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基于风险等级的重金属污染耕地土壤修复技术集成体系研究

王进进[1,2], 杨行健[1,2], 胡　峥[1,2], 张玉龙[1,2], 徐会娟[1,2], 李永涛[1,2*]

(1.华南农业大学资源环境学院, 广州 510642; 2.中英环境科学研究中心, 华南农业大学, 广州 510642)

摘　要: 重金属单项控制技术在我国农田土壤修复中已有很多应用,但是面对复杂的土壤污染现状,缺乏基于不同风险等级的控制技术和治理体系,难以应对污染日益严重的不利局面,因此需要将各种单项修复技术进行合理的集成,形成污染耕地修复处理技术的筛选与集成方法体系。本研究基于适用于农田土壤修复的单项技术,包括植物修复技术、农艺修复技术、间套种技术、土壤淋洗技术和土壤钝化技术等,归纳和总结出不同类型技术的技术特性,形成土壤单项修复技术知识库,根据土壤污染风险等级、土壤理化性质、技术特性和人为因素等提出一种适宜的土壤修复技术筛选与集成的方法,为我国农田土壤修复/安全利用和可持续利用管理提供技术支撑。

关键词: 土壤修复;风险等级;技术集成
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Research on the risk level-based technology integration for the remediation of heavy metals polluted farmland

WANG Jin-jin[1,2], YANG Xing-jian[1,2], HU Zheng[1,2], ZHANG Yu-long[1,2], XU Hui-juan[1,2], LI Yong-tao[1,2*]

(1.College of Natural Resources and Environment, South China Agricultural University, Guangzhou 510642, China; 2.Joint Institute for Environmental Research & Education, LEC-SCAU-GIG, Guangzhou 510642, China)

Abstract: Soil remediation measures have been applied extensively in heavy metal polluted farmland in China. Because the control technology and remediation system are insufficient basing on different risk levels, it is difficult to deal with the soil pollution which has increasingly and seriously negative effects. Thus, it is necessary to integrate reasonably remediation technologies to find out a systematic method which is effective for the remediation of heavy metal polluted farmland. This study is conducted to summarize and make conclusion the characteristics of various technologies which are suitable for polluted soil remediation, including phytoremediation, agronomic measure, interplanting, soil leaching and soil passivation, etc. On this basis, we are trying to propose an integration between methodology and technology considering risk levels of pollution, physical and chemical properties of soil, technical characteristics and human activities, etc. This research provides an effective approach to technical support for the remediation and sustainable utilization of heavy metals polluted farmlands in China.

Keywords: soil remediation; risk level; technology integration

当前世界各国对土壤污染修复技术均进行了广泛的研究,但与欧美等发达国家相比,我国土地污染研究起步较晚,且一般为单一的物理、化学与工程方法,缺乏基于不同风险等级的控制技术、分级管理和治理体系,难以应对污染日益严重的不利局面,不足以支撑农产品安全生产和产地环境可持续发展的现

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作者简介: 王进进(1988—),男,安徽颍上人,讲师,主要从事重金属污染与修复模式研究。E-mail:wangjinjin@scau.edu.cn
***通信作者:** 李永涛　E-mail:yongtao@scau.edu.cn
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实需求，难以成为保障农田农产品安全生产的主导技术，而且大部分研究成果尚未进行大规模生产实践。我国地域辽阔，不同地区土壤类型、气候、水文等有较大差异，耕地污染类型多样，生态环境风险不等，因此我国耕地土壤污染防控技术的研究是一项长期、复杂、艰巨且极其迫切的任务。

由于土壤环境的复杂性，用原有的物理、化学、植物及微生物等单一的方法对复合污染进行修复，都很难达到较好的效果，因此需要将各种单项修复技术进行合理的集成，形成污染耕地过程控制技术体系。耕地土壤修复技术的集成需要基于不同风险等级的控制技术，综合考虑各个单项技术的特点、资金投入、分级管理和治理模式。根据不同地区农业资源实际问题，针对不同类型农田污染开展安全利用技术研究，形成相应的技术体系与模式，使这部分耕地的持续安全利用成为可能，是应对人口迅速增长、耕地面积减少、环境日趋恶化局面的必然选择，其生态效益、环境效益和社会效益将十分巨大。

1 适用于耕地土壤修复的单项技术入库

重金属污染耕地修复的技术集成首先需要对现有的、适用于农田土壤修复的单项技术进行总结、归纳和入库。我们选取了植物修复技术、农艺修复技术、间套种技术、土壤淋洗技术和土壤钝化技术等几大类技术，通过国内外文献调研、相关国家环境保护部门门户网站查阅以及专家咨询、研讨等方式，系统收集和整理现行的耕地土壤修复技术进行入库。根据现有的各项重金属单项控制技术的研究及工程应用案例，我们凝练出适用于农田土壤修复的单项技术推荐及其相应的技术特性，具体如表1~表6。

2 不同污染风险等级农田土壤的单项修复治理技术归纳

现阶段污染修复项目资金投入较大，试验技术繁杂，鉴于有些技术的投资与运行参数不完整、实际应用时间不长、推广价值有待检验等原因，试点选取的技术可偏向于植物修复、微生物修复、电化学修复等原位修复技术。经济条件宽裕的省区，可因地制宜地开展各类修复技术的试点示范。表7归纳了适用于不同污染风险等级农田土壤的修复治理技术。

3 重金属污染耕地修复技术集成总体思路及筛选步骤

依据农田污染的生态净化功能与机制建立农田

表1 植物修复技术推荐及技术特性

Table 1 Recommendation and technical characteristics of phytoremediation technology

植物 Plants	技术开发程度 Degree of technological development	适合的重金属 Heavy metals	污染程度/污染风险 Pollution level/risks	去除效率 Removal efficiency	修复时间 Remediation period	成本 Cost	适合土层厚度 Soil layer/cm	生长条件 Growth conditions	适合的土壤pH Soil pH	技术体系可信程度及可维护性 Credibility and maintainability	二次污染 Secondary pollution	参考文献 References
东南景天	Ⅰ	Cd和Zn	中和高	Ⅱ	Ⅴ	Ⅰ	0~100	<1400 m的阴湿地带；常见于华南地区	范围较宽；偏酸性土壤对修复有一定促进作用	Ⅳ	Ⅰ	[1]
蜈蚣草	Ⅰ	As、Pb和Hg	中和高	Ⅲ	Ⅴ	Ⅰ	0~20	喜温暖潮湿，常见于广西、广东、云南等地		Ⅳ	Ⅰ	[2]
龙葵	Ⅰ	Cd和Pb	中和高	Ⅲ	Ⅴ	Ⅰ	0~80	适宜温度22~30 ℃，对土壤环境要求低，喜生于田边，全国均可见		Ⅳ	Ⅰ	[3]
天蓝遏兰菜	Ⅰ	Cd	中和高	Ⅲ	Ⅴ	Ⅰ	—	—		Ⅳ	Ⅰ	[1]
伴矿景天	Ⅰ	Cd和Pb	中和高	Ⅱ	Ⅴ	Ⅰ	0~100	—		Ⅳ	Ⅰ	[4-6]
海州香薷	Ⅱ	Cu	中和高	Ⅱ	Ⅴ	Ⅰ	—	生于山坡路旁或草丛中，常见于辽宁、山东、河南、江西和广东		Ⅳ	Ⅰ	[7-8]
苎麻	Ⅳ	Hg	中和高	Ⅱ	Ⅴ	Ⅰ	—	适宜温度15~32 ℃，生于草坡或山谷，雨量要求800 mm以上，常见于广西、广东、云南和贵州	酸性(pH<4.4)影响生长	Ⅳ	Ⅱ	[9-10]

注：表中“Ⅰ”表示最优，“Ⅱ”表示优，“Ⅲ”表示良好，“Ⅳ”表示一般，“Ⅴ”表示略低，“—”表示没有相关数据。技术开发程度表示技术目前的应用规模；适合土层厚度由植物根系长度范围确定；适合的土壤pH指除过酸或过碱外，以上植物均可用于修复，其中偏酸环境利于重金属浸出，进而有利于植物修复；技术体系可信程度及可维护性指与其他技术相比，此技术的可信度及是否便于维护。下同。

Note: ‘Ⅰ’ means the best, ‘Ⅱ’ means the better, ‘Ⅲ’ means good, ‘Ⅳ’ means general, ‘Ⅴ’ means slightly lower, ‘—’ means that there is no revelant data. Degree of technological development meant represents the current application scale of the technology; Soil layer means determined by the length range of plant roots; Soil pH means all phytoremediation measures can be used except for in peracid or alkali soils, more suitable in acidic environment since heavy metals are more labile; Credibility and maintainability means the credibility and maintainability of the technology, compared with other technologies. The same below.

表2 低累积作物技术推荐及其技术特性

Table 2 Recommendation and technical characteristics of low accumulation crop technology

植物 Plants	技术开发程度 Degree of technological development	适合的重金属 Heavy metals	污染程度/污染风险 Pollution level/risks	成本 Cost	技术体系可信程度及可维护性 Credibility and maintainability	二次污染 Secondary pollution	参考文献 References
玉米	Ⅰ	Cd、Cu和Pb	中和低	Ⅰ	Ⅲ	Ⅰ	[11-12]
大豆	Ⅱ	Cd和Pb	中和低	Ⅰ	Ⅲ	Ⅰ	[12-13]
甘蓝	Ⅱ	Cd	低	Ⅰ	Ⅳ	Ⅰ	[14]
白菜	Ⅲ	Pb	低	Ⅰ	Ⅳ	Ⅰ	[13,15-16]
芹菜	Ⅱ	Pb和Cu	低	Ⅰ	Ⅳ	Ⅰ	[14]
胡萝卜	Ⅲ	Cd	低	Ⅰ	Ⅳ	Ⅰ	[17]
莴苣	Ⅲ	Pb、Cd和Cu	低	Ⅰ	Ⅳ	Ⅰ	[12,16]

表3 间作套种技术推荐及其技术特性

Table 3 Recommendation and technical characteristics of intercropping technology

植物 Plants	技术开发程度 Degree of technological development	适合的重金属 Heavy metals	污染程度/污染风险 Pollution level/risks	去除效率 Removal efficiency	修复时间 Remediation period	成本 Cost	适合土层厚度 Soil layer/cm	适合的土壤pH Soil pH	对作物产量的影响 Effects on crop yield	技术体系可信程度及可维护性 Credibility and maintainability	二次污染 Secondary pollution	参考文献 References
伴矿景天+玉米间作	Ⅰ	Cd和Pb	中和低	Ⅱ	Ⅴ	Ⅰ	0~100	范围较宽;偏酸性土壤对修复有一定促进作用,但也增加作物的污染风险	增产	Ⅳ	Ⅱ	[4,6]
三叶鬼针草+生菜套种	Ⅱ	Pb	低	Ⅲ	Ⅴ	Ⅰ	0~20		—	Ⅳ	Ⅲ	[18]
东南景天+玉米间作	Ⅰ	Cd和Pb	中和低	Ⅱ	Ⅴ	Ⅰ	0~80		增产	Ⅳ	Ⅱ	[19-21]
东南景天+大豆间作	Ⅱ	Cd和Pb	中和低	Ⅱ	Ⅴ	Ⅰ	0~80		增产	Ⅳ	Ⅱ	[21]
龙葵+大葱间作	Ⅲ	Cd	中和低	Ⅲ	Ⅴ	Ⅰ	0~20		无影响	Ⅳ	Ⅱ	[22]
鸡眼草+番茄或萝卜	Ⅳ	Cd、Pb和As	中和低	Ⅲ	Ⅴ	Ⅰ	0~20		—	Ⅳ	Ⅱ	[2]

表4 水肥管理技术推荐及技术特性

Table 4 Recommendation and technical characteristics of water and fertilizer management technology

肥料 Fertilizers	技术开发程度 Degree of technological development	适合的重金属 Heavy metals	污染程度/污染风险 Pollution level/risks	成本 Cost	技术体系可信程度及可维护性 Credibility and maintainability	二次污染 Secondary pollution	参考文献 References
有机肥	Ⅰ	Cd和Pb	低和中	Ⅰ	Ⅰ	Ⅳ	[9,23-26]
腐植酸肥	Ⅱ	Hg、Cd和Pb	低和中	Ⅱ	Ⅱ	Ⅱ	[10,27]
氮磷钾肥	Ⅰ	Cd和As	低和中	Ⅰ	Ⅰ	Ⅳ	[22-24,28-31]
富硒叶面肥	Ⅲ	Cd	低和中	Ⅱ	Ⅲ	Ⅱ	[22,27]
叶面硅肥	Ⅱ	重金属	低和中	Ⅱ	Ⅱ	Ⅱ	[32]

表5 土壤淋洗技术推荐及技术特性

Table 5 Recommendation and technical characteristics of soil leaching technology

淋洗剂 Eluants	技术开发程度 Degree of technological development	适合的重金属 Heavy metals	污染程度/污染风险 Pollution level/risks	去除效率 Removal efficiency	修复时间 Remediation period	成本 Cost	适合土层厚度 Soil layer/cm	适合的土壤pH Soil pH	适合的土壤传导率 Soil conductivity/cm·s^{-1}	适合的有机质含量 Organic matter content/%	技术体系可信程度及可维护性 Credibility and maintainability	二次污染 Secondary pollution	参考文献 References
EDDS	Ⅱ	As、Pb和Hg	中和高	Ⅱ	Ⅱ	Ⅴ	均可	范围较宽;偏酸性土壤对修复有一定促进作用	>10^{-5}	<10	Ⅲ	Ⅳ	[33-35]
柠檬酸	Ⅱ	Cd和Pb	中和高	Ⅲ	Ⅱ	Ⅴ					Ⅲ	Ⅰ	[33,36-41]
皂素	Ⅲ	Hg、Cd和Pb	中和高	Ⅱ	Ⅱ	Ⅴ					Ⅲ	Ⅱ	[39,42-43]
茶皂素	Ⅳ	Cd	中和高	Ⅲ	Ⅱ	Ⅴ					Ⅲ	Ⅱ	[44]
清水	Ⅰ	重金属	轻	Ⅴ	Ⅱ	Ⅰ					Ⅱ	Ⅰ	—

污染的分级分类管控技术模式具有重要意义。根据污染源和污染物情况,确定污染农田风险等级,基于各项单项过程控制技术进行不同风险等级耕地过程控制技术的组合集成,针对不同风险等级的污染耕地

表6 钝化技术推荐与技术特征

Table 6 Recommendation and technical characteristics of immobilization technology

钝化剂 Passivants	技术开发程度 Degree of technological development	适合的重金属 Heavy metals	污染程度/污染风险 Pollution level/risks	去除效率 Removal efficiency	修复时间 Remediation period	成本 Cost	土壤pH Soil pH	技术体系可信程度及可维护性 Credibility and maintainability	二次污染 Secondary pollution	参考文献 References
石灰	Ⅰ	重金属	中和高	Ⅰ	Ⅰ	Ⅰ	2~5	Ⅰ	Ⅲ	[45]
石灰石	Ⅰ	重金属	低	Ⅲ	Ⅰ	Ⅰ	4~7	Ⅰ	Ⅰ	[45]
堆肥	Ⅰ	Pb、Cd、Cu和Zn	低	Ⅳ	Ⅱ	Ⅰ	均可	Ⅱ	Ⅲ	[46]
磷矿粉	Ⅲ	Pb	中和高	Ⅰ	Ⅰ	Ⅱ	均可	Ⅰ	Ⅱ	[47-48]
沸石	Ⅱ	Pb、Cd、Cu、Zn、Hg和Ni	高和中	Ⅰ	Ⅰ	Ⅱ	均可	Ⅰ	Ⅰ	[49]
生物炭	Ⅱ	Pb、Cd、Cu和Zn	中和低	Ⅱ	Ⅱ	Ⅱ	4~8	Ⅱ	Ⅰ	[50-54]
凹凸棒石	Ⅱ	Pb、Cd和Hg	中和低	Ⅲ	Ⅰ	Ⅱ	均可	Ⅰ	Ⅰ	[55-57]
钢渣	Ⅲ	Cd、As和Cr	中和低	Ⅲ	Ⅰ	Ⅰ	均可	Ⅱ	Ⅳ	[58-59]
羟基磷灰石	Ⅲ	Pb	中	Ⅱ	Ⅰ	Ⅱ	6~9	Ⅰ	Ⅱ	[60-63]
针铁矿	Ⅳ	Cd、As和Cr	中	Ⅱ	Ⅰ	Ⅲ	均可	Ⅱ	Ⅱ	[64]
赤泥	Ⅱ	重金属	中和高	Ⅰ	Ⅰ	Ⅰ	均可	Ⅰ	Ⅳ	[65-67]
微生物	Ⅳ	重金属	低	Ⅳ	Ⅱ	Ⅳ	6~8	Ⅳ	Ⅰ	[68]

表7 不同污染风险等级农田土壤修复治理技术汇总

Table 7 Summary of soil remediation techniques for farmland of different pollution risk levels

污染风险等级 Pollution level/risks	大类技术 Types of technology	潜在技术 Potential technologies
高	植物修复技术	东南景天、伴矿景天、龙葵、天蓝遏蓝菜、海州香薷和苎麻超富集技术
	工程物理技术	客土法、换土法、隔离包埋技术
	土壤淋洗技术	EDDS、柠檬酸、皂素和茶皂素淋洗技术
	土壤钝化技术	石灰、磷矿粉、沸石和赤泥钝化技术
中	植物修复技术	东南景天、伴矿景天、龙葵、天蓝遏蓝菜、海州香薷和苎麻超富集技术
	低累积作物技术	低累积玉米和大豆技术
	水肥管理技术	有机肥、腐植酸肥、氮磷钾肥、富硒叶面肥、叶面硅肥
	间作套种技术	伴矿景天+玉米间作、东南景天+玉米间作、东南景天+大豆间作、龙葵+大葱间作、鸡眼草+番茄或萝卜技术
	土壤淋洗技术	EDDS、柠檬酸、皂素和茶皂素淋洗技术
	土壤钝化技术	石灰、磷矿粉、沸石、生物炭、凹凸棒石、羟基磷灰石、针铁矿和赤泥钝化技术
低	低累积作物技术	低累积玉米、大豆、甘蓝、白菜、番薯、芹菜、胡萝卜和莴苣技术
	水肥管理技术	有机肥、腐植酸肥、氮磷钾肥、富硒叶面肥、叶面硅肥
	间作套种技术	三叶鬼针草+生菜套种、伴矿景天+玉米间作、东南景天+玉米间作、东南景天+大豆间作、龙葵+大葱间作、鸡眼草+番茄或萝卜技术
	土壤钝化技术	石灰石、堆肥、生物炭、凹凸棒石、微生物
	土壤淋洗技术	清水

需要因地制宜地选取合适的过程控制组合技术体系。耕地土壤污染的风险管控模式和技术集成体系的选择需要考虑污染风险等级、污染源、污染途径、污染土壤特性、单项技术体系特性五个影响因素。在修复技术的选择上需要确保污染农田的修复效果以及农田安全利用和风险控制的要求，优先选择能够降低污染物毒性、迁移性和含量的技术。

在选取的单项过程控制技术入库后，需要建立单项过程控制技术的筛选机制。根据耕地污染风险等级，结合影响区域耕地土壤环境质量的因素，并考虑耕地土壤污染修复的单项过程控制技术主要受土壤特性、单项技术的适用性等方面因素的影响。在两个影响因素中选取特征因子如土壤pH、土壤机械组成等，开展典型案例分析、专家经验论证，将各个单项过程控制技术的特点与特征因子对应。构建单项过程控制修复技术体系中单项技术的筛选机制，以为后续

土壤环境保护和综合管控模式和技术集成体系做基石铺垫。

技术选取的基本原则是:(1)短期效果;(2)长期效果;(3)对污染物毒性、迁移性和数量减少的程度;(4)可操作性;(5)成本;(6)符合应用与其他相关要求;(7)全面保护人体健康与环境;(8)政府的接受程度;(9)公众接受程度。

上述内容中推荐了一些可行的技术,而技术的选择需要结合具体的农田土壤环境质量特征来进行。因此,重金属污染农田土壤修复技术的筛选步骤应如图1进行。

(1)基于污染风险筛选:根据第2部分提到的待修复农田土壤环境质量调查,提取出污染农田土壤污染风险等级和重金属等信息,在表1~表5中初步筛选出符合污染等级和重金属类型的技术群1。

(2)基于土壤理化性质筛选:在技术群1中,按照技术开展所对应的农田土壤相关性质指标(如土壤pH、土壤传导系数、土壤污染的深度等),筛选出技术群2。

(3)基于技术特性筛选:在技术群2中,依据小类技术的技术特性(如开发程度、可维护性、修复效率等),筛选出技术群3。

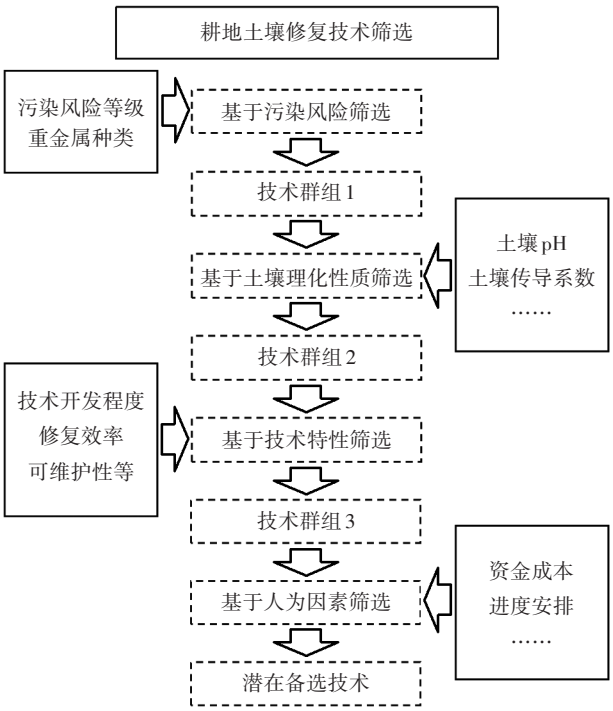

图1 重金属污染农田土壤修复技术的筛选步骤

Figure 1 Screening steps of remediation techniques for heavy metal contaminated farmland soils

(4)基于人为因素筛选:在技术群3中,按照修复过程进度安排、资金成本等因素,筛选出技术群4,即潜在备选技术,相关人员可在本技术群中选出合适的技术。若技术群4中包含两种以上的技术,则需要进一步开展实验论证。

4 重金属污染农田集成修复技术展望

综上可知,单项修复治理技术都有各自的技术特点和适用范围,它们在重金属类型相对单一的农田土壤上可以发挥良好的效果。然而,随着工业的不断发展,投入农田中的污染物类型日趋复杂。不同污染源作用下,农田土壤中重金属的类型、浓度和价态均有差异。因此,很难仅靠单项技术完成大面积的农田修复。在单项技术无法达到修复目标时,应考虑进行有效的技术集成。可根据污染源、污染物类型和浓度,确定农田污染等级,并基于各单项修复治理技术进行合理的技术集成,形成几套针对于不同风险等级的且具有潜在推广价值的组合技术。

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