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城市夜间人造光污染对环境微生物组的影响初探

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摘要:光影响微生物代谢及其与环境和其他生物的相互作用,进而影响不同环境中微生物分布及多样性。然而,随着城市化进程的加剧,灯光污染问题日益严重,给生物体带来了不利影响。光对于某些微生物的生存是必需的,但是夜间人造光(Artificial Light at Night, ALAN)打破了自然的昼夜节律,将通过多种途径显著干扰微生物的自然行为和生态平衡,进而影响微生物的群落和功能。这种影响可能会对城市生态系统的健康和功能产生深远的后果,最终威胁到人类健康。因此,本综述重点关注城市灯光,系统阐述了灯光对城市不同生境下微生物的影响,同时讨论了夜间人造光驱动的生态功能变化及其潜在危害,并探讨了人造光在生态修复中的应用。综述最后提出了夜间人造光对城市微生物影响研究的重点关注方向,为城市灯光规划和环境质量提升提供了科学的理论依据。
关键词:光污染;城市微生物;群落分布;功能影响

An initial exploration of the impact of urban nighttime artificial light pollution on the environmental microbiome

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Abstract: Light significantly shapes microbial metabolism and their interactions with environments and other organisms, and thereby affecting microbial community compositions and diversity in different ecosystems. The pollution of light in urban areas would increase with urban intensification and adversely influence biological entities. Though light is essential for certain microorganisms, artificial light at night (ALAN) disrupts natural circadian rhythms and profoundly alters microbial behaviors and ecological balances through various pathways, ultimately reshaping microbial communities and functions in urban ecosystems. Such disruptions may trigger cascading consequences for urban ecosystem health and functionality, posing threats to human beings. This review focused on ALAN pollution in urban areas, systematically elucidating its impacts on microbial dynamics across diverse urban habitats such as soil, water, and air. Additionally, this paper investigated the changes of microbial ecosystem functions and potential health risks associated with ALAN, and discussed the application of ALAN in ecological restoration. At last, this review prospected the important research fields about ALAN, including the mechanism of ALAN impacts on urban microbiome and their functions, and the influences of ALAN on human health. The review would offer theoretical basis for city light planning, improvement of environmental quality, and ensuring human health.

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Key Words: light pollution at night; urban microorganisms; community distribution; functional impacts

城市微生物是指在城市环境中生活和繁衍的微生物群体,包括细菌、真菌、病毒、原生动物和藻类等,广泛分布于不同环境中,如空气、土壤、水体、沉积物及植物等[1—4]。这些微生物在维持城市生态系统健康、促进物质循环、降解污染物、增强生物多样性及调节生态平衡方面发挥着关键作用,同时也能通过影响人类居住环境和人体微生物的组成和多样性对人体健康产生影响。例如,城市化进程中,环境微生物多样性的减少可能会导致人类微生物失衡,引发过敏性炎症和其他相关疾病[5]。研究发现,城市空气微生物多样性降低是儿童哮喘发生频率增加的重要原因[6]。此外,在 2012 年至 2019 年期间中国太原市室内微生物组发生显著变化,其中普雷沃氏菌属(*Prevotella*)对鼻炎症状具有较好保护性[7]。城市叶际、根系微生物如磷酸盐溶解微生物在提高植被覆盖率、增强植物抗性、改善环境质量、缓解热岛效应和恢复受污染地区(例如棕地)的生态环境和生物多样性等城市绿化领域发挥着重要作用[8]。城市土壤微生物在缓解土壤污染、调控碳氮循环和改善土壤环境中扮演着至关重要的角色[9]。城市土壤生物多样性(包括细菌、真菌、原生动物和无脊椎动物的多样性)与包括生态系统多功能性、生态系统功能的多个阈值、生态系统功能的多个维度以及关键的生态系统服务的生态系统功能呈显著正相关关系[10]。

光通过影响微生物代谢及其与环境和其他生物的相互作用进而影响微生物在不同环境中分布及多样性。它不仅是光合微生物进行能量转换和生长的基础,还在非光合微生物的生态适应和生理活动中发挥重要作用。例如,在地球早期历史中,原核生物中光合作用的出现从根本上改变了大气成分,并深刻影响了生物的进化进程[11]。然而,城市环境中人工光源,尤其是 ALAN 的广泛使用和污染,严重打破了自然的昼夜节律,对城市微生物的影响尤为显著,并对人类健康构成威胁[12]。研究表明,光污染干扰了微生物的生物钟和代谢活性,导致其种群数量波动,成为影响城市土壤中细菌、真菌和原生生物群落结构的重要因素[13]。王志辉等人的研究显示,ALAN 暴露会减少草地植物叶际微生物多样性,并抑制其功能,同时降低真菌病原体发生几率[14]。此外,不同波长的光对微生物的作用也各不相同,可能产生生物抑制或者生物刺激的效果[15]。

综上所述,ALAN 将通过多种途径显著干扰城市微生物的自然行为和生态平衡,进而对城市微生物分布、多样性、群落组成及其活性产生影响。这些影响可能会对城市生态系统的健康和功能产生深远的后果(图 1)。因此,本综述聚焦于城市灯光,系统阐述了灯光对城市微生物群落结构及活性的影响及其影响途径。同时,讨论了 ALAN 驱动的生态功能变化及潜在危害,并探讨了其在生态修复中的应用。最后,本文对光与城市微生物的研究方向提出了展望,旨在为城市灯光规划及环境质量提升提供科学的理论依据。

1 全球视角下的 ALAN 污染研究进展

ALAN 污染即人工光源在夜间产生的过量、不合理光照,严重干扰自然光照周期与强度分布。主要源于城市照明(路灯、景观照明)、交通设施(汽车灯、信号灯)、工业照明以及商业广告照明等。研究表明,从 2012 年至 2016 年,全球人工照明覆盖的户外区域年均增长率达到了 2.2%[16]。截至 2016 年,全球超过 80%的人口以及超过 99%的美国和欧洲人口处于光污染影响的夜空之下[17]。此外,在全球范围内,基于地面视觉估计的夜空亮度指标从 2011 年至 2022 年的年均增长率约为 10%[18]。Ye 等通过结合夜间遥感影像、城市大数据等多源异构数据,系统研究了杭州中心城区夜间光照状态,发现研究区域的 ALAN 强度和面积在过去十年中分别增加了 82%和 42%[19]。因此,夜间光照环境的管理已成为一个亟待解决的问题。

ALAN 对人类健康具有多种负面影响,其中包括睡眠障碍、肥胖、癌症、心血管疾病、代谢性疾病、认知功能和心理等,目前已成为全球性公共卫生问题[20—23]。当今睡眠不足也是影响人类健康的重要原因之一,先前研究发现,夜间光照每增加 10nW/[cm^2 SR],睡眠不足的风险在县级地区增加 2.19%,在大城市增加 13.77%[24]。一项对来自中国 162 个研究地点的 98658 名参与者的研究表明,在每个性别和年龄类别中均观察到 ALAN 暴露与普遍肥胖的显著关联,尤其是在男性和老年人中,ALAN 每增加 1 个五分位数,男性一般肥

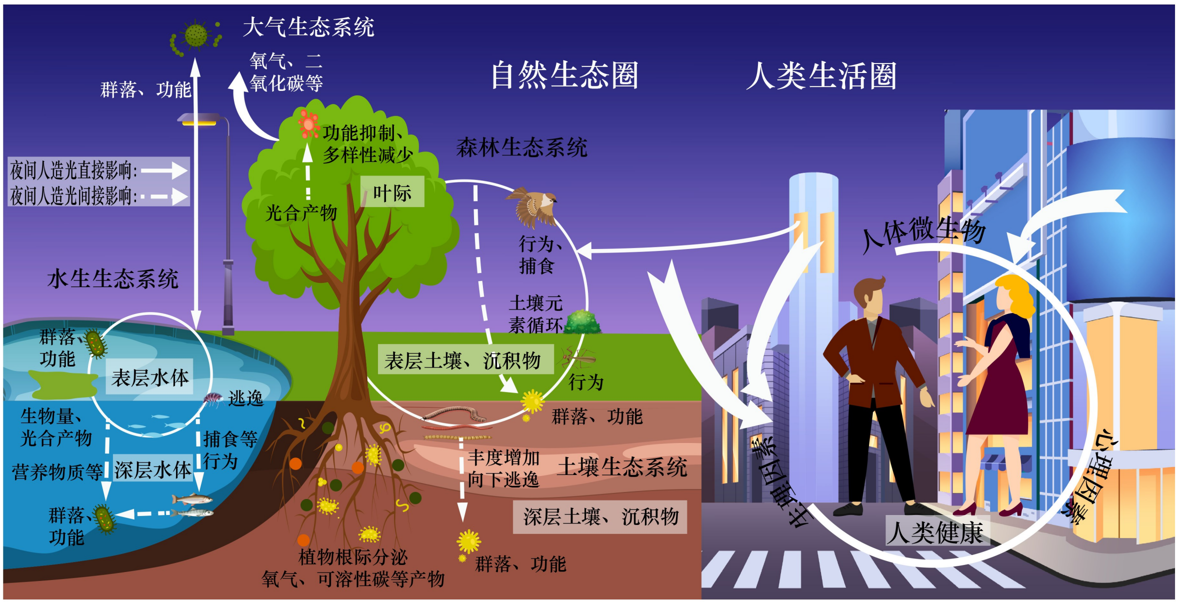

图 1　夜间人造光直接、间接影响微生物示意图

Fig.1　Schematic diagram of direct and indirect effects of artificial light at night on microorganisms

胖的几率增加 14%,60 岁以上的成年人增加≥24%[25]。在美国 464371 名参与者中,Dong 等人发现 ALAN 与甲状腺癌风险之间存在正相关,与 ALAN 的最低五分位数相比,最高的五分位数与风险增加 55%相关[26]。

ALAN 影响几乎所有被研究的物种,干扰物种的生物节律,改变它们与环境的互动。如改变初级生产者的生物量、光合产物;鸟类、鱼类、昆虫等的迁徙、繁殖和捕食行为[27—29]。ALAN 也可以直接干扰微生物的生理和生态过程,还可通过改变其他生物的行为和分布规律来间接影响微生物群落的结构和功能。因此,理解 ALAN 对城市微生物的影响对保护城市生态系统的健康和功能具有重要意义。

2　ALAN 对城市微生物群落及其活性影响

ALAN 作为现代城市生活中不可获取的一部分,将通过不同的途径对城市中不同类型生态系统,如水体、沉积物、土壤、叶际及空气产生深远影响。ALAN 改变这些环境中的微生物群落的组成及活性造成影响。这些影响不仅局限于微生物本身,还可对整个生态系统平衡、功能及稳定性造成一定的威胁,最终影响环境质量和人类健康,值得研究人员关注。

2.1　ALAN 对城市水体微生物的影响

城市河流水体中微生物分布及其群落组成受多种环境因素影响,包括速效钾等营养物质及理化性质。例如,Wang 等人发现蓝细菌、放线菌门和厚壁菌门在水中以及放线菌门和浮游菌门在沉积物中的分布在不同季节间存在显著差异;表层水中细菌存在显著的空间差异[30—31]。ALAN 不仅直接影响微生物的生理活动,还可通过调节溶解氧和营养物质的分布等间接影响微生物群落及其功能。

ALAN 对不同深度水体中微生物的影响方式存在不同。在深层水体中,由于光的衰减,对微生物的影响主要表现为间接影响,即上层生物变化造成的理化性质变化造成下层水体理化变化,进而改变深层水体生物群落及其功能。Ludvigsen 等人发现多数中上层浮游生物群落在 ALAN 存在下表现出强烈光逃逸,然而,在深至 100m 的水体中,ALAN 可能会对以浮游动物为食的鱼类产生影响[28]。当夜间暴露在弱 ALAN 下时,特立尼达孔雀鱼(*Poecilia reticulata*)能够更快地从避难所出来,可改变捕食者与猎物之间的相互作用[32]。研究表明,ALAN 暴露对水体微生物群落结构有明显影响并改变真菌群落结构及其相互关系[33—36];Song 等人通过室内微宇宙实验发现,光能够增加降解难降解有机物的特殊细菌和真菌的生物量,并促进强氧化性物质的

生成[37]。

此外,水生初级生产者的生物量及群落组成也受到 ALAN 的影响。由于人造光的存在,水生初级生产者的生物量将减少,而一些如蓝藻和硅藻等更适合低光照度的生产者可因 ALAN 低光照而受益[27],从而改变水生初级生产者的群落组成。这些 ALAN 引起的变化可能改变水体中营养物质的种类及含量的重新分配,对生物成员包括微生物之间的相互作用产生连锁反应,进一步影响水体生态系统中微生物的群落组成、丰度及功能。

2.2 ALAN 对城市土壤与沉积物微生物群落及其活性影响

ALAN 对土壤与沉积物微生物的直接影响主要集中在表层,包括影响微生物的代谢活动、群落结构以及土壤元素循环[38—40]。朱永官研究团队发现,ALAN 可显著影响城市土壤微生物的群落组成,并通过改变细菌间的互作关系而影响土壤中微生物反硝化潜力[41]。研究表明,ALAN 增加了城市土壤中真菌的系统发育多样性,但同时显著降低了细菌中与甲烷营养和反硝化相关的关键功能基因相对丰度[13]。另一项研究的研究者发现两种深度土壤中的细菌多样性在 UV-B 辐射下明显下降,且增强的 UV-B 辐射显著改变了可培养细菌群落组成以及土壤微生物的总体活性[42]。Franz Hölker 通过田间和实验室实验发现,与未接受 ALAN 的沉积物相比,ALAN 暴露的沉积物中光合自养生物(如硅藻、蓝藻)的丰度显著增加。此外,在长期 ALAN 暴露的夏季沉积物中,生态系统的净产量经历了从负向正的转变,这表明 ALAN 可能对沉积物微生物群落的结构和功能产生了深远影响[43]。

森林、地底等低透光性环境中,ALAN 通过影响动植物的行为和分布,间接影响微生物的途径更为广泛。例如,ALAN 暴露的森林雌性大山雀在活动开始时间上有所提前[44],而繁殖季节夜间高强度 ALAN 导致雨燕(Apus apus)整夜活跃,代替了在巢中栖息的行为[29]。这种变化可能导致鸟粪沉积的增加,从而导致土壤酸化、富营养化和盐碱化,进而提高城市森林土壤中病原真菌丰度,减少与亚硝酸盐氧化、硝酸盐还原和纤维素分解相关的细菌、以及内生和腐生真菌群落的丰度,最终降低有机物分解速度和植物对疾病的抵抗力[45]。在一个高度控制的 Ecotron 设施中进行的实验表明,夜间 ALAN 的增加将降低植物生物量达到峰值期间植物生物量与土壤呼吸,同时导致植物食性线虫的丰度增加,出现线虫群落均质化,且微生物表现出更高的碳利用效率[46]。

2.3 ALAN 对城市叶际微生物群落及其活性影响

叶际是指植物地上部分的表面,包括叶片、茎和果实等,是微生物群落重要的栖息地。叶际微生物对植物健康和生态系统元素循环及稳定具有重要作用[47]。Wang 等人对三种草地植物(L.chinensis、V.sepium 和 A.altaicus)叶际微生物的研究中发现,ALAN 暴露降低了植物叶际细菌和真菌的多样性。ALAN 减少了细菌群落中包括三羧酸循环、脂肪酸降解、氧化磷酸化、类固醇激素生物合成等关键代谢途径功能基因的丰度,降低了如鞘氨醇单胞菌属(*Sphingomonas*)等有益功能细菌的丰度,使叶状微生物网络结构变得更加脆弱;降低了如发酵壳针孢属(*Zymoseptoria*)等致病真菌的丰度,可能减少植物真菌病害的发生[14]。另外研究表明,长时间的光照暴露将抑制植物白粉病[48]、镰刀菌[49]和灰霉病[50]等病害的发生,有利植物生长和健康。

ALAN 也可通过改变植物生理,如光合作用、激素水平、叶片形态和化学组成进而间接影响叶际微生物群落。Alsanius 等人对温室种植的向日葵进行白色 LED、红蓝 LED 和高压钠灯三种灯光处理发现,不同光处理影响叶际真菌群落物种丰度和均匀度,红蓝 LED 处理下子囊菌门(*Ascomycota*)相对丰度低于白色 LED 处理,担子菌门(*Basidiomycota*)相对丰度与其他处理有差异;不同灯光处理对细菌群落多样性影响不显著。叶位和光源差异造成的叶温等因素会影响细菌群落组成[51]。对置于低、中、高三种不同光强下培养的生菜(Lactuca sativa L.),研究发现光强度导致叶状圈中原核生物群落(细菌和古细菌)的分类组成发生显著变化,并改变了生菜叶片所有测定的代谢物组[52]。

2.4 ALAN 对城市空气微生物群落及其活性影响

城市空气颗粒物中携带的微生物与土壤、水体、植物以及人体微生物之间存在着复杂的联系。这些微生

物通过定殖于人体皮肤、黏膜和呼吸系统,可引起各种疾病,包括细菌感染、过敏反应、心血管疾病等。例如,栗利娟等人研究发现,厦门空气灰尘中检测到了大量的高风险抗生素耐药基因,且在冬季和城市幼儿园中这些基因的丰度高于夏季和城郊幼儿园[6]。*Firmicutes* 和 *Proteobacteria* 是城市空气中占主导地位的微生物门类,空气微生物群落及其中致病微生物的丰度受多种因素影响[53]。目前,关于 ALAN 对空气微生物群落及健康风险的研究较少,主要集中于在特定 ALAN 光源对空气微生物的消杀作用以及空气净化方面。比如,竹涛等人的研究表明,波长在 200—230nm 的紫外线不仅会对空气中微生物 DNA 造成损伤,还会影响其蛋白质,并且这种损伤受微生物的重新激活机制影响较小[54]。许多研究采用 TiO_2 或其衍生材料作为光催化剂,利用紫外线对空气中的室内污染物进行光降解,以消除挥发性有机化合物(VOC)和病毒[55]。然而,日常 ALAN 对空气微生物群落动态变化、群落组成及其相应的影响机制尚不明确。深入解析 ALAN 对空气微生物及其健康风险的影响,对城市灯光管理及城市规划具有重要意义,同时能够为改善空气质量和保护人类健康提供重要的科学依据。

3　ALAN 影响微生物的途径

ALAN 将通过直接和间接的途径对城市生态系统中微生物群落组成、多样性及其活性产生显著影响。直接作用方面,ALAN 能够改变微生物的生长环境,如通过影响光照强度、光周期等参数,影响微生物的光合作用、代谢活动和沉降模式,从而调控其种群数量和群落结构。间接影响方面,光污染可影响城市生态系统中的其他生物及非生物因子,例如植物的光周期感知、光合作用及蒸腾作用和动物的昼夜节律,水体和土壤理化性质等,这些变化会进一步影响微生物的生存环境,进而改变微生物群落组成和活性。

3.1　ALAN 对微生物的直接影响

光对微生物的直接影响是多方面的,包括对其生长、形态建成、代谢产物合成以及生理周期等的调控。昼夜节律是所有真核生物及部分原核生物生理过程的基本特性之一。由于地球的自转和公转,产生了昼夜与季节的光周期性变化,陆地生命体为了在 24 小时内优化生理功能,进化出内源性的分子生物钟,使其行为、生物和代谢节律与外界环境线索同步,以适应光周期性[56]。因此,光周期的变化,如夜间人造光污染增加了光照时间,将会显著影响微生物的生物钟,从而改变其生理活动和代谢过程。

微生物通过特定的光感受器(Photoreceptors)感知环境中的光信号。光感受器是一类能够吸收光并将其转化为化学信号的蛋白质。不同类型的微生物拥有不同种类的光感受器(表 1),它们对光的强度、波长等都具有不同的响应,在调控微生物光响应机制中发挥着关键作用。

光感受器直接影响微生物的趋光性,使其能够向适宜的光环境移动,以满足生长和代谢所需[103],或促使细菌远离过高的光强或短波长的紫外线(UV)辐射等不利光环境,从而避免光毒性或者其他损伤[104]。Monize 等人研究了 450nm、520nm 和 630nm 三种不同波长的可见光对多食棘阿米巴、白色念珠菌、分枝杆菌、铜绿假单胞菌和金黄色葡萄球菌的影响。结果显示,不同波长的光对微生物产生了生物抑制或生物刺激的效果,具体表现因微生物种类而异[15]。此外,陈思羽等人研究发现,在丝状真菌 *Podospora anserin*a 中,光敏色素基因 PaPhy1 和 PaPhy2 在有性生殖和无性发育中发挥作用[105],将影响该真菌在环境中分布及丰度。

3.2　ALAN 对微生物的间接影响

光不仅能直接作用于微生物,影响其生理活动,还可以通过一系列的间接途径对微生物的生长节律和生长发育等生命活动产生影响。这些途径主要包括:光合产物的分配、环境温度的变化、根际微生物与植物根系的相互作用以及物种间的相互作用关系等。

3.2.1　ALAN 影响植物光合产物及动物的组成及分配

ALAN 影响植物光合作用,导致植物分泌物种类和数量发生改变,水下人工光源可以促进沉水植物刺苦草(Vallisneria spinulosa Yan)根系如磷酸盐、山嵛酸和乙醇酸等代谢分泌物的释放,增加孢子菌科(*Sporomusaceae*)和梭状芽胞杆菌科(*Clostridiaceae*)细菌在根系周围的积累[106]。在城市环境中,藻类等原生

表 1 拥有不同种类的光感受器的微生物种类

Table 1 Microorganisms with different types of potoreceptors

光敏蛋白质 Photoprotein	发色团 Chromophore	感光性 Phot sensitivity	种类 Type	引用 Reference
细菌色素 Acteriophy Tochrome	线性四吡咯化合物	红光/远红光或近红外线;紫外线 A 到近红外线	*Acaryochloris marina*;*Agrobacterium fabrum*; *Agrobacterium tumefaciens*;*Anabaena sp*; *Azospirillum brasilense Sp*7; *Bradyrhizobium japonicum*; *Bradyrhizobium sp. strain*;*Croceicoccus marinus OT*19; *Deinococcus radiodurans*;*Fremyella diplosiphon*; *Magnetospirillum magneticum*;*Pseudomonas aeruginosa*; *Pseudomonas syringae pv syringae B*728*a*; *Pseudomonas syringae pv tomato DC*3000; *Rhodopseudomonas palustris*;*Rhodobacter sphaeroides*; *Synechocystis sp. PCC* 6803; *Thermosynechococcus elongatus BP*-1; *Xanthomonas campestris*;	[57—68]
光氧电压结构域 Light-Oxygen-Voltage Sensing Domain	黄素单核苷酸	蓝色光	*Bacillus subtilis*;*Botrytis cinerea*; *Brucella abortus*;*Brucella melitensis*; *Caulobacter crescentus*;*Dinoroseobacter shibae*; *Erythrobacter litoralis*;*Listeria monocytogenes*; *Methylocystis*;*Phaeodactylum tricornutum*; *Pseudomonas mendocina*;*Pseudomonas putida*; *Pseudomonas syringae pv Syringae*; *Rhizobium leguminosarum*;*Rhodobacter sphaeroides*; *Synechococcus elongatus*;*Xanthomonas citri subsp. Citri*;	[69—84]
蓝光利用黄素 Blue Light Using Flavin	黄素腺嘌呤二核苷酸	蓝色光	*Acinetobacter baumannii*;*Acinetobacter nosocomialis*; *Beggiatoa sp.*;*Escherichia coli*; *Euglena gracilis*;*Klebsiella pneumonia*; *Oscillatoria acuminata*;*Rhodobacter sphaeroides*; *Rhodopseudomonas palustris*;*Synechocystis sp. PCC* 6803; *Xanthomonas citri subsp. Citri*;	[79, 85—90]
光活性黄色蛋白 Photoactive Yellow Protein	对香豆酸	蓝色光	*Burkholderia phytofirmans*;*Chromatium salexigens*; *Halochromatium salexigens*;*Halorhodospira halophila*; *Idiomarina loihiensis*;*Rhodobacter capsulatus*; *Rhodobacter sphaeroides*;*Rhodopseudomonas palustris*; *Rhodospirillum centenum*;*Rhodospirillum salexigens*; *Rhodocista centenaria*;*Rhodothalassium salexigens*; *Salinibacter ruber*;*Stigmatella aurantiaca*; *Thermochromatium tepidum*;	[91—94]
视紫红质 Rhodopsin	视网膜素	绿色光/橙色光	*Acetabularia acetabulum*;*Anabaena sp. PCC* 7120; *Candidatus Actinomarina minuta*; *Candidatus Pelagibacter ubique HTCC*1062; *Coccomyxa subellipsoidea*;*Dokdonia donghaensis*; *Exiguobacterium sibiricum*;*Gloeobacter violaceus*; *Haloarcula argentinensis*;*Haloarcula vallismortis*; *Halobacterium sp. AUS*-2;*Haloquadratum walsbyi*; *Halorhodospira halophila*;*Halorubrum chaoviator*; *Halorubrum sadomense*;*Haloterrigena thermotolerans*; *Leptosphaeria maculans*;*Nonlabens marinus S*1-08; *Oxyrrhis marina*;*Phaeosphaeria nodorum*; *Photobacterium sp. LC*1-200;*Salinibacter ruber*; *Thermus thermophilus*;*Uncultured bacterium HOT* 75*m*4; *Uncultured bacterium Med*12;*Vibrio sp. AND*4;	[95—97]
隐花色素 Cryptochrome	黄素腺嘌呤二核苷酸	紫外线/蓝色光	*Arabidopsis thaliana*;*Chlamydomonas reinhardtii*; *Drosophila melanogaster*;*Gloeobacter violaceus*; *Phaeodactylum tricornutum*;*Synechocystis sp. PCC* 6803;	[98—102]

生物在 ALAN 的作用下,其光合作用可能会延长,使生物量、色素含量及葡萄糖等光合产物的增加[107—110]。ALAN 可诱导共生体中光合作用光抑制,引起珊瑚物种的脂质氧化损伤,最终导致光合作用速率降低[111]。植物分泌物可作为碳源等成为叶际微生物等环境微生物营养物质,影响环境微生物多样性及群落组成。植物分泌物丰富时,微生物的呼吸作用和酶活性都会相应提高,从而促进其生长。在土壤中,增加碳源可以提高微生物的生物量,不同的碳源会导致微生物群落结构和组成的显著变化[112—113]。在反硝化系统中,使用不同的碳源(如甲醇、甘油、乙酸和葡萄糖)会导致微生物调整为不同的代谢模式和生态结构[114]。另外,持续的 ALAN 会抑制植物的光合作用和呼吸作用,破坏其叶片在白天的碳平衡模式;在高 ALAN 条件下,植物的生物量与土壤含水量降低,可提高微生物的碳利用效率[46,115]。

ALAN 会对城市生态系统中的动物在不同维度产生影响。ALAN 增强将增加植物性线虫的丰度,提高线虫群落的均一性[46]。此外,线虫、飞蛾、萤火虫、蚜虫、毛毛虫等昆虫行为、群落丰度均受 ALAN 的影响,进而改变植物的光合作用产物分配和植物残体的输入量以及对微生物的直接捕食压力,最终影响微生物的食物来源和群落结构[116—118]。鸟类是受 ALAN 影响较大的生物,ALAN 会改变鸟类在城市环境中分布的种类和数量[119]。鸟类粪便中存在大量的微生物,鸟类数量和种类的改变将影响其肠道微生物向环境微生物的释放,进而导致不同 ALAN 城市区域环境微生物群落组成及多样性发生改变[120]。

3.2.2　ALAN 影响生态系统温度

ALAN 将改变不同环境生态系统的温度,比如提高空气、水体及土壤温度[121]。由于温度是调节微生物生长和代谢的关键因素,温度的升高或降低会直接影响微生物的酶活性、细胞分裂速度以及整体代谢速率,从而对其生命活动产生显著影响[122]。雷骋昊等人的研究表明,增温对杉木人工林土壤中微生物呼吸和代谢熵产生了显著影响;随着温度升高,微生物生物量碳在 8 月份和 12 月份别降低了 32.1% 和 59.8%,说明温度变化直接影响了土壤微生物的生物量和代谢活性[123]。此外,V.Vasenev 等人在莫斯科的研究中发现,城市升温使土壤微生物呼吸作用平均增加了 5%——10%,最高可达 25%[124]。因此 ALAN 介导的系统温度上升可能对不同生态系统中微生物多样性、群落组成及功能造成一定影响。理解 ALAN 介导的温度变化对城市微生物的影响,对预测和缓解城市化对生态系统功能的潜在影响至关重要。

3.2.3　ALAN 影响生物物种间的互作关系

光周期作为调节光合作用和根际微生物活动的关键因素,对城市生态系统中的微生物群落产生了深远影响。城市环境中的 ALAN 通过增加自然光周期,对根际微生物群落的组成和功能活性将产生显著影响。研究显示,不同的光周期对人工湿地中污染物的去除效果有显著差异。较长光周期可以增强光合色素的沉积和植物根系活性,从而增加氧气和可溶性有机碳向根际输送,促进根际微生物的硝化和反硝化过程[125]。徐建明团队通过对比正常光照节律和完全黑暗条件下水稻根际活性微生物群落的研究发现,组别间存在不同的昼夜节律的分类群,光照诱导水稻根际产生的氧气和可溶性有机碳增加塑造根际微生物群落昼夜节律的关键驱动因素。此外,研究还观察到,光照显著增加了根际环境物种的生态位重叠程度,进而改变了根际微生物的共存模式[126]。Christina Diamantopoulou 等人的研究表明,绿色(525nm)、红色(624nm)和广谱白色 LED 光源的 ALAN 对绿色微藻和硅藻组合的影响具有波长依赖性。研究发现,所有测试的 ALAN 波长都对微藻和硅藻组合生物量和多样性产生了影响,其中红色和绿色 ALAN 的影响最为显著,导致了整体丰度的增加,并选择性富集了特定硅藻物种[127],改变了体系中微藻与硅藻的互作关系。由此可见,城市 ALAN 可以通过影响生物物种间的互作关系,改变微生物群落及其功能,进而影响整个城市生态系统的功能和稳定性。

3.3　ALAN 对城市不同类群微生物群落结构及功能的影响。

ALAN 显著影响城市环境中细菌的生理活动、代谢途径及群落结构,比如降低城市土壤中参与甲烷代谢和反硝化过程的功能细菌丰度[13,41];研究表明,ALAN 将影响城市叶际微生物参与三羧酸循环等生物合成过程[14],降低细菌丰度和均匀度[51]。另外,ALAN 可增加水体中降解难降解有机物的细菌生物量,减轻水生生态系统中铬、铅、纳米银颗粒对叶片凋落物分解的负面影响,进而改变水体细菌群落组成[33—35]。

ALAN 对不同城市环境中真菌群落物种丰度和均匀度影响不一,比如其可降低草地植物叶际真菌丰度[14],但增加了城市土壤真菌系统发育多样性[13]。另外,光的波长不同对不同真菌产生的抑制或刺激作用,将影响其群落物种丰度和均匀度[15]。ALAN 可通过改变水体中营养物质种类及含量等,进而影响真菌间、真菌与其他物种间的相互作用,从而影响水体生态系统中真菌群落组成、丰度及功能[33—36]。

ALAN 干扰原生生物的光感受机制,改变其生物节律和代谢活动,进而影响其种群数量和结构。ALAN 延长光照时间,干扰衣藻、硅藻等单细胞藻类和草履虫、太阳虫等原生动物的昼夜节律,影响其生理活动和代谢过程[103,128—129]。此外,ALAN 可改变原生生物所在生境的溶解氧和营养物质分布,并通过改变捕食者与被捕食者之间的作用关系,间接影响原生生物群落[32,107—108]。

ALAN 影响环境中病毒群落及功能的相关研究较少。研究发现,ALAN 将增加鸟类中西尼罗河病毒抗病毒反应基因的转录丰度[130]。目前,大部分研究主要集中于紫外线和蓝光等人造光在病毒的灭活和消毒方面的应用潜力[131—132]。ALAN 对城市环境中病毒群落多样性及组成的影响仍十分缺乏。深入探究 ALAN 对城市病毒组成的影响,解析其中的影响机制,对保护环境及保障人类健康具有重要意义。

4 人造光驱动的微生物在生态修复中的应用

光对生态系统的影响是复杂且多面的:一方面,人造光可导致微生物多样性下降和生态功能受损,导致生态系统稳定性下降;另一方面,通过特定波长的光源调控有益微生物生长等技术,为生态修复提供了新的思路。

在植物工厂和智能温室中,人造光被广泛应用于提供适宜的环境条件,以提高作物的产量和质量。近年来,光合微生物在生态修复领域的应用研究也取得了显著进展。采用特定种类的光合细菌降解杀虫剂、重金属、染料、原油和异味等污染物,成为传统污染处理方法的经济有效替代方案[133]。有研究开发了一种新型的光催化—微生物耦合系统,能够在光照条件下同时去除有害藻类和微囊藻毒素,并增强微生物的反硝化作用[134]。另外,深圳大学研究团队也开发了一种结合光催化和生物降解技术(ICPB),该技术结合了光催化反应和微生物处理的优势,显著提高了硝酸盐在低碳条件下的还原率和氮转化效率,为低碳水体硝酸盐的还原提供了新的方法[135]。

光驱动的微生物体系在有机污染土壤修复中也表现出其高效性。例如,通过太阳能电池耦合的新型光驱动系统和天然赤铁矿掺杂的土壤基质,形成的光驱动赤铁矿-微生物协同系统,能够强化有机污染土壤的修复过程[136]。这一系统利用光能驱动微生物加速了有机污染物的降解。另一个土壤修复热点是人造光介导下的植物修复。研究表明,红蓝光组合用于照射 *Noccaea caerulescens*,可以改变植物产生和排出的碳水化合物,从而为土壤中的微生物提供营养,不仅显著增加了土壤脲酶、转化酶和磷酸酶等关键酶的活性,还增强了植物对金属的吸收能力及其抗氧化性,适用于多金属污染土壤的修复[137—138]。Nadine 等通过对不同人工光照处理下的落叶松(Larix decidua)根际微生物分析表明,增加光照强度导致如假单胞菌属(*Pseudomonas sp.*)等一些特定微生物物种的相对丰度发生变化,同时嗜甲烷菌的总体丰度及膜转运和碳水化合物代谢的预测基因在根际土壤中显著增加,进而增强土壤的修复能力[139]。此外,人造光的长期照射可能导致土壤微生物群落的失衡,影响土壤生态系统的稳定性[13]。因此,在生态修复工程中应用人造光时,需综合考虑其对土壤微生物的潜在负面影响,并制定相应的调控策略。

人造光驱动的微生物修复技术在污染水体中的应用已取得显著成效,特别是在城市河流和湿地的修复中。如 Song 等人通过室内微宇宙实验,发现在光和微生物联合降解的条件下,能够增加降解难降解有机质的特殊细菌和真菌的含量,促进水中凋落物的降解[37]。ALAN 暴露可以改变真菌群落结构及其相关性,并增强了 β-葡萄糖苷酶(β-G)活性和微生物生物量的增加,减轻水生生态系统中铬、铅、纳米银颗粒对叶片凋落物分解的负面影响[33—35]。Wang 等研究发现,水下人造光源能增加刺苦草根系和沉积物中如孢子菌科(*Sporomusaceae*)和梭状芽胞杆菌科(*Clostridiaceae*)细菌的积累、蓝藻门(叶绿体和蓝藻)和光合细菌(红杆菌)

在叶际上的附着,及甲基寡养菌科(*Methyloligellaceae*)在水和沉积物中的生长,进而提高刺苦草吸收去除总氮(TN)、铵态氮(NH_4^+)、总磷(TP)和磷酸根(PO_4^{3-})等污染物的效率[106,140]。

尽管已有研究揭示了人造光与微生物生态修复的潜在协同作用,但仍存在一些局限性。首先,现有研究多集中于特定环境或微生物群落,缺乏对不同环境介质和微生物群落的广泛性和长期效应的系统研究。其次,人造光的应用在生态修复中的具体机制尚不完全清楚,特别是在不同光照条件下的表现存在显著差异。未来的研究应重点关注跨环境介质和微生物群落的系统研究,以全面评估人造光对微生物生态的广泛性和长期效应,以及应深入探讨人造光在生态修复中的具体机制,特别是在不同光照条件下的优化应用。

5 展望

5.1 深入研究 ALAN 对城市微生物组成、多样性及功能的影响及其机制

ALAN 对城市生态系统中的微生物多样性和群落构建具有显著影响。然而其影响途径及机制仍十分不清楚,亟需深入探究全球气候变化及城市化过程中 ALAN 对城市生态系统微生物多样性、群落构建和功能性状的影响,并解析其影响途径与机制。将对城市灯光规划及城市建设管理提供重要的科学依据。

5.2 着重 ALAN 对人体健康的影响研究

ALAN 暴露可通过影响环境系统如环境微生物,环境污染物等进而间接影响人类健康。另外,ALAN 暴露与多种人类健康问题直接相关,包括睡眠障碍、昼夜节律紊乱、心血管疾病、代谢问题以及某些癌症的风险。目前关于夜间对人体健康的影响较少,尤其是通过改变环境或者人体微生物、病毒影响人类健康的生物学机制不明。因此,后续研究可专注人类健康,探究 ALAN 暴露影响人类健康的微生物学、病毒学机制及途径,将为相关干预措施的制定及技术开发提供科学依据,为保障人类健康及社会可持续发展提供重要的科学数据支撑。

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