



草酸调控零价铁对土壤和水体中污染物去除的研究进展

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摘要 零价铁对变价重金属和有机污染物具有良好的还原和吸附作用, 在土壤和水体污染修复中具有较大的应用潜力. 草酸作为一种有机小分子酸, 能有效改善零价铁的表面氧化层, 增强其电子转移能力, 并促进亚铁离子的氧化还原循环反应过程, 从而显著提升零价铁的性能. 本文通过对比草酸调控前后的性能差异, 阐明了草酸调控的优点, 探讨了草酸调控零价铁在去除铬、三氯乙烯, 以及硝酸盐等污染物的研究进展; 揭示了草酸调控零价铁在吸附、还原及高级氧化体系中对污染物的去除机制; 明确了草酸调控零价铁的结构与污染物去除的关键调控因素, 并对草酸调控零价铁在土壤和水体修复中的应用前景进行了展望. 本研究为草酸调控零价铁去除污染物的机理研究和实际应用提供理论依据和技术参考.

关键词 零价铁, 草酸, 土壤, 水体

零价铁作为一种廉价且环境友好的还原剂, 在土壤和水体污染修复领域得到了广泛应用^[1]. 为提高零价铁对环境中污染物的去除性能, 现有研究主要聚焦于两个方向: 一是将零价铁负载于高比表面积的多孔材料, 如生物质炭、活性炭、膨润土、海泡石及蒙脱石等, 可有效降低零价铁在环境介质中的团聚^[2-7]. 二是通过掺杂硫元素和过渡金属如钡、镍、铜等, 硫的加入增强了零价铁的疏水性, 从而提高其电子选择性; 钡、镍过渡金属则有助于抑制零价铁的氧化, 保持其反应活性^[8-11]. 然而, 实际应用中发现零价铁容易从载体上脱落, 影响其去除效率. 同时, 引入硫元素和过渡金属可能引发新的污染问题. 草酸(oxalic acid, OA)作为一种天然有机酸, 其引入可避免新污染物的产生. 草酸具有良好的螯合性和还原性, 能够与多种金属离子形成稳定络合物^[12], 有效去除重金属离子. 研究已证实, 草酸可改善零价铁的氧化层, 缓解腐蚀产物在表面

堆积, 显著提升零价铁在环境介质中污染物的去除效果^[13]. 尽管草酸调控零价铁的研究已经取得部分进展, 但目前对其研究体系和成果的系统性总结尚显不足. 因此本文综合分析了当前领域的文献资料, 比较了草酸调控前后零价铁表面结构的差异, 并探讨了草酸调控零价铁在直接还原反应, 以及作为催化剂参与过硫酸盐和芬顿反应中的作用. 进一步揭示了其对典型重金属、有机污染物及无机阴离子污染物去除的机制和反应路径, 为草酸调控零价铁在土壤及水体处理新污染物领域提供理论依据.

1 草酸调控零价铁对土壤和水体中重金属去除的研究进展

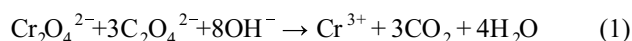
1.1 草酸调控零价铁对Cr(VI)去除的研究进展

土壤和水体中的Cr(VI)污染修复一直受到广泛关

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Ni Z, Li H Y, Kang Z Y, et al. Research progress on the oxalic acid-regulated zero-valent iron for pollutant removal in soil and water column (in Chinese). Chin Sci Bull, 2024, 69: 3934–3942, doi: 10.1360/TB-2024-0392

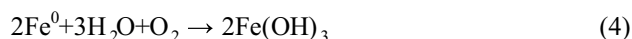
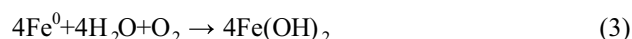
注^[14]。作为一种天然有机酸,草酸在酸性条件下能与Cr(VI)发生还原反应,其分子上的羧基在反应中提供电子而被氧化。在此过程中,Cr(VI)被还原成Cr(III),同时生成CO₂等产物(式(1)):



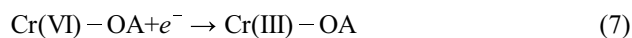
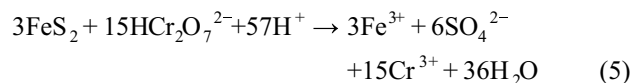
然而,自然条件下草酸对Cr(VI)还原反应速率较慢,反应半衰期由几个月到数年不等^[15],在采用草酸直接还原Cr(VI)的研究中,草酸不仅能够将其还原为Cr(III),还倾向于形成稳定的Cr(III)络合物。进一步研究表明,在高温和强酸性条件下,草酸能够促进Cr(III)络合物向Cr(III)的转化^[16]。Hug等人^[17]发现,当Cr(VI)溶液中存在草酸及Fe(II)、Fe(III)等离子时,草酸能够与Fe(III)形成络合物,在光照条件下可将Fe(III)还原为Fe(II),这极大地增强了Cr(VI)的去除效率。因此,Liu等人^[18]在零价铁对Cr(VI)去除实验中,探究了草酸存在条件下对零价铁去除效果的变化,实验结果表明草酸与溶液中的Fe(II)发生络合反应(式(2)):



形成的络合Fe(II)替代了Fe(II)成为主要的电子供体,这减缓了零价铁表面的Fe(II)与水与氧气反应生成Fe(OH)₂和Fe(OH)₃的腐蚀过程(式(3~4)),从而显著提高了对Cr(VI)的还原速率。



在深入研究草酸改性零价铁的改性因素时,唐景春团队^[19]通过添加草酸来提升二硫化铁-生物炭复合材料对Cr(VI)的去除性能实验中发现,92.75%的Cr(VI)通过还原、沉淀去除,另外7.75%则通过吸附和表面络合去除(式(5)~(7)):



为了验证草酸对二硫化铁-生物炭复合材料提升效果的特殊性,该团队还使用了柠檬酸和乙二胺四乙酸进行对比实验,结果表明草酸的提升效果最为显著。当浓度为0.25g L⁻¹的草酸与FeS₂-生物炭复合材料联用时,对初始浓度为50 mg L⁻¹的Cr(VI)去除率可以达到100%。

草酸的加入不仅增强了二硫化铁-生物炭复合材料与Cr(VI)反应的电子转移过程,还促进了Fe(II)的氧化还原循环,从而显著提高了去除Cr(VI)的能力和稳定性^[20]。在硫改性纳米零价铁去除Cr(VI)的过程中,在酸性条件下,草酸促进了Fe(II)从硫化纳米零价铁上的溶解,并通过均相反应增强了对Cr(VI)的电子利用率。在中性和碱性条件下,草酸促进了Cr(VI)向硫化纳米零价铁表面的扩散、吸附和络合,从而增强了电子的选择性^[21]。

此外,草酸还用作改善零价铁表面壳层的改性剂。通过与草酸二水化合物进行球磨,张礼知团队^[22]成功制备出草酸改性零价铁材料。实验证明,球磨过程中产生的FeC₂O₄·2H₂O壳层取代了零价铁的Fe₂O₃壳层,并且这种新的壳层比原始的Fe₂O₃壳层具有更高的质子传导性,从而使Cr(VI)的去除速率常数提高了15~80倍(图1)。在此基础上,采用湿球磨法制备的草酸改性零价铁-生物炭复合材料,已经成功应用于土壤中Cr(VI)的去除,结果表明,该复合材料相较于单纯的零价铁有更高的电子释放速率,增加了溶液中Fe(II)的浓度,展现出对土壤中Cr(VI)更优的去除效果^[23]。进一步研究表明,通过球磨法制备的草酸改性零价铁材料在去除实际废水中Cr(III)与乙二胺四乙酸(EDTA)形成的络合物方面也展现出显著效能。相较于原始氧化层,草酸改性零价铁所形成的FeC₂O₄·2H₂O壳层能够更有效地生成¹O₂,该活性氧物种可选择性地破坏Cr-O和Cr-N键,从而精确地解络Cr(III)-EDTA,且不产生有害的Cr(VI)。解络后释放的Cr(III)离子通过原位沉淀在氧化零价铁表面,形成Cr(OH)₃沉淀,以沉淀去除的方式离开废水溶液中^[24]。在利用草酸来改性零价铁表面氧化壳层的实验中,光辐照照射方式也被用于提高草酸对零价铁表面氧化壳层的改性效果,从而进一步提升零价铁对Cr(VI)的去除效果^[25]。

1.2 草酸调控零价铁对除Cr(VI)外重金属去除进展

在土壤和水体中关注的污染物除Cr(VI)之外,其他污染物如砷等,草酸调控零价铁对它们的去除作用的研究也陆续开展^[26]。Zhang等人^[27]在探讨矿山土壤与农田土壤中重金属污染物的去除方法时,提出了利用有机酸淋洗方法来整合去除土壤中重金属的技术。然而,单纯有机酸淋洗土壤对重金属去除效果并不理想。为此,他们在有机酸中添加了纳米零价铁以期增强去除效率。实验结果表明,当纳米零价铁浓度为34.25 g L⁻¹

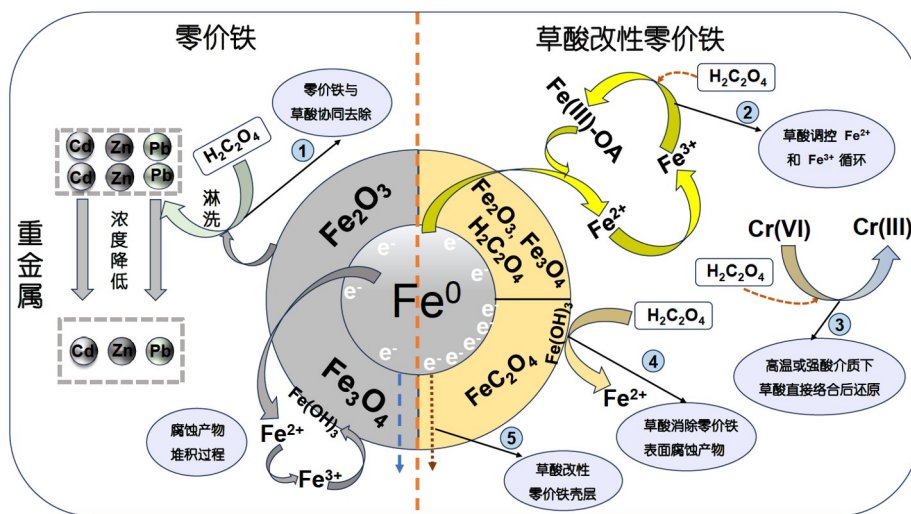


图1 (网络版彩色)零价铁与草酸调控零价铁对重金属的去除机理

Figure 1 (Color online) The removal mechanism of heavy metals by zero-valent iron with oxalic acid modulation of zero-valent iron

时,使用草酸溶液淋洗矿山土壤,对Cd、Pb和Zn的去除效率最高,分别为49.50%、62.84%和46.66%。在零价铁活化过硫酸盐用于三价砷(As(III))的氧化去除研究中,Liang等人^[28]发现Fe(II)的快速析出导致零价铁铁芯的快速腐蚀,从而改变了零价铁的形貌,这对As(III)去除过程是不利的。因此,Liu等人^[29]尝试将草酸加入体系中以控制游离Fe(II)的浓度,从而通过调节反应速率来获得更高的去除能力。实验结果显示,引入草酸后,零价铁活化过硫酸盐对As(III)的最终去除效果从35.6%提升至44.5%。有关草酸调控零价铁去除重金属的实验方法和去除效果,请见表S1。

综上所述,草酸调控零价铁去除重金属主要的调控机制,一方面是通过优化重金属离子与零价铁之间的电子选择性,另一方面是通过改变零价铁表面的壳层结构,从而增强其质子传导能力(图1)。然而,这些成果仍需进一步的实证研究以验证其有效性和可靠性。未来研究应重点关注草酸调控零价铁去除重金属的具体方法和作用机理,以期为土壤和水体污染的修复提供更为高效和可靠的技术支持。

2 草酸调控零价铁去除土壤和水体中有机污染物研究进展

2.1 草酸调控零价铁对土壤和水体中氯代烃去除研究进展

草酸调控零价铁在对有机污染物的修复中也表现

出显著的应用潜力^[30]。Tso等人^[31]的研究揭示了草酸在一定浓度下,能通过其强络合作用促进零价铁钝化层的溶解,进而形成可溶解的络合物,有效提升对三氯乙烯的去除效率。此外,在含有表面活性剂十二烷基硫酸钠的零价铁还原体系中,探究草酸对三氯乙烯降解效能的影响,研究结果表明,草酸的引入能显著减轻十二烷基硫酸钠对Fe(II)催化过碳酸钠体系的抑制效应。同时,草酸的加入也扩展了该体系适用pH的范围,使得三氯乙烯在更宽的pH条件下能得到有效去除^[32]。在利用球磨法制备草酸改性零价铁材料以直接去除三氯乙烯的研究中,草酸的引入显著改变了零价铁表面的铁(氢)氧化物层组成,从而生成了不饱和配位的Fe(II)位点,这些位点作为高效的吸附中心,增强了三氯乙烯的吸附作用。此外,形成的FeC₂O₄壳层有效提升了电子转移效率。实验结果显示,相较于未改性的零价铁,草酸改性零价铁对三氯乙烯的降解率提高了10倍^[33]。在探讨实际地下水中可能共存的Cr(VI)与三氯乙烯复合污染问题时,张颖团队^[34]采用了一种新型的纳米零价铁基材料,该材料通过羧甲基纤维素钠与草酸钠的双重改性,以增强对Cr(VI)和三氯乙烯的去除效能。实验结果显示,该复合材料通过静电吸引、还原反应以及共沉淀机制,有效实现了对Cr(VI)的吸附去除;同时,通过物理吸附与还原脱氯过程,对三氯乙烯也进行了有效降解。对于四氯化碳的去除,Matheson指出零价铁表面的氧化物涂层会导致脱氯反应速率快速降低^[35]。兰叶青团队^[36]采用零价铁与草酸结合的方法,在pH为3.5

时,草酸的加入能通过与Fe(III)形成有机配体,消除零价铁表面的Fe(OH)₃钝化膜,使零价铁去除四氯化碳的速率提高18倍。

综上所述,草酸改性零价铁去除氯代烃的主要方式是通过消除零价铁表面的氧化壳层和去除表面产生的Fe(OH)₃腐蚀产物。然而,环境条件(如pH)和化学物质间的相互作用对去除效果有显著影响。因此,在实际应用中,必须对这些因素进行精确控制和优化,以确保氯代烃污染物的高效和安全去除。

2.2 草酸调控零价铁对土壤和水体中有机染料去除研究进展

除了氯代烃有机污染物,草酸调控零价铁对土壤和水体存在的有机染料废水修复也表现出了显著的去除效果^[37]。目前,高级氧化体系被广泛用于去除水中的有机染料污染物,但传统芬顿反应的最佳pH范围较窄,且反应过程中产生的Fe(III)离子因沉淀从溶液中分离,降低反应速率^[38]。草酸作为一种强络合能力的有机酸,在芬顿反应体系中作为络合剂,可以提高Fe(II)的氧化还原能力,改善铁络合物与氧化剂的反应性^[39]。此外,草酸改性零价铁还被添加到过氧化钙体系中,以去除水体中的染料污染物。实验结果表明,草酸的引入显著促进了关键活性离子Fe²⁺和Fe³⁺的循环反应,有效增加了羟基自由基的生成量,进而提升了草酸改性零价铁体系对有机染料甲基橙的去除效率^[40]。在另一项关于去除有机染料罗丹明中,过去的研究通常使用经超声辐照的铁基材料作为芬顿型催化剂^[41],但这些声子-芬顿体系通常需要很长时间才能对污染物进行降解。Li等人^[42]引入草酸到该体系中,结果表明草酸的添加显著提高了超声波泡沫铁(通过将零价铁粉与黏合剂结合后在氨基甲酸乙酯中烧结得到)对罗丹明污染物的去除率,且随着草酸量的增加,去除效果更加显著,在罗丹明浓度为5 mg L⁻¹, pH为3的条件下,去除率可达92.16%。此外,研究表明,通过球磨法处理零价铁与草酸二水化合物,能够形成FeC₂O₄·2H₂O壳层,该壳层可以有效替代零价铁表面的氧化层,进而显著提升零价铁的质子传导性^[43]。在偶氮染料污染物的去除过程中,经球磨处理得到的零价铁-草酸复合材料,因其表面形成了高质子传导速率的FeC₂O₄·2H₂O壳层,从而促进了H⁺的还原为H。同时,这一壳层通过促进Fe²⁺向Fe³⁺的转化的反应过程,提供了更多的电子以促进H⁺的还原,实验结果显示,偶氮染料的去除速率提高了1.17倍并且在

4~10的宽pH条件下都表现出了良好的去除效果^[44]。在将球磨得到的零价铁-草酸复合材料加入芬顿反应的研究中,通过对二甲基丙烯酸乙二醇酯的去除实验发现,FeC₂O₄·2H₂O壳层有利于质子快速转移到内部Fe⁰,从而加速质子的消耗-再生循环,使得更多Fe(II)的产生用于芬顿反应,实验结果表明二甲基丙烯酸乙二醇酯去除的速率常数提高了500倍。重要的是,在连续13个循环中,零价铁-草酸复合材料对芬顿活性几乎没有衰减,并且适用于3.5~9.5的宽pH范围^[45]。除了在芬顿体系中,球磨法得到的零价铁-草酸复合材料也可以作为过硫酸盐体系的活化剂,提高过硫酸盐的活性,从而提高去除有机污染物的效率^[46]。在零价铁还原去除硝基苯的过程中,单纯添加草酸虽能溶解零价铁的氧化层,但草酸也会与零价铁本身发生反应。这一反应会导致零价铁的比表面积减小,进而降低表面活性点的数量,从而对零价铁还原硝基苯的效果产生不利影响^[47]。因此,Wu等人^[48]使用草酸和零价铁球磨后得到的零价铁-草酸复合材料来进行硝基苯酚的去除,由于零价铁-草酸复合材料具有更高质子传导性特性,使过硫酸盐的活化能力显著提升,而且溶解的草酸盐可以与铁离子形成络合物,显著降低电势差,导致过硫酸盐分解为活性物质的表面结合Fe(II)快速提高,从而显著增强对硝基苯酚的去除效果。关于草酸调控零价铁对不同有机污染物的种类、去除方法、实验pH以及最终的去除效果,请见表S2。

综合现有研究,草酸调控零价铁在去除有机污染物方面表现出显著优势。与未经调控的零价铁相比,草酸改性零价铁的表面氧化层得到有效改善,使得关键催化离子Fe(II)的产出速率显著提升(图2)。这一变化使得草酸调控零价铁在芬顿体系和类芬顿体系体系中均表现出积极的促进作用。芬顿体系和类芬顿体系是目前常用的两种高级氧化体系,在有机污染物的去除中扮演着重要角色。因此,草酸调控零价铁在有机污染治理领域具有重要的应用价值。

3 草酸调控零价铁对土壤和水体中无机阴离子去除研究进展

草酸调控零价铁在土壤与水体修复领域中对无机阴离子污染物的去除效果研究,已受到越来越多的关注。硝酸盐可能导致土壤和水体富营养化,从而破坏水生生态系统^[49]。溴酸盐作为一种有毒副产品,被国际癌症研究机构归类为2B类致癌物质^[50]。Wang等人^[51]通过

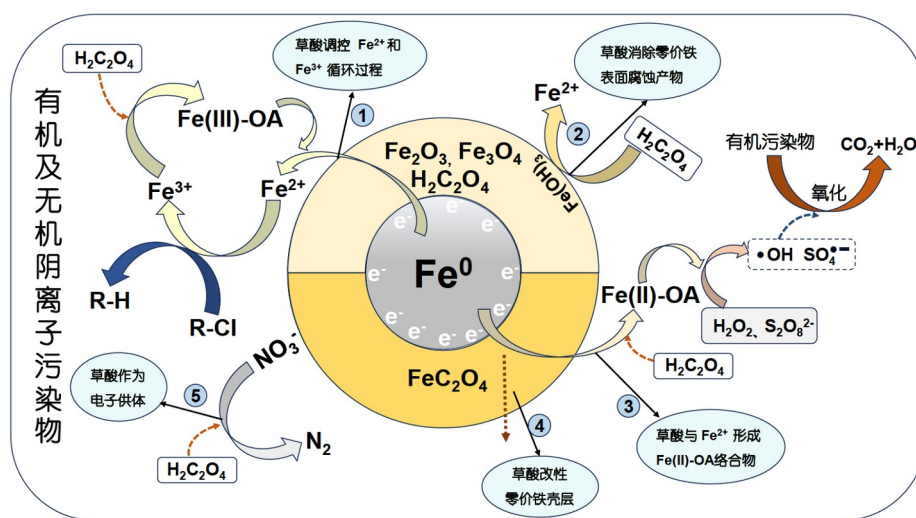


图 2 (网络版彩色)草酸调控零价铁对有机污染物和无机阴离子污染物的去除机理

Figure 2 (Color online) Research progress on oxalic acid modulation of zero-valent iron for removal of organic pollutants and inorganic anions

向纳米零价铁中掺杂铜和锰, 并利用膨润土作为载体, 在紫外线照射和草酸存在的条件下, 活化过硫酸盐以实现硝酸盐的高效去除. 在该系统中, 草酸作为还原过程中的主要电子供体, 草酸通过生成还原性自由基, 将过硫酸盐氧化体系转变为还原体系, 从而提高了亚硝酸盐的还原速率, 并在草酸浓度为 15 mmol L^{-1} 时达到最高去除率 97.55%. 在零价铁还原去除溴酸盐的过程中, 由于零价铁在还原反应中提供电子, 其还原能力迅速下降. 尽管通常可以通过酸洗来恢复零价铁的还原能力, 但这种再生处理既耗时又需要大量酸^[52]. 研究表明, 添加对氧化金属具有高亲和力的有机酸和聚羧酸盐, 可以防止钝化层的形成, 并提升还原反应的效率^[53]. 因此, Lin 等人^[54]对酸洗后的零价铁添加草酸进行溴酸盐去除实验, 结果表明, 在仅含微量草酸的条件下, 酸洗后的零价铁对溴酸盐的还原效果显著提高. 草酸调控零价铁对无机阴离子污染物的去除方法、实验 pH 以及最终的去除效果, 请见表 S2.

综上所述, 草酸调控零价铁在去除无机阴离子污染物中, 主要通过改善零价铁反应过程中氧化物的积累, 以及作为电子供体参与无机阴离子去除, 从而提高其去除效果(图 2). 然而, 迄今为止, 针对草酸调控零价铁技术去除无机阴离子污染物的研究尚不充分, 亟须开展相关研究.

4 结论和展望

综上所述, 草酸作为一种自然界中天然存在的小

分子有机酸, 本身具有通过还原络合作用去除重金属的能力. 相较于目前广泛采取的双金属改性, 利用草酸改性零价铁去除土壤和水体中的污染物, 可有效避免二次污染. 同时, 相较于将零价铁负载于高比表面积材料, 草酸调控工艺简单, 易于实际操作. 本文通过系统性综述表明, 草酸改性能够改善零价铁表面的氧化壳层, 缓解表面腐蚀产物的堆积, 有效提升其电子转移能力, 并促进了亚铁离子这一关键活性离子的氧化还原循环, 同时作为电子供体参与无机阴离子污染物的去除(图 3). 相较于单纯的零价铁, 草酸调控后的零价铁在对变价重金属、有机污染物和无机阴离子污染都表现出更强的去除性能. 草酸调控零价铁未来在理论研究和实际场地的研究展望如下所述.

场地研究展望: (1) 为了增强草酸调控零价铁的实际处理效能, 可以通过改善材料制备工艺, 比如细化零价铁颗粒、调整草酸浓度等方法来提高其反应活性. 此外, 还可以通过优化操作条件, 包括 pH、温度和反应时间等, 进一步提升去除效率. (2) 目前的研究主要集中在少数污染物上, 对于场地中存在复合污染物的处理的研究尚显不足. 后续研究应当拓宽范围, 深入探讨更多种类污染物的去除效果, 尤其是复合污染物的处理能力. (3) 对于草酸调控零价铁材料而言, 长期稳定性是一个关键问题. 研究该材料在不同环境条件下的腐蚀速率和性能变化, 对于确保其在环境修复中的应用能够长期保持有效性和稳定性至关重要.

理论研究展望: (1) 深入探究草酸与零价铁之间的

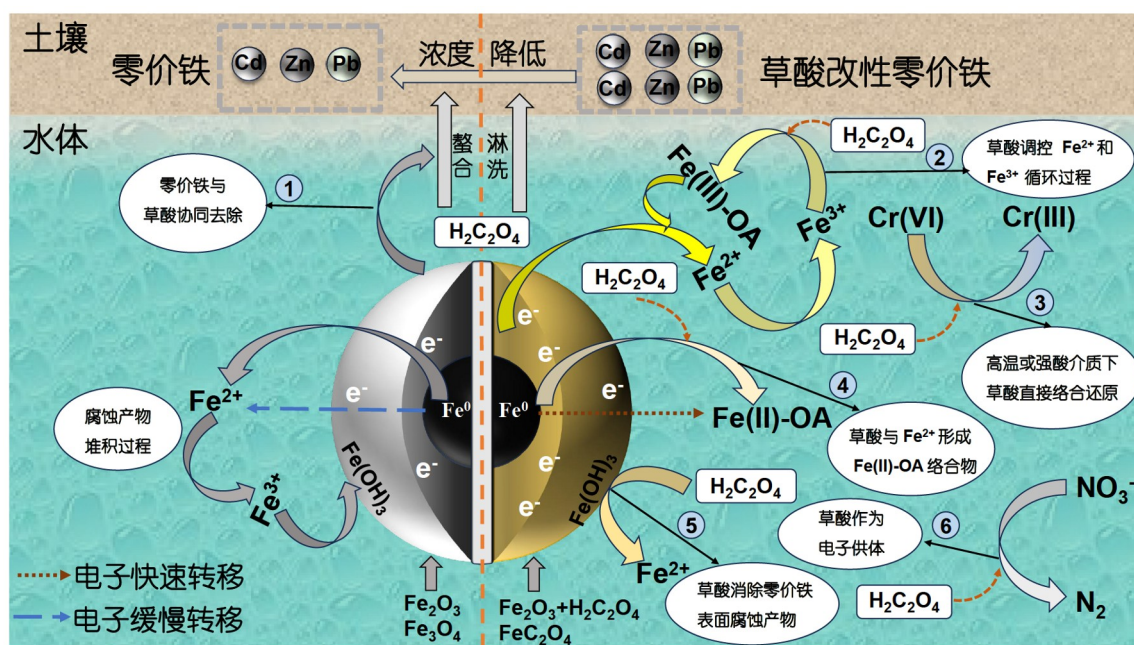


图3 (网络版彩色) 零价铁与草酸调控零价铁对土壤和水体中污染物的去除机理概述

Figure 3 (Color online) Overview of the mechanism of removal of pollutants from soil and water column by zero-valent iron and oxalic acid modulated zero-valent iron

相互作用机制, 包括草酸分子在零价铁表面的吸附过程、草酸与铁离子的配位作用以及这些过程对零价铁表面性质的影响. 这将有助于从分子层面上理解草酸调控零价铁的机理, 为优化材料设计提供理论依据. (2) 研究草酸调控零价铁技术在不同环境条件下的反应动力学和反应路径, 包括不同pH、温度、氧化还原电位等条件下的影响. 这将有助于建立更为精确的模

型, 预测和调控草酸调控零价铁的修复效果. (3) 探索草酸调控零价铁技术与其他环境修复技术的耦合应用, 如生物修复、电化学修复等, 以实现多机制、多过程的协同修复效应.

综上所述, 草酸调控零价铁在环境修复领域显示出巨大的应用前景. 然而, 仍需通过深入研究解决上述挑战, 以确保其高效、安全和可持续的应用.

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补充材料

表S1 草酸调控零价铁对土壤和水体中重金属去除的研究进展

表S2 草酸调控零价铁对有机污染物和无机阴离子去除的研究进展

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Summary for “草酸调控零价铁对土壤和水体中污染物去除的研究进展”

Research progress on the oxalic acid-regulated zero-valent iron for pollutant removal in soil and water column

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Zero-valent iron (Fe^0), which adsorbs and reduces typical heavy metals and organic pollutants, has emerged as a promising and environmentally friendly reductant for soil and water pollution remediation. However, Fe^0 tends to form surface oxides and corrosion products that reduce its electron transfer rate and overall efficiency, thereby degrading its performance. Accordingly, researchers have modulated Fe^0 with oxalic acid (OA) to improve its surface properties and enhance its pollutant-removal capabilities. This review systematically summarizes the research progress on OA-modulated Fe^0 in soil and water pollution remediation. We begin by discussing the advantages of OA modulation, highlighting its ability to improve the electron transfer rate of Fe^0 by altering the surface oxide layer on Fe^0 and promoting the redox cycle of ferrous ions. Through these processes, OA modulation enhances the removal of heavy metals, organic pollutants, and inorganic anions. We discuss the removal of Cr(VI) as a case study of heavy-metal removal. OA effectively promotes the reduction of Cr(VI) to Cr(III) by acting as an electron donor, forming stable complexes with Fe(II). OA also facilitates the removal of Cr(III)-EDTA complexes by generating singlet oxygen ($^1\text{O}_2$) and promoting $\text{Cr}(\text{OH})_3$ precipitation. We then explore the application of OA-modulated Fe^0 in the removal of other heavy metals such as As(III), Cd, Pb, and Zn, demonstrating its potential for eliminating a wide range of heavy-metal contaminants. In the realm of organic pollutants, OA-modulated Fe^0 can potentially remove chlorinated hydrocarbons such as trichloroethylene (TCE), perchloroethylene (PCE), and organic dyes. OA effectively eliminates the passivating $\text{Fe}(\text{OH})_3$ layer on Fe^0 , facilitating direct electron transfer and enhancing the adsorption and reduction of chlorinated hydrocarbons. In addition, OA promotes the generation of hydroxyl radicals in advanced oxidation processes such as the Fenton reaction and peroxymonosulfate (PMS) activation, enabling the efficient degradation of organic dyes. OA-modulated Fe^0 also promises to remove inorganic anions such as nitrate and bromate. OA donates electrons during nitrate and bromate reduction, promoting the formation of reactive intermediates and enhancing the overall removal efficiency. We conclude by discussing the key factors influencing the performance of OA-modulated Fe^0 , namely, the OA concentration, pH, reaction time, and the presence of other chemical species. As guides for future research, we propose optimizing OA-modulated Fe^0 materials, investigating the removal of complex pollutants, and coupling OA-modulated Fe^0 with other remediation technologies such as bioremediation and electrochemical remediation. Overall, this review demonstrates the considerable potential of OA-modulated Fe^0 in soil and water pollution remediation. By improving the surface properties and electron transfer capacity of Fe^0 , OA offers a promising and sustainable solution to a wide range of environmental contaminants. OA-modulated Fe^0 offers several advantages over traditional Fe^0 : improved stability, reduced Fe^0 leaching, and enhanced removal efficiency. As OA is a naturally occurring organic acid, OA modulation is also more environmentally friendly than other modification methods such as metal doping or the immobilization of Fe^0 on carriers. Future research should focus on optimizing the preparation of OA-modulated Fe^0 materials, investigating the removal of complex pollutants, and exploring the coupling of OA-modulated Fe^0 with other remediation technologies such as bioremediation and electrochemical remediation. Investigating the long-term stability of OA-modulated Fe^0 under different environmental conditions is essential for ensuring the effectiveness and sustainability of this technology in real-world applications.

zero-valent iron, oxalic acid, soil, water column

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