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水上光伏覆盖率对水生态环境的影响机制研究进展

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摘要:通过系统梳理 94 篇关于水上光伏电站对水生态系统影响相关的文献,分析了水上光伏电站对水体非生物要素(水温、溶解氧浓度、营养盐浓度及污染物分布)、水生生物(浮游植物、水生植物、浮游动物、鱼类及鸟类)的影响,认为光伏面板覆盖率是驱动生态效应的核心因子,且水上光伏电站通过光-热耦合胁迫重塑浮游植物群落结构,抑制沉水植物光合作用,改变鱼类代谢节律及鸟类迁徙行为,并触发跨营养级生态级联效应。结合分区布局与材料优化、平衡发电效益与生态保护,提出了水上光伏覆盖率动态调控策略,即水域核心区覆盖率小于 30%,生态缓冲区覆盖率设置为 30%~60%;指出未来需进一步深入解析光热效应与气候变化的叠加响应机制,构建水动力-生态耦合模型,推动水上光伏发电向多能互补、生态协同的可持续模式发展。

关键词:水上光伏电站;水面覆盖率;生态影响;水环境;水生生物

Research progress on impact mechanism of floating photovoltaic coverage ratio on aquatic ecological environment

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Abstract: Through a systematic review of 94 pieces of literature related to the impact of floating photovoltaic power stations on aquatic ecological environments, the effects of such power stations on abiotic factors in water bodies (water temperature, dissolved oxygen concentration, nutrient concentration, and pollutant distribution) and aquatic organisms (phytoplankton, aquatic plants, zooplankton, fishes, and birds) were analyzed. It concludes that the photovoltaic panel coverage ratio is the core factor driving ecological effects. Floating photovoltaic power stations reshape phytoplankton community structures through light-thermal coupled stress, inhibit the photosynthesis of submerged plants, alter fish metabolic rhythms and birds' migration behaviors, and trigger cross-trophic-level ecological cascade effects. By combining zonal layout and material optimization while balancing power generation benefits and ecological protection, a dynamic regulatory strategy for the floating photovoltaic coverage ratio is used: Coverage ratio in core water areas should be less than 30%, while that in ecological buffer zones should be set between 30% and 60%. It also points out the need for future research to further analyze the superimposed response mechanisms of photothermal effects and climate change, construct hydrodynamic-ecological coupling models, and promote the development of floating photovoltaic power generation toward a sustainable model featuring multi-energy complementarity and ecological synergy.

Key words: floating photovoltaic power station; water surface coverage ratio; ecological impact; water environment; aquatic organism

随着能源短缺和传统能源环境污染问题愈加突出,发展清洁能源的需求日益紧迫[1]。世界各国正优先考虑开发太阳能,尤其是太阳能光伏发电技术[2],以减轻能源生产对环境的负面影响[3-4]。水上光伏电站不仅可以有效缓解太阳能需求与土地供应限制之间的紧张关系[5],且比地面光伏平均效能高出 11%[6]。此外,水上光伏有极高的脱碳潜力,在全球范围内每年可减少 4.5 亿 t CO_2 排放[7],同时太阳能光伏面板的铺设可有效减少水体蒸发,平均水面蒸发抑制率达 32.7%[8-9]。

全球水上光伏产业历经三阶段演进:技术验证期(2007—2013 年)、加速发展期(2014—2016 年)、爆发式增长期(2017 年至今),其演化轨迹呈现显著非线性特征。自 2017 年起,全球累计装机容量呈现指数型增

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长趋势[10],至 2019 年末突破 2 GW 阈值[11],预计 2026 年的年装机量将达 4.1 GW[12]。地域分布呈现显著空间异质性,亚洲市场占据全球 67%以上份额并形成极化现象[13],其中中国虽起步较晚但实现了跨越式发展,现已形成全球最大规模水上光伏矩阵(装机总量突破 10 GW 阈值)并主导国际市场[10,14]。从工程维度划分,系统架构包含固定式与漂浮式两类范式,部署环境涵盖淡水与海水基质[15]。功能创新层面,水光互补模式通过水电调峰实现功率平滑输出,有效提升电网消纳能力[16-17];渔光互补系统则构建光伏-水产复合生态系统,通过遮光效应抑制藻类过度繁殖,同步降低蒸发强度,改善水体热力学环境并提升渔业经济收益[18]。目前,水上光伏建设正朝着多能互补、生态协同的第四代能源系统方向迭代演进。

随着水上光伏电站快速发展,其对水生态环境的影响逐渐受到关注。水生态系统作为地球生态环境的核心,由非生物与生物要素紧密交织、相互作用构成。光照、水温、溶解氧等非生物要素是水生生物生存繁衍的基础[19],水上光伏通过减少水体辐照度、降低水体表面风速显著改变水温等非生物指标,进而影响水生生物。在生物层面,水生态系统承载着丰富的生物多样性,其复杂的食物链和食物网依靠各营养级生物维持稳定[20]。浮游植物等微生物贡献着水生系统的初级生产力,水生植物和水生动物在稳定食物网中发挥关键作用。但水上光伏建设会干扰各营养级生物,最终可能破坏食物网结构。目前,水上光伏建设对水生系统影响的研究缺乏系统性,内在机制尚不明确。

本文通过分析 94 篇相关文献,系统梳理和总结水上光伏对水体非生物要素以及水生生物的生物量和物种组成、生物多样性的影响,并指出水上光伏电站对生态环境影响未来需重点关注的问题,以期为我国太阳能资源的合理开发利用以及水生态环境保护提供理论支持与实践指导。

1　水上光伏电站对水体非生物要素的影响

水体的理化性质等非生物要素,如水温、溶解氧、营养盐浓度及污染物分布,是维系水生态系统功能的基础框架。水上光伏电站的覆盖显著改变了这些非生物要素的时空格局,一方面水上光伏面板通过影响入水辐射量,改变水体热量;另一方面,光伏组件材料的环境迁移(如微塑料析出、酚类化合物溶出)存在直接引入新污染物的风险。这些非生物参数的连锁变化,通过光-热-氧-营养盐的级联效应,重塑了水环境的功能边界。

1.1　对水温的影响

水温调控水生态系统的物理、化学和生物过程[21]。水上光伏影响下,水温呈现显著的双峰型特征,表明光伏面板覆盖率对水体热动力特性具有非线性调控效应。当水上光伏电站覆盖率从 0 增至 10%时,表层水温微弱波动被水体较高的热容量(水体热容量为 4.2 kJ/(kg·K))及混合层热惯性有效缓冲[22];当覆盖率突破 10%临界阈值后,系统发生非线性相变,水温呈现先降后升的分段响应特征。迈瓦尔德湖模拟结果也证明[23],在低覆盖率阶段(小于 10%),短波辐射衰减主导冷却效应[24],主要是源于垂向传热抑制及蒸发冷却强化[23,25];当覆盖率超过阈值,长波辐射增强与传导热通量输入协同驱动水温上升,水体热惯性缓冲效应减弱,叠加风驱表层流削弱导致的水体分层加剧,形成热累积正反馈机制[26-27](图 1)。然而,目前针对覆盖率影响阈值的研究仍十分有限,亟须建立基于水-光-气耦合模型的动态监测体系,以精准解析水上光伏电站-水域生态系统的热力学调控阈值及其生态水文耦合机制。

1.2　对溶解氧的影响

溶解氧是水体生化条件改变的敏感指标。水上光伏覆盖率对水体溶解氧含量有着非线性调控机制。Li 等[28]发现,水上光伏覆盖率显著驱动溶解氧含量的倒 U 形变化,当覆盖率为 50%时溶解氧含量最高,主要是由于光伏组件遮蔽短波辐射引发水体冷却。Sánchez 等[29]也发现随着水温降低,溶解氧饱和度增加,冷却效应会通过增强水-气传质系数促进氧气扩散[30]。然而,覆盖率超过 50%时,受水上光伏遮蔽影响,水生系统光合作用和呼吸作用平衡被打破,短波辐射透过率骤降,导致光合作用速率与呼吸作用速率显著失衡,形成氧亏效应[30-31],溶解氧含量转而下降。同时,施工期沉积物再悬浮使水体浊度上升,湍流系数衰减和化学需氧量提升,导致溶解氧含量下降[32]。因此,为降低生态影响,低覆盖率区(<30%)可采用高透光的晶硅组件,而中高覆盖率区可以配置浮式曝气系统与藻类竞争抑制剂。此外,未来可针对不同区域特点,确定不同最优覆盖率,使资源开发与生态环境保护协同发展。

1.3　对富营养化状况的影响

氮、磷是造成水体富营养化的决定因素[33-34]。研究表明,覆盖率显著驱动水体总磷(TP)浓度呈现双峰

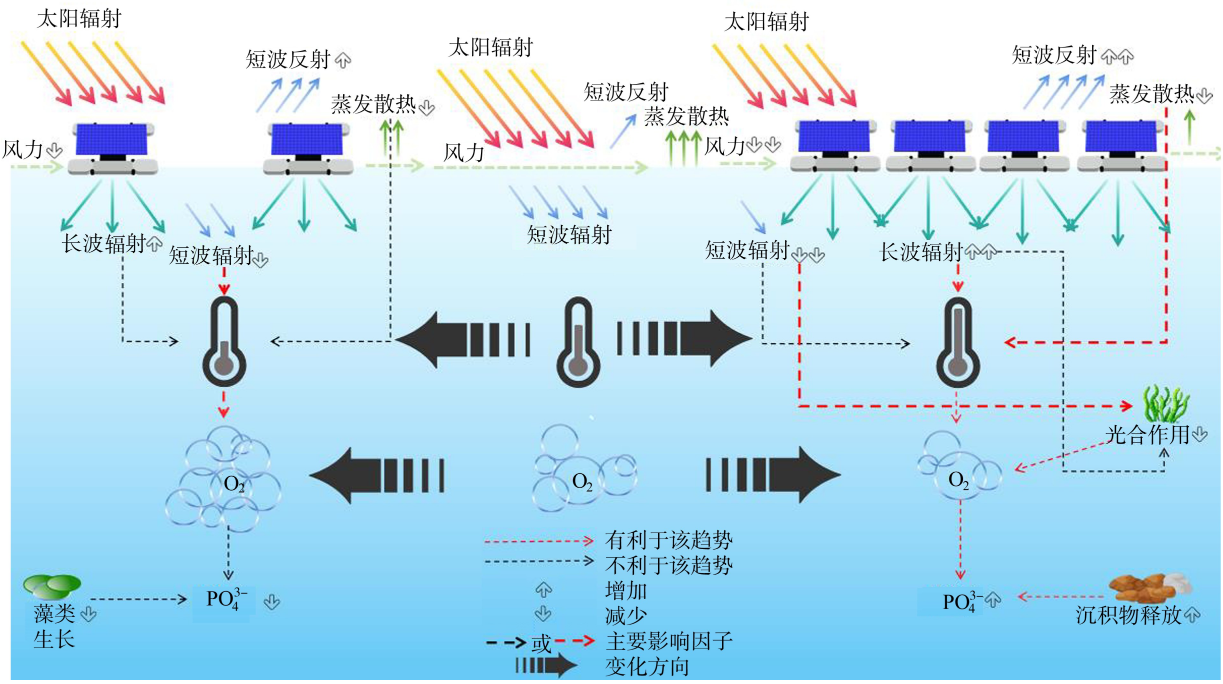

图1 水上光伏电站对水温、溶解氧、磷酸盐的影响

Fig. 1 Effect of floating photovoltaic power station on water temperature, dissolved oxygen, and phosphate

响应特征,当光伏覆盖率增至50%时,正磷酸盐浓度先下降11.65%后回升至初始水平[35],其动态演变受微生物矿化、藻类光抑制及沉积物再释放、厌氧释磷速率等多重调控[36-39]。其降低趋势是由于低覆盖率导致的适度遮光和降温,有效控制藻类生物量[39],使沉积物-水系统中藻类介导的磷释放过程被抑制[38];其上升趋势则是因为缺氧条件,厌氧释磷速率加快,促进了沉积物中磷的释放,使正磷酸盐的释放量远高于好氧条件[39]。同时,水体总氮(TN)浓度在低覆盖率下无显著变化[40],而在覆盖率大于50%的区域因沉积有机物矿化加速导致TN、TP累积风险增加[41]。而叶绿素a(Chl-a)浓度呈现阈值型响应特征,低覆盖率因光抑制解除导致Chl-a浓度异常升高,而高覆盖率下遮光效应与水温调控使Chl-a浓度显著下降[41-44]。当前研究在剂量效应方面存在一定争议,Lee等[40]基于6个监测点数据认为水上光伏电站对各类指标均无显著影响,而宋鑫等[41]通过干湿季的88组采样揭示了覆盖率大于50%时光伏板的覆盖降低了浮游植物对营养盐的利用率,可控制水体进一步富营养化。未来可通过构建光-热-营养盐耦合模型,量化水上光伏电站调控效应的时空异质性,探究对应藻类抑制与沉积物释放主导区,并提出生态友好型调控区间。

1.4 对污染物的影响

水上光伏电站对水体污染物的调控作用体现为直接释放与间接光化学效应的双重路径。直接污染途径涉及光伏组件与浮体材料的环境迁移,如晶硅电池封装材料中含有的酚类抗氧化剂(如BHT)在pH为6.5~7.5条件下有溶出风险,其释放风险与光伏覆盖率正相关[45]。水上光伏主要浮体材质高密度聚乙烯(HDPE)在光照条件下会显著浸出溶解有机碳(DOC)和总溶解氮(TDN)[46],尤其在加速中波红斑效应紫外线辐照条件下,每千克高密度聚乙烯DOC和TDN浸出量分别高达91~282 mg和1 805~2 285 mg[47]。人为活动可能会导致水上光伏体系中不同成分中的微塑料、有机碳、重金属和准金属在更大程度上浸出[45],如封装材料(如EVA)的降解会直接释放微塑料和有机碳,并破坏关键屏障,导致内部重金属与准金属被加速释放。在酸性雨水及破损条件下,晶硅组件中铅的浸出比例可达初始含量的17.9%~24.4%[48]。因此,材料选择对生态风险具有决定性调控作用。间接调控机制表现为光催化降解活性的空间异质性,如光降解在去除双氯芬酸[49]、有机磷[50]等有机污染物的过程中发挥重大作用。而光降解过程仅在光线充足的白天活跃,其过程包括光照导致的电子直接跃迁和光敏剂接收光子以产生的活性中间体降解污染物,因此光照显著调控光降解速率[51]。而水上光伏面板的覆盖会对进入水体的光照进行遮挡,使污染物的光降解过程受到抑制,但其对不同污染物的影响程度与作用机制仍需要进一步研究。

2　水上光伏电站对水生生物的影响

水环境与水生生物通过物质循环、能量流动和生物地球化学循环等过程紧密关联,水环境的理化性质(如水温、溶解氧)为水生生物提供生存基础,而水生生物的活动(如摄食、代谢)则改变水体理化指标,二者相互作用形成动态平衡。一方面,非生物要素的改变通过间接调控,重塑了水生生物群落的结构与功能,即光强抑制、水温波动等通过光-温-氧级联效应间接影响生物群落;另一方面,光伏组件本身的存在也直接对生物生存起到调控作用,即光伏面板的物理遮挡、材料浸出物直接作用于生物体。例如,面板遮光直接限制沉水植物收到的光照强度,而浮体释放的微塑料可通过摄食进入鱼类消化道[46]。本文将按生物类型(浮游植物、水生植物、浮游动物、鱼类及鸟类)分类阐述水上光伏电站的影响趋势及机理,并揭示其复合作用对食物网稳定性的潜在风险。

2.1　对浮游植物的影响

浮游植物作为水生系统的核心初级生产者,通过光合固碳驱动碳循环与能量流动,其生物量分布与群落结构直接调控水体营养状态[52]。光伏面板通过遮蔽太阳辐射引发浮游植物光抑制效应,当覆盖率大于 30% 时,光合固碳速率下降,导致总生物量显著减少[5-6,11,53-58](图 2)。群落结构响应呈现阈值特征:低覆盖率区(<30%)硅藻占优(占比>60%),高覆盖率区(>60%)绿藻的占比增加[58]。水温调控效应进一步加剧生物量衰减[59],光伏覆盖导致春季表层水温降低 0.2℃、夏季降低 0.8℃[60],抑制了浮游植物酶活性,并影响了浮游植物对营养物质的吸收、利用效率,水温每降低 1℃时,浮游植物的丰度下降 9%[61]。此外,由于覆盖率会影响溶解氧含量,浮游植物的缺氧风险也会显著增大[62-63]。因此,应定量解析光-热-氧协同驱动效应,精准调控光伏覆盖率,实现生物量和藻类毒素释放抑制的协同优化,为水体污染防控和生态修复提供新范式。

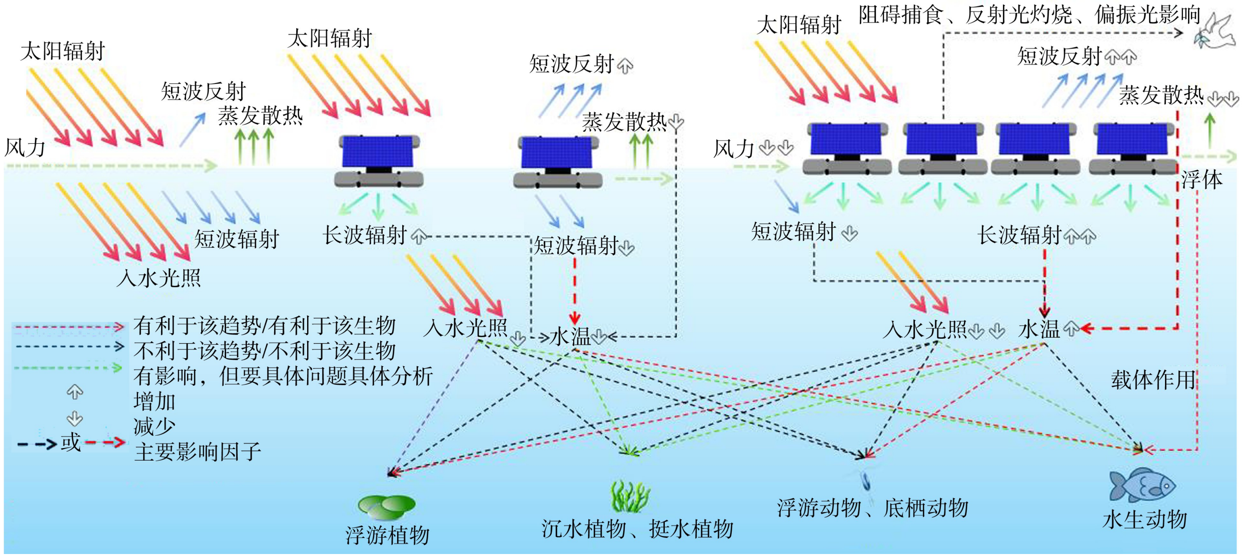

图 2　水上光伏电站对水生生物的影响

Fig. 2　Effect of floating photovoltaic power station on aquatic organisms

2.2　对水生植物的影响

水生植物对光伏覆盖的响应呈现多维环境胁迫的级联耦合机制。光照调控方面,以芦苇为例,低辐照度通过抑制光系统Ⅱ(PⅡ)电子传递链活性,限制 ATP/NADPH 供给,导致卡尔文循环中核酮糖-1,5-二磷酸羧化酶羧化效率下降[64];而高光强则通过光抑制效应(如 D1 蛋白光氧化降解)和活性氧(ROS)累积引发光损伤[65]。沉水植物同样也会受到光照的影响,如苦草叶长与光强负相关[66]。其中物种适应性差异表现为遮光耐受型(如篦齿眼子菜通过扩大捕光色素蛋白复合体适应低光)与光敏感型(如大茨藻依赖高光驱动的 C4 代谢途径)的分化[67]。而光伏覆盖带来的水温波动通过影响酶促反应动力学和膜流动性,对不同类植物实施不同的调控作用,如黑藻、苦草喜温,金鱼藻耐寒[68-69],三者输出结果各有不同。此外,营养盐再分布触发植物离子稳态重构,轻度富营养化促进沉水植物硝酸盐同化和硝酸还原酶活性提升[70],但其在重度富营养化的水中则限制植物生长[71]。各类富营养化元素占比影响不同,如高氮磷比通过铁-磷共沉淀效应诱导

菹草铁限制性生长抑制[72]。光伏面板的安装可能导致营养物质的释放,从而对水生植物产生影响。此外,水体中的污染物质如重金属等能通过干扰植物的细胞生理活动来抑制其生长[68]。

2.3　对浮游动物和底栖动物的影响

水上光伏通过光照调控与热力学扰动,对浮游与底栖动物形成光-热耦合胁迫,进而重构其群落动态。水上光伏建设带来的光衰减直接抑制浮游动物光周期依赖性发育,例如甲壳类幼体孵化同步性破坏[73],并通过异养代谢与摄食行为解耦改变营养级联效应,典型表现为乌鳢幼鱼暗适应摄食强度提升[74]。水温波动通过热适应性阈值分化驱动浮游动物优势物种转变,当春秋季温度变化±1℃,会引发27%的丰度增减,以及温/冷水种的演替[62]。同时,水温也是影响底栖动物空间分布的主要环境因子,研究发现夏季大型底栖动物种类数量显著高于秋冬季[75]。综上,水上光伏建设会通过光-热协同效应使浮游动物生物量衰减及底栖群落功能冗余度下降,并重构生物群落结构。

2.4　对水生动物及鸟类的影响

水上光伏通过光胁迫、热力学扰动、溶解氧梯度重构及物理结构效应驱动水生动物生态位重塑。光照调控直接影响鱼类行为策略,如许氏平鲉群体游动的平均速度会随光照强度的增加而加快[76],而山女鳟在高光照条件下摄食效率与生长率优势验证光强驱动的生物能量分配优化[76]。水温也会影响鱼类的生理活动,当水温超过临界温度时则会导致鱼类机体内代谢紊乱、活动能力降低,甚至死亡[77],而适度遮阴可拓展养殖物种的热适应窗口,同步改善生长速率与繁殖成功率[78-79]。缺氧条件对鱼类生长有不利作用[80-81],溶解氧质量浓度低于5 mg/L时不利于有氧代谢产能,低于1 mg/L甚至引发窒息级联反应,会导致大规模鱼类死亡[82],光伏覆盖区的水温下降与溶解氧含量协同提升机制为渔业资源增殖提供潜在增益[83]。人工结构效应表现为光伏基质的生态工程功能,例如贝类附着生物量累积与类礁体聚集效应提升鱼类空间利用效率[84],然而偏振光干扰与栖息地破碎化导致鸟类迁徙导航紊乱及碰撞死亡率上升,由此形成捕食压力缓释与鸟类多样性衰减的拮抗效应[85-87]。上述多维环境因子的非线性互馈作用最终驱动水生动物群落结构与能流路径的拓扑重构。

2.5　对水生系统食物网的影响

水上光伏通过温度介导的代谢异速增长与光周期调控重构营养级联效应。浮游动物摄食效率呈现温度依赖性阈值响应[88],例如拟长腹剑水蚤在5~25℃范围内摄食率随水温上升呈线性增长,而桡足类在超过30℃时因酶热变性导致摄食抑制[89]。鱼类代谢率则遵循Arrhenius动力学模型,水温升高诱导摄食量增加[90-91],但光伏遮阴区温降引发浮游动物与鱼类间的营养传递效率衰减,例如拟长腹剑水蚤的能量通量下降导致鱼类营养供应不足[89]。光周期通过调控摄食节律影响能量传输路径,食蚊鱼日间摄食强度优势[92]、叉尾斗鱼仔鱼光驱动摄食正反馈[93]与乌鳢幼鱼暗适应摄食策略[75]形成多维光响应谱,而银鱼双峰摄食模式揭示光周期相位调谐的物种特异性[91]。

为系统量化上述光-热协同扰动对食物网结构的级联影响,生态网络分析提供了一种系统建模与能流路径解析的有效工具[94]。生态网络分析基于食物网拓扑结构与能流矩阵,可量化表征不同光伏覆盖率下能量在网络中的传输效率、循环指数、系统冗余度及关键物种/路径的贡献度变化。例如,通过构建浮游植物-浮游动物-鱼类简化能流网络,可模拟不同覆盖率(如<30%、30%~60%、>60%)下光抑制与水温变化对各营养级间能量通量的影响,识别系统脆弱性节点与能流瓶颈。光伏覆盖导致的浮游植物初级生产力下降可通过生态网络分析量化为系统总能流的降低[95],而中高覆盖率下营养级联解耦可体现为网络互惠性下降与循环流比例异常波动,提示系统稳定性衰减[96]。因此,未来研究可结合水文-生态耦合模型与生态网络分析方法,动态模拟不同光伏布局情景下食物网的能流重组过程,从而为制定覆盖率调控阈值与生态修复策略提供定量依据。

综上,光-热协同扰动通过代谢速率失配与摄食节律紊乱触发食物网结构重塑,结合生态网络分析方法可进一步量化能流路径变化及其系统级影响,并从跨营养级能量流动态与非线性互作网络视角解析其生态级联效应。

3　结　语

本文系统分析了水上光伏开发对水生态系统的影响,认为水上光伏电站覆盖率是主导其生态环境效应

的关键因子。非生物参数呈非线性响应,水温与溶解氧含量随覆盖率增加分别呈现阈值转折(先降后升)及倒 U 形变化(先升后降),但富营养化响应方向仍需系统验证。水上光伏电站覆盖率对水生态系统的影响机理复杂性源于多因子互馈作用,包括短波辐射衰减与风速降低对水温的拮抗效应,以及溶解氧-藻类生长-营养盐循环的级联反馈等。生物层面,水上光伏电站通过光-热耦合胁迫重塑群落结构,适度遮光抑制浮游植物生物量,降低富营养化风险,浮游与底栖动物丰度及多样性衰减,鱼类和鸟类呈现物种特异性响应(如代谢节律紊乱、迁徙行为干扰)。食物网能流路径因摄食效率异变(如浮游动物温度依赖性摄食阈值)及营养级联解耦而拓扑重构,加剧生态风险不确定性。

未来的水质影响研究中,需要充分考虑水上光伏组件覆盖率、面板材料其设置形式等对水生态系统的不同影响,细化覆盖率设置梯度等试验条件,综合分析找到生态效益最高点和生态风险最低点,并设置对应环境保护方案。为了平衡水上光伏电站发电效益与生态保护,可采用覆盖率动态调控策略即根据不同水域的生态需求,进行分区布局。在水域核心区,将水上光伏电站覆盖率控制在 30%以下,以减少对水生生物的负面影响;在生态缓冲区,将覆盖率设置在 30%~60%之间,兼顾发电效率与生态修复功能。还可进一步深入考虑水上光伏面板的倾角及水上光伏电站的结构设置对水生态系统的影响,探究其改善水上光伏负面影响的潜在效能,为水上光伏系统建设提供环境友好的解决方案。此外,目前已有研究仅关注部分藻类及少量鱼类,缺乏对水生系统食物网中各参与者间相互作用的探究,亟待从生态系统整体层面全面解析水上光伏系统的环境影响。未来的水上光伏产业需基于多尺度优化策略平衡发电与生态保护,包括动态调控覆盖率、分区布局、优化面板倾角与结构设计、强化生态功能(如人工基底效应),同时构建水动力-生态耦合模型,量化覆盖率梯度对能流网络的阈值效应,最后开展跨营养级互作研究,解析水上光伏电站驱动的正/负反馈机制。通过机理-模型-调控三位一体框架,实现水上光伏电站与水生态系统的协同优化。

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