

砂培条件下施加钙、砷对蜈蚣草吸收砷、磷和钙的影响

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摘要:在砂培条件下, 研究施加钙、砷对蜈蚣草生长和砷、磷和钙的吸收及转运的影响。添加砷对蜈蚣草的生物量(根、叶柄和羽叶的干物重)虽未达到显著影响($p < 0.05$), 但添加 0.1 mmol/L 砷时, 表现出刺激生长效应。提高介质中钙浓度明显抑制蜈蚣草根系生长, 钙浓度过高还会显著限制地上部生长。供应 0.03 mmol/L 钙时, 蜈蚣草羽片砷浓度为 4218 mg/kg, 明显高于 2.5 和 5 mmol/L 钙处理下相应的砷浓度。砷的转运系数(羽片/根)随着介质中砷浓度的升高而增大, 随着介质中钙浓度的升高而减少。这说明一定范围内提高介质中砷浓度促进砷向地上部运输, 而钙却明显抑制砷向地上部转运。钙和砷浓度过高时, 植株均会出现中毒症状。钙中毒表现为叶脉变褐和叶肉坏死; 而砷中毒现象表现在叶尖和叶缘变褐。介质中砷限制蜈蚣草根对磷的吸收, 但对地上部磷浓度无显著影响。介质中添加砷, 植物体内钙浓度升高, 可能起缓解砷毒的作用。钙、砷对蜈蚣草羽片砷累积量和总累积量均有极显著的交互作用, 钙是负交互效应, 砷是正交互效应。添加 2.5 和 5.0 mmol/L 钙时, 相对于 0.03 mmol/L 钙处理分别减少地上部砷累积量 20.8% 和 73.1%。这表明在应用蜈蚣草进行植物修复时, 介质中出现过高浓度的钙是不利于提高土壤修复效率。

关键词:钙; 砷; 磷; 交互; 蜈蚣草

Effects of Ca and As addition on As, P and Ca uptake by hyperaccumulator *Pteris vittata* L. under sand culture

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Abstract: Arsenic, P and Ca uptake by *Pteris vittata* L., as affected by Ca and As additions, were studied under sand culture. The 3×3 factorial experiment was conducted with three As concentrations (0, 0.1 and 0.2 mmol/L) and three Ca concentrations (0.03, 2.5 and 5.0 mmol/L). Although biomass of root, petiole and pinna of *Pteris vittata* L. were not significantly ($p < 0.05$) affected by As addition levels, petiole and pinna dry biomass production responded to As treatments in an identical way, and plant treated with 0.1 mmol/L had the highest dry matter weight (22% and 26% greater than 0 and 0.2 mmol/L As treatments, respectively) followed by plants treated with 0 and 0.2 mmol/L. When plants were supplied

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with Ca at rates of 0.03 and 2.5 mmol/L, a significant increase in the petiole and pinna dry matter was observed as compared with those of 5.0 mmol/L Ca treatment. Addition of Ca at rate of 5.0 mmol/L significantly increased As concentration of petiole but decreased that of pinna compared to those of 0.03 mmol/L. Plant treated with 0.03 mmol/L Ca had the highest As concentration, 4218mg/kg, in pinna compared to those of 2.5 and 5.0 mmol/L. Ratio in As concentration of pinna to root enhanced with increasing As concentration in media, while reduced with increasing Ca concentration, showing that Ca inhibited As translocation. Pinna suffered As toxicity presenting brown coloration and necrosis at the tips and margins. Vein became dark and part mesophyll gangrened, because of Ca phytotoxicity for the fern. Arsenic in nutrient solution significantly depressed root P nutrient, however it had less effect on aboveground P concentration. Comparing to control, As application enhanced Ca concentration in root (12% more than control) and pinna (13% more than control), reduced that in petiole (22% less than control). There was significantly interaction of Ca and As on plant As accumulation, and Ca was negative while As was positive. Added Ca at rate of 2.5 and 5.0 mmol/L, plants accumulated 6019 and 2014 mg/pot, respectively, which were 79% and 26% of total As accumulation by plant treated with 0.03 mmol/L. It indicated that excessive Ca in growth media might make against for efficiency of As removal from contaminated soils where phytoremediation using *Pteris vittata* L. is applied.

Key words: Calcium; arsenic; phosphorus; interaction; *Pteris vittata* L.

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环境中的砷污染问题越来越引起人们的关注。蜈蚣草(*Pteris vittata* L.)是近年报道的首例砷超富集植物,能够高效富集大量的砷^[1,2]。通过人工种植蜈蚣草7个月后,土壤中砷的修复效率达到8%^[3]。蜈蚣草是一种钙质土壤的指示植物,在热带和亚热带地区都有广泛分布^[4]。通过对中国南方各省的蜈蚣草调查发现,它一般生长在石灰性土壤,石壁和墙缝中。在钙质土壤或添加石灰土壤中,砷的有效性主要受土壤溶液中钙浓度的限制^[5]。钙是否会影响蜈蚣草对砷酸盐的吸收,这对蜈蚣草应用于砷污染土壤的修复至关重要,因为土壤中钙和砷往往同时出现:①砷酸钙作为杀虫剂自1800年开始(美国于1960年禁用)就应用于农业土壤,已造成大面积土壤砷污染^[6];②砷矿附近一般为钙质土壤或石灰性土壤;③过去人们为减轻土壤砷毒,经常施用大量的石灰^[7]。

钙是植物(包括蜈蚣草)必需的重要营养元素,同时又与砷在环境中的行为紧密相关,但钙对蜈蚣草吸收和累积砷的影响尚不清楚。本文在室内砂培条件下,研究钙砷交互对蜈蚣草生长和吸收累积砷的影响,同时探讨植物砷磷和钙磷的互作关系。

1 材料与方法

将蜈蚣草孢子(采自湖南)撒在装土(土壤取自北京,石灰性潮土)的塑料盆中育苗,待其长出3~4叶时,先用去离子水浸泡根部,去除附在根表的土壤,再将蜈蚣草移栽在砂培介质中,在人工气候箱中培养。培养条件为:14h光照,日/夜温度为26℃/20℃,湿度为85%。以缺钙改进的Hoagland为基础营养液进行砂培试验。砂培中各元素的浓度(mmol/L)为:N 4.8、P 0.4、K 2.0、Mg 0.25、Na 0.2、Fe 2.24×10^{-2} 、Mn 2.3×10^{-3} 、B 1.15×10^{-2} 、Zn 1.9×10^{-4} 、Cu 8×10^{-5} 、Mo 5×10^{-5} 、Cl 0.2、S 0.28。采用3×3完全试验方案,即3个钙水平:0.03、2.5和5mmol/L(以下分别简称低钙、中钙和高钙处理)和3个砷水平:0、0.1和0.2mmol/L(以下分别简称无砷、中砷和高砷处理)。以Ca(NO₃)₂为钙源,以Na₂HAsO₄为砷源。试验另设一个2.5 mmol/L CaCl₂和0.1 mmol/L Na₂HAsO₄处理,以排除Ca(NO₃)₂为钙源时NO₃⁻的影响。在未添加砷处理的营养液中,由于化学试剂带来的杂质,其砷浓度为 5.3×10^{-5} mmol/L。营养液每4d换1次,以维持各处理浓度。植物在砂培条件下生长150d,根、叶柄和羽叶分开收获。各部分先用自来水洗净,再用去离子水冲洗3遍。杀青,烘干至恒重,用玛瑙研钵磨碎。样品用HNO₃-HClO₄(5:1)消煮,消煮液转移到容量瓶中定容,待测。待测液中砷采用原子荧光法测定^[3](AFS-2202,海光)。磷用钒钼磷法测定^[8]。预备试

验表明采用该法测定磷时样品中砷对磷的结果无干扰。钙采用原子吸收法测定^[9](德国 Analytik Jena AG 公司, AAS vario 6 型号)。将国标(GBW-07603)作为分析质量控制,其结果在允许误差范围内。

试验数据先进行双因子固定的双因素方差分析;再进行补充分析,即分别对单个因子的各个水平进行多重比较。数据统计采用 SAS(SAS Institute Inc., 1996)(PROC ANOVA 和 PROC GLM)软件分析。

2 结果与讨论

2.1 施加钙、砷对蜈蚣草生长的影响

营养液中不同砷浓度对蜈蚣草的生长(根、叶柄和羽片的干物重)虽没有达到 $p < 0.05$ 的显著水平影响,但添加中砷处理时,植物地上部生物量最高,比无砷处理的地上部干物量提高了 22%,比高砷处理的地上部干物重提高了 26%(表 1)。地上部与根部的比率也以中砷处理最高,其次是高砷处理和无砷处理。砷不是植物必需元素,但一定浓度内可对植物生长有明显刺激的效应^[10, 11],砷的超富集植物蜈蚣草也有类似现象。在不同钙水平下,添加砷对根部生长的影响并不一致,在低钙处理下,根部生物量随着介质中砷浓度的升高而显著减少;在中钙处理下,根部生物量却随着介质中砷浓度升高而增大;高钙处理根部生长对砷的反应无明显规律。

表 1 不同砷、钙处理对蜈蚣草生物量的影响(平均数±标准差)

Table 1 Effect of As and Ca addition on biomass production of *Pteris vittata* L. (Mean±SD)

Conc. (mmol/L)		生物量 Biomass (g/pot DW)				冠根比
As	Ca	根 Root	叶柄 Petiole	羽叶 Pinna	总量 Total	Shoot/Root
0	0.03	1.45±0.25	0.62±0.34	1.63±0.21	4.00±0.37	1.76±0.21
0	2.5	0.61±0.13	0.52±0.19	1.13±0.38	2.26±0.71	2.68±0.44
0	5	0.33±0.11	0.30±0.38	0.37±0.19	0.77±0.36	1.60±0.50
0.1	0.03	1.37±0.26	0.91±0.09	1.64±0.16	3.91±0.47	1.89±0.26
0.1	2.5	0.86±0.27	0.80±0.32	1.40±0.45	3.05±1.03	2.55±0.18
0.1	5	0.34±0.12	0.29±0.14	0.53±0.19	1.16±0.43	2.48±0.67
0.2	0.03	1.05±0.32	0.62±0.25	1.28±0.49	2.95±1.05	1.76±0.23
0.2	2.5	0.91±0.25	0.65±0.21	1.36±0.34	2.93±0.76	2.23±0.40
0.2	5	0.24±0.16	0.13±0.13	0.36±0.21	0.73±0.50	2.10±0.40
0.1	2.5(CaCl ₂)	1.05±0.44	0.74±0.29	1.33±0.43	3.13±1.10	2.06±0.48
ANOVA TEST						
As conc.		NS	NS	NS	NS	NS
Ca conc.		***	***	***	***	***
Ca conc. × As conc.		NS	NS	NS	NS	NS
Duncan Multiple Range Test						
As conc.						
0		0.80a	0.48a	1.04a	2.33a	2.01a
0.1		0.85a	0.66a	1.19a	2.71a	2.31a
0.2		0.73a	0.47a	1.00a	2.20a	2.03a
Ca conc.						
0.03		1.29a	0.72a	1.51a	3.61a	1.80b
2.5		0.79b	0.66a	1.30a	2.75b	2.48a
5		0.30c	0.24b	0.42b	0.88c	2.06b
Ca form						
Ca(NO ₃) ₂		0.86a	0.80a	1.40a	3.05a	2.55a
CaCl ₂		1.06a	0.74a	1.33a	3.13a	2.06a

NS, $p \geq 0.05$; *, $p < 0.05$; **, $p < 0.01$; ***, $p < 0.001$

介质中不同钙浓度对蜈蚣草的生长有显著影响(表 1)。生长在低钙处理的植物根部生物量最大,其次是中钙和高钙处理,各处理间差异都达到 $p < 0.05$ 的显著水平。植物供应低钙和中钙时,地上部的生物量明显高于高钙处理,分别高出 237%和 195%。生长在高钙处理下的植物似乎蒸腾量小,对水分的吸收量

低,在每次换营养液时,水分残留量远高于其它处理。供应中钙时,冠根比为 2.48,显著高于其它处理。在等钙量的 $\text{Ca}(\text{NO}_3)_2$ 与 CaCl_2 处理中,其相应的的干物重和冠根比均无显著影响,这表明不同陪伴阴离子对生长没有明显的影响,造成生物量差异的是钙浓度不同的缘故,而不是硝酸盐浓度影响的结果。

Handreck 认为,营养液中 Ca/Mg 比率在 2~10 之间时,不会影响蕨类植物的生长,钙供应过多时会引起植物出现缺镁的症状^[12]。在无土栽培条件下,营养液中添加少量的钙,蕨类植物(*Nephrolepis exaltata* L.)会生长得更好^[13~15]。蜈蚣草虽是钙质土壤的指示植物,但本研究表明,介质中含钙浓度过高也会明显抑制其生长。高钙(镁浓度为 0.25mmol/L, $\text{Ca}/\text{Mg}=20$)处理下蜈蚣草生物量远低于中钙($\text{Ca}/\text{Mg}=10$)和低钙($\text{Ca}/\text{Mg}=0.12$)处理下的生物量,并且植物羽片叶脉变褐,叶肉部分坏死,呈现缺镁的症状。肖细元等研究钙、砷对蜈蚣草吸收转运金属元素的影响时发现,钙处理显著限制镁的吸收,高钙处理羽片中镁浓度极低,该结果也证实本文的推测^[16]。应当指出的是,如果 Handreck 提出的蕨类植物的适宜 Ca/Mg 比率为 2~10 对蜈蚣草也基本上适用的话,那么添加钙浓度更低时,提高钙浓度是否会促进蜈蚣草的生长和砷的吸收则有待探讨。

2.2 施加钙、砷对蜈蚣草植株中砷、磷和钙浓度影响

蜈蚣草体内砷浓度和转运系数(叶/根)随着营养液中添加砷量的提高,而明显增大。在高砷处理中,植株中砷浓度和转运系数分别为 7486 mg/kg 和 5.84,均为最高(表 2)。砷在蜈蚣草体内分布始终遵循下述规律:羽片>叶柄>根。本次试验中,蜈蚣草羽片中砷的最大浓度为 10381 mg/kg(高砷和低钙处理)。在高砷的条件下,羽片出现砷中毒现象,开始叶尖变褐,然后羽叶边缘变褐坏死。

表 2 不同砷、钙处理对蜈蚣草砷浓度的影响(平均数±标准差)

Table 2 Effect of As and Ca addition on As concentration of *Pteris vittata* L. (Mean±SD)

Conc. (mmol/L)		砷浓度 As conc. (mg/kg)			羽叶/根
As	Ca	根 Root	叶柄 Petiole	羽叶 Pinna	Pinna/Root
0	0.03	6±5	9±9	24±18	4.43±3.00
0	2.5	6±4	8±2	17±4	3.74±2.36
0	5	5±1	22±24	12±5	2.19±0.86
0.1	0.03	913±139	1089±196	4219±328	4.71±0.78
0.1	2.5	836±173	1156±316	3558±519	4.35±0.80
0.1	5	855±945	1525±138	3994±743	4.78±1.43
0.2	0.03	1344±672	1640±221	8410±1855	6.92±1.99
0.2	2.5	1406±447	1697±378	6779±772	5.29±2.12
0.2	5	1376±183	2394±425	7268±753	5.31±0.45
0.1	2.5(CaCl_2)	809±168	1108±130	3771±329	4.82±1.08
ANOVA TEST					
As conc.		***	***	***	*
Ca conc.		NS	***	**	NS
Ca conc. × As conc.		NS	*	NS	NS
Duncan Multiple Range Test					
As conc.					
0		6c	13c	18c	3.45b
0.1		868b	1257b	3923b	4.61ab
0.2		1375a	1910a	7486a	5.84a
Ca conc.					
0.03		754a	913b	4218a	5.35a
2.5		750a	953b	3451b	4.46a
5		745a	1314a	3758ab	4.09a
Ca form					
$\text{Ca}(\text{NO}_3)_2$		836a	1156a	3558a	4.36a
CaCl_2		809a	1108a	3771a	4.82a

NS, $p \geq 0.05$; *, $p < 0.05$; **, $p < 0.01$; ***, $p < 0.001$

介质中钙浓度由 0.03 升高到 5.0mmol/L 蜈蚣草根砷浓度无显著变化,叶柄中砷浓度升高,但羽片中砷浓度降低。这说明钙可促进砷由根部向叶柄转运,却限制其进一步向羽片转运。总的来说,增加介质中钙浓度降低根向羽片的转运系数(表 2)。钙、砷对蜈蚣草叶柄中砷浓度有显著的正交互效应。

Tu 和 Ma 在土培条件下研究了蜈蚣草对 $\text{Ca}_3(\text{AsO}_4)_2$ 、 AlAsO_4 、 FeAsO_4 、 Na_2HAsO_4 和 K_2HAsO_4 等不同形态砷的吸收和转运的试验结果表明,供应 $\text{Ca}_3(\text{AsO}_4)_2$ 时蜈蚣草羽片中砷浓度最高,因而他们推测钙促进这种植物对砷的吸收转运^[17]。一些研究指出,土壤中添加钙或钙结合砷可以提高植物对砷的吸收,这是由于增大土壤 pH 和减少砷的吸附,增加了土壤砷的有效性的缘故^[18~21]。Xie 和 Huang 报道添加钙可增强砷对水稻的毒性,使其产量下降^[22]。分析他们的数据发现,钙可提高叶片中砷的浓度,但抑制其向稻米中转运。这意味着钙似乎有利于砷由根部向地上部转运,但限制砷向植物某些器官转运。因此,到目前为止关于钙如何影响植物中砷的转运过程还有待进一步研究。

在本试验中,介质中砷和钙浓度对根部磷浓度影响最大,添加砷降低根部磷浓度,高钙处理根部磷浓度远高于其他处理(表 3),可能是钙和磷在根部质外体中大量沉淀引起的。羽片中磷浓度不受营养液中砷、钙浓度的影响,各处理之间的羽片磷浓度差异均不显著。植物体内磷浓度分布规律为:根>叶柄>羽叶,这与砷的分布趋势正好相反。

表 3 不同砷、钙处理对蜈蚣草磷浓度的影响(平均数±标准差)

Table 3 Effect of As and Ca addition on P concentration of *Pteris vittata* L. (Mean±SD)

Conc. (mmol/L)		磷浓度 P conc. (mg/kg)		
As	Ca	根 Root	叶柄 Petiole	羽叶 Pinna
0	0.03	6622±2871	3311±52	2874±566
0	2.5	7203±810	2963±315	2685±205
0	5	9276±1987	3245±73	2522±298
0.1	0.03	4825±915	3081±291	2331±211
0.1	2.5	4407±1602	2841±282	2426±653
0.1	5	6717±2537	2913±551	2654±565
0.2	0.03	4994±2161	3105±149	2656±514
0.2	2.5	4275±711	2686±399	2493±242
0.2	5	8492±4134	3420±348	2641±311
0.1	2.5(CaCl_2)	5572±1674	2979±290	2300±293
ANOVA TEST				
As conc.		**	NS	NS
Ca conc.		*	*	NS
Ca conc. × As conc.		NS	NS	NS
Duncan Multiple Range Test				
As conc.				
0		7701a	3173a	2694a
0.1		5316b	1945a	2470a
0.2		5921ab	3070a	2597a
Ca conc.				
0.03		5480b	3163a	2620a
2.5		5295b	2830b	2535a
5		8162a	3192a	2606a
Ca form				
$\text{Ca}(\text{NO}_3)_2$		4407a	2841a	2426a
CaCl_2		5572a	2979a	2300a

NS, $p \geq 0.05$; *, $p < 0.05$; **, $p < 0.01$; ***, $p < 0.001$

因砷酸盐和磷酸盐物理化学性质近似,它们在普通植物(如 *Holcus lanatus* L. 等)的吸收和转运过程中存在拮抗效应^[23]。蜈蚣草是砷的超富集植物,在本研究中地上部砷的最大浓度远高于其磷浓度,但没有影

响磷的转运和地上部磷营养。有研究表明,蜈蚣草中磷酸盐和砷酸盐是通过相同的通道吸收^[24],可磷砷并非通过相同的机制向地上部转运^[25]。蜈蚣草中砷主要以亚砷酸盐形态向地上部转运和储存^[26~28],亚砷酸盐不会对磷酸盐的转运产生明显的拮抗作用。

由表 4 中分析可看出,介质中砷对植株钙浓度的影响由根到羽叶逐渐加强,对根部钙浓度影响未达到显著水平($p < 0.05$),对叶柄中钙浓度达到 $p < 0.05$ 的显著水平影响,对羽叶中钙浓度达到 $p < 0.01$ 的极显著水平影响。这种趋势与植物砷浓度分布规律相同,说明植物钙营养与植物砷浓度可能有某种联系。与对照处理相比,添加砷提高根部(比对照多 12%)和羽片(比对照多 13%)钙浓度,但减少叶柄中钙浓度(比对照少 22%)(表 4)。这说明砷促进蜈蚣草对钙的吸收,促进钙由叶柄向羽叶的转运。中钙和高钙处理可极显著提高植物钙浓度,但氯化钙和硝酸钙这两种不同钙源对植物钙营养影响并不显著。

表 4 不同砷、钙处理对蜈蚣草钙浓度的影响(平均数±标准差)

Table 4 Effect of As and Ca addition on Ca concentration of *Pteris vittata* L. (Mean±SD)

Cconc. (mmol/L)		钙浓度 Ca conc. (mg/kg)		
As	Ca	根 Root	叶柄 Petiole	羽叶 Pinna
0	0.03	7223±458	2722±238	7826±400
0	2.5	13555±1193	6044±762	16408±1262
0	5	12915±1068	9069±3578	17855±2326
0.1	0.03	10613±1582	2379±295	11223±744
0.1	2.5	13677±2816	4636±634	19586±3125
0.1	5	14991±145	6294±1432	19539±2152
0.2	0.03	6446±883	2233±441	7398±378
0.2	2.5	16305±2980	5654±867	18841±475
0.2	5	13612±1841	7912±648	18810±1311
0.1	2.5(CaCl ₂)	10976±1142	5164±812	17943±2023
ANOVA TEST				
As conc.		NS	*	**
Ca conc.		***	***	***
Ca conc. × As conc.		NS	NS	NS
Duncan Multiple Range Test				
As conc.				
0		11230b	5945a	14030b
0.1		13094a	4436b	16783a
0.2		12121ab	5266ab	15017b
Ca conc.				
0.03		8094b	2445c	8816b
2.5		14512a	5444b	18278a
5		13839a	7758a	18735a
Ca form				
Ca(NO ₃) ₂		13677a	4636a	19586a
CaCl ₂		10977a	5164a	17943a

NS, $p \geq 0.05$; *, $p < 0.05$; **, $p < 0.01$; ***, $p < 0.001$

前人的研究也报道添加砷可增加植物体内钙浓度。Cox 研究表明,欧洲油菜(*Brassica napus* L.)地上部钙浓度与砷添加浓度成直线正相关^[29]。Marin 发现添加砷处理的水稻中钙浓度显著高于对照处理^[30]。Carbonell-Barrachina 等报道在豆科植物(*Phaseolus vulgaris* L.)钙浓度随介质中砷浓度的增加而增加^[31]。植物受砷毒胁迫时,通过改善植物钙营养达到解毒或自我保护的目的,在砷超富集植物中,植物体内钙可

能也有缓解植物砷毒的作用。

2.3 施加钙、砷对蜈蚣草富集砷的影响

表 5 不同砷、钙处理对蜈蚣草砷累积量的影响 (平均数±标准差)

Table 5 Effect of As and Ca addition on As accumulation of *Pteris vittata* L. (Mean±SD)

Conc. (mmol/L)		砷累积量 As accumulation (mg/pot)			
As	Ca	根 Root	叶柄 Petiole	羽叶 Pinna	总量 Total
0	0.03	5±3	7±8	36±22	48±14
0	2.5	4±4	4±2	20±11	28±16
0	5	2±1	2±1	5±1	8±5
0.1	0.03	1260±341	995±230	6934±1195	9189±1589
0.1	2.5	718±283	902±425	4874±1426	6495±2096
0.1	5	293±122	448±254	2091±645	2832±900
0.2	0.03	1503±1014	984±360	11232±5439	13720±6705
0.2	2.5	1325±675	1052±195	9157±2289	11535±2470
0.2	5	314±213	295±286	2592±1533	3201±2025
0.1	2.5(CaCl ₂)	833±362	825±364	5059±1810	6717±2406
ANOVA TEST					
As conc.		**	***	***	***
Ca conc.		***	***	***	***
Ca conc. × As conc.		NS	NS	**	*
Duncan Multiple Range Test					
As conc.					
0		3b	4b	20b	27b
0.1		757a	782a	4633a	6172a
0.2		1048a	777a	7660a	9485a
Ca conc.					
0.03		923a	662a	6067a	7652a
2.5		683a	652a	4684a	6019a
5		203b	248b	1563b	2014b
Ca form					
Ca(NO ₃) ₂		718a	903a	4874a	6495a
CaCl ₂		822a	825a	5059a	6717a

NS, $p \geq 0.05$; *, $p < 0.05$; **, $p < 0.01$; ***, $p < 0.001$

蜈蚣草中砷的累积量同时受介质中砷水平和钙水平的限制。随着砷添加量的增大,蜈蚣草累积砷量显著增加。添加中钙和高钙处理的地上部砷累积量分别为 5336 和 1811 mg/pot,为低钙处理的 79.2%和 27%。在低钙处理时,羽片中砷累积量占总砷累积量的比例为 79.3%。其次为高钙处理(78.6%)和中钙处理(78%)。蜈蚣草低钙处理砷累积总量最高(7562 mg/pot),其次是中钙处理(6019 mg/pot)和高钙处理(2014 mg/pot)(表 5)。介质钙和砷水平对蜈蚣草羽片中砷累积量和植株总砷累积量均有显著的交互作用,其中钙为负交互效应,而砷为正交互效应。

虽然已有证据表明,添加钙可促进植物累积砷^[32]。但这个规律不适合蜈蚣草,提高介质中钙水平会减少其对砷的富集。在植物修复或生态恢复过程中,为改良土壤 pH 和肥力,添加石灰或含钙肥料是必需的^[33, 34],然而如果应用蜈蚣草进行砷污染土壤的修复时,盲目施用钙,可能会降低植物累积砷量,从而导致其修复效率低下。

3 结论

砂培试验表明,随着介质中砷浓度的升高,蜈蚣草体内砷浓度及转运系数均增大,但介质中过高的钙浓度不仅抑制蜈蚣草的生长,降低羽片砷浓度,还大幅度减少地上部砷的累积量。过量钙和砷均会导致蜈蚣草出现组织变褐坏死中毒症状,钙中毒症状出现在叶脉和叶肉,而砷中毒症状先出现在叶尖和叶边缘。

用蜈蚣草修复砷污染土壤时,石灰或含钙添加剂需谨慎用,否则会减少砷累积,降低植物修复效率。

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