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水分管理和外源硒对水稻吸收累积铅的影响

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摘要: 通过盆栽试验, 研究了不同水分管理和外源亚硒酸盐的添加对水稻根际铅的动态变化和水稻吸收累积铅的影响。结果表明, 淹水显著增加了根表铁膜对铅的吸附和根系对铅的吸收, 淹水下苗期和成熟期水稻根系铅含量分别是非淹水处理时的4.2~8.5和1.4~1.5倍; 淹水降低了地上部的铅分配, 在苗期和成熟期分别降低85.9%~86.7%和51.8%~74.0%。加硒降低了土壤溶液、苗期水稻根系和地上部的铅含量以及成熟期水稻根表铁膜、根系和茎中的铅含量。与对照相比, 淹水和非淹水下加硒处理使苗期水稻根系铅含量分别降低了5.4%~24.3%和2.7%~61.7%, 使成熟期水稻根系铅含量分别降低了56.1%~64.1%和53.8%~63.2%。水稻籽粒中的铅含量在不同处理间无显著差异。因此, 水分管理和外源硒的添加显著影响了水稻根系对铅的吸收, 而对水稻籽粒对铅的累积无显著影响。

关键词: 铅; 水稻; 水分管理; 亚硒酸盐; 吸收; 累积

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Lead Uptake and Accumulation in Rice (*Oryza sativa* L.) with Water Management and Selenite Fertilization

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Abstract: Lead (Pb) accumulation in rice grains has been identified as a potential threat to human health. Our study investigated the effects of varied rates of selenite fertilization (0, 0.5 and 1.0 mg·kg⁻¹) on the dynamics of Pb in soil solutions, and its uptake and translocation by rice under different water management scenarios (aerobic and flooded) in pot experiments. Plants were harvested at seedling stage and at maturity to determine the Pb contents, and soil solutions were extracted during the growing season to monitor the Pb dynamics. Results showed that flooding the soil significantly increased Pb concentrations in DCB extracts and rice roots both at seedling stage and maturity. Root Pb contents in flooded treatments were 4.2-8.5 and 1.4-1.5 times higher than those under aerobic conditions at rice seedling stage and maturity. Flooding also decreased the percentage of Pb in rice shoots. The Pb content in soil solutions, rice seedlings, rice roots and stems at maturity were significantly decreased by selenite additions. Relative to the control treatment, selenite additions decreased the rice root Pb contents by 5.4%-24.3% and 2.7%-61.7% under flooding and aerobic conditions at seedling stage, respectively; while decreased Pb in rice root by 56.1%-64.1% and 53.8%-63.2% respectively, at maturity. No significant differences existed in grain Pb levels among the treatments. Results demonstrated that water management regimes and selenite additions affected Pb uptake by rice roots significantly, but had no significant influence on Pb accumulation in rice grains.

Key words: lead; rice; water management; selenite; uptake; accumulation

铅(lead, Pb)是一种强毒性的重金属, 主要来自工农业生产中废弃物的排放以及大气沉降等, 在土壤中的溶解度小, 且无法再降解, 在土壤中累积后可通过植物的富集作用进入人体, 对生命健康造成较强的威胁^[1]。随着现代社会的快速发展, 我国农田土壤铅污染的现象也在加重, 据报道, 在广东乐昌区的一个铅锌矿区, 稻田土壤的铅含量为1486 mg·kg⁻¹, 糙米的铅含量高达4.67 mg·kg⁻¹^[2], 超出食品安全国家标准中稻米铅限量值(0.2 mg·kg⁻¹, GB 2762-2017)的二十多倍。因此, 控制水稻中铅污染的研究受到了广泛的关注。

土壤铅对植物的毒性取决于土壤中铅的生物有

效性, 而有效性与土壤的理化性质有关, 如土壤质地、pH、氧化还原电位(Eh)、有机质、陪伴离子等。有研究发现, 随着土壤pH的升高, 水稻籽粒中的铅含量显著升高^[3]。水分管理可以通过影响土壤的Eh而影响铅化物的其他阴离子基团的形成, 从而影响铅在土壤中的溶解性^[4]。

近些年来, 有研究发现, 硒(selenium, Se)元素能够与多种重金属(如镉、砷、汞等)产生拮抗效

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应,减轻其对植物的毒害作用,降低植物的重金属积累^[5~7]。Hu等^[8]的研究发现,外源硒的添加可以降低水稻的铅含量。硒是人和动物必需的微量营养元素之一,在人体的抗氧化系统,生殖系统,免疫系统发挥了重要作用^[9]。在土壤中,植物对硒的吸收也受土壤的理化性质等影响,Li等^[10]的研究发现,土壤添加亚硒酸钠后,淹水下水稻籽粒及秸秆中硒含量低于非淹水。

因此,为了进一步探讨硒对铅的调控作用,本试验模拟土壤条件下硒对水稻吸收转运铅的影响,并设置了全生育期淹水和湿润灌溉两个水分管理模式,观察整个生长周期中土壤溶液中铅的动态变化以及水稻对铅的积累,旨在为降低水稻铅污染措施的实施提供理论依据。

1 材料与方法

1.1 植物培养

供试植物:水稻(*Oryza sativa* L.),品种为准两优608,为籼型两系杂交水稻。

供试土壤:采自湖南省湘潭市某乡镇的稻田表层(0~20 cm),土壤基本理化性质为:pH 7.3,有机质:28.1 g·kg⁻¹,总氮:2.4 g·kg⁻¹,速效磷:15.8 mg·kg⁻¹,速效钾:115.3 mg·kg⁻¹;总铅:300.9 mg·kg⁻¹,总硒:0.3 mg·kg⁻¹。按照 Tessier 等^[11]连续分级提取方法获得土壤铅的各形态含量,可交换态:0.9 mg·kg⁻¹,碳酸盐结合态:60.7 mg·kg⁻¹,铁锰氧化物结合态:94.4 mg·kg⁻¹,有机结合态:28.6 mg·kg⁻¹,残渣态:116.3 mg·kg⁻¹。

土壤风干后过5目的筛,装入20(直径)cm×20(高)cm的塑料花盆(每盆装土2.5 kg)中,施入浓度分别为175、30和75.5 mg·kg⁻¹的氮肥、磷肥和钾肥为基肥。然后将亚硒酸盐(Na₂SeO₃)以溶液的形式充分混入土壤中,添加浓度(以硒计)为0、0.5和1.0 mg·kg⁻¹,分别表示为CK、Se0.5和Se1.0。每个处理3个重复。设置了两种不同的水分管理模式:非淹水(每天补充去离子水使土壤持水量保持70%)和淹水(每天补充去离子水使水面保持在土面以上1~2 cm)。装盆时,每盆土埋入1支土壤溶液取样器(Rhizon MOM 10 cm length, 2.5 mm OD, Rhizosphere Research Products, Wageningen, The Netherlands)。最后用保鲜膜将盆盖住,平衡一周后播种。

种子发芽前先用30% H₂O₂消毒15 min,洗净后在饱和CaSO₄中浸泡过夜。待种子吸涨后,置于

去离子水中漂浮的网格上,使种子半浸入水。种子发芽后,挑选生长一致的幼苗移栽至花盆中,每盆4株水稻。

培养地点:中国农业大学西校区资环温室。温度:25℃±3℃/20℃±3℃(白天/黑夜);光照强度:240~350 μmol·(m²·s)⁻¹(14 h);相对湿度:60%~70%。

1.2 取样与测定

水稻生长35 d和150 d后,分别取苗期样(每盆取2株)和成熟期样(剩下的2株)。洗净后,苗期样将根系和地上部分开,成熟期样将根、茎、叶、颖壳、糙米分开。用DCB浸提根表铁膜,步骤如下^[12]:将根系放入150 mL烧杯中,加入60 mL含有0.03 mol·L⁻¹柠檬酸三钠(Na₃C₆H₅O₇)和0.125 mol·L⁻¹碳酸氢钠(NaHCO₃)的混合提取液(现用现配)浸没整个根系,并加入1.2 g连二亚硫酸钠(Na₂S₂O₄),在室温下静置。60 min后,将提取液转移至100 mL容量瓶,用去离子水冲洗根系组织并定容至100 mL,过0.45 μm滤膜。浸提后的根系和地上部都用去离子水洗净,75℃下烘干48 h,记录干重,磨碎。定量称取待测样品,用HNO₃消煮(MARS-5微波消解仪),定容,过滤。

在水稻移苗后第2、9、24、38、82、148 d,通过土壤溶液提取器提取20 mL土壤溶液。每次取完后,立即将土壤溶液分为2份,一份用于测定pH、Eh值,另一份取5 mL土壤提取液,用10%的HNO₃稀释至10 mL,用于铅含量的测定。

用ICP-MS(Agilent ICP-MS 7500ce, Agilent Technologies, Santa Clara, CA, USA)测定DCB浸提液,消解液以及土壤溶液中的铅含量。测定过程中采用生物成分分析标准物质大葱(GBW10049 GSB-27)和空白样品进行质量控制。回收率为85%~105%。

1.3 数据处理

本试验数据为3次重复的平均值和标准误差,使用Excel进行数据处理,并采用SAS软件进行方差分析(多重比较采用Duncan法),图采用Sigmaplot 12.5绘制。

2 结果与分析

2.1 水分管理和外源硒对土壤溶液铅含量的影响

在水稻整个生长周期,水分管理对土壤溶液中的铅含量无显著影响(除了第3次取样时,非淹水下土壤溶液的铅含量显著大于淹水下)。外源硒的

添加降低了土壤溶液中的铅含量, 且在前两次时显著降低($P < 0.05$). 水稻移栽 9 d (第二次取样) 时, 与对照相比, 非淹水和淹水下添加硒分别使土壤溶液中的铅含量降低了 58.3% ~ 61.4% 和 44.3% ~ 46.8% [图 1(a)]. 土壤溶液的 pH 范围为 6.7 ~ 7.6, 淹水略微降低了土壤溶液的 pH 值[图 1(b)]. 从水稻分蘖期开始, 对土壤溶液的 Eh 值进行监测, 发现淹水下土壤溶液的 Eh 值显著大于非淹水, 且两者之间的差异随培养时间的增大而减小[图 1(c)]. 加硒处理对土壤溶液的 pH 和 Eh 值均未显著影响.

2.2 水分管理和外源硒对苗期水稻铅含量的影响

不同水分管理对苗期水稻根表铁膜和根系的铅含量均有显著影响, 且加硒处理显著影响了水稻体内的铅含量($P < 0.05$). 水稻根表铁膜和根系的铅含量在淹水时分别为非淹水时的 4.0 ~ 6.2 和 4.2 ~ 8.5 倍. 非淹水时, 外源硒的添加使根系和地上部的铅含量分别降低了 2.7% ~ 61.7% 和 8.5% ~ 43.9%; 在淹水时分别降低了 5.4% ~ 24.3% 和 24.1% ~ 24.3% (图 2).

2.3 水分管理和外源硒对成熟期水稻铅含量的影响

水分管理对成熟期水稻根、茎、叶中的铅含量有显著影响, 加硒处理显著影响了水稻铁膜、根和茎的铅含量, 且水分管理和加硒处理之间的相互作用显著影响了水稻铁膜和茎对铅的积累($P < 0.05$). 非淹水时水稻茎、叶中铅含量分别为淹水时的 1.4 ~ 2.7 和 2.4 ~ 7.9 倍. 然而根系和铁膜中的铅含量却为淹水时大于非淹水, 淹水时分别是非淹水的 1.4 ~ 1.5 和 2.2 ~ 2.4 倍. 与对照相比, 加硒显著降低了水稻根表铁膜、根系和茎中的铅含量, 在非淹水时分别降低了 45.9% ~ 65.8%、53.8% ~ 63.2% 和 56.3% ~ 67.7%, 在淹水时分别降低了 21.7% ~ 54.6%、56.1% ~ 64.1% 和 37.7% ~ 52.5%. 籽粒和颖壳的铅含量在不同水分处理和不同硒处理间均无显著差异. 非淹水时水稻各部位的铅含量为根系 > 根表铁膜 > 叶 > 茎 > 颖壳 > 籽粒, 淹水时铅含量为根表铁膜 > 根系 > 叶 > 茎 > 颖壳 > 籽粒(图 3).

2.4 水分管理和外源硒对水稻铅分配的影响

苗期和成熟期水稻各部位的铅分配如图 4 所示. 水分管理显著影响了铅在苗期水稻根系和地上部的分配, 非淹水时, 水稻地上部铅分配比为 11.7% ~ 16.9%, 显著小于根系和铁膜的铅分配($P < 0.001$). 淹水使地上部的铅分配降低了 85.9% ~

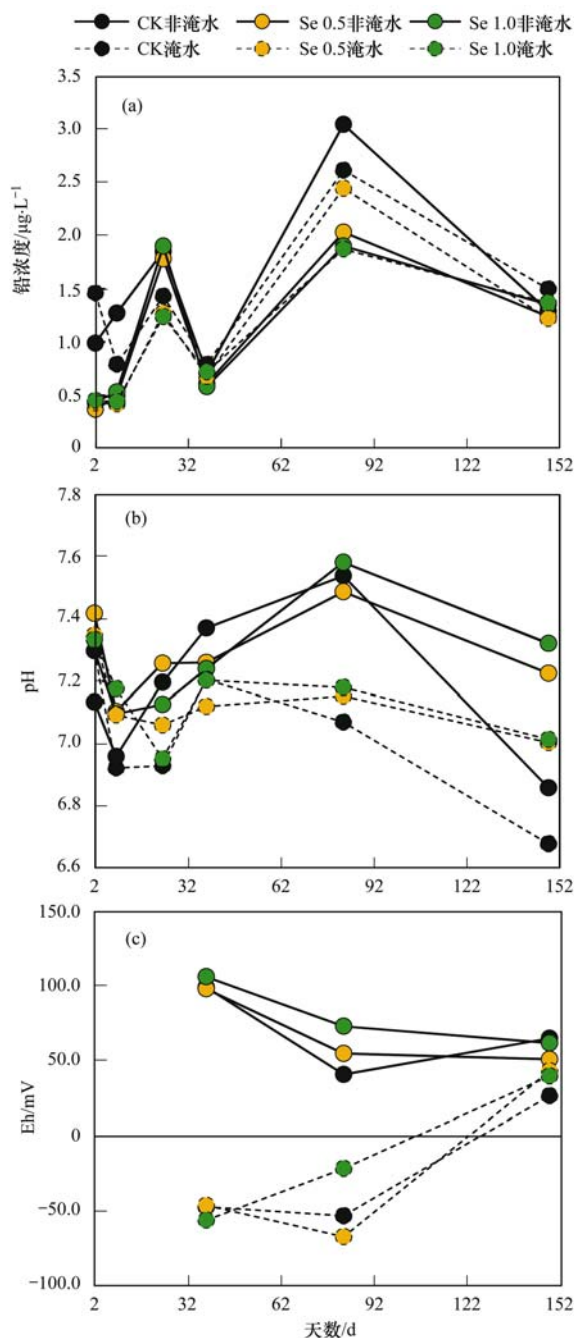
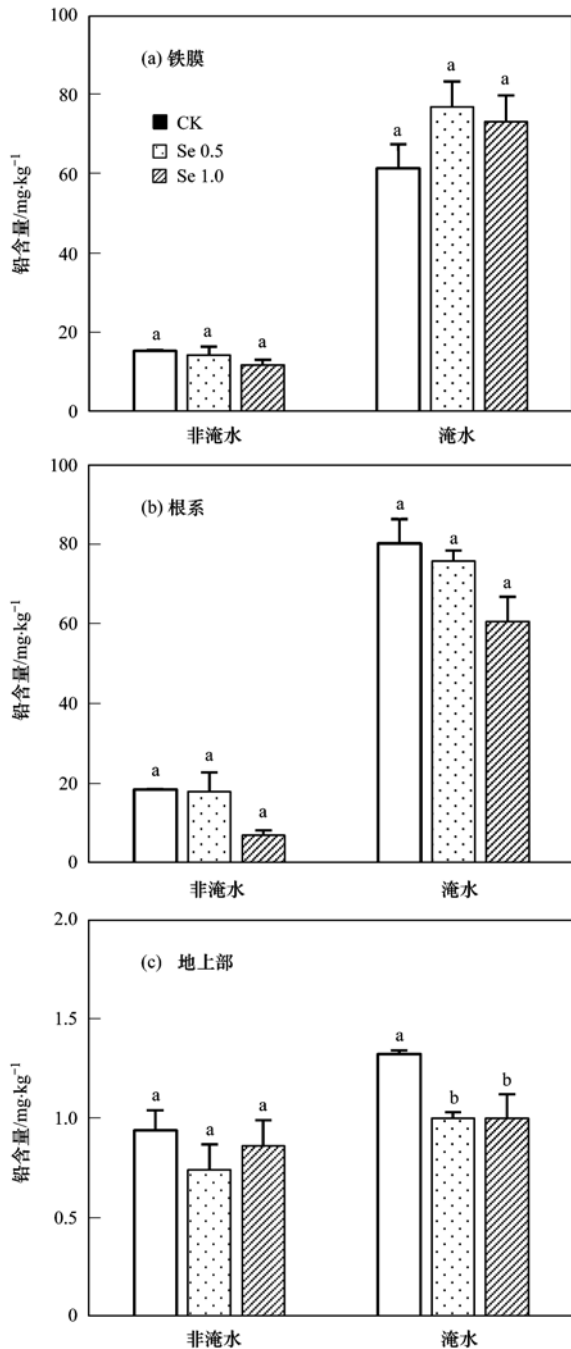


图 1 水分管理和外源硒对土壤溶液中铅含量以及土壤溶液 pH 和 Eh 的影响

Fig. 1 Effect of water management and selenite addition on the Pb concentration in soil solutions and the soil solution pH and Eh

86.7% ($P < 0.001$), 使根系铅分配比增加了 10.7% ~ 53.0% ($P < 0.001$), 对铁膜中的铅分配无显著影响. 加硒显著增加了铁膜中的铅分配, 在非淹水和淹水时分别增加了 3.2% ~ 22.7% 和 16.8% ~ 19.3% ($P < 0.01$), 降低了根系的铅分配比($P < 0.05$) [图 4(a)].

对于成熟期的水稻, 淹水也使铅在天上部和根系的分配比分别降低了 23.0% ~ 64.4% 和 26.0%



数据表示均值 + 标准误差 ($n=3$),

图中不同字母表示不同硒处理差异显著 ($P < 0.05$)

图2 水分管理和外源硒对苗期水稻根表铁膜、根系及地上部铅含量的影响

Fig. 2 Effect of water management and selenite addition on the Pb content in iron plaque on rice root surfaces, rice roots and shoots at the seedling stage

~27.7% ($P < 0.01$), 而使铁膜的铅分配分别增加了 109.8% ~ 119.2% ($P < 0.001$)。加硒增加了地上部的铅分配, 降低了根系的铅分配, 在非淹水和淹水时分别使地上部铅分配比增加了 75.2% ~ 95.4% 和 226.5% ~ 322.5% ($P < 0.01$), 使根系的

分配比降低了 22.8% ~ 26.1% 和 32.7% ~ 37.7% ($P < 0.001$) [图 4(b)]。

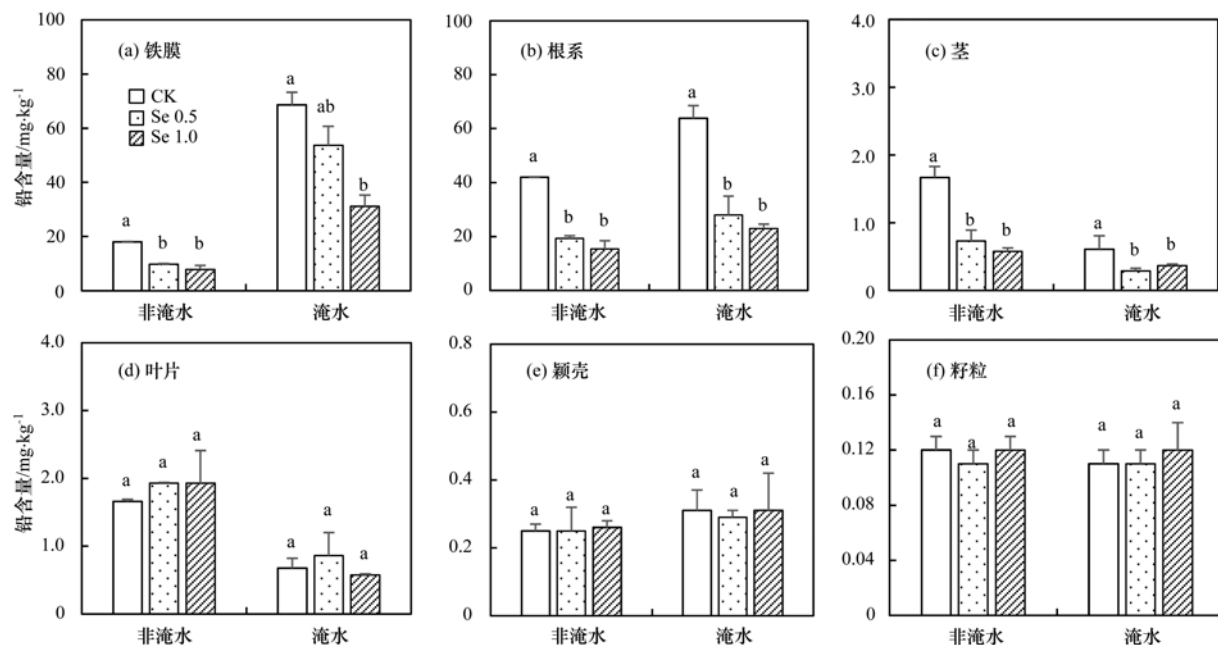
与苗期相似, 成熟期水稻中的铅分配也为地上部小于根系或根表铁膜, 而籽粒中铅仅占植物总铅量的 0.9% ~ 3.2%。非淹水下成熟期水稻铅各部位的铅分配比为根系 > 根表铁膜 > 叶 > 茎 > 籽粒 ≈ 颖壳, 淹水下为根表铁膜 > 根系 > 叶 > 茎 ≈ 籽粒 ≈ 颖壳 [图 4(b)]。

3 讨论

本研究发现, 淹水对土壤溶液中的铅含量无显著影响, 增加了根表铁膜和根系的铅含量。有研究表明, 酸性条件下, 淹水使土壤中铁锰氧化物等还原而消耗大量质子, 导致土壤 pH 上升, 土壤固相表面的负电荷增加, 因对铅离子的吸附能力增强, 使土壤中的可交换态铅含量降低^[13]。而本试验中, 淹水使土壤 pH 略微下降, 这可能是由于碱性土淹水后大量碳酸盐溶解, 土壤中的 P_{CO_2} 上升导致^[14]。pH 较低时, 土壤中的难溶态金属如碳酸盐结合态、氢氧结合态等的溶解性升高, 从而增加了金属的有效性^[15, 16]。淹水导致土壤 Eh 降低, 一方面可使土壤中氧化性 Fe(III)、Mn(III/VI)、 NO_3^- 、 SO_4^{2-} 等发生还原作用生成 Fe^{2+} 、 Mn^{2+} 、 NO_2^- 、 S^{2-} 等^[17], 减少易溶或微溶性复合物 $PbSO_4$ 、 $Pb(NO_3)_2$ 的形成^[18], 而形成难溶的 PbS 沉淀^[4]; 而 Fe^{2+} 可通过沉淀-氧化作用形成溶解度低的无定型氧化铁^[19], 增加了对铅的吸附, 从而降低了土壤中铅的有效性。另一方面, 淹水后铁锰氧化物的还原溶解也可以将吸附的铅离子重新释放出来^[20]。本试验土壤中有 31.4% 的铅以铁锰氧化物结合态 (94.4 $mg \cdot kg^{-1}$) 的形式存在。因此, 淹水对铅有效性的影响是这几个过程共同作用的结果。

此外, 淹水导致水稻根系表面的铁膜增加 (在苗期和成熟期分别增加 49.3% ~ 59.3% 和 7.9% ~ 29.7%), 此铁膜既可以作为铅的隔离层而减少根系的吸收^[21], 又可以作为重金属源而促进植物对铅的吸收^[22]。Zhou 等^[23]的研究发现, 铁膜的增加降低了水稻根系对镉的吸收, 却增加了对铅的吸收, Ye 等^[24]对香蒲的研究也发现了这一规律。铁膜对铅的吸附能力极强^[25], 水稻中的铅主要富集在根表的铁膜及根系中, 较难向地上部转运^[26, 27]。淹水后铁膜增多, 对铅的吸附增大, 因此地上部的分配显著减少。

本试验结果表明, 土壤淹水对水稻根表铁膜和



数据表示均值 + 标准误差 ($n = 3$), 图中不同字母表示不同硒处理差异显著 ($P < 0.05$)

图3 水分管理和外源硒对成熟期水稻根表铁膜、根系、茎、叶、颖壳和籽粒中铅含量的影响

Fig. 3 Effect of water management and selenite addition on the Pb content in iron plaque on rice root surfaces, rice roots, stems, leaves, husks and grains at maturity

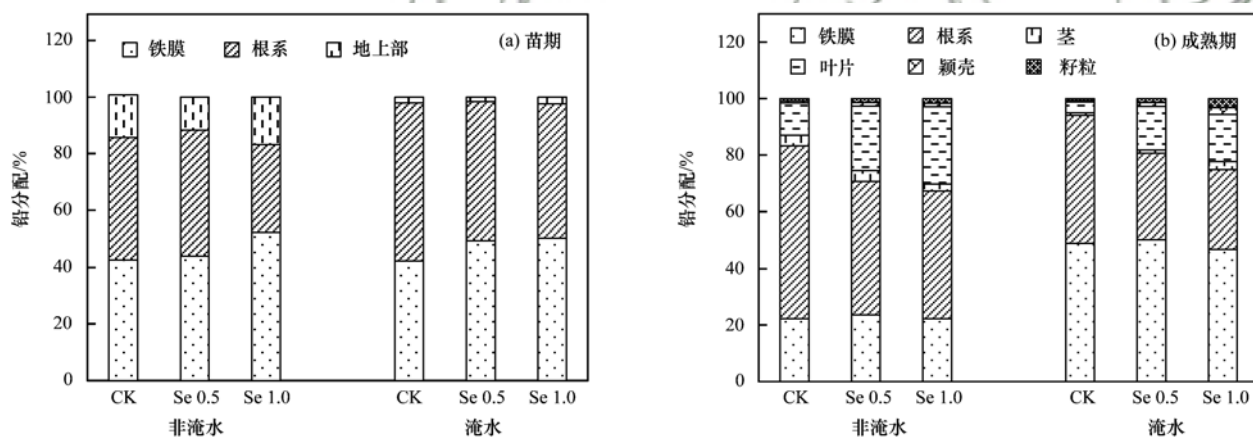


图4 水分管理和外源硒对铅在水稻苗期和成熟期各部位所占比例的影响

Fig. 4 Effect of water management and Se treatments on the percentages of Pb in different components of rice at the seedling stage and at maturity

根系铅含量的增加效果为苗期 > 成熟期; 且淹水增加了苗期水稻地上部的铅含量, 却降低了成熟期水稻茎、叶中的铅含量. 根表铁膜的形成量随着生育期的延长而减少, 对铅的吸附能力也在减弱^[28], 因此作为“铅源”对根系吸收铅的促进作用也在减弱. 胡莹等研究也发现, 分蘖期时, 水稻根表铁膜的增加促进了根系对铅的吸收和累积, 在孕穗期促进了根系的吸收而抑制了向茎、叶的转运^[29]. 方志萍等^[30]发现成熟期水稻籽粒中的铅含量与根表铁膜的数量呈显著负相关. 因此, 淹水对水稻铅吸收转运的影响在不同生育期的影响不全一致.

外源硒的添加, 显著降低了苗期水稻对铅的积累, 且降低了成熟期水稻根表铁膜、根系和茎中铅含量. 有人提出, SeO_3^{2-} 可与 Cd^{2+} 或 Pb^{2+} 形成 CdSeO_3 或 PbSeO_3 复合物^[31], 降低土壤溶液中 Cd^{2+} 或 Pb^{2+} 的有效性. 且根际的 SeO_3^{2-} 发生还原作用转化为 Se^{2-} , 从而与重金属离子形成难溶的复合物如 Cd-Se 、 Hg-Se , 抑制根系对铅的吸收^[32,33]. 本试验中, 加硒后土壤溶液中的铅含量低于对照, 可能就是形成了 PbSeO_3 或者 Pb-Se 沉淀. 铅由根系表皮吸收后, 通过共质体和质外体途径进入维管柱并向地上部运输^[1]. 有研究发现, 加硒可以促进

水稻根系内皮层凯氏带的形成^[34],可能因此阻断了皮层与维管柱之间的质外体运输途径,减少了铅进入维管柱。铅离子进入根系细胞后,可与植物螯合肽(PC_s)发生络合而后存储在液泡中,而减少对细胞器的伤害。加硒可促进 PC_s 合成前体 GSH 的形成^[7, 35],因此,硒也可能通过增强 PC_s 与铅的络合作用减少铅的毒性和植物对铅的吸收。

然而,加硒或水分管理均未影响籽粒中的铅含量。植物主要通过叶片和根系吸收铅,而影响糙米中铅含量的介质排序为:大气铅 > 水铅 > 土壤铅^[4],叶片的吸附与吸收对植物累积铅的贡献比植物经根系吸收转运大得多。而植物根系从土壤中吸收的铅大部分被局限于根系组织^[1]。因此,在水稻生长后期,可能水稻通过叶片对籽粒中铅积累的影响大于土壤中的硒产生的影响。铅的移动性很小,本试验中,籽粒中的铅仅占植物总铅的 0.9% ~ 3.2%。因此硒与铅在水稻根际及根表的作用可能还未影响到籽粒对铅的积累。亚硒酸盐的添加显著促进了水稻籽粒对硒的积累,淹水下添加 0.5 mg·kg⁻¹ 硒使籽粒硒含量达到 0.28 mg·kg⁻¹,可以满足富硒水稻(0.15 ~ 0.30 mg·kg⁻¹, DB61/T556-2012)生产的要求。然而添加 1.0 mg·kg⁻¹ 硒时,尤其非淹水条件下,使硒含量高于这个范围(> 1.0 mg·kg⁻¹)。过量的硒对人体也有毒害作用,因此在选择硒调控铅污染时,选择适合的浓度很重要,这需要进一步地探讨。

4 结论

(1) 铅胁迫下,土壤淹水增加了水稻根表铁膜和根系的铅含量,且在苗期的增加效果更明显;增加了苗期水稻地上部的铅含量,却降低了成熟期水稻茎、叶中的铅含量。

(2) 外源硒的添加,显著降低了苗期水稻根系和地上部对铅的积累,且降低了成熟期水稻根表铁膜、根系和茎中铅含量;而对成熟期水稻籽粒中的铅含量无显著影响。

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