5(d)~5(f)].与未施用炭化苹果枝的相比,施用0.5%的炭化苹果枝使叶片 $\cdot\text{O}_2^-$ 生成速率、 H_2O_2 和MDA含量在处理第4 d分别下降28.1%、41.82%和43.75%,处理第12 d分

别下降36.07%、20.00%和30.86%;而SOD、POD和CAT活性在处理第4 d分别提高16.28%、39.17%和48.72%,处理第12 d分别提高41.67%、52.31%和32.08%.施用1%的炭化苹果枝使叶片 $\cdot\text{O}_2^-$ 生成速率、 H_2O_2 和MDA含量在处理第4 d分别下降30.48%、49.98%和50.01%,处理第12 d分别下降49.97%、20.00%和30.86%;而SOD、POD和CAT活性在处理第4 d分别提高18.60%、48.33%和56.41%,处理第12 d分别提高72.22%、64.62%和59.38%.总体来说,施用1%的炭化苹果枝效果好于0.5%的.

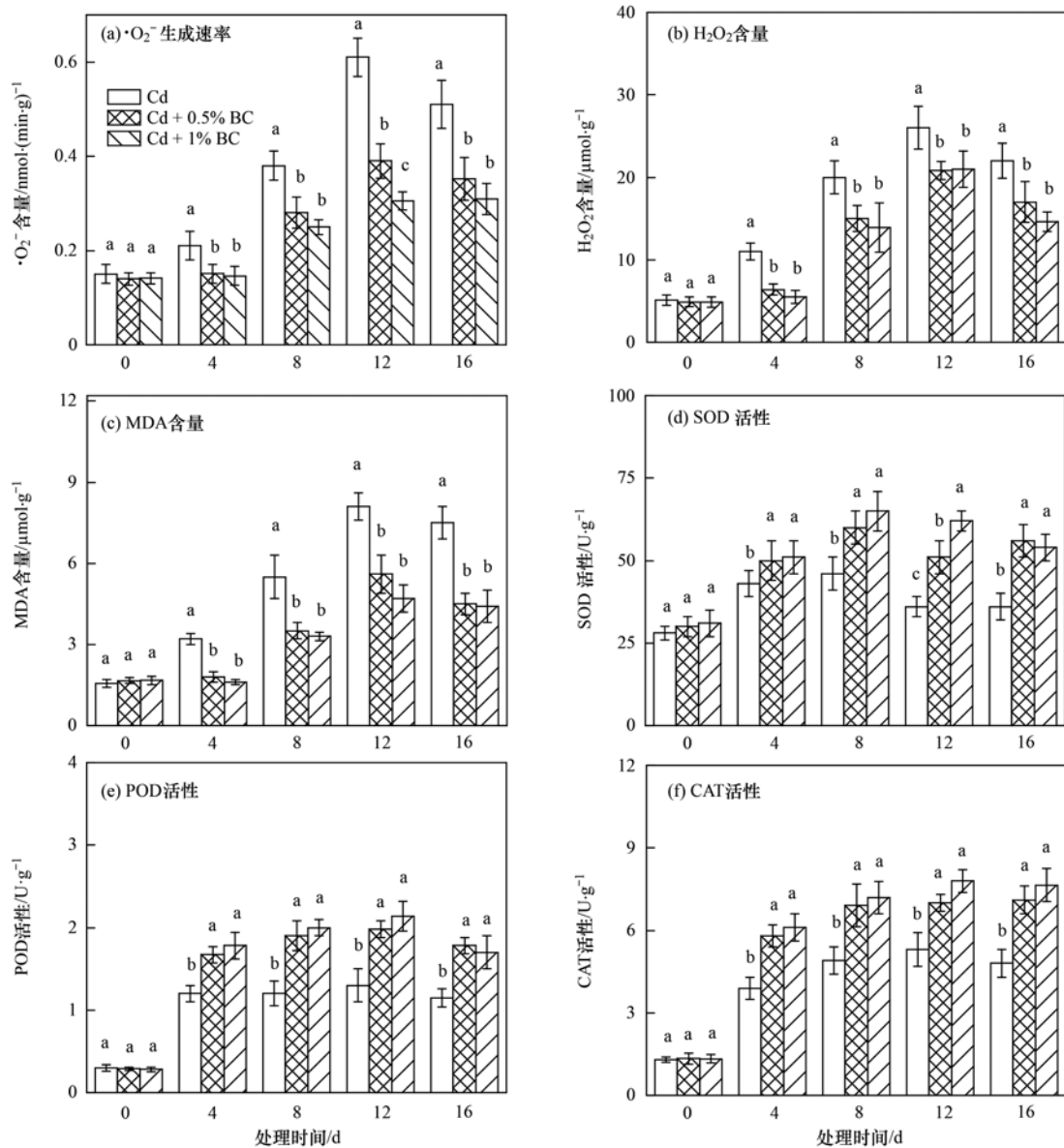


图5 Cd、Cd+0.5%BC和Cd+1%BC处理对平邑甜茶叶片抗氧化性能的影响

Fig. 5 Effects of Cd, Cd+0.5% BC, and Cd+1% BC on oxidation resistance in leaves of *Malus hupehensis*

2.4 炭化苹果枝对平邑甜茶根系细胞死亡和叶片光合性能的影响

由图6可知,在盆土中施入0.5%和1%的炭化苹果枝后再灌入镉溶液,平邑甜茶根系细胞死亡数

量比未施用炭化苹果枝的显著降低;施入0.5%和1%的炭化苹果枝使根系细胞死亡数量在处理第4 d分别下降22.73%和24.24%,处理第12 d分别下降22.73%和29.09%,炭化苹果枝用量1%的效果好

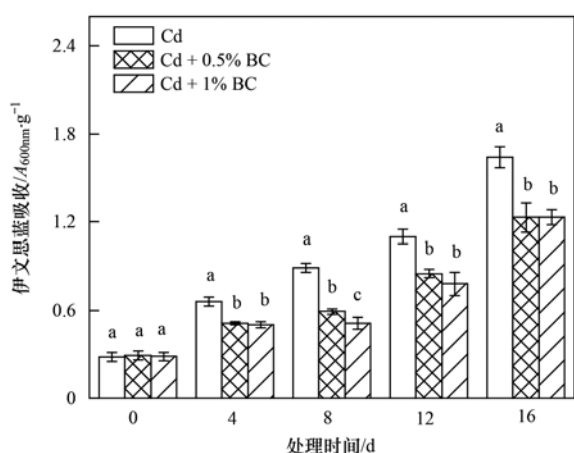


图6 Cd、Cd + 0.5% BC 和 Cd + 1% BC

处理对平邑甜茶根系细胞死亡的影响

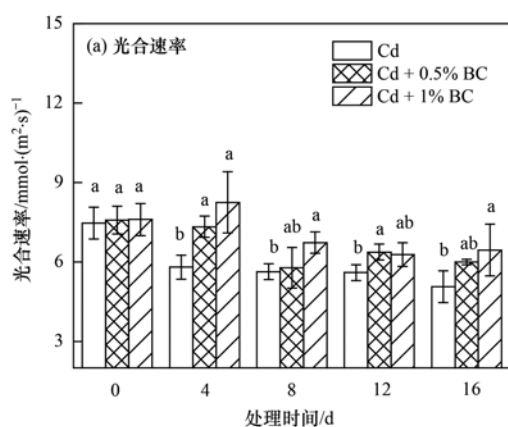
Fig. 6 Effects of Cd, Cd + 0.5% BC, and Cd + 1% BC on cell death in the roots of *Malus hupehensis*

图7 Cd、Cd + 0.5% BC 和 Cd + 1% BC 处理对平邑甜茶叶片光合速率和叶绿素相对含量的影响

Fig. 7 Effects of Cd, Cd + 0.5% BC, and Cd + 1% BC on the photosynthetic rate and relative chlorophyll content of leaves of *Malus hupehensis*

量分别提高 8.28% 和 10.18%, 第 12 d 分别提高 6.35% 和 4.92%。

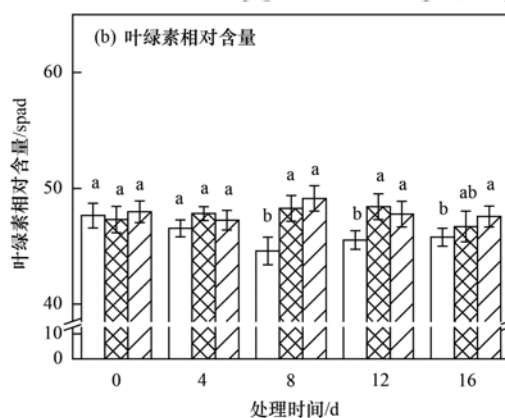
3 讨论

生物炭是作物秸秆、木屑等植物材料以及其他有机物质在完全或部分缺氧条件下,经高温热解而成的富碳且性状稳定的物质,包括竹炭、木炭和秸秆炭等^[29]。生物炭不仅能改善土壤质量,还对重金属具有较强的吸附作用,并影响植物对镉的吸收和积累。Kamran 等^[30]的研究就发现施用阿拉伯金合欢木片生物炭(300℃热解 3h 制得),不仅降低了土壤 DTPA-Cd 含量,也降低了生长在该环境中油菜根系和嫩芽镉含量。Liu 等^[17]的研究也发现,向土壤中施用小麦秸秆生物炭(450℃热解 2 h 制得)能够降低玉米根茎叶等组织中镉含量。炭化苹果枝是利用苹果废枝制得的具有特殊微孔结构(图 1)木本植物生物炭,本研究发现施用 0.5% 和 1% 的炭化苹果枝(处理第 8~16 d)不仅显著降低了盆土 DTPA-Cd

于 0.5% 的,表明在盆土中施用炭化苹果枝能明显缓解镉对平邑甜茶根细胞造成的伤害,较高用量(1%)好于较低用量(0.5%)。

在盆土中施入 0.5% 和 1% 的炭化苹果枝后再灌入镉溶液,多数平邑甜茶叶片光合速率比未施用炭化苹果枝的显著提高[图 7(a)]:与未施用炭化苹果枝的相比,施用 0.5% 和 1% 的炭化苹果枝在处理 4 d 使叶片光合速率分别提高 26.38% 和 42.24%,处理第 12 d 分别提高 13.75% 和 12.14%。总体来说,炭化苹果枝用量 1% 的效果好于用量 0.5% 的。

在处理第 8~16 d,施用 0.5% 和 1% 的炭化苹果枝提高了平邑甜茶叶片叶绿素相对含量[图 7(b)];与未施用炭化苹果枝的相比,施用 0.5% 和 1% 的炭化苹果枝在处理 8 d 使叶片叶绿素相对含



含量,也降低了平邑甜茶根茎叶镉积累量,这些表明炭化苹果枝可能通过减少土壤 DTPA-Cd 含量而降低植株镉积累。之所以有这种效果,应主要在于炭化苹果枝(苹果枝生物炭)含有丰富的无机碳、磷、呈碱性、具有较大的比表面积及表面含有多种活性官能团等,无机碳和磷可与 Cd 作用形成 CdCO_3 和 $\text{Cd}_3(\text{PO}_4)_2$ 等沉淀,呈碱性的 OH^- 也可与 Cd^{2+} 相互作用,较大的比表面积和多种活性官能团能够增强炭化苹果枝的吸附作用^[21]。此外,炭化苹果枝丰富的孔隙和独特的沟壑(图 1)对提高炭化苹果枝对镉等物质的吸附能力会有积极作用。

镉胁迫能够导致植物细胞死亡^[31,32],细胞死亡与 ROS 过量积累所导致的膜脂过氧化产物 MDA 的增加有关^[33],MDA 含量越高,细胞死亡概率越大。本研究发现镉处理使平邑甜茶根系镉积累、MDA 含量和细胞死亡比率增加,施用炭化苹果枝后再经镉处理,根系镉和 MDA 积累及细胞死亡比率均降低。

正常情况下,植物体内 ROS 含量处于动态平衡

状态,而镉等重金属胁迫会打破这种平衡状态而产生氧化损伤.抗氧化酶能够将 ROS 转化为活性较低的物质^[34,35]进而缓解氧化损伤,抗氧化酶的活性明显影响植物的耐镉能力^[36].对处于镉胁迫下的小白菜,施用水稻秸秆生物炭(550℃热解 2 h 制得)能够提高叶片 SOD、POD 和 CAT 活性,降低叶片 MDA 和 H₂O₂ 积累^[37].本研究结果显示,与盆土未施用炭化苹果枝的相比,在施入炭化苹果枝的盆土中灌入 CdSO₄,平邑甜茶根系镉含量降低, SOD、POD 和 CAT 活性提高,·O₂⁻ 生成速率、H₂O₂ 和 MDA 的积累降低,细胞死亡数量减少.植物体内镉积累会破坏抗氧化酶系统,损伤细胞超微结构^[38],在施入炭化苹果枝的盆土中灌入 CdSO₄,平邑甜茶镉积累相对降低,镉胁迫所导致的细胞损伤也必然减轻.

叶片光合速率和叶绿素含量的高低与重金属对植物的毒害程度有关^[39~41].施入炭化苹果枝的盆土灌入 CdSO₄,平邑甜茶叶片叶绿素含量和光合速率高于未施用的,这主要在于叶片镉积累降低而减弱了镉对叶绿体、叶绿素合成和叶片光合功能的损伤^[10,38],也与减少了 ROS 积累而减弱了 ROS 对叶片色素的氧化作用有关^[42],因为黄瓜幼苗 H₂O₂ 等 ROS 积累时伴随着光合速率的下降^[43],而施用炭化苹果枝也确实降低了 CdSO₄ 所导致的平邑甜茶叶片 H₂O₂ 积累.

减少镉在植物器官的积累是降低镉伤害的根本途径,生长在含镉土壤中的果树主要通过根系吸收镉,土壤 DTPA-Cd 含量能显著影响根系对镉吸收.施用炭化苹果枝不仅降低盆土 DTPA-Cd 含量,也降低平邑甜茶体内镉积累量.根系和叶片镉积累量的降低,是减少镉处理下·O₂⁻ 生成速率、H₂O₂ 和 MDA 积累和根细胞死亡及提高叶片光合速率的前提,因此炭化苹果枝能够减少平邑甜茶镉积累和镉伤害,主要在于炭化苹果枝能够降低土壤 DTPA-Cd 含量,减少植株对镉的吸收积累,进而减轻根系细胞及叶片光合性能所受到的伤害.

4 结论

(1)施用质量分数 0.5% 和 1% 的炭化苹果枝能够通过减少土壤 DTPA-Cd 含量而降低苹果砧木的镉积累量,1% 的用量比 0.5% 效果更显著.

(2)施用炭化苹果枝能够通过提高镉处理下苹果砧木根系和叶片抗氧化酶活性,降低·O₂⁻ 生成速率、H₂O₂ 和 MDA 的积累量,进而减轻氧化胁迫导致的根细胞死亡及对光合作用的抑制.

参考文献:

[1] Zoffoli H J O, do Amaral-Sobrinho N M B, Zonta E, et al.

Inputs of heavy metals due to agrochemical use in tobacco fields in Brazil's southern region [J]. *Environmental Monitoring and Assessment*, 2013, **185**(3): 2423-2437.

[2] Yousaf B, Amina, Liu G J, et al. The importance of evaluating metal exposure and predicting human health risks in urban-periurban environments influenced by emerging industry [J]. *Chemosphere*, 2016, **150**: 79-89.

[3] Shen T L, Liu L, Li Y C, et al. Long-term effects of untreated wastewater on soil bacterial communities [J]. *Science of the Total Environment*, 2019, **646**: 940-950.

[4] Vassanda Coumar M, Parihar R S, Dwivedi A K, et al. Impact of pigeon pea biochar on cadmium mobility in soil and transfer rate to leafy vegetable spinach [J]. *Environmental Monitoring and Assessment*, 2016, **188**(1), doi: 10.1007/s10661-015-5028-y.

[5] Zhang M, Shan S D, Chen Y G, et al. Biochar reduces cadmium accumulation in rice grains in a tungsten mining area-field experiment: effects of biochar type and dosage, rice variety, and pollution level [J]. *Environmental Geochemistry and Health*, 2019, **41**(1): 43-52.

[6] He S Y, Yang X E, He Z L, et al. Morphological and physiological responses of plants to cadmium toxicity: a review [J]. *Pedosphere*, 2017, **27**(3): 421-438.

[7] Jan S, Alyemeni M N, Wijaya L, et al. Interactive effect of 24-epibrassinolide and silicon alleviates cadmium stress via the modulation of antioxidant defense and glyoxalase systems and macronutrient content in *Pisum sativum* L. seedlings [J]. *BMC Plant Biology*, 2018, **18**, doi: 10.1186/s12870-018-1359-5.

[8] Ye W L, Wu F, Zhang G Y, et al. Calcium decreases cadmium concentration in root but facilitates cadmium translocation from root to shoot in rice [J]. *Journal of Plant Growth Regulation*, 2020, **39**(1): 422-429.

[9] Uruguchi S, Mori S, Kuramata M, et al. Root-to-shoot Cd translocation via the xylem is the major process determining shoot and grain cadmium accumulation in rice [J]. *Journal of Experimental Botany*, 2009, **60**(9): 2677-2688.

[10] 王利, 杨洪强, 范伟国, 等. 平邑甜茶叶片光合速率及叶绿素荧光参数对氯化镉处理的响应 [J]. *中国农业科学*, 2010, **43**(15): 3176-3183.

Wang L, Yang H Q, Fan W G, et al. Effect of CdCl₂ treatment on photosynthetic rate and chlorophyll fluorescence parameters in *Malus hupehensis* leaves [J]. *Scientia Agricultura Sinica*, 2010, **43**(15): 3176-3183.

[11] Romero-Puertas M C, Rodríguez-serrano M, Corpas F J, et al. Cadmium-induced subcellular accumulation of O₂⁻ and H₂O₂ in pea leaves [J]. *Plant, Cell & Environment*, 2004, **27**(9): 1122-1134.

[12] Cho U H, Seo N H. Oxidative stress in *Arabidopsis thaliana* exposed to cadmium is due to hydrogen peroxide accumulation [J]. *Plant Science*, 2005, **168**(1): 113-120.

[13] 冯汉青, 杜变变, 王庆文, 等. 镉胁迫下活性炭对小麦幼根的保护作用 [J]. *生态学报*, 2016, **36**(10): 2962-2968.

Feng H Q, Du B B, Wang Q W, et al. The role of activated carbon in protecting the roots of wheat seedlings under cadmium stress [J]. *Acta Ecologica Sinica*, 2016, **36**(10): 2962-2968.

[14] Abid M, Danish S, Zafar-Ul-Hye M, et al. Biochar increased photosynthetic and accessory pigments in tomato (*Solanum lycopersicum* L.) plants by reducing cadmium concentration under various irrigation waters [J]. *Environmental Science and Pollution Research*, 2017, **24**(27): 22111-22118.

[15] Azhar M, Rehman M Z U, Ali S, et al. Comparative effectiveness of different biochars and conventional organic materials on growth, photosynthesis and cadmium accumulation in

- cereals[J]. Chemosphere, 2019, **227**: 72-81.
- [16] Abbas T, Rizwan M, Ali S, *et al.* Effect of biochar on cadmium bioavailability and uptake in wheat (*Triticum aestivum* L.) grown in a soil with aged contamination [J]. Ecotoxicology and Environmental Safety, 2017, **140**: 37-47.
- [17] Liu L, Li J W, Yue F X, *et al.* Effects of arbuscular mycorrhizal inoculation and biochar amendment on maize growth, cadmium uptake and soil cadmium speciation in Cd-contaminated soil[J]. Chemosphere, 2018, **194**: 495-503.
- [18] Fang B, Zhu X Q. High content of five heavy metals in four fruits: evidence from a case study of Pujiang County, Zhejiang Province, China[J]. Food Control, 2014, **39**: 62-67.
- [19] Wang Q Y, Liu J S, Cheng S. Heavy metals in apple orchard soils and fruits and their health risks in Liaodong Peninsula, Northeast China[J]. Environmental Monitoring and Assessment, 2015, **187**(1), doi: 10.1007/s10661-014-4178-7.
- [20] Guo J, Yue T L, Li X T, *et al.* Heavy metal levels in kiwifruit orchard soils and trees and its potential health risk assessment in Shaanxi, China [J]. Environmental Science and Pollution Research, 2016, **23**(14): 14560-14566.
- [21] Ali A, Shaheen S M, Guo D, *et al.* Apricot shell-and apple tree-derived biochar affect the fractionation and bioavailability of Zn and Cd as well as the microbial activity in smelter contaminated soil[J]. Environmental Pollution, 2020, **264**, doi: 10.1016/j.envpol.2020.114773.
- [22] He J L, Zhou J T, Wan H X, *et al.* Rootstock-scion interaction affects cadmium accumulation and tolerance of *Malus* [J]. Frontiers in Plant Science, 2020, **11**, doi: 10.3389/fpls.2020.01264.
- [23] 曹辉, 李燕歌, 周春然, 等. 炭化苹果枝对苹果根区土壤细菌和真菌多样性的影响[J]. 中国农业科学, 2016, **49**(17): 3412-3423.
- Cao H, Li Y G, Zhou C R, *et al.* Effect of carbonized apple branches on bacterial and fungal diversities in apple root-zone soil [J]. Scientia Agricultura Sinica, 2016, **49**(17): 3412-3423.
- [24] 农云军, 谢继丹, 黄名湖, 等. 超声提取-ICP-MS 法测定土壤中有效态铅和镉[J]. 质谱学报, 2016, **37**(1): 68-74.
- Nong Y J, Xie J D, Huang M H, *et al.* Measurement of available lead and cadmium in soil by ICP-MS with ultrasonic extraction [J]. Journal of Chinese Mass Spectrometry Society, 2016, **37**(1): 68-74.
- [25] 邹琦. 植物生理学实验指导[M]. 北京: 中国农业出版社, 2007. 166-167.
- [26] Zhang Y P, Jia F F, Zhang X M, *et al.* Temperature effects on the reactive oxygen species formation and antioxidant defence in roots of two cucurbit species with contrasting root zone temperature optima[J]. Acta Physiologiae Plantarum, 2012, **34**(2): 713-720.
- [27] 赵世杰, 史国安, 董新纯. 植物生理学实验指导[M]. 北京: 中国农业科学技术出版社, 2002. 98-99.
- [28] Steffens B, Sauter M. Epidermal cell death in rice is regulated by ethylene, gibberellin, and abscisic acid[J]. Plant Physiology, 2005, **139**(2): 713-721.
- [29] Lehmann J, Gaunt J, Rondon M. Bio-char sequestration in terrestrial ecosystems-a review [J]. Mitigation and Adaptation Strategies for Global Change, 2006, **11**(2): 403-427.
- [30] Kamran M, Malik Z, Parveen A, *et al.* Ameliorative effects of Biochar on rapeseed (*Brassica napus* L.) growth and heavy metal immobilization in soil irrigated with untreated wastewater [J]. Journal of Plant Growth Regulation, 2020, **39**(1): 266-281.
- [31] Zhang W W, Wang Z P, Song J F, *et al.* Cd²⁺ uptake inhibited by *MhNCED3* from *Malus hupehensis* alleviates Cd-induced cell death[J]. Environmental and Experimental Botany, 2019, **166**, doi: 10.1016/j.envexpbot.2019.103802.
- [32] Pormehr M, Ghanati F, Sharifi M, *et al.* The role of SIPK signaling pathway in antioxidant activity and programmed cell death of tobacco cells after exposure to cadmium [J]. Plant Science, 2019, **280**: 416-423.
- [33] Fiala R, Repka V, Čiamporová M, *et al.* Early cadmium-induced effects on reactive oxygen species production, cell viability and membrane electrical potential in grapevine roots[J]. Vitis, 2015, **54**(4): 175-182.
- [34] Caregnato F F, Koller C E, MacFarlane G R, *et al.* The glutathione antioxidant system as a biomarker suite for the assessment of heavy metal exposure and effect in the grey mangrove, *Avicennia marina* (Forsk.) Vierh [J]. Marine Pollution Bulletin, 2008, **56**(6): 1119-1127.
- [35] Shahzad B, Tanveer M, Che Z, *et al.* Role of 24-epibrassinolide (EBL) in mediating heavy metal and pesticide induced oxidative stress in plants: a review[J]. Ecotoxicology and Environmental Safety, 2018, **147**: 935-944.
- [36] Wu Z C, Zhao X H, Sun X C, *et al.* Antioxidant enzyme systems and the ascorbate-glutathione cycle as contributing factors to cadmium accumulation and tolerance in two oilseed rape cultivars (*Brassica napus* L.) under moderate cadmium stress [J]. Chemosphere, 2015, **138**: 526-536.
- [37] Kamran M, Malik Z, Parveen A, *et al.* Biochar alleviates Cd phytotoxicity by minimizing bioavailability and oxidative stress in pak choi (*Brassica chinensis* L.) cultivated in Cd-polluted soil [J]. Journal of Environmental Management, 2019, **250**, doi: 10.1016/j.jenvman.2019.109500.
- [38] 徐勤松, 施国新, 杜开和. 镉胁迫对水车前叶片抗氧化酶系统和亚显微结构的影响[J]. 农村生态环境, 2001, **17**(2): 30-34.
- Xu Q S, Shi G X, Du K H. Effect of Cd²⁺ on antioxidant system and ultrastructure of *Ottelia alismoides* (L.) Pers. leaves [J]. Rural Eco-Environment, 2001, **17**(2): 30-34.
- [39] Shi G R, Cai Q S. Cadmium tolerance and accumulation in eight potential energy crops [J]. Biotechnology Advances, 2009, **27**(5): 555-561.
- [40] Zhang Z, Liu C F, Wang X M, *et al.* Cadmium-induced alterations in morpho-physiology of two peanut cultivars differing in cadmium accumulation [J]. Acta Physiologiae Plantarum, 2013, **35**(7): 2105-2112.
- [41] Zhou J T, Wan H X, He J L, *et al.* Integration of cadmium accumulation, subcellular distribution, and physiological responses to understand cadmium tolerance in apple rootstocks [J]. Frontiers in Plant Science, 2017, **8**, doi: 10.3389/fpls.2017.00966.
- [42] 蒋明义, 杨文英, 徐江, 等. 渗透胁迫下水稻幼苗中叶绿素降解的活性氧损伤作用[J]. 植物学报, 1994, **36**(4): 289-295.
- Jiang M Y, Yang W Y, Xu J, *et al.* Active oxygen damage effect of chlorophyll degradation in rice seedlings under osmotic stress [J]. Acta Botanica Sinica, 1994, **36**(4): 289-295.
- [43] 厉书豪, 李曼, 张文东, 等. CO₂ 加富对盐胁迫下黄瓜幼苗叶片光合特性及活性氧代谢的影响[J]. 生态学报, 2019, **39**(6): 2122-2130.
- Li S H, Li M, Zhang W D, *et al.* Effects of CO₂ enrichment on photosynthetic characteristics and reactive oxygen species metabolism in leaves of cucumber seedlings under salt stress [J]. Acta Ecologica Sinica, 2019, **39**(6): 2122-2130.

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