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# 微塑料对湖泊生态系统初级生产者的影响

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**摘要**:塑料的广泛应用导致大量微塑料进入环境,尤其是水环境,从而产生环境风险。浮游植物等自养生物是湖泊系统的主要初级生产者,是湖泊食物链的关键组成部分,为食物链的上游提供能量和物质基础。同时,浮游植物也是对微塑料响应最敏感的类群。了解湖泊浮游植物等初级生产者对微塑料的响应是探究微塑料对湖泊生态系统功能影响的重要基础。总结了全球湖泊生态系统微塑料的丰度、类型、尺寸、来源等分布特征,系统分析了微塑料暴露对浮游植物等初级生产者细胞结构、基因表达和生长,以及对浮游植物叶绿素 a 含量、光合活性的影响,并总结了其中的影响机制。总体而言,微塑料会降低初级生产者的叶绿素 a 含量,剂量越高、尺寸越小,这种抑制作用越强烈;同时,微塑料也会作用于初级生产者,造成细胞膜损伤、DNA 损伤,调控其相关功能基因表达,抑制其生长和光合活性等。然而,湖泊生态系统微塑料的实际检出浓度远低于室内暴露实验中的添加剂量,微塑料结构和组分也更为复杂,野外观测结果与室内培养实验之间还不能建立直接的对应关系。因此,未来的相关研究应集中在如何有效联系野外观测结果与室内培养实验结果,进一步聚焦建立可靠的、可应用推广的微塑料浓度与初级生产者之间的剂量-效应关系模型,探究微塑料对湖泊初级生产者的作用机制,为刻画微塑料对湖泊生态系统初级生产者及其功能的作用机制提供科学支撑。

**关键词**:微塑料浓度;初级生产者;细胞结构;光合作用;叶绿素 a;剂量-效应关系

# Impacts of microplastics on primary producers of lake ecosystems

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**Abstract**: As a result of the increasing global production and usage of plastics, a large amount of microplastics has been widely detected in many environmental media, especially in the aquatic environment, causing environmental risks. Autotrophic organisms including phytoplankton, aquatic plants and some autotrophic microorganisms are the main primary producer in lake ecosystems, and are the key components of the lake food chain, providing energy and material base for upstream of the food chain. In addition, as the main primary producers in freshwater, phytoplankton is the most sensitive component and respond fast to environmental changes. Therefore, phytoplankton was used as indicator for assessing the status of lake ecosystem function and stability. Understanding the response of phytoplankton to microplastics is crucial for clarifying the effect of microplastics on lake ecosystem functioning. Here, we summarized the distribution characteristics (abundance, type, and size) and source of microplastics in global lake ecosystems, and systematically analyzed the effects and the involved mechanisms of microplastics exposure on the cellular structure, gene expression and growth, as well as the content of Chlorophyll a and photosynthetic activity of phytoplankton and other aquatic organisms. In summary, the

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microplastics could inhibit the chlorophyll a content and photosynthetic activity of the primary producers. The higher the dose and the smaller the size, the stronger the inhibitory effect of microplastics. Microplastics could cause cell membrane damage, DNA damage, regulate the functional gene expression, and inhibit the growth of the primary producers, simultaneously. The impact of microplastics on primary producers in lakes could subsequently lead to an impact on lake function. However, the actual level of microplastic concentrations in lake ecosystem was much lower than the dose of additives in the incubation experiment in lab, and the structure and components of microplastics in lake are more complex than that in the incubation system in lab. Thus, the direct correspondence between field investigation and indoor incubation experiment could not be built yet. Therefore, future research should conduct incubation studies with microplastics that are closer to the environmental concentrations and compositional characteristics in lake ecosystem, and focus on how to build an efficient linkage of the results obtained in field investigation and indoor incubation experiment. A reliable and universal dose-effect relationship model between microplastic concentrations and the primary producers should be established to explore the mechanism of microplastics impact on lake primary producer and productivity, as well as provide scientific support for clarifying the mechanism of microplastics impact on lake ecosystem functioning.

**Key Words**: microplastics concentrations; primary producer; cell structure; photosynthesis; Chl-a; dose-effect relationship

随着塑料在各个领域的广泛使用,在生产、运输、使用和废弃等环节,大量塑料进入生态系统[1]。研究发现,物理破碎[2]、光降解[3]和生物降解[4—5]等会使塑料聚合物发生改变,产生微塑料( $<5000$ μm)[6]。化妆品[7]、洗涤剂[8]、药物载体[9]等所添加的微塑料以及工业释放的塑料颗粒[10]也是环境微塑料的直接重要来源[11]。常见的微塑料包括:聚乙烯(PE)、聚丙烯(PP)、聚丙乙烯(PS)、聚氯乙烯(PVC)、聚酰胺(PA)和聚对苯二甲酸乙二醇酯(PET)等[12—13]。其中小于 100 nm 的微塑料可细称为纳塑料(nanoplastics)[14]。

环境中的微塑料会对生物体产生毒性效应,威胁生态系统的功能和稳定性[15]。湖泊生态系统是内陆水体微塑料重要的汇[16]。由于其微纳级别的尺寸,进入湖泊生态系统的微塑料能够进入生物体内,并通过食物链传递和富集[17]。影响生物体的正常新陈代谢,造成组织损伤,抑制生长,甚至导致生物死亡[18]。微塑料的多孔结构、比表面积大、高疏水性及环境稳定性等特点,使其易吸附其他污染物(如:重金属,有机污染物),造成复合污染[19],对湖泊生态系统的生物产生持久性影响[20]。

湖泊生态系统发挥着水资源供给、洪水调蓄、水质净化、维持生物多样性、调节生态地球化学循环等服务功能[21—24]。浮游植物在湖泊生态系统的自养生产中占主导地位[25],是湖泊生态系统的主要初级生产者[26]。浮游植物等初级生产者在碳循环等物质循环功能过程中起到了不可忽视的重要作用[27—28]。同时,浮游植物也是湖泊生态系统对环境扰动响应敏感且强烈的生物组分,可以作为湖泊生态系统变化的指示生物[29—30]。微塑料广泛分布在湖泊中[31—32],其对湖泊生态系统中浮游植物等初级生产者和初级生产力的影响反映了湖泊生态系统功能对微塑料污染的响应。

目前国内外关于微塑料的相关研究主要集中在海洋,对湖泊微塑料还缺乏系统了解[33—34]。针对湖泊生态系统中微塑料的相关研究主要集中在两方面:一方面是基于野外调查的微塑料分布特征研究,一方面是基于室内培养实验开展的微塑料对初级生产者的生物效应研究,但这两方面研究之间还缺乏有效的链接[35—37]。而关于微塑料对湖泊生态系统功能的研究则是通过对功能过程的参与者的毒性效应进行间接推断,缺乏直接证据[38—39]。本文对国内外微塑料在湖泊中的浓度分布特征、对湖泊初级生产者细胞结构、功能基因表达、光合作用和生长的影响进行梳理和分析,总结微塑料对湖泊生态系统初级生产者的影响机制,并对未来微塑料对湖泊生态系统影响的研究需要重点关注的方向进行了探讨,对于微塑料污染防控、湖泊生态系统功能维护具有重要意义。

## 1 湖泊生态系统中微塑料来源、浓度及影响因素

进入湖泊生态系统的陆源微塑料主要来自工业生产、城市生活和农业生产过程[40—42]。陆地微塑料制品可以通过风或地表径流以及不充分的废物处理进入湖泊[43—44]:(1)农业活动产生的微塑料(塑料大棚、塑料地膜、污水灌溉等)能够通过农田排水和径流进入湖泊生态系统[45—46];(2)城市生活来源的微塑料(包括生活废弃物、污水排放、车辆轮胎等降解产生的微塑料[47—48])通过暴雨和城市排水进入湖泊生态系统,污水直接排放也给湖泊输送微塑料[49];(3)工业源的微塑料(包括工业粉尘[50—51]、垃圾焚烧填埋[52]、工业排放[46]以及渔业捕鱼工具使用尼龙微塑料[53—54])通过风、地表径流或直接排放进入湖泊。

亚洲作为生产和使用微塑料的主要区域[55],湖泊生态系统中微塑料的含量显著高于其他区域,微塑料的浓度范围为 0.127—34000 个/$m^3$,其中,微塑料的最高浓度出现在中国的鄱阳湖(表 1)。

**表 1　全球淡水湖泊表层水体微塑料浓度**

**Table 1　Microplastics concentrations in surface water of global freshwater lakes**

| 湖泊 Lake | 微塑料平均浓度(最小-最大浓度) Average concentration of microplastics (Min-Max)/(个/$m^3$) | 形状 Shape | 类型 Type | 颜色 Color | 采样方法(网孔径) Samling method (pore size) | 国家 Country | 参考文献 References |
|---|---|---|---|---|---|---|---|
| 洞庭湖 | 1191.70 | 纤维状 | PE | 透明 | P (50 μm) | 中国 | [56] |
| 洪湖 | 2867.50 | 纤维状 | PE | 透明 | P (50 μm) | 中国 | [56] |
| 太湖 | (3400—25800) | 纤维状 | 玻璃纸 | 蓝色 | T (333 μm) | 中国 | [57] |
| 鄱阳湖 | (5000—34000) | 纤维状 | PP PE | 彩色 | P (50 μm) | 中国 | [58] |
| Lake Phewa | 1510 | 纤维状 | — | 透明 | P (75 μm) | 尼泊尔 | [59] |
| Lake Baikal | 291 | 碎片状 | PP | — | T (20 μm) | 俄罗斯 | [60] |
| Lake Maggiore | 8.24 | 碎片状 | PE | 透明 | T (50-300 μm) | 意大利 | [61] |
| Lake Meirama | 1.84 | 纤维状 | PES | 透明 | T (50-300 μm) | 西班牙 | [61] |
| Lake Neagh | 2.27 | 碎片状 | PE | 透明 | T (50-300 μm) | 爱尔兰 | [61] |
| Lake Stechlin | 4.25 | 纤维状 | PA | 蓝色 | T (50-300 μm) | 德国 | [61] |
| Lake Plastic | 0.26 | 纤维状 | PES | 黑色 | T (50-300 μm) | 加拿大 | [61] |
| Lake Tahoe | 5.44 | 碎片状 | PP | 透明 | T (50-300 μm) | 美国 | [61] |
| Lake Rotorua | 1.80 | 纤维状 | PVC | 黑色 | T (50-300 μm) | 新西兰 | [61] |
| Lake Michigan | 0.54 | 纤维状 | PP | — | T (333 μm) | 美国 | [62] |
| Lake La Salada | 143.30 | 纤维状 | — | 黑色 | P (47 μm) | 阿根廷 | [63] |
| Lake Hovsgol | 0.13(0.01—0.28) | 碎片状、薄膜状 | — | — | T (355 μm) | 蒙古 | [64] |

PE: 聚乙烯 Polyethylene; PP:聚丙烯 Polypropylene; PES:聚醚砜 Polyether sulfone; PA:聚酰胺 Polyamide; PVC:聚氯乙烯 Polyvinyl chloride; P:代表用收集器收集水体滤网过滤后获取微塑料样品, Pump;T:代表用网在水体表面拖拽收集,Trawl;Pore size:收集网和过滤网的孔径;微塑料浓度单位个/$m^3$代表每立方米水体中微塑料的个数

其次是位于尼泊尔的 Lake Phewa 和俄罗斯的 Lake Baika,浓度分别为 1510 和 291 个/$m^3$。欧洲其他地区和北美洲的湖泊中微塑料的含量水平较低,浓度在 0.26—8.24 个/$m^3$之间。微塑料浓度最低的湖泊是位于蒙古的 Lake Hovsgol(0.13 个/$m^3$)。这些湖泊中微塑料的主要类型为 PE 和 PP,这两类微塑料也是全球产量最大的两种类型[65]。湖泊中常见的微塑料形状为纤维状和碎片状,主要来自于纺织品、渔网、塑料制品的裂解和老化。湖泊中广泛分布的微塑料颜色为透明色、黑色、蓝色,其中彩色微塑料更容易被生物摄食,具有更高的毒性潜力[66]。

湖泊生态系统中微塑料浓度的影响因素主要有:(1)湖泊距离微塑料生产源头的距离。距离微塑料生产源头较近的湖泊,发挥着汇集微塑料的作用,通常微塑料的含量相对较高[67]。(2)区域社会经济发展水平。

人口密度较大、经济发达的地区,微塑料含量更高[68—70]。(3)湖泊生态系统的水文特征。湖泊水文特征直接影响微塑料的水平运移[71—72],封闭程度较高的湖泊微塑料含量更高[56]。(4)湖泊富营养化程度。微塑料的含量与湖泊总氮含量呈现显著正相关关系[73]。值得注意的是,微塑料的收集方法会影响微塑料含量的测定结果,采用捕网拖拽收集方法只能收集到大于网孔尺寸的微塑料,在数量上远小于用小孔径滤网获得的微塑料,滤网获得的微塑料还包括更小尺寸的纳塑料[60]。

## 2 微塑料对湖泊生态系统初级生产者细胞结构和功能基因表达的影响

目前微塑料对湖泊生态系统初级生产者的影响研究均是基于单一微塑料类型的室内添加及培养实验。通过设计不同剂量和不同尺寸微塑料的室内毒性实验,考察对以浮游植物为代表的初级生产者不同生理、生化以及遗传指标的影响。可能的影响机制总结如下:附着在植物细胞表面,阻碍光照、气体交换、电子和营养物质传输,抑制光合作用和生物生长[74—75];进入细胞内,对叶绿体造成损伤,影响光合活性[76—77];造成 DNA 损伤,影响功能基因的表达[78—79]。活性氧(Reactive oxygen species, ROS)水平升高,导致氧化应激损伤,过氧化物与细胞膜的脂质过氧化反应,产生丙二醛(malondialdehyde, MDA),造成细胞膜损伤[78, 80—81]。而植物体也会产生一系列的抗氧化酶以清除过量的过氧化物(图 1)。

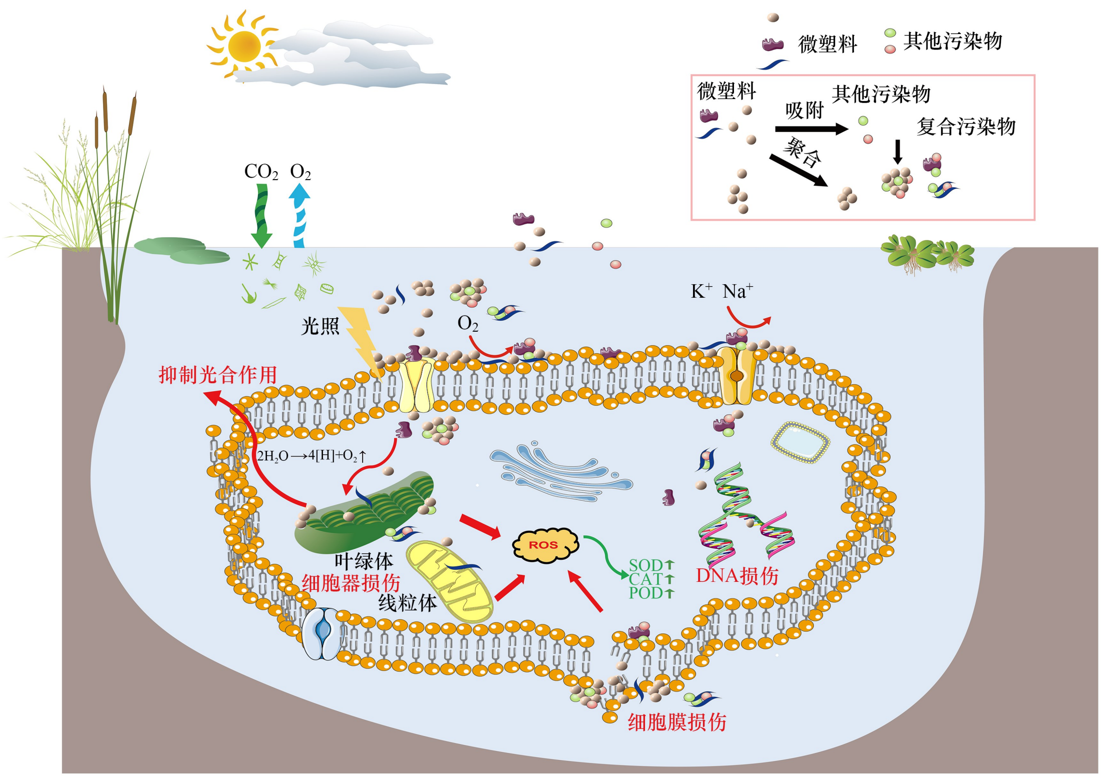


**图 1 微塑料对湖泊初级生产者的影响机制示意图**

**Fig.1 Mechanisms of microplastics impacts on lake primary producers**

ROS:活性氧 Reactive oxygen species;SOD:超氧化物歧化酶 Superoxide dismutase;CAT:过氧化氢酶 Catalase;POD:过氧化物酶 Peroxidase

### 2.1 微塑料对初级生产者细胞结构的影响

微塑料对藻类的细胞膜损伤是最为常见的影响之一[82]。附着在藻类细胞上的微塑料,能够阻碍气体交换和营养物质运移的通道,影响藻类生长,导致氧化应激损伤, ROS 水平升高[83—84]。较小尺寸的微塑料能够破坏藻类细胞壁和细胞膜,甚至进入细胞内,造成细胞器损伤[77]。与此同时,植物体也会产生一系列的抗氧化酶清除 ROS[54]。当氧化应激损伤细胞膜时,会与细胞膜磷脂双分子层发生脂质过氧化反应,产生 MDA。

MDA 的含量通常可以用来反映植物细胞遭受胁迫的严重程度[80]。当微塑料附着在藻类细胞表面时,还会阻碍光照和电子传输,引起 ROS 水平提高,促进细胞膜脂质过氧化,导致 MDA 含量增加[81]。此外,微塑料能够与微藻形成异质团聚(hetero-aggregation),也会对藻类造成细胞壁变形、细胞膜损伤等结构变异[85—86]。微生物分泌的胞外聚合物(exopolymeric substances, EPS)在减轻微塑料对细胞膜的破坏方面发挥了重要的作用。EPS 是由蛋白质和多糖组成的高分子聚合物,能够使细胞壁厚度增加,较高含量的多糖还能够作为一种抗氧化剂,减轻氧化应激损伤[87]。

### 2.2　微塑料对初级生产者功能基因表达的影响

微塑料的胁迫除了对藻类的细胞产生物理损伤和氧化应激损伤外,还会影响相关功能基因的表达,并最终影响叶绿素 a 含量和光合活性[79]。尺寸为 1 μm 的微塑料改变了铜绿微囊藻(*Microcystis aeruginosa*)光合作用和与能量相关的基因转录水平。与叶绿体和固碳相关的基因 *psbA*, *rbcL*, *rbcS* 等在微塑料暴露下表达上调,表明微塑料对藻类光合作用和叶绿体损伤具有反馈调节作用[78]。微塑料对初级生产者功能基因表达的影响除了与尺寸相关外,也会受到暴露时长的影响。随着暴露时长的增加,在暴露 78 天后,尺寸大于 400 mm 的高浓度微塑料会导致莱茵衣藻(*Chlamydomonas reinhardtii*)参与糖类生物合成途径的功能基因表现出强烈的过表达[88]。微塑料还能够通过影响碳、氮、氨基酸和脂质代谢通路来影响有机质的积累。微塑料的暴露能够使与氨基酸有关的代谢通路的丰度普遍下调,这将导致藻类蛋白质合成受到抑制,抗氧化的能量下降。而藻类则能够通过调节自身代谢产物的合成来抵抗微塑料的胁迫[89]。

## 3　微塑料对湖泊生态系统初级生产者光合作用和生长的影响

### 3.1　微塑料对初级生产者叶绿素 a 含量的影响

叶绿素 a 是浮游植物和水生植物光合过程中的核心色素,其含量可以用来指示浮游植物和水生植物的初级生产力[90]。微塑料对湖泊生态系统浮游植物和水生植物叶绿素 a 含量的影响可能会导致其初级生产力和固碳潜力的变化,进而影响湖泊生态系统的碳循环[91—94]。已有的研究表明,微塑料普遍抑制初级生产者的叶绿素 a 含量[95—96]。抑制作用大小与微塑料浓度、类型、尺寸等因素相关[97—99]。微塑料对浮游植物叶绿素 a 含量的抑制作用随着微塑料暴露剂量的增加而增强[100—103]。小尺寸的微塑料能够抑制初级生产者叶绿素 a 含量,并且随着尺寸的减小,抑制作用增强;大尺寸的微塑料对其影响并不明显[104]。然而,PS 对沉水草本植物苦草(*Vallisneria natans*)叶绿素 a 含量的抑制作用并未随着尺寸的减小而增加。这可能是由于暴露于沉水植物根部的微塑料进入植物内部后,借助蒸腾作用到达植物顶部的微塑料含量和性质发生变化,从而导致诱导植物光合和生长发生的变化存在差异[105]。与原始微塑料相比,老化的微塑料的孔隙和比表面积增加,吸附能力更强,对湖泊浮游植物叶绿素 a 的抑制作用更强[102]。老化过程中的微塑料还可以作为载体与重金属等元素相互作用,对浮游植物叶绿素 a 含量造成更严重的抑制作用[106]。另外,初级生产者的类型也会导致微塑料对叶绿素 a 含量抑制作用的差异[91,107](表 2)。

### 3.2　微塑料对初级生产者光合作用活性的影响

叶绿素荧光参数能够反映光合作用对各种扰动的响应程度[74,113],微塑料对浮游植物光系统Ⅱ最大光化学量子产量($F_v/F_m$)和光系统Ⅱ的潜在活性($F_v/F_0$)的影响反映了微塑料对浮游植物光合活性的影响。当微塑料附着在藻类细胞膜上时,会聚集遮挡光照,从而导致 $F_v/F_m$ 和 $F_v/F_0$ 比值降低[75]。微塑料类型和受试生物类型的不同均会导致响应结果存在差异(表 2)。暴露于 250—1000 mg/L PE 的栅藻(*Scenedesmus armatus*)和微囊藻(*Microcystis aeruginosa*) 的光合活性受到显著抑制作用[92]。5—100 mg/L 的 PS(300—600 nm)暴露下,莱茵衣藻(*Chlamydomonas reinhardtii* )的光合活性降低[85]。一般来说,微塑料对光合活性的影响随着剂量的增加而增强[103]。同时,尺寸可能是导致 PS 的影响存在差异的另一个决定性因素, 尺寸越小,抑制作用越强。小尺寸的微塑料能够进入细胞内,富集在叶绿体上,损伤叶绿体,从而影响浮游植物的光合活性[114]。由于浮游植物光合过程会消耗水生环境中的 $CO_2$,因此 $CO_2$的消耗速率是评估浮游植物光合作用活性的关键

指标之一[76]。微塑料的暴露会导致小球藻(*Chlorella vulgaris*)和栅藻(*Scenedesmus armatus*)消耗的 $CO_2$减少,这可能是由于藻类细胞吸附的微塑料的遮光效应和阻碍 $CO_2$气体交换和细胞吸收养分的途径造成的。

**表 2 微塑料对湖泊生态系统初级生产者的影响**

**Table 2 Effects of microplastics on primary producers in lake ecosystem**

| 受试对象 Test organism | 类型 Type | 大小 Size | 剂量 Concentration/(mg/L) | 暴露时间 Exposure time/h | 影响 Effect | 文献 References |
|---|---|---|---|---|---|---|
| 三角褐指藻 *Phaeodactylum tricornutum* | PS | 1 μm | 0.1, 1, 10 | 120 | 降低叶绿素 a 含量; 显著降低了 $F_v/F_m$比值 | [74] |
| 蛋白核小球藻 *Chlorella pyrenoidosa* | PS | 0.1, 1 μm | 10—100 | 720 | 降低光合活性;抑制生长;细胞膜受损 | [75] |
| 小球藻 *Chlorella vulgaris* 斜生栅藻 *Scenedesmus obliquus* | PS | 0.02 μm | 1.8—6.5 | 24 | 阻碍光合作用 | [76] |
| 蛋白核小球藻 *Chlorella pyrenoidosa* | PS | 1, 5 μm | 2, 10, 50 | 240 | 降低叶绿素 a 含量;细胞膜损伤;抑制藻类生长;改变光合作用和能量代谢相关基因转录水平 | [78] |
| 莱茵衣藻 *Chlamydomonas reinhardtii* | PS | 300—600 nm | 5, 25, 50, 100 | 240 | 降低叶绿素 a 含量;降低光合作用活性;细胞膜损伤; | [85] |
| 莱茵衣藻 *Chlamydomonas reinhardtii* | PE, PP | 400—1000 μm | 400 | 1680 | 参与糖类生物合成途径的微藻基因出现了强烈的过度表达 | [88] |
| 紫萍 *Spirodela polyrhiza* (L.) *Schleid* | PVC | 3.87 μm | 0, 10, 100, 1000 | 168 | 抑制生长;影响碳代谢等功能过程 | [89] |
| 金鱼藻 *Ceratophyllum demersum L.* | PS, Cd | 100 nm | 5, 10 | 336 | 高剂量复合污染降低叶绿素 a 含量;影响糖代谢基因表达 | [91] |
| 栅藻 *Scenedesmus armatus* 铜绿微囊藻 *Microcystis aeruginosa* | PE | 212—300 μm | 250, 500, 1000 | 672 | 抑制生长;抑制光合活性 | [92] |
| 斜生栅藻 *Scenedesmus obliquus* | PS | 0.07 μm | 0.22—150 | 504 | 降低叶绿素 a 含量;抑制生长 | [93] |
| 铜绿微囊藻 *Microcystis aeruginosa* | PS | 10 nm | 1 | 192 | 降低叶绿素 a 含量;抑制生长 | [94] |
| 铜绿微囊藻 *Microcystis aeruginosa* | PS, Pb | 10 nm | 1 | 192 | 复合污染促进生长;降低叶绿素 a 含量,但小于单独污染 | [94] |
| 小球藻 *Chlorella vulgaris* | PS | 0.5 μm | 1,5,50, 100,1000 | 480 | 降低叶绿素 a 含量;抑制生长 | [101] |
| 莱茵衣藻 *Chlamydomonas reinhardtii* | PVC | 50—100 μm | 10—200 | 96 | 降低叶绿素 a 含量 | [102] |
| 凤眼莲 *Eichhornia crassipes* | PS | 100 nm | 0.1, 1, 10 | 672 | 降低叶绿素 a 含量; $F_v/F_m$ 没有显著下降 | [103] |
| 黑藻 *Hydrilla verticillata* | PS, BPF | 100 nm | 1, 10 | 384 | 联合暴露显著降低叶绿素含量;降低光合活性;抑制生长 | [107] |
| 中肋骨条藻 *Skeletonema costatum* | PVC | 1 μm | 0, 1, 5, 10, 50 | 96 | 降低叶绿素 a 含量;降低光合效率;抑制生长 | [108] |
| 杜氏藻 *Dunaliella tertiolecta* 假微型海链藻 *Thalassiosira pseudonana* 小球藻 *Chlorella vulgaris* | PS | 0.05—6 μm | 25, 250 | 72 | 抑制生长 | [109] |
| 近头尖状胞藻 *Raphidocelis subcapitata* | PE | 63—75 μm | 25, 50, 100 | 504 | 作为藻类生长基质,促进生长 | [110] |
| 狸藻 *Utricularia vulgaris* | PS | 500 nm | 0—10 | 360 | 降低叶绿素 a 含量;抑制生长 | [111] |
| 栅藻 *Scenedesmus armatus* 铜绿微囊藻 *Microcystis aeruginosa* | PE, OC | 250—300 μm | 125 | 672 | 复合污染抑制生长;抑制光合 | [112] |

PS:聚苯乙烯 Polystyrene;Pb:铅 lead;Cd:镉 cadmium;BPF:双酚 F Bisphenol F;OC:有机污染物 Organic contamination;$F_v/F_m$:光系统Ⅱ最大光化学量子产量,其中 $F_v=F_m-F_0$:为可变荧光;$F_m$ 为最大荧光产量

### 3.3　微塑料对湖泊生态系统初级生产者生长的影响

微塑料胁迫导致微藻类的生长出现明显抑制,并且随着接触剂量的增加,抑制作用会增强[75,109—110]。尺寸为 1 μm 的 PS 对铜绿微囊藻(*Microcystis aeruginosa*)的生长抑制作用呈现出显著的剂量依赖性(2—10 mg/L)[115]。微塑料的尺寸越小,其对浮游植物的生长抑制作用越明显[85,116]。直径为 1 mm 的 PVC 对铜绿微囊藻的生长没有显著影响。与之相比,尺寸为 1 μm 的微塑料显著抑制了铜绿微囊藻的生长,暴露 96 小时后最大生长抑制率高达 39.7%[108]。长期暴露于 400 mg/L 的 PP 下,莱茵衣藻(*Chlamydomonas reinhardtii*)生长的抑制率为 18%[88]。微塑料与藻类细胞的吸附是影响藻类生长的主要原因。微塑料吸附聚集在藻类细胞上,阻碍光照、气体和营养物质的传输,进而影响藻类生长[78]。除了抑制作用外,一定剂量的微塑料能够促进藻类的生长。有研究发现,当剂量大于 10 mg/L 时,微塑料能够轻微地促进藻类生长,这可能与微塑料表面的功能官能团有关[117]。微塑料可以作为藻类生长的基质,促进其生长[110]。

## 4　微塑料与其他污染物复合污染对湖泊生态系统初级生产者的潜在影响

由于微塑料具有比表面积大、表面极性低等特点,使得其容易吸附各类有机和无机污染物,例如重金属、抗生素、持久性有机污染物(POPs)等[117—118]。这些污染物难降解、易迁移、并且随营养级逐渐累积[119]。微塑料与其他污染物的复合污染对湖泊初级生产者的影响更复杂。微塑料类型、形状、尺寸、老化,以及环境温度、pH、离子强度等都是影响微塑料吸附其他污染物的重要因素[119—120]。在自然水环境中,微塑料表面一般带有负电荷,与带正电荷的金属离子之间通过静电吸引促进了吸附行为[121]。老化微塑料吸附行为的增强,是因为老化后微塑料比表面积和含氧官能团增加,从而增加其吸附金属离子和疏水性有机污染物的能力[122—123]。湖泊水体 pH 变化会影响微塑料对其他污染物的吸附特征[124—126],其吸附金属离子的能力随着 pH 的增大而增强[127]。吸附过程是吸热反应,因此微塑料对其他污染物的吸附过程可能随着温度的升高而增强[128]。

塑料制品在生产过程中会添加大量增塑剂、着色剂、阻燃剂等化学添加剂,增强了塑料制品的物理化学特性,也带来了潜在的有机和重金属污染风险[129—130]。这些复合污染物能够加剧对初级生产者的物理损伤和遮挡效应,诱导功能基因差异表达,导致光合作用减弱,同时对叶绿素 a 含量和植物生长的抑制作用更强[47,91,131],影响湖泊生态系统的初级生产者的功能和初级生产力[112]。在微塑料与铜、铅、锌联合影响下,复合污染物对藻类生长和叶绿素 a 含量的影响最高达 70.43% 和 64.09%,远高于微塑料单独作用下的抑制率[101]。

## 5　研究展望

目前在实际环境中对微塑料的研究主要集中在单位面积或体积下微塑料数量的测定,并尝试通过不同流域、流域的不同位点的对比分析,考察可能的来源和浓度特征的影响因素。对于浓度分布特征背后所蕴含的湖泊生态系统对微塑料浓度的响应特征,还缺乏系统而深入的研究。因此,尚无法建立起实际环境中微塑料浓度与湖泊生态系统响应之间的剂量-效应关系。这方面的研究目前只能通过室内的毒性实验进行补充。

而室内培养实验结果表明,微塑料通过影响湖泊初级生产者细胞结构、基因表达、生长以及初级生产者的叶绿素 a 含量、光合作用活性等,对湖泊生态系统功能造成潜在影响。这些研究为后续工作的开展提供了良好的借鉴和参考。但是,室内培养实验添加的微塑料含量往往大于实际环境中的微塑料含量,并且大多是采购的标准品,类型固定,结构和颜色单一,无法反映实际湖泊生态系统中微塑料的含量和特征。与环境浓度相当剂量的室内微塑料暴露下,微塑料对初级生产者往往没有显著影响。因此,通过室内培养实验获得的微塑料与初级生产者之间的剂量-效应关系并不能很好地反映湖泊初级生产者对微塑料响应的实际情况,更无法反映湖泊生态系统功能的响应。因此,在未来的研究中应从以下几个方面开展深入研究:

(1)开展系统的野外观测实验。开发可靠的监测和测量手段,对湖泊生态系统中微塑料的浓度进行全面

地监测,分析湖泊生态系统中实际的微塑料浓度、类型、尺寸等特征,刻画其分布特征。进一步结合长期定位监测湖泊浮游植物实验,探究微塑料的分布特征对湖泊初级生产者的影响;

(2)开展结合功能过程终产物测定的室内培养实验。目前关于微塑料对生态系统功能的研究大多是通过分析对功能过程参与生物的毒理效应来间接推测,缺乏对功能过程影响的直接观测。浮游植物是湖泊固碳过程的主要参与者,而目前关于微塑料对湖泊固碳过程的研究还缺乏基于室内水-气界面二氧化碳等产物浓度观测数据的支撑,即通过室内培养实验获得的微塑料的毒性效应数据还无法与湖泊碳交换通量数据建立直接的剂量-效应关系。在继续开展室内培养实验的同时,应结合二氧化碳等气体吸收与释放的观测实验。未来相关研究应不再局限于微塑料对生物的毒性效应,推测微塑料对生态系统功能影响的间接方法。而是直接从定量的角度关注微塑料对碳循环等功能过程的影响,建立微塑料与功能过程主要产物的剂量-效应关系;

(3)开展更接近于实际湖泊中微塑料浓度和组成特征的毒性机理研究。在开展室内培养实验的时候,依据野外实际情况选择添加的微塑料,尽可能地还原实际湖泊中丰富的次级微塑料的浓度、类型、尺寸和颜色特征,获得更具代表性的室内培养实验结果。并进一步将毒理研究的结果与微塑料对功能过程的影响结合,通过尺度转化等方法考察和验证微塑料对湖泊生态系统功能的作用及其机制,最终建立野外环境下微塑料与湖泊系统功能之间的毒性效应模型。

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