煤矸石改良土壤与矿区生态修复研究进展*

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摘要:针对煤炭开采伴生的巨量煤矸石堆存所引发的土地侵占、土壤退化及环境污染问题,系统论述了煤矸石作为潜在土壤改良剂与矿区生态修复材料的资源化利用途径。煤矸石富含硅铝矿物、有机质及微量元素,通过微生物与水热活化改性技术处理,能够提升其中硅、钾、磷等关键养分的生物有效性,兼具环境友好与低能耗优势。研究结果表明,活化后的煤矸石能显著优化退化土壤的孔隙结构、增强其保水保肥性能、提升土壤有机质含量与肥力水平,并在促进土壤固碳方面发挥积极作用;在矿区生态修复方面,改性煤矸石成功应用于沉陷区复垦工程,同时可配制人工土壤,从而有效支撑植被重建与水土保持。利用改性煤矸石改良土壤和修复矿区生态系统,不仅为煤矸石的高值化、规模化利用提供了有效途径,在推动矿区生态重建、退化土壤改良及助力"双碳"目标实现方面也具有重要的实践意义。

关键词:煤矸石;土壤改良;微生物活化;矿区生态修复;固废高值利用

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Research Progress on Soil Improvement with Coal Gangue and Ecological Restoration of Mining Areas

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Abstract: Problems including land occupation, soil degradation and environmental pollution are often triggered by massive coal gangue stockpiles generated alongside coal mining. Resource utilization approaches of coal gangue as potential soil amendments and materials for ecological restoration of mining areas were systematically discussed. Coal gangue is rich in silicon-aluminum minerals, organic matter and trace elements. After being modified by microbial and hydrothermal activation technologies, the bioavailability of key nutrients such as silicon, potassium and phosphorus in coal gangue is improved, and this treatment method has both environmental friendliness and low energy consumption. The research results indicate that the pore structure of degraded soil is significantly optimized, the water and fertilizer retention capacity is enhanced, the content of soil organic matter and fertility level are raised, and positive effects on soil carbon sequestration are achieved by activated coal gangue. In terms of ecological restoration of mining areas, modified coal gangue has been successfully applied in reclamation projects of subsidence areas, and artificial soil can be prepared with it to effectively support vegetation reconstruction and soil and water conservation. Effective approaches for the high-value and large-scale utilization of coal gangue are offered by applying modified coal gangue to soil improvement and mining ecosystem restoration, and important practical significance is also shown in advancing ecological reconstruction of mining areas, ameliorating degraded soil and facilitating the realization of the "Dual Carbon" goals.

Key words: Coal gangue, Soil improvement, Microbial activation, Ecological restoration of mining areas, High-value utilization of solid waste

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0 引言

以煤炭为主的化石燃料仍主导着世界能源消费格局,2022 年全球煤炭消费量增长超 7%,其中我国煤炭产量达 45.6 亿 t,约占全球产量的一半[1-2]。在煤炭开采、洗选和加工过程中会产生大量煤矸石,这种黑灰色岩石的碳含量和热值均低于原煤,产量约占煤炭产量的 15%~20%[3-4]。作为世界最大产煤国,我国的煤矸石产量巨大,截至 2022 年,我国煤矸石堆存量已突破 70 亿 t[5],堆积而成的矸石山约 1 700 余座[6]。巨量煤矸石堆积不仅占用大量土地资源,还会引发多重安全与环境问题,包括土壤退化、自燃风险[7-8]、有毒气体释放、重金属污染及地质灾害等[9-10],这些环境问题不仅显著破坏生态稳定,也严重阻碍了煤炭产业的低碳转型与高值化发展。因此,应寻求煤矸石的资源化高效利用途径,以减轻煤矸石对生态环境的不利影响,实现废物的二次利用。

过度耕作与长期使用化肥导致土壤有机质和腐殖质持续流失,土壤退化问题日益严峻[11]。全球三分之一的土壤因侵蚀、荒漠化、盐碱化、板结和污染出现严重退化[12],相关研究表明,科学添加煤矸石可有效改善土壤质量,缓解传统化肥对土壤的负面影响[13]。为此,国家有关部委密集发布了多部鼓励煤矸石生态化利用的文件,《关于推进大宗固体废弃物综合利用产业集聚发展的通知》《关于加快推动工业资源综合利用的实施方案》《"十四五"大宗固体废弃物综合利用的指导意见》均明确鼓励在风险可控的前提下利用煤矸石等进行土壤治理、生态修复及农肥生产[14]。面对我国农田土壤改良、盐碱风沙土治理等现实需求,煤矸石凭借其储量巨大、可就地取材、功能适配的优势,展现出广阔的应用前景,其生态化利用有望迎来重大发展机遇。

我国煤矸石用于土壤改良与矿区生态修复的研究历程可追溯至上世纪末。早在 1990 年,相关研究根据煤矸石的物理化学性质将其用于复垦种植,报道显示第二年的牧草亩产可达 400 kg 左右[15];进入 21 世纪,研究重点转向基础应用探索,学者们开始系统评估煤矸石直接回填复垦的可行性、其对土壤理化性质的基本影响以及先锋植物筛选,为后续研究积累了重要的实证数据[16-17]。随着国家生态文明建设推进,也推动了煤矸石规模化处置与资源化利用技术的研发;研究内容从早期相对单一的物理填充应用,深化至通过改性活化技术提升材料性能,应用目标也从单纯的复垦拓展到土壤结构改良、养分缓释、重金属固定、水土保持及固碳减排等多功能协同,并进一步探索了其在人工土壤配制、硅基肥料开发等领域的应用潜力[18-19]。

正是在这样的政策驱动与现实需求双重背景下,如何深度挖掘煤矸石作为土壤改良与生态修复材料的核心价值,并克服其潜在环境风险,成为当前研究的焦点与难点。本文围绕煤矸石资源化利用的难题,系统探讨了其作为潜在土壤改良剂与生态修复材料的科学基础与应用前景。研究成果为煤矸石的大规模、高值化、环境友好型利用提供了重要的理论支撑与技术路径,对实现"以废治废"、推动矿区生态重建与农业土壤可持续改良具有重要意义。

1 煤矸石的性质

煤矸石属于硅铝质材料[20],主要化学成分为 SiO_2 和 Al_2O_3,并含有少量 Fe_2O_3、CaO、MgO、Na_2O 和 K_2O,见表 1。不同产区煤矸石的化学成分及含量存在一定差异[21],其中 $SiO_2+Al_2O_3$ 含量在 65%以上,具有潜在火山灰活性,其含量的差异直接影响矿物结构稳定性,含量越高煤矸石惰性越强,常需更剧烈的物理粉碎或碱性水热活化以破坏结构、释放有益元素。成分分析表明,煤矸石与土壤的化学成分具有一定相似性,这可能源于其共同的地质背景[22],同时,多数煤矸石具有较高的烧失量,表明其有机碳含量较高,该特性为其土壤化利用提供了有利条件,也为微生物活化提供了适宜碳源,但需关注堆存过程中的自燃风险[23]。碱性氧化物(CaO、MgO、K_2O、Na_2O)的含量差异直接影响煤矸石的 pH,碱性氧化物含量高的煤矸石自身呈碱性,更适用于酸性土壤改良或矿区修复,但在微生物活化时需筛选出有耐碱功能的菌种。煤矸石矿物组成复杂多样,主要包含石英、高岭石、伊利石、蒙脱石、石灰岩、长石、白云石、菱锰矿和黄铁矿等[24-25],其丰富的黏土矿物为改善土壤结构和肥力提供了便利条件[26]。因此,针对不同产区煤矸石的成分特性,需因地制宜地优化活化技术路线,在充分释放有益组分生物有效性的同时,有效控制环境风险,实现安全高效的土壤改良与生态修复目标。

通过与其他工业固体废弃物的对比[2](见表 2)发现,煤矸石含有更高水平的氮(N)、磷(P)、钾(K)和硫(S),这些成分有助于提升土壤肥力。虽然硫在某些煤炭加工利用项目中被视为有害成分,但适

量硫元素能有效促进作物生长并提高产量[35]。煤矸石具有发达的孔隙结构和比表面积,可改善土壤通气性并防止板结[36]。除此之外煤矸石还富含钒、铬、铜、钴、镍、锌、铅等微量元素,虽然含量普遍低于0.1%,但地表地质作用可能促使放射性元素释放并迁移至周边土壤和水系,对生态环境和人体健康造成危害[37]。

综上,煤矸石内在的土壤改良潜力与其伴生的环境风险构成了其资源化利用的双重属性。因此,开发高效、绿色的改性活化技术,在充分释放其有益组分的同时有效稳定或去除有害物质,是实现其安全、高值化应用的关键所在。

表 1 我国不同地区煤矸石的主要化学成分

Table 1 The main chemical components of coal gangue in different regions of China %

地区	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	TiO_2	烧失量	参考文献
山西大同	46.10	30.90	3.10	1.20	0.50	—	1.30	1.10	15.30	[27]
山西宁武	47.10	30.70	4.30	1.20	0.50	0.33	1.10	1.10	13.70	[27]
山西太原	54.63	24.63	2.17	0.15	0.82	0.35	2.52	0.69	13.45	[28]
内蒙古鄂尔多斯	45.90	16.00	4.71	0.74	1.37	0.99	3.36	0.78	8.03	[29]
安徽淮北	53.24	22.09	5.97	1.43	0.39	0.32	0.95	—	13.36	[30]
湖南益阳	69.30	20.80	3.81	0.24	0.43	0.36	2.07	1.34	11.50	[31]
山东德州	52.92	22.71	8.20	7.71	2.08	0.58	2.13	—	0.96	[32]
新疆伊犁	59.10	17.79	5.34	0.31	1.36	0.08	2.58	0.92	—	[33]
辽宁阜新	56.34	27.84	5.10	4.31	1.82	0.72	3.56	0.75	—	[34]

表 2 4 种典型工业固体废弃物的理化性质对比[2]

Table 2 Comparison of physical and chemical properties of four typical industrial solid wastes[2]

固体废弃物	pH (1∶5)	电导率/(mS/cm)	比表面积/(m^2/g)	有机碳含量/%	全氮含量/%	全磷含量/%	全钾含量/%	全硫含量/%
煤矸石	6.90～8.93	0.26～2.20	0.52～7.24	3.50～21.2	0.19～0.87	0.23～0.47	0.86～2.71	0.55～4.90
粉煤灰	3.10～12.8	3.20～7.60	2.50～14.8	0.45～1.70	0.01～0.12	0.01～1.08	0.01～0.28	0.01～0.58
赤泥	9.00～13.1	10.0～60.8	5.31～64.1	0.60～1.28	＜0.02	0.01～0.08	0.10～1.82	0.10～0.60
脱硫石膏	6.50～8.46	0.84～2.60	0.38～6.68	0.16～2.40	＜0.01	0.01～0.42	0.05～1.35	8.20～20.9

2 煤矸石的活化

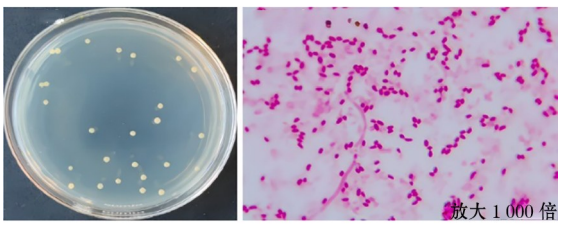
煤矸石的固有性质虽具潜力,但其养分有效性低、潜在污染物风险高等缺陷限制了其直接应用,因此,需经适当改性以提升其性能、活化有益组分、增强水肥保持能力并降低污染与生物毒性,目前,活化方法主要分为物理活化(包含机械活化、热活化及微波活化)、化学活化、微生物活化和水热活化。鉴于煤矸石物理活化与化学活化已有较多研究[38-39],本节将重点探讨微生物活化与水热活化这两种改性方法。

2.1 微生物活化

相较于物理化学方法,微生物活化因其环境友好、能耗低、选择性高等优势,在煤矸石养分释放与污染控制方面展现出独特潜力。微生物改性技术利用微生物代谢作用降解煤矸石中的矿物组分,促进养分元素释放,最终获得微生物肥料[40]。研究证实,丛枝菌根真菌(AMF)与解磷细菌(PSB)对有机物分解及养分释放具有协同促进作用,其中解磷细菌能将有机磷和无机磷转化为可溶性形态,显著提升矿物中磷的有效性并促进植物生长[41]。而硅酸盐细菌对特定晶体结构的硅酸盐矿物具有选择性溶蚀作用,可明显促进硅、钾元素的释放[42]。

Zhu 等[43]成功分离得到嗜麦芽窄食单胞菌(*Stenotrophomonas maltophilia* YZ1,见图 1),经 YZ1 菌处理后,可使煤矸石中的有效磷显著溶解释放,同时还能促进有效钾和有效硅的溶解,煤矸石中有效磷、有效钾和有效硅含量分别达到 278.4 mg/kg、1 305.3 mg/kg 和 522.7 mg/kg,较处理前分别提升了 58.0 倍、8.5 倍和 2.8 倍。Liu 等[44]分离出了产气芽孢杆菌(*Bacillus aerius*),该菌株可有效促进煤矸石中营养元素的溶解释放,并能显著提高煤矸石中有效钾、有效磷、碱解氮及类腐殖质等植物必需养分的释放效率。通过优化溶钾条件后发现,产气芽孢杆菌即使在高温环境下仍能显著提升有效钾的溶出效率,进一步研究表明,该菌株可附着于煤矸石表面并促进其生物降解,同时分泌胞外酶及小分子有机酸来增强营养元素的溶解释放作用。这些研究证实,

通过精准筛选和利用功能微生物菌株,不仅能实现煤矸石中硅、钾、磷等关键养分的高效生物活化,更能同步达成硫污染物的深度脱除。



(a) 菌落形态 (b) 微观形态

图 1 菌株 YZ1 的菌落形态和显微形态[43]

Fig.1 Colony morphology and microscopic morphology of strain YZ1[43]

此外,微生物处理还能实现煤矸石中重金属离子的吸附固定。Chen 等[45]发现经过氧化亚铁硫杆菌(*A. ferrooxidans* SOB-1)和氧化硫硫杆菌(*A. thiooxidans* SOB-2)处理的煤矸石中总硫含量从 2.06%降至 1.18%、黄铁矿硫含量从 0.66%降至 0.14%、硫酸盐硫含量从 1.02%降至 0.52%,其中黄铁矿和硫酸盐脱硫率分别达到 78.79%和 49.02%。因此,筛选高效功能菌株有望实现煤矸石养分活化与污染控制的双重目标。

2.2 水热活化

水热改性技术采用专用的密闭反应容器,以水溶液为反应介质,在高温高压条件下形成亚临界水状态,促使煤矸石发生水解、解聚、聚合、异构化、脱水、芳构化和缩合等多种转化反应[46]。煤矸石水热改性的关键参数包括反应温度、停留时间、压力、固液比和反应介质,其中温度是最关键的决定因素,当温度达到反应活化能阈值时,化学键断裂并引发多种反应[47]。

煤矸石水热改性通常采用碱性溶液作为反应介质,可加速 Si—O—Si 和 Si—O—M(M 为 Al、Mg 等)键的断裂,进而通过水热缩合或凝胶反应合成具有不同形貌和性能的新型功能材料[48]。与化学改性相比,碱性水热改性后的煤矸石表面含有更丰富的碱性官能团和微孔结构,具有更大的比表面积、更宽的孔径分布和显著提升的吸附能力[49]。同时,碱性水热改性可同时活化煤矸石中的养分和去除污染物,制备出高活性且环保的硅基复合肥料[50]。尽管水热活化法是一种科学、高效且多功能的改性技术,但该方法对昂贵复杂反应装置的依赖,限制了其规模化应用,目前仍处于实验室阶段。未来可探索简化反应装置设计或开发连续化水热工艺以降低设备成本;同时考虑与微生物活化等低能耗技术联用,通过分步处理来实现活化效率与经济效益的协同优化。

经微生物或水热活化改性后,煤矸石克服了原始材料的诸多缺陷,实现了"有害元素减量、有益元素增效"的转变,为其实施规模化的农业与环境应用奠定了关键基础。

3 煤矸石在土壤改良中的应用

随着土壤退化问题不断加剧,煤矸石作为兼具土壤兼容性与功能可调性的固废资源,其改良土壤的应用价值备受关注。通过活化,煤矸石中有益组分(如硅、钾、有机质等)的生物有效性显著提升,同时重金属与硫污染物得以高效去除,为退化土壤修复提供了安全可靠的材料基础。

3.1 优化土壤结构

煤矸石富含有机质,是承载氮、磷、钾的理想基质,科学合理地将其添加到土壤中,可降低土壤黏性并改善孔隙度,添加煤矸石的土壤孔隙结构能促进矿肥溶解及水中氧气扩散,从而优化植物根系对养分的吸收和呼吸作用,最终促进植物生长[51]。

多孔改性煤矸石的添加能改善土壤结构,丰富的孔隙结构既能截留水分子又能输送氧气,其低饱和导水率可有效阻隔水分流失,从而显著提升干旱沙土的保水能力,同时有利于植物根系对养分的吸收与呼吸作用,并显著提升土壤的微生物量[52]。研究发现,通过草木灰活化煤矸石可制备硅钾基改良剂,用于改善土壤理化性质,提升有效硅的溶出效率,提高植株 K^+/Na^+ 比和硅含量,减轻细胞膜损伤,进而促进盐渍土中植物生长;相较于单一硅肥或钾肥,该改良剂还含有钙、铁、镁等多种矿质元素,具有更全面的促生效果,所用原料均为低成本固废,且制备工艺较商品化硅/钾/硅钾肥料更为简便,除盐碱土外,该改良剂还可应用于污染土壤、干旱区、沙质土及贫瘠土壤等逆境环境[53]。此外,改性煤矸石的特性使其适用于重金属污染土壤的修复,施用改性煤矸石后,土壤有效态砷含量降低 17.94%~29.81%、镉含量降低 14.22%~30.41%,并将不稳定态砷、镉转化为稳定态。同时使硫酸盐还原菌功能基因丰度提升 43.39%~381.28%,促进硫酸盐还原反应产生的硫化物与 As、Cd 形成沉淀,降低其生物有效性[54]。

因此,煤矸石作为土壤修复原料,不仅能优化土

壤结构,还可显著增强土壤生物活性、提升有机质含量并改善养分水平。

3.2 提升土壤肥力

煤矸石富含硅元素、有机质及植物生长必需的微量元素,为复合肥生产提供了物质基础,但煤矸石中稳定的惰性有机质难以被微生物和植物利用,需通过适当活化提升活性有机质含量,对促进微生物群落功能、恢复土壤肥力至关重要[55]。

经改性处理的煤矸石有效硅含量显著提高,研究发现,经活化后煤矸石有效 SiO_2 含量可提升 320 倍,总 K_2O 含量达 13.30%;有机质含量提升至 13.68%,活性有机质增加 1.73 倍;同时实现 83.41% 的硫去除率及重金属高效稳定化,显著降低环境风险[50]。当煤矸石、$CaCO_3$ 和玉米秸秆按一定配比煅烧时,有效硅含量高达 22.97%,且有毒金属离子含量在 52.87 mg/kg 以下,可作为高效安全的煤矸石基硅肥[56],既能减少植物蒸腾损耗、提高养分利用效率,又能增强植物对生物/非生物胁迫的抵抗性,显著提升极端环境下植物的存活能力[57]。同时,补充有效硅可显著改善土壤持水性能,优化微生物群落结构,并降低植物体内重金属积累[58]。

土壤微量元素缺乏会直接或间接影响农业生产和人体营养健康,在中国约 72%的国土存在硒缺乏问题,改性煤矸石富含多种活性态微量元素,以硒元素为例,其活化率可达 81.24%,施用改性煤矸石硒肥将有效提升盐碱地与干旱地区作物的抗逆性,保障作物稳产,同时,煤矸石还可作为复合营养补充剂,为贫瘠土壤提供适度的活性、有机质及氮磷钾元素,在保障植物与微生物生长必需养分的同时,其特有的分子态养分缓释特性既能防止养分流失,又能促进作物吸收,显著提高养分利用率[59]。

3.3 促进土壤固碳

自工业革命以来,全球温室气体排放量逐年上升。土壤有机碳库作为陆地生态系统中最大的有机碳库,其微小变动都可能导致大气二氧化碳浓度的显著变化,影响碳循环与全球气候变化,加剧温室效应[60]。土壤呼吸作为碳循环的关键环节[61],对我国实现"碳达峰、碳中和"目标以及缓解气候变化具有重要意义。

富含有机质的煤矸石,经转化后作为外源有机物施入农田,短期内会显著改变本土有机碳的分解速率,在淋溶作用下,煤矸石中的可溶性有机碳会向周边土壤迁移。改性处理能有效疏松煤矸石结构,显著增大其比表面积和总孔容,增加孔隙数量,同时弱化石英等矿物的强度并提高煤矸石的反应活性,这些变化有助于改善土壤的保水透气性,提升土壤有机质含量,并增强土壤整体的保水保肥能力[62]。煤矸石的添加可提升土壤活性有机碳组分含量,在提高土壤总 CO_2 排放速率和累积释放量、促进土壤有机碳矿化的同时,还能改变土壤源 CO_2 释放动态,显著降低其累积排放量。同时,煤矸石对土壤有机碳累积激发效应具有抑制作用[63],通过减少"老碳"流失并促进"新碳"生成,最终有利于土壤有机碳的净积累与稳定。

综上,煤矸石通过孔隙结构优化、养分缓释及固碳增效,显著提升了退化土壤生态功能。这一改良成效不仅有助于农田生产力再生,更能成为矿区土地重构与植被恢复的重要基质基础,直接推动"煤矸石-土壤改良剂-生态修复载体"的转化。

4 煤矸石在矿区生态修复中的应用

矿区土地损毁与生态失衡的治理亟须低成本、高效率的解决方案,煤矸石经改良后,其物理结构与化学特性高度适配生态修复需求,尤其在沉陷区重构、人工土壤配制及植被重建中展现出独特优势。

4.1 土壤复垦

改性煤矸石除了直接用于改良农田土壤理化性质外,在解决煤炭开采造成的土地损毁问题,即矿区土壤复垦中,凭借其来源广、成本低、性能适配等优势,展现出巨大的应用价值。

煤炭开采在推动经济快速增长的同时,也引发了严峻的生态与环境问题。我国采煤沉陷区总面积已达 135 万 hm^2,且以每年 7 万 hm^2 的速度持续扩张,沉陷区形成的永久性洼地会严重破坏土壤性质,阻碍养分循环并抑制植物生长。当前复垦工程主要采用填埋技术,煤矸石凭借其综合性优势,已成为应用最广泛的回填材料:作为采矿固废,其产量约占煤炭产量的 15%~20%,具有来源稳定、就地可取的特点,降低了运输成本;现有利用率不足 15%,堆存量已达 38 亿 t,且年增 2 亿 t,利用后可缓解矸石堆存对土地的压占,减少矸石堆放造成的环境污染;煤矸石适中的水力传导性、吸附特性及淋溶行为适合作为填埋材料[64],通过对煤矸石复垦沉陷区进行了长期监测发现,经过 10 a 重构后,土壤指标接近损前状态[51]。可见,煤矸石用于沉陷区复垦,不仅是解决其堆存问题的有效途径,更在节约成本、减少环

境压力、促进生态恢复方面体现出“以废治废、变废为宝”的循环经济理念,是矿区绿色转型的重要实践。

煤矸石在土壤复垦方面具有较大的应用潜力,但在选择用作土壤复垦原料时,必须重视不同类型煤矸石的化学组分差异,既要遵循行业标准控制有毒有害物质,更需探索最优利用策略,以实现最佳效益。

4.2 生态修复

随着矿区开采规模不断扩大,生态破坏问题日益凸显,植被损毁、土地退化、水土流失及重金属污染已成为普遍存在的生态问题,亟须采取适宜的措施进行生态修复[65]。植被是矿区受损生态系统最为有效的修复措施之一,然而矿区土壤质地较差,主要由大粒径砾石颗粒组成,保水蓄水能力差,高温时易形成坚硬层,不利于植物萌发与根系生长[66]。

传统的修复方式主要为覆盖表土,但由于我国土壤资源日益紧缺,导致覆土成本高昂,同时取土区也存在二次破坏的风险[67]。研究发现,以煤矸石配制的人工土壤可为矿区生态修复奠定良好基础,试验中种植的苏丹草生长状况良好,且人工土壤的重金属指标达标,为植物提供了优良的生长环境,此外,这种人工土壤还能显著提升养分利用率,同时增强水土保持性能,因此可通过优化煤矸石利用的方式,改善矿区土壤条件,提升植被恢复潜力[68-69]。Gao Hongyu 等[70]利用煤矸石制备出一种多孔类土壤生态修复材料,其孔隙结构疏松丰富,总孔隙率高达 67.65%;该材料的水土保持性能是普通土壤的 4 倍,且流失率低至 2.74%,较普通土壤流失率降低 75%,盆栽试验表明,冰草、仙人掌、金合欢、小麦、玉米和苜蓿在该材料中的成活率与正常土壤栽培条件下基本一致。除此之外,在砂岩土壤中添加煤矸石可显著提升基质中有机质、全氮、全磷、全钾、速效氮和速效钾含量,优化种植基质的营养构成,有效促进木地肤(*Kochia prostrata*,藜科常见小半灌木)的生长,为实现干旱矿区植被恢复提供了有效途径[71]。

实践证明,煤矸石在沉陷区复垦、人工土壤构建及植被恢复中的成功应用,标志着其从“土壤改良剂”向“生态修复引擎”的功能跃迁,这一资源化链条的闭环,即煤矸石→改良土壤→修复矿区,不仅可以化解固废堆存困境,还能够以“以废治废”的模式推动矿区生态重建与低碳转型。

5 结论与展望

(1) 煤矸石富含硅铝矿物、有机质及微量元素,其多孔结构与土壤化学组成的天然兼容性,为改良退化土壤与矿区生态修复提供了物质基础。

(2) 微生物活化与水热活化等改性技术,可显著提升煤矸石中硅、钾、磷等养分的生物有效性,同步实现重金属稳定化与硫污染物脱除,这种“变废为益”的转化,有效克服了原始煤矸石环境风险高、活性低的缺陷,为其安全利用提供了技术保障。

(3) 活化煤矸石可实现土壤结构改良、增强土壤保水保肥性能及养分缓释;用作矿区复垦的低成本材料,可加速生态重建进程;所衍生的硅基复合肥能显著改善作物生长状况。此外,改性煤矸石在固碳减排与水土保持方面的效能,进一步拓宽了其生态修复方面的应用广度。

(4) 未来研究应着重于以下几个方面:一是开发低能耗、高效率的煤矸石复合活化工艺,如微波-微生物耦合或碱性水热-生物淋滤联合处理,以提升煤矸石所含养分的释放效率并降低处理成本;二是系统评估长期施用改性煤矸石对土壤微生物群落结构、酶活性及碳氮循环功能基因的影响,明确其生态安全性;三是深入研究煤矸石基材料与适生植物-功能微生物的协同修复机制,尤其在重金属-盐碱复合污染场地的应用潜力;四是构建基于煤矸石成分特性与区域环境特征的分类分级利用标准,建立以风险管控为核心的全链条监管技术体系,推动煤矸石资源化利用向标准化、精准化和产业化发展,为矿区土地治理与农业绿色转型提供科技支撑。

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