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# 不同水分条件对蜈蚣草修复砷污染土壤的影响

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**摘要:** 采用室内盆栽实验研究了不同土壤含水量(绝对含水量 10% ~ 60%)对蜈蚣草的生物量、砷富集及蜈蚣草和土壤中砷的形态的影响。结果表明,土壤含水量 35% ~ 45% 的范围内蜈蚣草的修复效率显著高于其他处理,可达到 4.48% ~ 5.00%。在此水分区间内,植物细胞的质膜透性较小且植株的生物量较大。蜈蚣草地上部和地下部的最大干重出现在 45% 的含水量下,分别为 2.95 g·plant<sup>-1</sup> 和 11.95 g·plant<sup>-1</sup>。适宜的水分条件利于蜈蚣草吸收和累积土壤中的砷,35% 的含水量下植株地上部和地下部的砷含量可分别达到 307.3 mg·kg<sup>-1</sup> 和 218.6 mg·kg<sup>-1</sup>,而总砷累积量在 40% 的含水量下达到峰值 2.81 mg·plant<sup>-1</sup>。将土壤含水量控制为 35% ~ 45%,还可提高蜈蚣草地上部中 As(V) 的还原效率,促进了蜈蚣草的砷解毒。研究结果对于蜈蚣草大规模种植和工程应用中的水分管理措施具有重要的指导意义。

**关键词:** 蜈蚣草; 砷; 土壤含水量; 植物修复; 修复效率

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## Effects of Soil Moisture on Phytoremediation of As-Contaminated Soils Using As-Hyperaccumulator *Pteris vittata* L.

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**Abstract:** A pot experiment was carried out to study the effects of soil moisture on the growth and arsenic uptake of As-hyperaccumulator *Pteris vittata* L. The results showed that the remediation efficiency of As was the highest when the soil moisture was between 35% -45%. *P. vittata* grew best under 45% water content, and its aboveground and underground plant dry weights were 2.95 g·plant<sup>-1</sup> and 11.95 g·plant<sup>-1</sup>, respectively; the arsenic concentration in aboveground and roots was the highest under 35% water content, and 40% content was the best for accumulation of arsenic in *P. vittata*. Moreover, controlling the soil moisture to 35%-45% enhanced the conversion of As(V) to As(III) in aboveground plant, and promoted arsenic detoxification in *P. vittata*. These above results showed that soil moisture played an important role in the absorption and transport of arsenic by *P. vittata*. The results of this study can provide important guidance for the large-scale planting of *P. vittata* and the moisture management measures in engineering application.

**Key words:** *Pteris vittata* L.; arsenic; soil moisture; phytoremediation; remediation efficiency

砷(As)是一种环境中广泛分布的类金属,在地壳中的含量丰度在所有地球元素中处于第 20 位。由于砷化物的开采和冶炼、有色金属的开发、含砷杀虫剂和除草剂的使用、煤的燃烧等人类活动,导致土壤和地下水砷浓度超过环境背景值<sup>[1]</sup>。人类可通过食用砷污染的蔬菜、粮食和皮肤暴露等途径摄入砷。长期暴露于砷环境中(即使在低浓度下),可引起生殖、发育、免疫和神经系统疾病。因此,砷污染治理是世界各国共同面临的重要环境课题<sup>[2,3]</sup>。

植物修复技术利用超富集植物从被污染的环境介质中去除污染物或降低污染风险,与其他修复技术相比,该技术成本低、环境友好,并且操作较为简便<sup>[4]</sup>。超富集植物是植物修复技术的核心,已有研究证实,砷超富集植物蜈蚣草(*Pteris vittata* L.)能有

效修复中低程度砷污染土壤<sup>[5]</sup>。该蕨类植物的砷富集能力强,并且适用范围广<sup>[6,7]</sup>。但是植物修复技术尚有诸多限制因素,如土壤中砷的生物有效性低,修复周期长,植物对土壤结构、水分、养分和温度等条件有一定的要求<sup>[8]</sup>。为了提高植物修复效率,国内外学者开展了大量的相关研究,Mandal 等<sup>[9]</sup>的研究表明,施用磷酸氢二铵能分别将蜈蚣草的生物量和体内砷含量提高 50% 和 100%;李文学等<sup>[10]</sup>研究发现,多次收获蜈蚣草并没有降低其对砷的积累速

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度,从而可通过增加收获次数提高修复效率;Liu等<sup>[11]</sup>发现,在蜈蚣草根部分接种丛枝菌根可以增加蜈蚣草生物量,促进蜈蚣草砷吸收。

土壤水分是植物生命活动的必要因子,由于蕨类植物通常生长于高湿环境下,因此水分条件直接影响其生长状况<sup>[12,13]</sup>。水分还可影响土壤理化性质,改变重金属的赋存形态,进而影响植物对重金属的吸收。好氧条件下土壤溶液中砷主要以As(V)形式存在;而随着土壤淹水,微生物的活动导致氧气、硝酸盐等电子受体的耗竭,接着便是铁、锰氧化物和As(V)的还原,部分As(V)转化为As(III)。As(V)被还原为As(III)后,被土壤固相吸附的强度降低,并且As(III)的活性和生理毒性高于As(V)<sup>[14,15]</sup>。目前改善植物修复效率多集中于施肥、添加螯合剂等手段,对于土壤水分对蜈蚣草生长和富砷能力的影响需要进一步比较研究。因此,本文拟通过研究不同水分条件下土壤中砷的形态特征以及对蜈蚣草生长和砷吸收的影响,揭示有利于提高植物修复效率的土壤水分条件。研究结果对于蜈蚣草大规模种植和工程应用中的水分管理措施具有重要的指导意义。

## 1 材料与方 法

### 1.1 实验材料

供试土壤取自湖南省郴州市邓家塘乡砷污染农田(113°02'E,25°48'N),为石灰性土壤发育的水稻土。土壤基本理化性质如下:pH值为7.90(水提取),有机质含量为45.50 g·kg<sup>-1</sup>,全氮为0.78 g·kg<sup>-1</sup>,全磷为0.56 g·kg<sup>-1</sup>,全钾为9.08 g·kg<sup>-1</sup>,总砷为168.80 mg·kg<sup>-1</sup>。供试蜈蚣草取自当地蜈蚣草育苗大棚,选择株高5~10 cm、4~5片羽叶幼苗、根茎大小一致的植株。

### 1.2 实验方法

#### 1.2.1 实验设计

室内盆栽实验共设置10个处理,土壤含水量(水分质量/烘干土质量×100%)分别为10%、15%、20%、25%、30%、35%、40%、45%、50%和60%,其中50%和60%为淹水处理。每盆装土1.9 kg,种植蜈蚣草3株,同一水分下4盆种植蜈蚣草,1盆不种植蜈蚣草作为对照处理。每天早晚各称重1次保持土壤含水量。温室温度控制在22~25℃之间,室内相对湿度控制在75%~80%。

#### 1.2.2 取样与测定方法

培养120 d后收获蜈蚣草和土壤,蜈蚣草先用

自来水冲洗干净,然后用去离子水洗涤3遍,植株上的水珠用滤纸吸干。每盆共3株植物样品:1株取样后立即进行叶片的质膜透性测定;1株保存在-80℃,用于测定砷形态;1株杀青,烘干后测定干重和总砷含量。将土壤样品等分成2份,1份保存于-80℃,用于测定砷形态;1份在室内自然风干,研磨,过100目筛,用于总砷含量测定。

采用HNO<sub>3</sub>:HClO<sub>4</sub>=5:1(体积比)消煮植物样品<sup>[16]</sup>,HNO<sub>3</sub>:H<sub>2</sub>O<sub>2</sub>=1:1(体积比)消煮土壤样品<sup>[17]</sup>,用氢化物发生-原子荧光光谱仪(AFS-9120型,北京吉天仪器有限公司)测定总砷含量,并采用国家标准物质(GBW-07603和GBW-07404)作为分析质量控制。土壤砷形态提取采用1.0 mol·L<sup>-1</sup>磷酸+0.1 mol·L<sup>-1</sup>抗坏血酸振荡离心萃取法<sup>[18]</sup>,植物砷形态提取采用1:1甲醇水提取法<sup>[19]</sup>,用原子荧光形态分析仪(SA-10型,北京吉天仪器有限公司)测定砷形态。质膜透性测定采用电导法(Bante510型,上海般特仪器有限公司),测量结果以相对电导率(%)表示。

本研究所用试剂硼氢化钾、盐酸、硝酸、过氧化氢为优级纯,其余均为分析纯,实验用水为超纯水(Cascade AN MK2,美国PALL公司)。

### 1.3 数据处理

数据采用Microsoft Excel 2010进行统计分析和制图,运用SAS 8.0软件完成相关指标的差异显著性检验( $P < 0.05$ )。

## 2 结果与讨论

### 2.1 土壤含水量对蜈蚣草生物量的影响

图1显示了土壤含水量对蜈蚣草生物量的影响。从中可以看出,蜈蚣草地上部和地下部生物量随土壤含水量升高均呈现先增加后减少的趋势。土壤含水量10%~45%范围内,蜈蚣草生物量随着土壤含水量的升高而显著增加( $P < 0.05$ ),并在45%含水量下地上部、地下部干重达到最大,分别为2.95 g·plant<sup>-1</sup>和11.95 g·plant<sup>-1</sup>。Leung等<sup>[20]</sup>研究了5%~16%的土壤含水量下蜈蚣草的生长状况,发现其生物量随着土壤含水量升高而增加。Liao等<sup>[21,22]</sup>研究发现,和蜈蚣草同属于蕨类的铁线蕨在10%土壤含水量下的生物量显著低于15%处理。

图2给出了土壤含水量对蜈蚣草叶片质膜透性的影响。从中可以看出,在10%的土壤含水量下,蜈蚣草叶片的相对电导率显著高于其他处理( $P < 0.05$ ),随后随着土壤含水量增加而迅速降低并逐

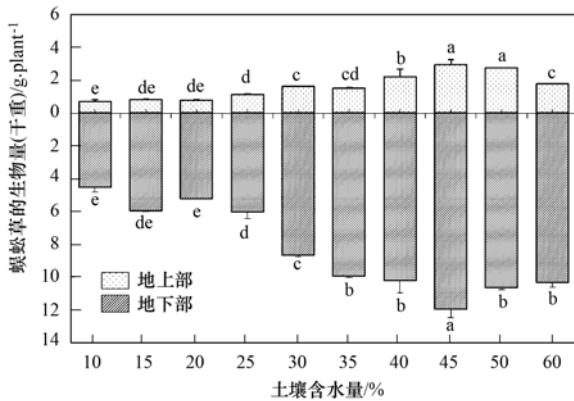


图 1 土壤含水量对蜈蚣草生物量的影响

Fig. 1 Effects of soil moisture on biomass of *P. vittata*

渐趋于稳定. 本研究中 10% 处理下相对电导率远高于其余处理, 说明蜈蚣草对土壤重度缺水较为敏感. 粗毛鳞盖蕨和蜈蚣草同属于蕨类, 孙昊等<sup>[23]</sup>研究发现, 重度干旱胁迫下(土壤含水量约为 7% ~ 13%)粗毛鳞盖蕨叶片的相对电导率显著增加.

蜈蚣草属于蕨类植物, 由于蕨类的维管组织不及种子植物发达, 因此其生殖发育过程对外界水分需求较高, 通常生长于温暖潮湿和半阴的环境中<sup>[13]</sup>. 当植物遭受干旱胁迫时, 细胞膜会发生过氧化作用使细胞液外渗, 表现为叶片的相对电导率上升<sup>[24]</sup>. 此时植物对土壤中营养物质的吸收能力减弱, 导致生物量减小. 因此本研究结果表明, 土壤缺水会降低蜈蚣草的生物量, 在种植过程中应保证土壤水分充足.

## 2.2 土壤含水量对蜈蚣草砷吸收和累积的影响

从表1可以看出, 土壤含水量对蜈蚣草砷的吸

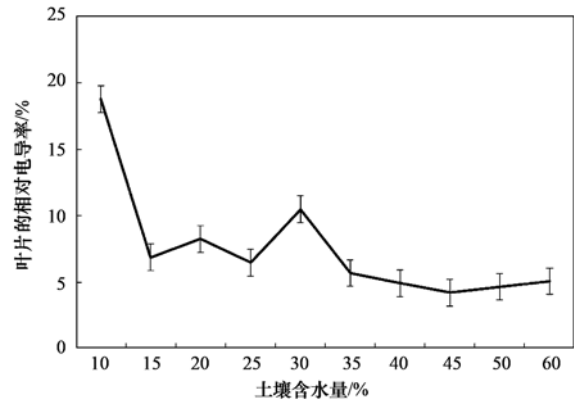


图 2 土壤含水量对蜈蚣草叶片质膜透性的影响

Fig. 2 Effects of soil moisture on cell membrane permeability of *P. vittata* leaves

收和转运会产生显著影响( $P < 0.05$ ). 从蜈蚣草不同部位总砷含量看, 砷含量随着土壤含水量的增加呈先上升后下降的趋势, 并且地上和地下部砷含量同时在 35% 处理下达到峰值. 蜈蚣草对砷的吸收和转运与细胞活性有关, 这是由于蜈蚣草对砷的吸收以主动运输为主, 现有研究认为 As(V) 通过磷酸盐吸收通道进入蜈蚣草, 而 As(III) 的吸收受限于代谢抑制物<sup>[25-27]</sup>. 因此在适宜的土壤含水量下蜈蚣草根系活力较高, 砷吸收能力强. 从转运系数看, 土壤含水量低于 25% 时转运系数较高, 意味着土壤水分降低会促进砷从根系向地上部转运, 而且降低幅度越大, 促进效果越明显. 这种促进作用可能是由于蜈蚣草在土壤水分降低时根系活力减弱, 为了帮助缓解砷累积引发的毒害, 因此加强了砷从根系向地上部的转运.

表 1 不同土壤含水量下蜈蚣草各部位的总砷含量

Table 1 Effects of soil moisture on total As concentration in different parts of *P. vittata*

土壤含水量/%	总 As 含量/ $\text{mg}\cdot\text{kg}^{-1}$		转运系数	富集系数	
	地上部	地下部		地上部	地下部
10	194.2 ± 2.1 <sup>d</sup>	83.9 ± 3.2 <sup>f</sup>	2.32 ± 0.11 <sup>a</sup>	1.12 ± 0.12 <sup>e</sup>	0.48 ± 0.02 <sup>g</sup>
15	249.9 ± 2.5 <sup>e</sup>	112.4 ± 8.0 <sup>de</sup>	2.23 ± 0.18 <sup>ab</sup>	1.50 ± 0.50 <sup>c</sup>	0.68 ± 0.05 <sup>ef</sup>
20	259.9 ± 6.5 <sup>bc</sup>	118.9 ± 3.0 <sup>cd</sup>	2.19 ± 0.11 <sup>abc</sup>	1.60 ± 0.60 <sup>bc</sup>	0.73 ± 0.02 <sup>de</sup>
25	256.0 ± 6.8 <sup>bc</sup>	133.6 ± 9.8 <sup>c</sup>	1.92 ± 0.09 <sup>c</sup>	1.56 ± 0.56 <sup>c</sup>	0.82 ± 0.06 <sup>cd</sup>
30	275.0 ± 7.3 <sup>b</sup>	139.6 ± 15.6 <sup>bc</sup>	1.99 ± 0.27 <sup>bc</sup>	1.70 ± 0.17 <sup>b</sup>	0.86 ± 0.10 <sup>bc</sup>
35	307.3 ± 17.3 <sup>a</sup>	218.6 ± 5.3 <sup>a</sup>	1.41 ± 0.11 <sup>d</sup>	1.89 ± 0.09 <sup>a</sup>	1.34 ± 0.03 <sup>a</sup>
40	306.4 ± 11.3 <sup>a</sup>	208.7 ± 11.5 <sup>a</sup>	1.47 ± 0.03 <sup>d</sup>	1.92 ± 0.09 <sup>a</sup>	1.31 ± 0.07 <sup>a</sup>
45	213.6 ± 5.3 <sup>d</sup>	157.8 ± 7.0 <sup>b</sup>	1.35 ± 0.03 <sup>d</sup>	1.30 ± 0.30 <sup>d</sup>	0.96 ± 0.04 <sup>b</sup>
50	213.1 ± 9.5 <sup>d</sup>	150.3 ± 7.9 <sup>bc</sup>	1.42 ± 0.01 <sup>d</sup>	1.30 ± 0.31 <sup>d</sup>	0.91 ± 0.05 <sup>b</sup>
60	197.5 ± 16.5 <sup>d</sup>	98.3 ± 6.3 <sup>ef</sup>	2.01 ± 0.04 <sup>bc</sup>	1.20 ± 0.06 <sup>de</sup>	0.60 ± 0.04 <sup>fg</sup>

不同土壤含水量下蜈蚣草砷累积量的变化情况见图3. 从中可以看出, 随着土壤含水量的上升, 蜈蚣草各部位的砷累积量先增加后减少, 地上部在

40% 处理下达到最大值 0.68  $\text{mg}\cdot\text{plant}^{-1}$ , 地下部在 35% 处理下达到峰值 2.17  $\text{mg}\cdot\text{plant}^{-1}$ . 砷累积量(植物干重 × 植物砷含量)可以反映植物提取土壤

中砷的能力,本实验中 40% 处理下蜈蚣草的生物量和体内总砷含量均较高,因此砷累积量较大。

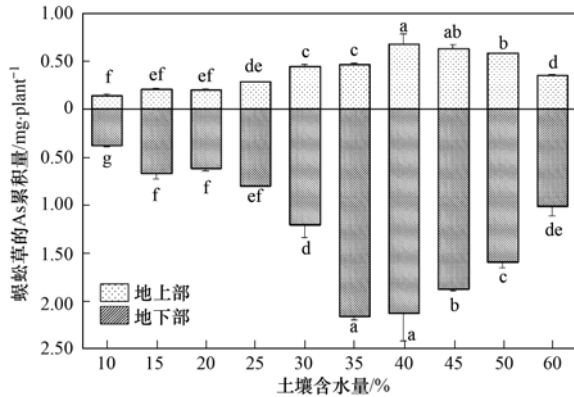


图3 土壤含水量对蜈蚣草砷累积量的影响

Fig. 3 Effects of soil moisture on the As accumulation of *P. vittata*

本研究通过计算植物砷累积量占土壤砷总量的比值得出不同水分处理条件下蜈蚣草的修复效率(图4)。结果表明,植物修复效率随着土壤含水量的升高呈现先增加后降低的规律。由图4可知,35%~45%水分区间内蜈蚣草的修复效率可达到4.48%~5.00%,显著高于其他处理( $P < 0.05$ )。而当含水量低于30%时,修复效率不足2.00%;在50%、60%含水量下修复效率分别为3.88%和2.43%。

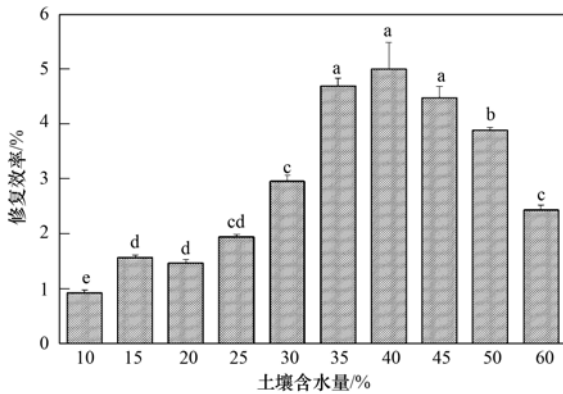


图4 土壤含水量对蜈蚣草修复效率的影响

Fig. 4 Effects of soil moisture on the remediation efficiency of *P. vittata*

### 2.3 不同土壤含水量下蜈蚣草地上部和地下部砷形态的变化

图5给出了不同土壤含水量下蜈蚣草各部位砷形态的变化情况。从中可知,在30%和35%处理下地上部以As(III)为主,而在地下部砷主要以As(V)形式存在,当含水量高于50%,As(V)比例显著升高( $P < 0.05$ ),比值接近90%。已有众多研

究发现蜈蚣草的地上部砷含量As(III) > As(V),在根系则主要以As(V)存在<sup>[19,28]</sup>。蜈蚣草的根部和羽叶都能将As(V)还原为As(III),该过程主要由砷酸还原酶介导<sup>[29~31]</sup>,砷酸还原酶通过催化谷胱甘肽(GSH)和As(V)反应,从而实现还原作用。蜈蚣草中As(III)的液泡区隔化是砷解毒的关键,As(III)与植物螯合肽(phytochelatin, PC)结合,随后从细胞质转移至液泡中<sup>[32]</sup>。本实验中30%~45%含水量下蜈蚣草地上部的As(III)比例较高,说明适宜的水分条件会促进蜈蚣草对砷的解毒能力。

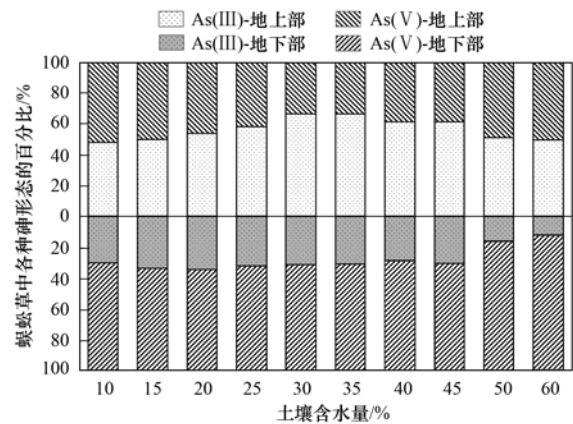


图5 不同土壤含水量下蜈蚣草体内As(III)和As(V)的百分比

Fig. 5 Effects of soil moisture on the arsenic species distribution in *P. vittata*

### 2.4 土壤含水量对土壤砷含量和形态的影响

图6给出了不同土壤含水量下的土壤砷含量。从中可以看出,在35%~45%的水分范围内土壤砷含量有所下降。40%处理下砷含量最低,为 $161.8 \text{ mg} \cdot \text{kg}^{-1}$ ,在该含水量处理下,单株蜈蚣草的砷累积量达到了最大值 $2.81 \text{ mg} \cdot \text{plant}^{-1}$ (每盆3株),占整盆土壤砷降低量的63%,说明植物吸收是导致土壤砷含量降低的主要原因。此外,土壤中可能存在砷的淋溶,导致土壤砷降低量高于植物砷累积量。通过比较不同水分条件下蜈蚣草的修复效率和土壤砷含量,将含水量控制为35%~45%有助于提高砷污染土壤的修复效果。

图7反映了土壤含水量对土壤砷形态的影响。从中可以看出,当含水量达到45%,种植蜈蚣草的土壤和对照土壤中均检测出As(III),并且As(III)占总砷的比例随着土壤含水量的增加而升高。已有研究表明,淹水时土壤的氧化还原电位(Eh)降低,会导致As(V)部分转化为As(III)<sup>[33,34]</sup>,并且土壤淹水后Eh值与水分含量仍然呈负相关关系<sup>[35]</sup>,因此本实验中45%~60%处理下As(III)占总砷比例依

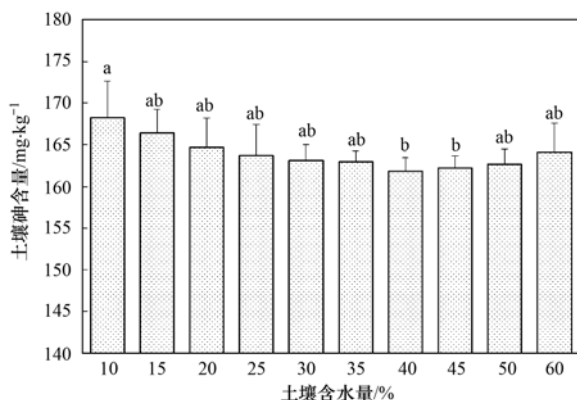


图6 土壤含水量对土壤砷含量的影响

Fig. 6 Effects of soil moisture on the arsenic concentration in soil

次升高. 种植蜈蚣草的土壤中As(Ⅲ)的比例比对照处理低,这可能是由于蜈蚣草吸收了土壤中的As(Ⅲ),Pickering等<sup>[28]</sup>研究发现As(Ⅲ)可被蜈蚣草直接吸收.

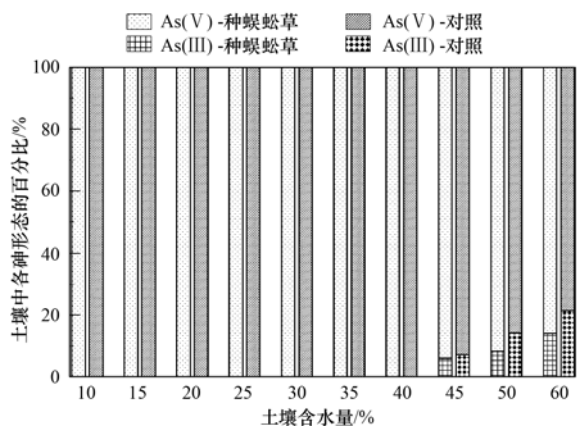


图7 不同土壤含水量下土壤中As(Ⅲ)和As(V)的百分比

Fig. 7 Effects of soil moisture on the arsenic species distribution in soil

### 3 结论

土壤水分条件会通过改变蜈蚣草的生长发育、砷吸收能力及土壤和蜈蚣草中砷的形态影响蜈蚣草对砷污染土壤的修复效率. 在应用蜈蚣草进行砷污染土壤的修复中,含水量35%~45%是首选的水分条件,在该水分区间内蜈蚣草的生物量和体内总砷含量较高,并且对土壤中砷的提取修复效率达到4.48%~5.00%,显著高于其余处理. 将土壤含水量控制为35%~45%,还可提高蜈蚣草地上部中As(V)的还原效率,促进了蜈蚣草的砷解毒.

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