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施磷肥土壤中钒的迁移转化规律研究

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摘要:为探究长期施用磷肥对耕作土壤中钒(V)的迁移累积规律的影响,研究通过模拟酸性和自然降雨条件下施重过磷酸钙土壤的淋溶过程,讨论了施肥前后土壤中钒的迁移转化特征及其影响因素。结果表明:渗滤液中钒主要以溶解态的形式存在(占比50.8%~90.4%),胶体吸附态含量较低;土壤的pH值直接影响了钒的迁移转化能力,酸性降雨可促使下层土壤中部分钒(IV)氧化为钒(V),同时影响残渣态钒向弱酸提取态和可还原态转化。研究表明,磷肥的施加和降雨的酸性增强均能促进土壤中钒的释放并且提高钒的生物有效性,但是在一定降雨量范围内,降雨酸性越强,土壤中钒的释放量越小;整体上钒的释放量较低;土壤中钒(V)与有效态钒显著相关,可作为土壤中钒潜在危害的评价指标。

关键词:耕作土壤;重过磷酸钙;钒;迁移转化

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Migration and transformation of vanadium in cultivated soil with phosphate fertilizer

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Abstract: To explore the effects of phosphate fertilizers on the migration and accumulation of vanadium(V) in cultivated soil, the leaching process of soil with superphosphate was simulated through an indoor soil column. Moreover, the migration and transformation characteristics of V in soil before and after fertilization and its influencing factors were discussed. V in the leachate mainly existed in the dissolved form (50.8%~90.4%), and the colloidal adsorption content state was low. The pH value of the soil directly affected the transformation of V in the soil. Acid leaching liquor promoted the oxidation of partial V(IV) to V(V) in the lower soil layer, and promoted the transformation of V from the residual form to the weak acid extractive and reducible form. Our results indicated that both the leaching of acid liquor and the application of phosphate fertilizer promoted the release of V and increased the bioavailability of V in the soil. Within a certain range of leaching, the lower the pH value of the leaching liquor, the smaller the release of V in the soil. However, the overall release of V was relatively low and the migratory aptitude was weak. There was a significant linear correlation between V(V) and the bioavailable fraction of V. The content of V(V) could be used as an evaluation index of the potential hazards of V in soil.

Keywords: cultivated soil; superphosphate; vanadium; migration and transformation

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钒(V)是一种过渡元素,也是人和动物必需的微量元素^[1-2]。随着钒污染对生物和生态系统毒害作用不断被发现,土壤中的钒通过食物链可能引发的农产品安全与人体健康效应引起了国内外学者的广泛关注^[3-8]。研究表明,土壤中钒含量与胃癌死亡率有非常显著的相关性($P<0.005$),与大肠癌死亡率也有较显著的相关性($P<0.05$)^[9]。土壤钒污染的主要来源包括煤、石油等燃料的燃烧,钒钛磁铁矿等含钒矿物的开采冶炼及农业施肥耕作等人类活动^[10-14]。目前,国内外学者主要关注于矿区冶炼及其废弃物引起的土壤钒污染^[1,15-19],而施肥等农耕活动有可能导致的环境钒污染问题却没有得到足够重视。

研究表明,钒广泛存在于化肥产品中,尤其是磷肥中含量较高^[20-23],且多以 NH_4VO_3 等可溶、毒性最强的五价钒氧盐形式存在,具有潜在的环境风险。磷肥的长期不当施用,不仅会导致土壤酸化和养分比例失调,还会促使钒等有毒有害污染物的释放,是农田土壤污染的重要来源^[24-26]。据统计,全球每年通过施肥进入土壤中的钒高达1500 t,对农田生态系统构成了严重威胁^[27]。另一方面,酸雨淋溶也会直接影响土壤中重金属的迁移性和生物有效性^[28-33]。Yang等^[16]采用Tessier法和Wenzel法研究了攀枝花耕作土壤和尾矿中钒的形态特征,发现自然条件下钒主要以稳定的残渣态存在,与Teng、汪金舫等研究一致^[34-37];但当环境条件发生变化时,土壤中有15%~20%的钒会向易迁移的形态转化,对环境具有一定的潜在风险。2012年开始的我国土壤环境质量例行试点监测结果表明,很多粮食产区土壤中除铅、镉、砷等元素超标比例较大外,钒的含量也已显著高于其背景值。而农田一旦发生重金属污染,由于其面积广大将非常难于治理,并直接威胁人体健康甚至生命安全。

因此,把施加磷肥的耕作土壤作为研究对象,系统开展磷肥钒释放特征研究,查明耕作土壤中钒迁移转化规律及主要影响因素,这不仅可以极大地丰富钒的环境地球化学的基础理论,还可以为我国钒的环境质量标准的制定和钒污染防治提供科学依据,具有重要的理论意义和应用价值。

1 材料与方法

1.1 供试土壤及磷肥样品

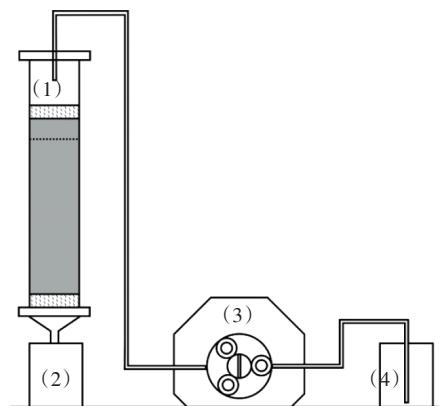
供试土样为取自北京郊区农田的表层褐土(0~20 cm),土壤样品经风干、去除杂物后,过2 mm尼龙筛,研磨后根据测试需求进一步过1 mm和0.15 mm的尼龙筛备用。表1为供试土样的基本理化性质。

从表1可以看出,供试土样pH值接近中性,有机质含量较高。机械组成上,按国际制土壤粒径分类,土质属于砂质壤土。矿物组成上,采用MDI Jade 6软件对XRD的测试结果进行拟合,结果显示,实验土样主要由石英、斜长石和蛭石等矿物组成。

供试磷肥为购自江苏的重过磷酸钙,为白色粒状,钒含量为 $39.6 \text{ mg} \cdot \text{kg}^{-1}$,未超过土壤环境质量标准(GB 15618—2008)的二级标准(pH为6.5~7.5的旱田中钒含量限量标准为 $130 \text{ mg} \cdot \text{kg}^{-1}$)。

1.2 实验方法

室内土柱实验:采用摩尔比为4:1的 H_2SO_4 和 HNO_3 混合液,加去离子水配制不同pH值的淋溶液,分别模拟酸雨条件(pH=2.0、4.5)和自然降雨过程(pH=7.0)。如图1所示,将风干土壤样品过2 mm筛后装入



(1)淋溶土柱(从上到下:石英砂、尼龙网、土壤、重过磷酸钙、土壤、尼龙网、石英砂);(2)渗滤液;(3)蠕动泵;(4)淋溶液
(1)Leaching soil column(From top to bottom:quartz sand,nylon mesh,soil,heavy superphosphate,soil,nylon mesh,quartz sand);
(2)Leachate;(3)Peristaltic pump;(4)Leaching solution

图1 土柱实验装置图

Figure 1 The sketch of the soil column adsorption experiment

表1 供试土样基本理化性质

Table 1 Physical and chemical properties of the investigated soil

pH	有机质/% Organic matter	阳离子交换量/ $\text{cmol} \cdot \text{kg}^{-1}$ Cation exchange capacity	机械组成 Mechanical composition/%			
			<2 μm	2~20 μm	20~200 μm	200~2000 μm
6.74	2.78	13.8	4.6	26.4	50.7	18.4

内径为4 cm、高35 cm的有机玻璃柱内,装填高度至15 cm时,施加重过磷酸钙,施磷浓度(以P₂O₅计)分别为0 g·kg⁻¹土和2 g·kg⁻¹土,上培土至总高20 cm。土柱填充完后,自土柱下端缓慢浸入一定体积的去离子水至饱水,静置24 h。淋溶速度为30 mL·h⁻¹,每日收集250 mL,共淋溶20 d 5000 mL,测定渗滤液中溶解态钒浓度和总钒浓度,并测定原土以及淋溶后土壤中钒的形态和价态以及土壤pH值和TOC值。土柱淋溶后,取土柱上层3 cm和下层3 cm土壤,测定其pH值与TOC值。测定时重复3次,取平均值。根据不同施肥量和不同pH值酸雨设定交叉实验(表2),实验同时进行。

表2 施肥土壤淋溶实验设计梯度

Table 2 The design gradient of leaching experiment of fertilized soil

施磷浓度(以P ₂ O ₅ 计)/g·kg ⁻¹ Concentration of phosphate fertilizer/g·kg ⁻¹	pH 2.0	pH 4.5	pH 7.0
0	A1	A2	A3
2	B1	B2	B3

1.3 土样中钒的释放率

为比较磷肥的施加以及不同pH值供试淋溶液对钒释放的影响,需计算土柱中钒的累积释放量和释放率,由式(1)和式(2)得出:

$$q = \frac{\sum_{i=1}^n C_i \times v}{m} \quad (1)$$

$$K = \frac{q}{S} \times 100\% \quad (2)$$

式中: q 为降雨淋溶下土壤中钒的累积释放量,μg·kg⁻¹; C_i 为第*i*次渗滤液中V浓度,μg·L⁻¹; v 为每次收集的渗滤液体积,mL; m 为供试土壤及磷肥质量,kg; K 为土柱中V的累积释放率; S 为土柱内钒的初始含量,包括施加磷肥中钒的含量,μg·kg⁻¹。

1.4 测试方法和数据分析

土壤pH值按照中华人民共和国农业行业标准(NY/T 1377—2007),通过PHS-3E型pH计测定,土水比为1:2.5;总有机碳的测定参考中华人民共和国国家环境保护标准(HJ 615—2011);阳离子交换量的测定参考中华人民共和国行业标准(SL 237—1999);土壤机械组成采用马尔文粒径分析仪MS2000进行分析;土壤矿物学特征通过X射线衍射仪分析其物相组成。

渗滤液中总钒浓度是从收集瓶中取25 mL渗滤液,根据HJ 678—2013中的方法消解后用ICP-AES

测定。另取12 mL渗滤液,5000 r·min⁻¹离心20 min,取5 mL上清液过0.22 μm滤膜,测定得出渗滤液中溶解态钒的浓度。

土壤中钒总量测定采用0.1 g土样加入5.0 mL硝酸、2.0 mL氢氟酸,放于ST-60型自动消解仪中消解,用ICP-AES测定(检出限为1 ng·g⁻¹);土壤中钒价态的分离采用0.25 g土样加入25 mL 0.1 mol·L⁻¹的Na₂CO₃溶液,水浴煮沸、冷却、离心、过滤后用ICP-AES测定钒(V)的含量,钒(IV)的含量通过总钒含量减去钒(V)的含量得到;土壤中钒化学形态的提取采用BCR逐级提取法^[38],将重金属形态分为弱酸提取态、可还原态、可氧化态、残渣态。其中,弱酸提取态、可还原态及可氧化态,是能被生物所吸收利用的形态,故三者之和被用于计算有效态钒的含量^[39]。

2 结果与讨论

2.1 淋溶过程对土壤理化性质的影响

图2表示在pH值为2.0、4.5和7.0的淋溶条件下,淋溶前后土柱上层3 cm和下层3 cm的土样pH值与TOC值的变化。土壤pH值在淋溶后明显降低,土壤上层pH值普遍低于下层。尤其是在pH=2.0淋溶条件下的土壤,上层pH值比下层低2~3,说明酸雨长期淋溶会造成土壤酸化,尤其对表层土壤影响较大。磷肥的施加对土壤pH值的影响不大。而土壤TOC值在淋溶前后基本保持不变,降雨淋溶和磷肥施加对其影响均不明显。

2.2 不同淋溶条件下土壤中钒的迁移特征

由图3可知,渗滤液中溶解态钒和总钒浓度变化趋势基本一致,A1、B1、A2、B2、A3、B3渗滤液中溶解

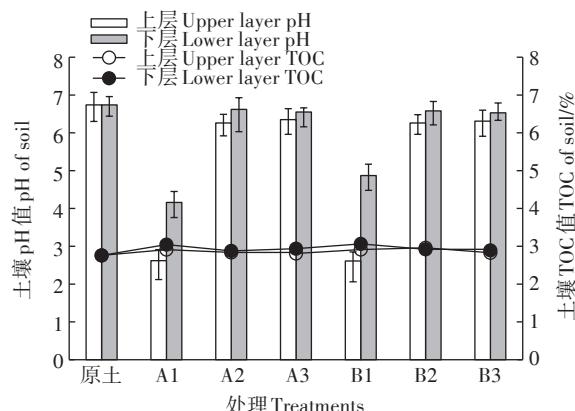


图2 淋溶前后土壤pH值和TOC值对比

Figure 2 The comparison of soil pH and TOC value before and after leaching

态钒与总钒的相关系数分别为0.878、0.996、0.923、0.973、0.943、0.977,均有非常显著的相关性($P<0.005$)。渗滤液中钒主要以溶解态形式存在(溶解态占比50.8%~90.4%),胶体吸附态含量较低,与胡少平^[40]、许端平等^[41]认为的渗滤液中重金属主要是以胶体吸附态的形式迁移的观点相反,可能是因为本实验中供试土样未受污染,渗滤液中钒浓度较低,因此胶体颗粒对其他重金属离子的吸附能力更强,且低浓度的钒在溶液中更易达到溶解平衡。

在pH=2.0的淋溶条件下,渗滤液中溶解态钒和总钒浓度在淋溶前期呈下降趋势,当淋溶量超过4000 mL(淋溶至第16 d)后,渗滤液中溶解态钒和总钒浓度开始增加;而在pH=4.5和pH=7.0淋溶条件下,渗滤液中溶解态钒和总钒浓度整体呈下降趋势。磷肥的施用增加了渗滤液中钒的浓度。

经分析得知,随着淋溶量增加至4000 mL后,在pH=2.0淋溶条件下渗滤液中钒的浓度逐渐高于pH=4.5和pH=7.0淋溶条件下钒的浓度。可能是因为在淋溶初期, H^+ 与土壤中的重金属化合物和碳酸盐反应,导致 H^+ 浓度下降。随着后期淋溶量增大,土壤中可与 H^+ 反应的物质越来越少,土壤溶液中 H^+ 浓度升高,使得游离钒离子增加,钒的可迁移性增大,渗滤液中钒浓度升高^[42~43]。在我国《生活饮用水卫生标准》(GB 5749—2006)中,尽管钒没有列入水质常规检验项目及非常规检验项目,但作为生活饮用水源水质的检验标准,饮用水源水中钒的最高容许浓度为50 $\mu\text{g}\cdot\text{L}^{-1}$ 。目前渗滤液中钒的浓度并不会对地下水造成危害;但在pH=2.0淋溶条件下,随着淋溶次数的增多,渗滤液中钒浓度逐渐升高,危害地下水环境的几率极大提高。

土柱渗滤液中钒的累积释放量和释放率如表3所示,在相同模拟降雨条件下,施加2 $\text{g}\cdot\text{kg}^{-1}$ (以 P_2O_5 计)重过磷酸钙的土样B1、B2、B3中钒的释放量分别比未施加磷肥的土样A1、A2、A3中钒的释放量增加了48.7%、36.2%、19.7%,即磷肥的施加增加了土壤中钒的释放,说明磷肥中磷酸根与钒酸根的竞争吸附作用促进了钒的释放,也可能是因为磷肥中可溶态钒含量较高,增加了钒的释放。

在施肥量相同的条件下,当淋溶液为pH=2.0时,钒的释放量仅为868.1 $\mu\text{g}\cdot\text{kg}^{-1}$ 和1291.0 $\mu\text{g}\cdot\text{kg}^{-1}$,而在pH=4.5和pH=7.0淋溶条件下,钒的释放量明显增大,即pH=2.0的淋溶条件不利于钒的释放。这是由于土壤溶液中钒主要以+5价的 VO_5^- 存在,在一定的降雨量

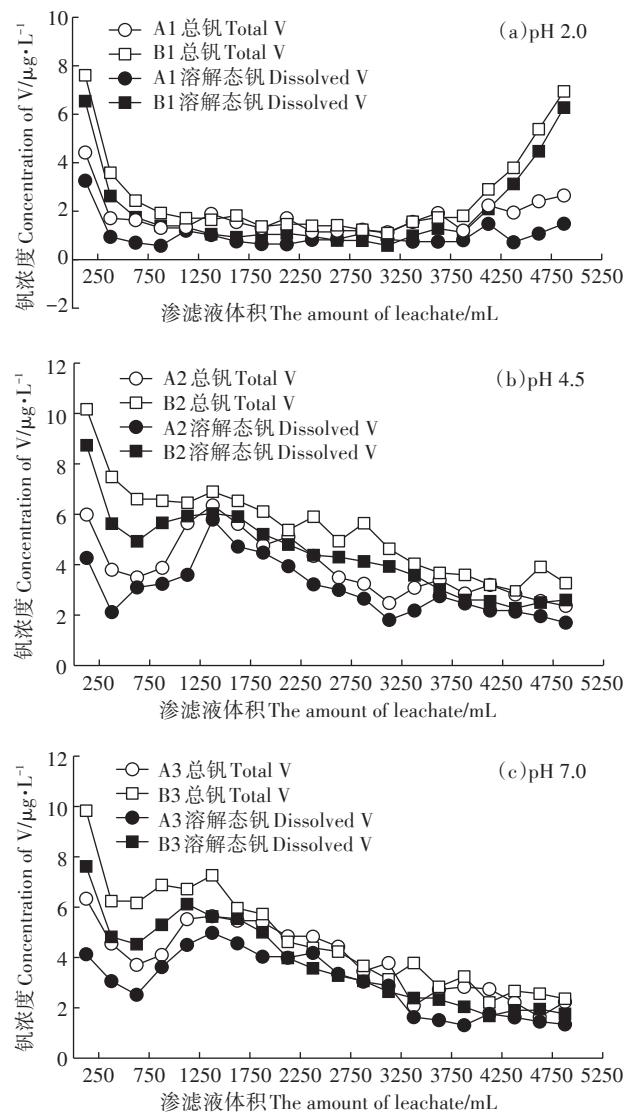


图3 渗滤液中总钒和溶解态钒浓度变化曲线
Figure 3 The concentration variation of total V and dissolved V in leachates

Table 3 The cumulative release amount and release rate of V in leachates

表3 渗滤液中钒的累积释放量和释放率

Table 3 The cumulative release amount and release rate of V in leachates

处理 Treatments	释放量 $q/\mu\text{g}\cdot\text{kg}^{-1}$ Release amount	释放率 $K\%$ Release rate
A1	868.1	1.06
B1	1 291.0	1.58
A2	1 594.0	1.94
B2	2 171.0	2.66
A3	1 597.0	1.95
B3	1 911.0	2.34

范围内,当酸性增强时, VO_5^- 离子将转化为多钒酸根复合阴离子,易于被黏土和有机质吸附固定而失去活

性,即pH在一定范围内的降低增加了土壤对钒的吸附,减少了钒的释放量,与黄艺、汪金舫等的研究结果一致^[44-45]。结合图3进行分析,当降雨淋溶量继续增大时,钒的释放量在强酸性淋溶条件下将会明显增大。总体上,土壤中钒的释放量较低,迁移性较差,与Yang等^[16]、商正松等^[42]的研究结果一致。

2.3 施肥后土壤中钒形态的转化

表4为原土中总钒含量、各形态钒含量及回收率,表5和图4则是淋溶后土壤中总钒及各形态钒含量,土壤中各形态钒含量之和与总钒含量相近,回收率在95.2%~102.8%,说明提取结果准确可信。

如表5所示,淋溶后土壤中钒含量总体低于原土钒含量 $82.0\text{ mg}\cdot\text{kg}^{-1}$,上下层土壤中钒含量相差不大。在三种不同淋溶条件下,施加磷肥的下层土壤总钒含量稍高于未加磷肥的样点,尤其是在pH=2.0的淋溶条件下,下层总钒含量较上层增加 $6.6\text{ mg}\cdot\text{kg}^{-1}$,说明长期的酸性溶液淋溶能促进磷肥中钒的释放,增强钒的迁移性,与Cappuyns等^[30]研究结果一致。结合表3渗滤液中钒的累积释放量,在pH=2.0条件下,渗滤液中钒的累积释放量和淋溶后土壤中的钒含量均相对另外两种淋溶条件较少。分析原因可能是:滞留在土柱中间段(除上层和下层土之外)的钒含量较多,且在pH=2.0时,土壤渗滤液中钒含量呈现先下降后上升的趋势,在pH=4.5和pH=7.0的条件下,渗滤液中钒含量呈现明显的下降趋势;因此随着总淋溶量的增大,pH=2.0条件下渗滤液中钒释放量增加的速度加快,钒的累积释放量增加的幅度变大。

淋溶前后土壤各形态钒含量如图4所示,对于弱酸提取态钒,未施加磷肥的下层土壤A1D、A2D、A3D中,含量分别为 0.44 、 0.95 、 $1.04\text{ mg}\cdot\text{kg}^{-1}$;施加磷肥的下层土壤B1D、B2D、B3D中,含量分别为 0.62 、 1.09 、 $1.01\text{ mg}\cdot\text{kg}^{-1}$ 。由此可见,经过pH=2.0渗滤液淋溶过的土壤下层弱酸提取态钒的含量比另外两种淋溶条件低;对于可还原态钒,经过pH=2.0渗滤液淋溶过的土壤,其上、下层的可还原态钒含量均低于另外两种淋溶条件下钒的含量。总体上,对比淋溶后的土壤上下层,弱酸提取态钒和可还原态钒含量下层明显高于上层,可氧化态钒含量差别不大,而残渣态钒含量下

表5 淋溶后土壤中总钒含量及回收率

Table 5 Total V content and recovery rate in soil after leaching

Treatments	总 V Total V/ $\text{mg}\cdot\text{kg}^{-1}$	回收率 Recovery rate/%
A1T*	78.0	97.3
A1D**	78.7	102.8
B1T	77.9	97.3
B1D	84.5	95.2
A2T	83.1	95.6
A2D	79.0	98.5
B2T	81.9	95.9
B2D	82.7	96.1
A3T	81.9	97.1
A3D	80.2	99.7
B3T	80.6	99.3
B3D	81.0	99.2

注:*T为上层3 cm土壤;**D为下层3 cm土壤,下同。

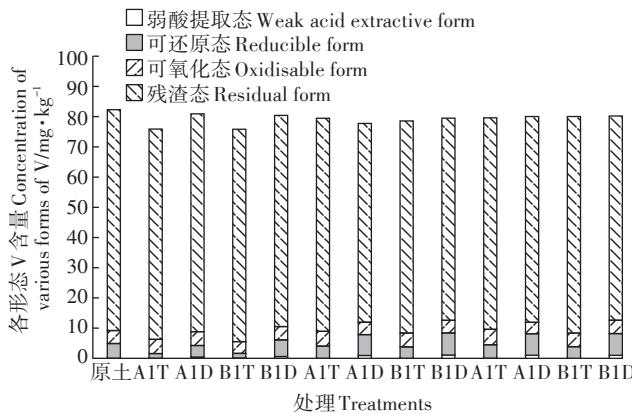


图4 淋溶前后土壤中各形态钒的含量

Figure 4 Content of various forms of V in soil before and after leaching

层低于上层,说明下层增加的弱酸提取态钒和可还原态钒,可能来自上层残渣态钒的溶解。

淋溶后土壤上、下层各形态钒所占比如图5所示。经过淋溶后,上层土壤中弱酸提取态钒所占比例与原土基本一致,而下层土壤中则显著高于原土;对于可还原态钒,原土中所占比例为5.85%,上层土壤可还原态钒所占比例均低于下层土和原土;对于残渣态钒,原土中占89.15%,淋溶后土壤中残渣态钒仍占有最大比例,且在pH=2.0淋溶条件下比pH=4.5和pH=7.0淋溶条件下的土壤中残渣态钒所占比例更大,这

表4 原土中各形态钒含量、总钒含量($\text{mg}\cdot\text{kg}^{-1}$)及回收率(%)

Table 4 The various forms V content, total V content($\text{mg}\cdot\text{kg}^{-1}$) and recovery rate(%) of the original soil

弱酸提取态 V Weak acid extraction of V	可还原态 V Reducible form of V	可氧化态 V Oxidizable form of V	残渣态 V Residual form of V	总 V Total V	回收率 Recovery rate
0.1	4.8	4.3	73.1	82.0	100.4

与弱酸提取态钒和可还原态钒恰好相反。

重金属的化学形态是影响重金属有效性、溶解性和迁移性最重要的因素之一^[46],一般认为在利用BCR法逐级提取的化学形态中,具有生物有效性的形态是弱酸提取态、可还原态及可氧化态。因此,三种淋溶条件均增加了下层土壤中钒的生物有效性,尤其是pH=4.5和pH=7.0两种淋溶条件。另外,磷肥的施加对pH=4.5和pH=7.0淋溶的土壤中钒的生物有效性影响不大,但是增加了pH=2.0淋溶的土壤中钒的生物有效性。

2.4 施肥后土壤中钒价态的转化

土壤中钒常见的价态是+4价和+5价,而钒的毒性随价态的升高而增强,其中钒(V)具有较强的迁移性和生物有效性,对环境危害较大^[47]。如图6所示,原土中钒(V)和钒(IV)的含量分别为4.5 mg·kg⁻¹及77.65 mg·kg⁻¹;在pH=2.0淋溶条件下,上层土壤中钒(IV)和钒(V)含量均低于原土,而下层土壤中钒(V)含量增加,说明酸性降雨淋溶增加了土壤中钒(V)的迁移量,并在下层累积;在pH=4.5和pH=7.0淋溶条件下,下层土壤中钒(V)含量明显增加,

钒(IV)含量有所降低,说明在一定pH条件下土壤中部分钒(IV)被氧化为钒(V),与邹宝方等研究结果一致^[48]。

图7表示淋溶前后土壤钒(V)所占比例,已知原土中钒(V)所占比例为5.4%,淋溶后上层土壤中钒(V)所占比例减小,下层明显增加。pH=2.0淋溶条件下,土壤中钒(V)所占比例明显较pH=4.5和pH=7.0淋溶条件低,说明在pH值升高时,土壤中部分钒(IV)被氧化为钒(V),与邹宝方等^[48]、Baes等^[49]的研究一致。

2.5 土壤中钒迁移转化的影响因素

为探究土壤中钒含量变化的影响因素,利用SPSS16.0软件对淋溶后12个土壤样品(A1T、A1D、A2T、A2D、A3T、A3D、B1T、B1D、B2T、B2D、B3T、B3D)pH值、TOC、有效态钒、钒(V)以及总钒含量进行相关性分析。如表6所示,土壤pH值与有效态钒含量表现出极显著正相关($P<0.01$),与钒(V)表现出显著正相关($P<0.05$),说明在一定降雨量范围内,酸性降雨的淋溶会降低土壤中有效态钒与钒(V)含量;土壤TOC与其他指标相关性差,淋溶后TOC未发生明显变化;有

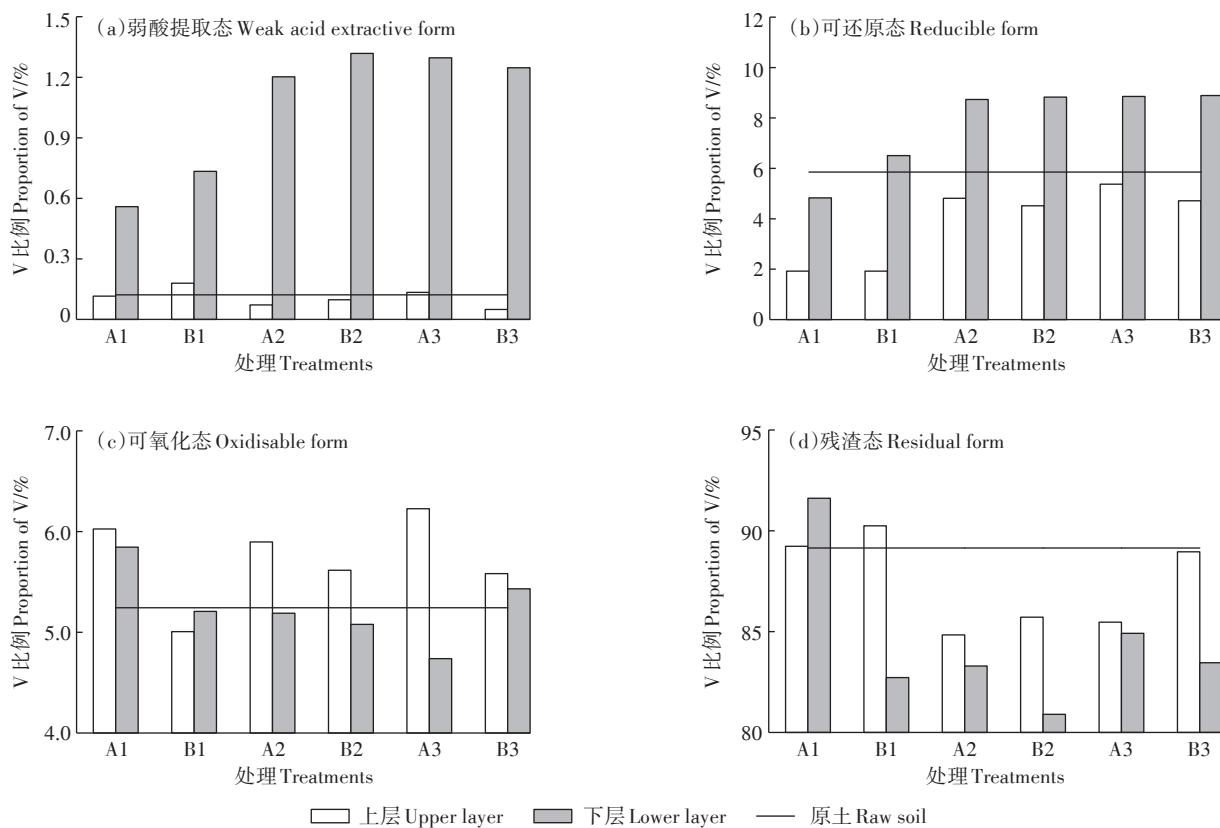


图5 淋溶前后土壤中各形态钒所占比例

Figure 5 The proportion of various forms of V in soil before and after leaching

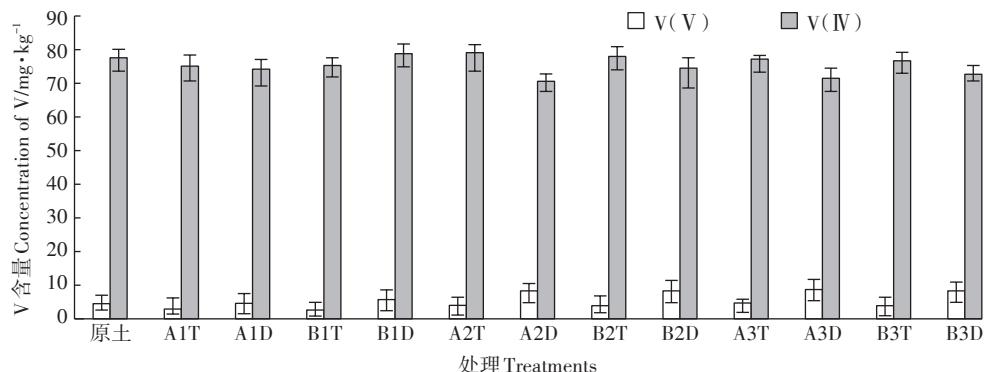


图6 土壤中钒(IV)和钒(V)的含量

Figure 6 The content of V(IV) and V(V) in soil

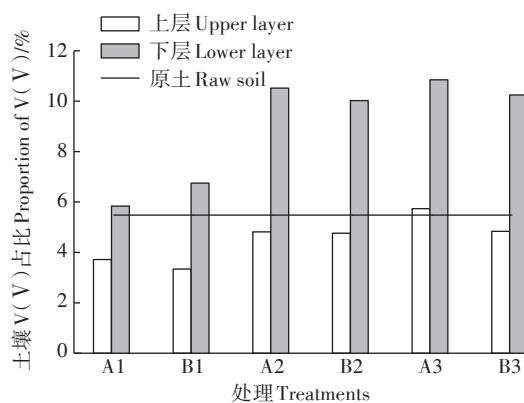


图7 淋溶前后土壤中钒(V)所占比例

Figure 7 The proportion of V(V) in soil before and after leaching

效态钒含量与钒(V)含量的相关系数达到了0.958($P<0.01$),说明钒(V)含量的增加会导致土壤中钒的生物有效性增强,对环境造成较大危害,因此土壤中钒(V)的含量也可作为土壤中钒潜在危害的评价指标。

3 结论

(1)磷肥的施加可促进土壤中钒的迁移和累积。在强酸性淋溶条件下,土壤渗滤液中钒含量呈现先下

降后上升的趋势;在弱酸性和中性降雨条件下,土壤渗滤液中钒含量呈现明显的下降趋势。整体上钒的释放量较小,且渗滤液中钒主要以溶解态形式存在。

(2)淋溶过程影响了土壤中残渣态钒向弱酸提取态和可还原态的转化,增加了下层土壤中有效态钒的含量。酸性降雨条件下,磷肥的施加促进了下层土壤中有效态钒的累积。

(3)酸性和自然降雨模拟条件下,土壤中部分钒(IV)被氧化为钒(V),同时磷肥的使用也促进了下层土壤中钒(V)的累积,增加了土壤中钒的生物有效性。

(4)相关性分析结果表明,影响土壤中钒迁移转化的主要因素是土壤pH值,且土壤中钒(V)与有效态钒含量呈极显著相关。因此土壤中钒(V)含量可作为土壤中钒潜在危害的评价指标。

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表6 土壤相关性分析表($N=12$)Table 6 Correlation analysis table of soil($N=12$)

项目 Items	pH	TOC	有效态钒含量 Available V content	钒(V)含量 V(V) content	总钒含量 Total V
pH	1				
TOC	-0.342	1			
有效态钒含量 Available V content	0.770**	0.045	1		
钒(V)含量 V(V) content	0.646*	0.067	0.958**	1	
总钒含量 Total V	0.556	0.075	0.439	0.215	1

注: *在0.05水平(双侧)上显著相关, **在0.01水平(双侧)上显著相关。

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