

◆健康保育与环境修复◆

高寒高海拔地区生态防护工程中土壤生境研究进展

李正虎¹, 杨杰倩², 瞿广飞², 罗代明³, 梁滔¹

(1. 云南勐绿高速公路投资开发有限公司, 云南 普洱 665099; 2. 昆明理工大学 环境科学与工程学院, 云南 昆明 650500; 3. 云南省公路科学技术研究院, 云南 昆明 650051)

[摘要] 新时代生态文明建设迫切要求高速公路项目必须走绿色发展之路, 降低对生态系统和保护物种的影响。针对高寒高海拔地区高速公路建设中边坡生态防护面临的植物生长困难问题, 探讨边坡土壤特性及其演化的生物化学过程, 促进边坡植被修复; 分析改善植被生长土壤生境的调控技术, 强调土壤-微生物联合技术在边坡防护工程中的合理应用, 以有效控制水土流失; 展望边坡生态防护技术的发展趋势及研究方向, 为未来的生态建设提供更加有效的解决方案。

[关键词] 高寒高海拔地区; 边坡防护; 土壤生境; 微生物; 植物

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Progress in soil habitat research for ecological protection engineering in cold and high altitude area

LI Zhenghu¹, YANG Jieqian², QU Guangfei², LUO Daiming³, LIANG Tao¹

(1. Yunnan Menglu Highway Investment and Development Co., Ltd., Puer 665099, China;

2. Faculty of Environmental Science and Engineering, Kunming University of Science and Technology, Kunming 650500, China;

3. Yunnan Highway Science and Technology Research Institute, Kunming 650051, China)

Abstract: The construction of ecological civilization in the new era urgently requires highway projects make a green development path to reduce the impact on ecosystems and protected species. Aiming at the difficult plant growth problems faced by the ecological protection of slopes in the construction of highway in cold and high altitude area, the soil characteristics of slopes and the biochemical process of their evolution are explored to promote the restoration of slope vegetation. The control techniques to improve the soil habitat for vegetation growth are analyzed, the rational application of soil-microbe joint technology in slope protection engineering is emphasized to effectively control of soil erosion. The development trends and research directions of slope ecological protection technology are forecasted to provide more effective solutions for future ecological construction.

Key words: cold and high altitude area; slope protection; soil habitat; microorganisms; plants

0 引言

《绿色交通“十四五”发展规划》指出新高速公路需全面落实绿色公路建设要求, 强化公路生态环境保护工作以降低项目对重要生态系统和保护物种的影响。高寒高海拔地区独特的生态环境与丰富的自然景观构成了珍贵的生态资源, 然而也面临高速公路等基础设施建设对其生态系统的影响^[1], 其中路堤边坡的生态破坏尤为明显^[2]。采用切实可行的生态防护措施成为高寒高海拔地区生态保护至关重要的任务。

土壤作为生态系统的基础, 土壤养分、植被类型和坡度位置显著影响植被改善土壤可蚀性的能力^[3-5]。高寒高海拔地区的土壤因其特殊的地理位

置和气候条件, 表现出独特的物理、化学和生物学特性, 直接关系着水土保持能力和生态系统的稳定性。与此同时, 微生物作为土壤生态系统中微小但不可或缺的组成部分, 通过参与养分循环、有机物分解、土壤固结等生物化学过程^[6-7], 对土壤质地和结构的形成以及植被的生态恢复发挥着不可替代的作用。笔者探讨高寒高海拔地区高速公路路堤边坡生态防护技术中土壤及其微生物因素的关联, 通

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[作者简介] 李正虎(1976-), 男, 云南曲靖人, 高级工程师。

[通信作者] 瞿广飞(1978-), 男, 云南曲靖人, 教授。

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过综述相关技术，为进一步的研究和实践提供有益指导，以实现高寒高海拔地区生态环境的可持续发展与保护。

1 高寒高海拔地区高速公路边坡的生态问题

1.1 高寒高海拔地区环境特征

高寒高海拔地区生态环境受到纬度和降水等多方面因素的影响^[8]，抗干扰能力差，系统结构易发生变化，功能极易被破坏，呈现出昼夜温差大、空气稀薄、太阳辐射强烈、冻融循环剧烈、无（少）雨期较长、土壤贫瘠等地域和气候特殊性^[9]，进而影响植物生长（见图1）。海拔愈高，气候愈干燥，施工扰动后造成的植被破坏愈难以自然恢复，故植物必须具备极强的抗寒、耐干旱和耐紫外线辐射的适应能力。此外，由于陡峭的地形，土壤覆盖相对较薄，高寒高海拔地区容易受到水土流失和侵蚀威胁^[10]。在高寒地区恶劣的生存条件下，植物表现出多样性低、生物量较小、生物链单一等特点，生态系统中物质和能量交换循环的速度缓慢，生态环境维持着极度脆弱的平衡^[11]。随着海拔的升高，植物类型主要为灌草、乔灌草、高山草甸，且植物多样性随海拔升高呈现先升后降的趋势，相同海拔各层级植物多样性为草本层 > 灌木层 > 乔木层^[12]。

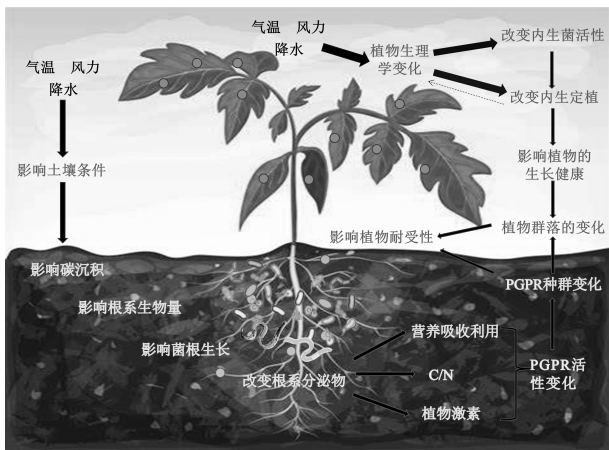


图1 高寒高海拔地区环境因素对土壤-植物-微生物系统的影响

Fig. 1 Effects of environment factors on soil-vegetation-microbial system in cold and high altitude area

1.2 高速公路建设对环境的影响

1.2.1 土壤本体

高速公路建设过程永久或临时占用的耕地、林地、草地和湿地等，改变了原有土地的利用方式，影响土壤生产力和农林业发展^[13]。公路建设过程中，原有土壤的表土层和腐殖质层遭到破坏，在一定程度上增强了风蚀、水蚀强度，且路基

材料的使用会改变相邻区域土壤的酸碱度。土壤质地组成比例发生变化，结构重排，孔隙度变大，水分减少，养分流失，不利于植被生长^[14]。除磷素外，路域土壤坡度越陡，氮素、有机质等养分流失越快^[15]。此外，运营过程中车辆尾气的长期积累使土壤趋于厌氧环境，降低土壤养分有效性^[16]；车辆排放污染物通过路面径流、大气等载体进入路域土壤，导致公路周边土壤中镉、铜、铅、锌等重金属含量升高^[17]，引起土壤细菌的物种丰度和群落结构变化^[18]，对道路附近的耕地土壤特性和农作物产量产生负面影响^[19]。

高寒高海拔地区高速公路建设过程中，因冻融循环的影响，可能会出现坡面破碎、坡体裂隙等边坡失稳变形的情况^[20]。施工期间开挖地表、铲除植被、修筑路堤等活动，会产生强烈的热侵蚀作用，改变土体与大气之间的热交换条件，引起冻土温度场发生变化，导致冻土区原有的冰-水-热平衡状况发生变化，加剧或引起更多冻土环境恶化现象^[21]。

1.2.2 生物多样性

由于高速公路施工期土地利用方式变更，公路沿线及周边植被面积减少，植被类型由多样化变为单一，导致植被生物量减少，生态服务功能下降^[22]。植被消失导致植物蒸散发的太阳辐射能（潜热通量）减少、地表温度升高、局部气候发生变化^[23]。受影响的植被有栽培植被、灌丛、草丛、针叶林和阔叶林^[24]等。边坡的植被覆盖层破坏导致大量的次生裸地以及严重的水土流失现象出现^[25]。

此外，公路建设会改变周边区域的物理环境，产生的污染干扰动物的生存和繁衍^[26]。高速公路建设一定程度上损害了土壤微生物性状和酶活性^[27]，降低了土壤生态系统活性。道路建设可能对土壤微生物群落产生不可逆的干扰，切断了土壤微生物与植物根系之间的物质、能量交换，破坏土壤结构、改变土壤物理性质，进而影响土壤微生物的生存和活动。此外，道路建设过程中的人类活动，如物体碾压、混凝土施工等，也会直接破坏土壤生态系统；通过引入外来物种等途径，对土壤微生物群落造成扰动。

2 高速公路边坡防护工程土壤生境研究

以往对土壤生境的研究主要集中在不同土质的森林、农田、湿地等土壤健康和污染物降解等方面（见表1），而对于高寒高海拔地区，尤其是高速公路边坡防护中土壤微生物的角色和影响，研究相对较少。

表1 微生物在不同土壤中的作用

Table 1 The role of microorganisms in different soils

土壤类型	微生物	微生物作用
稻田土壤	甲基孢囊菌、甲基暖菌	通过合成能量物质聚-β-羟丁酸(PHB)促进甲烷氧化,减少土壤中甲烷排放量 ^[28]
盐渍化土壤	丛枝菌根真菌、短小芽孢杆菌	改良植物根区土壤环境,激活土壤酶(脱氢酶、β-葡萄糖苷酶、酸性磷酸酶)和促进微生物生物量碳的产生,提高植物耐盐性 ^[29-30]
温带山毛榉林土壤	化能异养微生物	磷酸烯醇丙酮酸羧化酶基因丰富,通过碳同化羧化固定土壤孔隙中的CO ₂ ,调节土壤CO ₂ 排放来维持森林土壤碳储量 ^[31]
玉米田土壤	硝化细菌、亚硝化细菌	吸收简单的有机氮源降解分子,升高谷氨酸脱氢酶和谷氨酰胺合成酶活性,矿化有机氮并以矿物氮的形式吸收(矿化-固定-转运[MIT]途径) ^[32-33]
玉米田土壤	阴沟肠杆菌	产生吲哚乙酸刺激植物生长出更多的根毛,提高土壤全氮含量、植株氮吸收量和土壤固氮酶(NIT)活性;增加伯克霍尔德菌和慢生根瘤菌等固氮微生物的相对丰度 ^[34]
混凝土砂	巴氏芽孢杆菌	利用微生物尿素水解诱导CaCO ₃ 矿物质沉淀在土壤颗粒表面和接触物上,提高土壤强度和刚度的同时降低土壤孔隙度和导水率 ^[35]
稻田土壤	蜡样芽孢杆菌	产生葡萄糖酸、草酸、柠檬酸等有机酸,从而增加土壤中矿物的溶解度和植物对磷的吸收利用率;产生吲哚乙酸(IAA)激素,有助于根系的形成和幼苗的生长 ^[36]
碱性-钙质土壤	巨大芽孢杆菌、多黏芽孢杆菌	增加绿豆根瘤的数量,促进绿豆对氮和磷的吸收,改善绿豆生物量和产量;提高土壤中有机质、有效氮、磷、钾含量 ^[37]
镉污染土壤	芽孢杆菌、巨大芽孢杆菌	分泌IAA、乙酸、丙酸等有机酸,导致土壤酸化,或者直接溶解土壤中的Cd,提高芥菜对镉的吸收,调整土壤微生物群落结构 ^[38]
高浓度多重金属土壤	细菌	增加信号分子合成酶trpE、trpG、bjal等的丰度,调节细胞外聚合物的产生,完成细胞外金属螯合;增强谷胱甘肽、金属硫蛋白和甲硫氨酸等物质合成,完成细胞内金属螯合,去除土壤中的锌和镉 ^[39-40]
苏打盐化碱土	热单胞菌、短波单胞菌、寡养单胞菌	通过转运Na ⁺ 、H ⁺ 、Ca ²⁺ 和分泌海藻糖、脯氨酸等相容物质来调节细胞内外的酸碱平衡和渗透压,减少土壤盐碱化 ^[41]
石油污染土壤	烟曲霉、奥托氏菌、趋磁细菌	通过分泌胞外降解酶促进非(PHE)的降解,增强多环芳烃的矿化,分泌木质素水解酶来提高多环芳烃的降解速率 ^[42]
重金属污染土壤	根际细菌、丛枝菌根真菌	刺激金属的吸收和转运,降低根际金属的流动性和可用性,增强豆科植物对重金属的提取,提高植物对重金属的耐受性,促进植物生长发育 ^[43]
砂质壤土	枯草芽孢杆菌和固氮菌	分泌多糖,提高土壤团聚体稳定性,降低土壤径流量、水土流失量、含沙量和沉积物浓度 ^[44-45]
日本宇部斜坡碱性土壤	霍内克芽孢杆菌、地衣芽孢杆菌	产生碳酸钙并附着土壤颗粒来固化土壤,控制边坡水土流失 ^[46-47]
冻融土壤	枯草芽孢杆菌和固氮菌	形成生物结皮,提高土壤颗粒附着力和骨料稳定性,减少水土流失 ^[48]
哈尔滨花卉种植土壤	解鸟氨酸拉乌尔菌和黏质沙雷菌	增加超氧化物歧化酶、过氧化物酶和过氧化氢酶活性,能同时同化和还原钼酸盐,减轻钼对黑麦草的毒性,作为钝化剂和调理剂固定剩余的钼,便于植物提取 ^[49]
森林土壤	酸杆菌门和担子菌门	调节团聚体稳定性和抗细菌侵蚀能力 ^[50]

2.1 高寒高海拔地区土壤特性

高寒高海拔地区土壤的演化受到低温、冻土以及冻融循环等极端条件的长期影响,形成独特的寒冻土壤^[51]。长期低温条件导致土壤中的有机质分解速度和有机碳矿化速率极其缓慢^[52],有机物贮存在土壤中时间较长。高寒高海拔地区气候、植被类型以及地质岩石类型可能促进溶解性有机酸的释放,导致土壤呈现强酸性或酸性,对植被的恢复和生长构成不利影响,并限制大部分土壤真菌的生长和繁殖^[53]。同时,由于低温条件下微生物的活动大大减缓,土壤中养分的循环速度也相应降低,土

壤的养分供应相对有限,对植被的生长和土壤生态系统的稳定性构成了挑战^[54]。

高寒高海拔地区的季节冻土区完全融化期对应植物生长期,冻土融化后土壤水分增加,土壤中养分得到释放,促进植物生长^[55]。近年来,随着全球气温升高,多年冻土退化加快,公路工程的建设对冻土的扰动加剧了道路影响范围内冻土的融化,影响高寒高海拔地区公路的正常运营^[56]。土壤冻结无法有效固定植被根系或破坏植物根系结构,降低土壤酶的合成和分泌,使其难以吸收养分和水分^[57];而当冻土融化时,水分流失导致植物水分

供应不足,影响其生长和发育,增加了滑坡和泥石流等灾害的风险^[58]。高速公路边坡通常位于复杂多变的地势之上,土壤在陡峭的坡度上更容易发生侵蚀和侧向移动,对土壤稳定性构成了威胁。

2.2 高寒高海拔地区土壤微生物特征

尽管环境条件严苛,高寒高海拔地区仍具有特殊的微生物群落结构,并展现出对低温、干旱和营养物质匮乏等极端环境条件的强大适应性^[59]。土壤性质随海拔梯度的变化而显著变化,季节对土壤性质和微生物群落结构有显著影响^[60]。研究表明,青藏高原土壤细菌主要由放线菌门和变形菌门组成,并在多年冻土层及相关环境中检测到多种细菌、酵母、丝状真菌和微藻等产油微生物^[61]。子建文等^[62]对香格里拉高海拔山脉土壤中的微生物数量和种类进行调查,分离出苏云金芽孢杆菌、蜡样芽孢杆菌、痢疾志贺菌、侵肺巴斯德菌、栖稻黄色单胞菌等细菌951株。土壤微生物不仅在数量上丰富,而且在功能上也具有多样性,通过分解有机物、固氮和溶解磷等生物化学过程,显著提高土壤肥力并支持植物生长,对维持该区域生态平衡发挥着重要作用。冻融过程通过低温胁迫导致细胞裂解以及增强解冻后的微生物活性而使微生物群落产生变化^[63]。刘全全等^[64]从海拔4 718 m的纳木错湖边泥土中分离出一株耐低温、耐盐的厌氧梭状芽孢杆菌P4-1,其能够利用代谢产物改善土壤中的微环境并降解对甲苯磺酸盐。GOLINSKA等^[65]从智利阿塔卡玛大型毫米波天线阵表层土壤中(海拔3 018 m)发现了一株贫养杆菌1G6^T,其基因组中富含与冷热胁迫响应、抗氧化、抗紫外线辐射相关的应激相关基因,并能使用一氧化碳作为碳源和能源,在极端生境中具有显著的竞争优势。LI等^[66]从祁连山高海拔云杉林中分离出的新型类芽孢杆菌LC-T2^T具有快速适应环境、富集更多根际细菌和抑制病原菌的能力,对植物生长具有重要的促进作用。因此,保护土壤微生物多样性是保障植物健康和促进生态系统恢复的关键,维持和促进这些关键微生物群落的健康为边坡生态防护提供了坚实的微生物基础。

2.3 微生物对土壤结构和功能的影响

微生物多样性和功能对维持脆弱生态系统土壤的结构和稳定性至关重要,而且在土壤养分循环和植被生态恢复过程中扮演着关键角色^[67]。微生物参与营养元素的循环,促进土壤中有机磷的积累和生物可利用磷的释放^[68],固氮酶将大气中的N₂转化为

植物可利用的氮源^[69],微生物坏死体对土壤有机碳的贡献可达50%~80%,是土壤生物和植物生长的重要营养和能量来源,利于维持生态系统健康^[70]。

有机质贫瘠的高寒土壤中,一些细菌和真菌通过分解植物和动物有机残体,加速有机质的循环和再利用,形成富含腐殖质的土壤层,促进植物根系对营养的吸收利用^[71]。微生物菌株通过分泌有机酸,如乙酸、柠檬酸和琥珀酸等,降低土壤pH值,促进磷、铁、锌等微量元素的溶解和吸收,提高其在土壤中的有效性^[72]。一些特殊的微生物群落能够在低温和高辐射等极端环境条件下,有效地进行代谢繁殖,促进养分的生物可利用性,对高寒土壤的生物多样性和生态系统功能具有重要影响。此外,以细菌、蓝藻为主的微生物通过菌丝体和分泌物与表层土壤颗粒胶结形成生物结皮,具有增加土壤团聚性和表面粗糙程度、改善土壤肥力以及影响土壤水循环等功能。微生物分泌胞外聚合物(EPS)作为生物结合剂,可增加土壤水稳性团聚体含量、团聚体的几何平均直径和平均质量直径,从而改善土壤的孔隙率和通透性,增强土壤的水分保持能力和抗侵蚀能力^[73-74]。细菌和真菌黏附在硅酸盐黏土矿物、铁铝锰氧化物等土壤矿物表面并形成生物膜,通过风化作用改变矿物性质,创造有利于微团聚体形成的条件^[75]。

2.4 微生物对边坡植物的影响

实际工程中,由于土壤基材缺乏有机质和微生物,肥力持续性低,缺乏自我更新和营养补偿的能力,后期将导致土壤愈发贫瘠,植物群落退化甚至死亡。土壤微生物能够通过提供养分、促进植物根系生长和帮助植物抵抗病害来促进边坡植物的生长^[76]。同时,植被可通过产生凋落物和根系分泌物直接影响土壤微生物群落的结构及多样性^[77]。植物根际促生菌(PGPR)通过调节生长素、细胞分裂素和赤霉素等植物激素的产生和分布促进根系发育^[78],或改变土壤中某些无效元素的形态,使之有效化而利于植物吸收。SUN等^[79]研究植物根际双菌菌群的互养合作关系发现,根际益生芽孢杆菌SQR9与施氏假单胞菌能代谢互养,联盟促进了植物生长并帮助水稻缓解盐分胁迫。在高寒高海拔地区,为应对紫外线辐射、低温或重金属污染等生理挑战,细菌会产生胞外多糖并将其释放到环境中,以保护细菌免受环境变化的影响^[80],并提供抗氧化剂和营养物质以帮助植物生长。近年来,具有固氮、溶磷、解钾、分泌抗生素和产生植物激素

等多种功能的微生物菌株,已成为新型生物肥料开发应用的热点。施用微生物肥料能显著提高马缨丹、野牡丹和紫荆等边坡植物的光合速率和根长密度。香根草在极端酷冷的条件下仍能存活,且生长旺盛,对高寒高海拔地区控制边坡水土流失与滑坡以及边坡的绿化、美化等起到一定作用。但在边坡生态恢复早期阶段,土壤细菌会与植被竞争吸收无机氮,降低土壤中植被可直接利用的有效氮含量,限制植被生长发育^[81]。因此,在边坡生态恢复过程中应注重施加硝态氮肥,以缓解土壤氮素竞争,促进植被稳定生长,提高边坡生态系统的长期稳定性。

3 边坡土壤生境调控技术

土壤是边坡植被生长的基础,在困难立地条件下,借助人造措施来调控边坡植物生长的土壤环境对于公路边坡的生态防护至关重要。高寒高海拔地区存在土壤侵蚀和滑坡等地质灾害风险,植被覆盖是控制泥沙和降低土壤侵蚀速率的最有效方法^[82],改良土壤理化性质、营造良好的土壤结构是边坡植被重建的前提条件^[83]。高速公路建设过程产生的表层土壤中含有丰富的本土植物种子和微生物资源^[84],将其作为主要外土基质进行边坡喷播绿化,可有效提高边坡的植被覆盖率。在高寒高海拔地区,土壤的保水性可以减轻干旱条件下植物的水分胁迫,而保肥性则有助于提供植物所需的养分。葛高岭等^[85]采取土壤改良及多物种配植生态修复技术,对气候寒冷、土壤荒漠化、保水能力差的祁连山区实现裸露地面复绿,促进高寒湿地人工植被逐步向自然植被演替。李春林等^[86]采用团粒喷播技术,对拉萨空港新区风积沙地进行基质覆盖和植物引入,实现了高寒高海拔地区沙化土壤有机质、碱解氮、速效磷、有效钾养分含量的改良。在贫瘠的土壤中施用有机改良剂,也可以提高土壤的长期肥力,增加原生物质的矿化^[87]。研究表明,狗牙根和香根草能显著提高根土复合体的黏聚力,降低坡面径流速率和产沙速率,具有很好的固土护坡效果^[88]。随着海拔高度升高,土壤中有效养分含量以及酶活性先上升后下降,而土壤团聚体的结构却趋于稳定^[89]。因此,适当的土壤管理和保护措施以及合理的植物覆盖可以减少土壤侵蚀,维护土壤的生态功能,从而降低路堤边坡的地质灾害风险。

针对高寒高海拔地区植被生长周期长、土壤覆盖面积难以维持的问题,土壤-微生物联合技术的引入为生态防护提供了新的途径。土壤生物工程技

术,例如扦插、层栽、灌丛垫和梢捆等,采用存活植物及其他辅助材料来构筑边坡结构,能够增强公路边坡的稳定性和生物多样性,降低水土流失的风险^[90]。微生物修复技术则利用特定微生物的活性来促进土壤的固结和植被的生长,提高土壤的抗侵蚀能力,成为改善土壤质地和结构的有效途径。例如,微生物诱导碳酸钙沉淀(MICP)技术已被应用于提高不同土体的工程特性,通过微生物固结来降低土体渗透性和控制土壤侵蚀^[91]。ZHANG等^[92]提出由排水系统、土壤改良、植被保护和加固工程组成的DIGR体系,对黄土高原沟壑区的人工坡地有较好的防治效果。杨正启等^[93]针对西藏岩石、碎石土坡面等绿化困难的特殊地带,设计CBS植被混凝土生态护坡技术,将生态剂加入土壤基材中,固持基材养分和水分、促发芽助成活、提升基材冻融特性,达到恢复自然生态环境和美化景观的目的。郭富强等^[94]证实了岩石-土壤-植物-微生物四位一体的边坡生态修复技术在大煤山矿区的有效性,通过改善土壤物理化学性质和微生物环境,显著促进了植被覆盖率和矿山边坡生态恢复。

4 结论与展望

边坡生态防护是一项长期、系统性的工程,笔者从多方面综合分析高寒高海拔地区土壤生境及其微生物对植被恢复和生态防护的贡献,表明特殊环境条件对土壤结构和功能产生显著影响,土壤微生物通过参与碳氮磷循环、分泌胞外聚合物和分解有机残体等过程,对维持土壤稳定和促进植物生长具有不可替代的作用。边坡土壤生境调控技术通过改良土壤理化性质、利用土壤-微生物联合的新兴方法,能有效提高植被覆盖率和边坡稳定性。

面对气候变化和人类活动带来的多重挑战,未来研究应更深入地探讨土壤与微生物之间的相互作用机制,并开发适应高寒高海拔环境的微生物制剂,以提高土壤肥力和土壤稳定性,增强植被生长能力。同时,随着全球变暖对高寒地区的影响加剧,需要考虑生态防护技术的可持续性和适应性,加强实地案例研究和长期生态效应监测,评估和优化现有技术,确保其在不断变化的环境条件下的有效性。通过整合土壤与微生物因素,采用系统化的方法对高寒高海拔地区的边坡进行生态防护,为生态脆弱地区提供更有效、更持久的恢复策略,为高寒高海拔地区的生态保护和可持续发展提供更全面的策略和解决方案。

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