网络首发时间：2023-05-10 09:28:27
网络首发地址：https://kns.cnki.net/kcms/detail/11.2223.N.20230508.1755.001.html

ISSN 1000-0054
CN 11-2223/N
清华大学学报（自然科学版）
J Tsinghua Univ (Sci & Technol)

# 宿主无损光照消毒技术综述

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**摘　要：**细菌、病毒等病原体给人类社会造成巨大危害。化学药剂、热能和紫外线被广泛应用于灭活有害微生物，但这些方法也会对病原体的宿主产生无差别伤害。宿主无损光照消毒技术能够在不损伤宿主细胞的同时灭活病原体，因而受到越来越多的关注。目前主流的宿主无损光照消毒技术包括207～222 nm远紫外线(far-ultraviolet c，far-UVC)、抗菌蓝光(antibacterial blue light)和低功率超短脉冲激光消毒。该文综述了这3种技术的基本原理、研究动态、适用场景和优缺点；对比了宿主无损光照消毒技术与传统紫外线消毒技术的技术特点；从理论模型建立和实际应用2方面提出了宿主无损光照消毒技术的研究展望。宿主无损光照消毒技术将有助于阻止大规模疫情中有害病原体的传播，可为食品保鲜和医疗产品消毒提供一种新方案，具有广阔的应用前景。

**关键词：**生物光学；消毒技术；远紫外线；抗菌蓝光；飞秒激光
**中图分类号：**O439　　**文献标志码：**A
**DOI：**10.16511/j.cnki.qhdxxb.2023.21.011

细菌、病毒等病原体导致的大规模致命疫情通常会造成大量人员伤亡。截至2023年1月，新型冠状病毒感染(corona virus disease 2019，COVID-19)疫情已在全球造成超过683万人死亡[1]。各种消毒技术被用于阻止有害病原体的传播。根据灭活原理，这些技术可分为化学消毒和物理消毒。化学消毒主要通过改变环境的pH或氧化性使病原体的蛋白质结构变形，丧失原有功能[2]。例如，氯化物被广泛用于水体消毒和表面去污[3]。物理消毒可以进一步分为热能消毒和辐射消毒。热能消毒的原理与化学消毒类似，主要利用高温下微生物蛋白质变性这一特点灭活微生物[4]。辐射消毒可分为电离辐射消毒和非电离辐射消毒。光照消毒是一种非电离辐射消毒，消毒效果取决于光照的强度、剂量和波长等参数[5]。

常用的消毒技术在消毒时都会对病原体的宿主产生无差别伤害。化学、热能和电离辐射消毒会使病原体周围的生物组织的蛋白质或核酸结构发生改变，造成损伤。紫外线(ultraviolet，UV)是最成熟的光照消毒技术，但UV同样会对病原体周围生物组织的核酸造成损伤[6]。这些技术均不适合对存在人员活动的空间进行长时间消毒。故有必要研究一种可以长时间作用于活体动物及植物的消毒技术，在不损害宿主细胞的前提下灭活病原体，保护宿主不受病原体侵害。

宿主无损光照消毒技术能够特异性灭活有害病原体，而不损伤其周围的生物组织，具有重要的应用前景。如在COVID-19疫情中，对人员流动较大的场合进行实时的表面消毒，将有助于避免病原体在人体和物品之间传播。此外，宿主无损消毒技术在食品保鲜、蔬果花卉的采后处理和医疗产品消毒等领域也应用广泛。

目前主流的宿主无损光照消毒技术包括207～222 nm远紫外线(far-ultraviolet radiation c，far-UVC)、抗菌蓝光(antibacterial blue light)和低功率超短脉冲激光消毒。本文详细阐述了这3种技术的原理、研究动态、适用场景和优缺点。对比了宿主无损光照消毒技术与传统紫外线消毒技术的技术特点。为促进宿主无损光照消毒技术实现更精准、更节能、更安全的消毒效果，从理论模型和实际应

**收稿日期：**2023-02-24
**基金项目：**国家重点研发计划项目(2021YFB2802004)
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用2方面展望了该类技术的发展趋势。

## 1 原理和研究动态

### 1.1 207～222 nm远紫外线消毒

图1为100～700 nm光谱图和UVC灭活原理图示。其中，UV段按波长由小到大划分为极紫外线(extreme ultraviolet，EUV)、短波紫外线(UVC)、中波紫外线(ultraviolet radiation b，UVB)、长波紫外线(ultraviolet radiation a，UVA)；207～222 nm的far-UVC处于UVC段。UVC消毒是应用最为广泛的光照消毒技术，能够灭活各种微生物[7]，包括抗生素耐药菌[8]和冠状病毒[9-11]。UVC的灭活原理是UVC能使脱氧核糖核酸或核糖核酸(desoxyribonucleic acid or ribonucleic acid，DNA或RNA)链中的胸腺嘧啶分子形成环丁烷嘧啶二聚体(cyclobutane pyrimidine dimers)，阻止核酸物质的表达，从而消除病原体的复制和感染能力[12-13]。由于UVC的波长范围处于DNA或RNA的峰值吸收带[14]，因此UVC是消毒能力最强的紫外线。

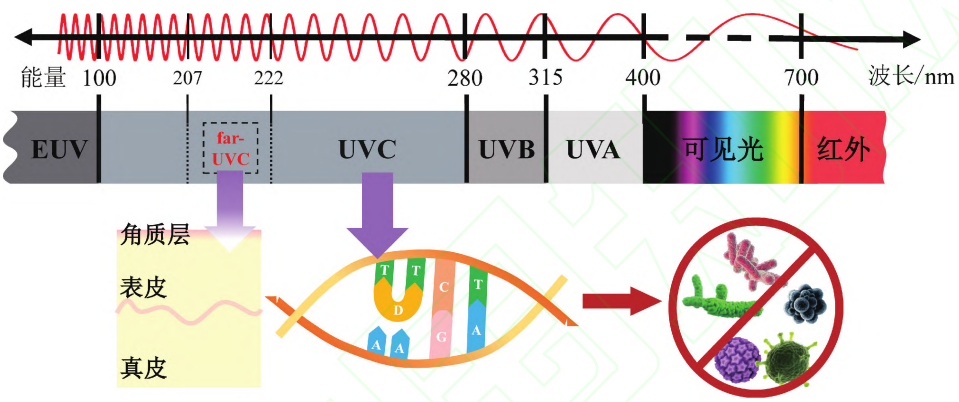


图1 100～700 nm光谱图和UVC灭活原理

大量研究表明，接受UV照射，病原体及其周围的活体组织都会出现核酸损伤情况。过量的UV对人体具有致癌性[15]。因此各国都对UV的最大照射剂量进行限制[13]。207～222 nm远紫外线波长较短，不足以穿透人类皮肤表面的角质层和眼睛外表面的泪膜[16]，被认为是一种安全的紫外线。2016年，Buonanno等[17]使用波长为207 nm、剂量为157 mJ/cm$^2$的远紫外线在无毛小鼠上进行哺乳动物皮肤细胞毒性的实验，结果表明：远紫外线具有无害性。文[18－19]在实验中长时间使用222 nm远紫外线对小鼠表皮进行照射，未导致突变或产生细胞毒性作用，这也验证了远紫外线的无害性。此外，Kaidzu等[20]证明，在30～600 mJ/cm$^2$的剂量下，远紫外线不会对大鼠的眼角膜造成损害。2020年，Fukui等[21]在人体上进行了大剂量的222 nm远紫外线照射实验。实验中，使用剂量为50～500 mJ/cm$^2$的222 nm远紫外线照射20名健康志愿者的背部，评估诱发红斑的情况，结果表明：所有受试者在所有剂量下均无红斑发生。

Buonanno等[22]和Welch等[16]验证了222 nm远紫外线可以有效灭活耐甲氧西林金黄色葡萄球菌(methicillin-resistant *Staphylococcus aureus*，MRSA)和H1N1流感病毒(具有“血球凝集素(hemagglutinin)第1型、神经氨酸酶(neuraminidase)第1型”的病毒)，并且对哺乳动物皮肤细胞没有毒性。这一性质在新型冠状病毒(severe acute respiratory syndrome coronavirus 2，SARS-CoV-2)暴发后引起了人们对该技术的广泛关注[13, 23]。文[24]使用远紫外线对2株以空气传播为传播途径的人类冠状病毒(HCoV-229E和HCoV-OC43)进行了灭活研究。由于人类冠状病毒的结构和静电特性与SARS-CoV-2的相似[25-26]，远紫外线也很有可能被应用于灭活SARS-CoV-2。207～222 nm远紫外线对不同微生物的灭活效果如表1所示。需要注意的是，由于光能密度受菌液密度、培养介质等因素影响，因此光能密度仅在实验条件下具有参考价值。

**表 1 207～222 nm 远紫外线对不同微生物的灭活效果**

| 类型 | 微生物种类 | 光能密度/（mJ·cm$^{-2}$） | lgCFU 减少量 | 文献 |
|---|---|---|---|---|
| 细菌 | MRSA | 75.0 | 0.90 | [27] |
| | 枯草芽孢杆菌 | 585.0 | 3.60 | [28] |
| | 单核细胞增生 Lister 菌（*Listeria monocytogenes*） | 174.0 | 4.58±0.02 | [29] |
| | 大肠杆菌（*Escherichia coli*） | 174.0 | 1.77±0.10 | [30] |
| | 鼠伤寒沙门氏菌（*Salmonella typhimurium*） | 261.0 | 2.27±0.51 | [30] |
| 病毒 | MS2 噬菌体 | 33.4 | 4.00 | [31] |
| | 轮状病毒 | 22.5 | 5.00 | [32] |
| | SARS-CoV-2 | 3.0 | 2.51 | [33] |
| | 杜兰病毒（Tulane virus） | 22.5 | 4.00 | [32] |
| 真菌 | 黑曲霉孢子 | 430.0 | 4.00 | [34] |
| | 白色念珠菌 | 72.0 | 约 3.00 | [35] |
| | 扩展青霉孢子 | 42.0 | 3.00 | [34] |

注：lgCFU 为菌落形成单位（colony forming units）的常用对数值。

目前学者们对远紫外线的研究有限，如对有关远紫外线的适用剂量标准和灭活动力学（inactivation kinetic）的研究就较为匮乏。Brantner 等[36]通过综述大量远紫外线研究，给出了建议的消毒剂量阈值，但缺少可以指导远紫外线剂量的权威标准。因此，尽管远紫外线不会导致传统 UVC 作用下常见的宿主核酸损伤问题，但仍必须遵守传统 UVC 剂量限制标准[37]，这在很大程度上限制了远紫外线的广泛应用。此外，难以通过已有文献中对特定微生物的灭活实验，对远紫外线灭活的剂量作出判断。其原因主要是不同微生物的 DNA 或 RNA 链中的胸腺嘧啶分子排布和数量不同，对远紫外线的敏感性存在差异。不同研究中，微生物所处环境对光能传输过程具有重要影响。相比固体介质，液体介质使用更低的光能密度即可获得近似水平的灭活率[29, 35]。病毒、细菌和真菌的微生物结构差异也可能影响紫外线传输。此外，环境的化学性质会影响微生物对远紫外线的抵抗能力。

## 1.2 抗菌蓝光消毒

20 世纪初，科学家发现，利用染料和可见光可以有效灭活微生物[38-39]。经过近 1 个世纪的研究，蓝光波段的可见光被证明可以在不添加其他物质的前提下灭活微生物，该技术被称为抗菌蓝光消毒。抗菌蓝光能灭活微生物是由于微生物内部存在某些可以吸收光能的内源性光敏剂（endogenous photosensitizer），如卟啉和黄素[40]等。这些内源性光敏剂能够将一些物质转化为活性氧（reactive oxygen species，ROS），ROS 具有强氧化性，能通过氧化邻近的生物大分子破坏微生物内部的细胞器等结构，进而使微生物失活[41-42]。

灭活过程的光敏反应见图 2，这些反应可分为Ⅰ型和Ⅱ型反应[43-44]。在Ⅰ型反应中，激发态三重态光敏剂 $T_1$ 参与电子转移（electron transfer）并产生超氧阴离子自由基（$O_2^{\cdot -}$）、过氧化氢（$H_2O_2$）、羟基自由基（HO·）。在Ⅱ型反应中，$T_1$ 激发三重态氧（$^3O_2$），生成单重态氧（$^1O_2$）。$^1O_2$ 和 HO· 都能对微生物细胞产生氧化伤害[45]，但 $^1O_2$ 是抗菌蓝光消毒过程中的主要毒性物质[44]。

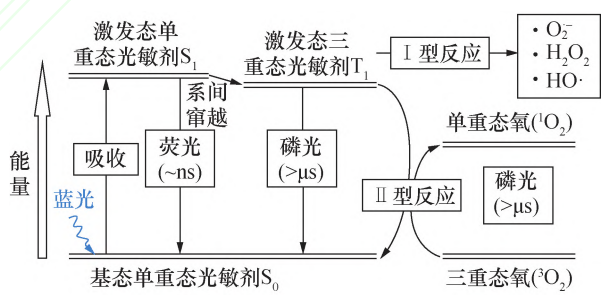


**图 2 抗菌蓝光消毒的光敏机制**

2008 年，Maclean 等[46]首次使用抗菌蓝光对金黄色葡萄球菌进行灭活。实验发现，400～425 nm 的紫蓝光均具有消毒能力，其中 405 nm 抗菌蓝光具有最佳的抗菌能力。文[47-48]认为，这是由于卟啉分子的最优吸收波长为 405 nm。文[49]还发现，相比革兰氏阳性细菌，革兰氏阴性细菌对 405 nm 抗菌蓝光的抵抗性更强。表 2 为抗菌蓝光对典型微生物的灭活效果。可以看出，抗菌蓝光对医疗相关的细菌（MRSA、淋病奈瑟菌等）和食品相关的细菌（大肠杆菌、单核细胞增生 Lister 菌、沙门氏肠炎杆菌等）以及一部分真菌均具有消毒能力。

**表 2 抗菌蓝光对不同微生物的灭活效果**

| 类型 | 微生物种类 | 光能密度/($J \cdot cm^{-2}$) | lgCFU减少量 | 文献 |
|---|---|---|---|---|
| 细菌 | 蜡状芽孢杆菌 | 306.0 | 2.30 | [50] |
| | 大肠杆菌 | 90.0 | 2.09 | [51] |
| | 摩拉维亚肠球菌(*Enterococcus moraviensis*) | 1 296.0 | 3.08 | [52] |
| | 单核细胞增生Lister菌 | 1 210.0 | 3.00 | [53] |
| | MRSA | 45.0 | 5.00 | [49] |
| | 淋病奈瑟菌(*Neisseria gonorrhoeae*) | 27.0 | 3.12 | [54] |
| | 金黄色葡萄球菌 | 306.0 | 4.00 | [50] |
| | 沙门氏肠炎杆菌(*Salmonella enteritidis*) | 450.0 | 1.40～2.10 | [55] |
| | 肉葡萄球菌 | 315.0 | 3.70 | [52] |
| 病毒 | ϕC31噬菌体 | 306.2 | 0.30 | [56] |
| | 诺如病毒 | 2 800.0 | 4.00 | [57] |
| 真菌 | 黑曲霉孢子 | 2 300.0 | 5.24 | [58] |
| | 灰葡萄孢菌 | 90.0 | 1.90 | [59] |
| | 白色念珠菌 | 576.0 | 5.02 | [58] |
| | 酿酒酵母 | 288.0 | 5.18 | [58] |
| | 匍枝根霉 | 90.0 | 3.20 | [59] |

在实际应用方面，高强度窄谱(high-intensity narrow-spectrum)抗菌蓝光可以在不损伤伤口愈合细胞的情况下维持组织的无菌性，从而用于伤口清创[60]。部分研究表明：抗菌蓝光能有效降低由创伤弧菌引起的烧伤感染风险[61]，以及被用于治疗中耳炎[62]、淋病[54]等。此外，抗菌蓝光可以灭活血浆中的细菌，用于血液制品生产[63]。

抗菌蓝光消毒是一种新的食品保鲜技术。研究发现，405±5 nm抗菌蓝光能在不破坏果实品质的前提下对鲜切芒果[64]、鲜切木瓜[65]、鲜切菠萝[66]表面的大肠杆菌、单核细胞增生Lister菌和沙门氏肠炎杆菌进行杀灭。抗菌蓝光对烟熏三文鱼[67]和新鲜鲑鱼保鲜[68]同样有效。此外，413 nm抗菌蓝光能够灭活悬浮在全脂牛奶中的金黄色葡萄球菌、大肠杆菌、铜绿假单胞菌(*Pseudomonas aeruginosa*)、鼠伤寒沙门氏菌和偶发分枝杆菌(*Mycobacterium fortuitum*)，且不会使牛奶成分发生显著变化[69]。在农产品采后处理领域，405 nm抗菌蓝光能抑制西红柿运输和储存过程中灰葡萄孢菌和匍枝根霉的生长，保持西红柿的理化质量[59]。

目前，关于抗菌蓝光的研究主要集中于细菌和真菌灭活，对病毒和原生动物灭活的研究有限。少数研究表明，抗菌蓝光对病毒的灭活需要1 kJ/$cm^2$以上的剂量[56-57]。病毒没有内源性光敏剂，故推测对病毒的灭活原理可能是光源发出的低水平UVA引起蛋白质氧化[70-71]，而非ROS氧化。因此，抗菌蓝光需要在外源性光敏剂的协助下才能通过ROS机制灭活病毒。近年来，利用姜黄素[72]、叶绿素[73]、核黄素[74]等由天然化合物提取的外源性光敏剂协同抗菌蓝光消毒成为该领域的一大热点。

### 1.3 低功率超短脉冲激光消毒

低功率超短脉冲激光通过机械振动使微生物失活，这与远紫外线和抗菌蓝光的光化学灭活机制不同。2007年，Tsen等[75]发现，强度大于50 mW/$cm^2$的低功率超短脉冲激光可以有效灭活M13噬菌体。这项技术被命名为选择性光子消毒(selective photonic disinfection，SEPHODIS)[76]。SEPHODIS的灭活原理是利用飞秒级的光脉冲通过冲击受激Raman散射过程直接激发病原体表面的蛋白质振动，破坏蛋白质之间的氢键等弱连接，诱导蛋白质重构，破坏病原体表面，阻止病原体感染细胞。

文[77-78]发现，低功率超短脉冲激光可以有效灭活小鼠巨细胞病毒(murine cytomegalovirus)、人类免疫缺陷病毒(human immunodeficiency virus，HIV)、人类乳头瘤病毒(human papillomavirus)、脑心肌炎病毒(encephalomyocarditis virus)和烟草花叶病病毒(tobacco mosaic virus)。这些病原体可以分为包膜RNA病毒、无包膜RNA病毒、包膜DNA病毒和无包膜DNA病毒，在结构上具有广泛性和代表性。表3为SEPHODIS对不同微生物的灭活效果，灭活条件为：波长425 nm，平均光功率50～140 mW，脉冲半峰全宽100 fs，照射时长1.0～1.5 h。

**表 3 SEPHODIS对不同微生物的灭活效果**

| 类型 | 微生物种类 | lgCFU减少量 | 文献 |
|---|---|---|---|
| 病毒 | 鼠诺如病毒 | 3.10 | [79] |
| | 脑心肌炎病毒 | 3.00 | [80] |
| | M13噬菌体 | 5.00 | [80] |
| | 甲型肝炎病毒 | 1.00 | [78] |
| | 小鼠巨细胞病毒 | 5.00 | [77] |
| | HIV | 2.00 | [78] |
| 细菌 | 单核细胞增生Lister菌 | 3.27 | [81] |
| | 鼠伤寒沙门氏菌 | 6.00 | [80] |
| 真菌 | 酿酒酵母 | 3.20 | [76] |

低功率超短脉冲激光的脉冲宽度、重复频率和波长都会影响消毒效果。根据机械振动理论，激光的脉冲长度最长为病原体振动周期的 1/4。重复频率提高会产生多重脉冲效应，使蛋白质振幅增大，降低灭活病原体所需的激光功率密度阈值[76]。此外，病原体内部存在的发色团会使 Raman 散射截面大幅度增加，使灭活病原体所需的激光功率密度阈值显著降低。80 MHz 的 425 nm 激光对 M13 噬菌体的灭活效果基本与 500 kHz 的 776 nm 激光一致，但前者所需要的激光功率密度阈值远低于后者[76, 82]。

低功率超短脉冲激光通过蛋白质机械振动灭活微生物，对微生物的种类没有限制。但一般认为，灭活病毒通过冲击受激 Raman 散射实现，而灭活细菌则主要是由于 425 nm 蓝光脉冲激光照射细菌产生的 ROS 损伤了其 DNA[80]。

在实际应用方面，不同的蛋白质具有不同的密度，振动持续时间存在差异，因此 SEPHODIS 可以通过不同的脉冲频率选择性灭活病原体，而不会对其他生物组织造成损害。由于其灭活过程中不会产生其他未知的中间产物，安全性更高，因此 SEPHOPIS 可以被用于疫苗生产[83-84]、血液制品消毒[78]和细胞培养基消毒[85]。

效率和成本限制了 SEPHODIS 的实际应用。机械振动需要持续若干小时才能改变微生物结构，这在要求实时消毒的场合是不太可能实现的。昂贵的飞秒激光器使 SEPHODIS 难以作为在公共场合大规模使用的消毒技术。此外，虽然 SEPHODIS 在理论上可以实现选择性灭活，但需要进行大量的实验以探索不同生物材料和病原体最适合的脉冲频率。

## 2 技术特点对比

宿主无损光照消毒技术均能在不损伤宿主细胞的同时灭活有害微生物，但由于其原理不同，这 3 种技术在灭活时长和灭活对象等方面均存在差异，因此分别适用于不同的场景。3 种宿主无损光照消毒技术与传统紫外线消毒技术对比如表 4 所示，表中还列举了其可能的应用方向。与传统紫外线消毒技术相比，宿主无损光照消毒技术在安全性方面具有优势，作为一种空间消毒技术，适用于在长时间有人员活动的空间中使用。特别是抗菌蓝光技术，由于波长为 400～470 nm，空间穿透性更强，有望解决当前紫外消毒产品无法对空间中较远距离的物体表面进行充分消毒的问题。

**表 4 3 种宿主无损光照消毒技术与传统紫外线消毒技术对比**

| 技术 | 远紫外线 | 抗菌蓝光 | 低功率超短脉冲激光 | 紫外线 |
|---|---|---|---|---|
| 波长 | 207～222 nm | 400～470 nm | — | 常用 254 nm |
| 灭活用时 | 短（s 级） | 较长（min 级） | 长（h 级） | 短（s 级） |
| 光源 | KrCl 准分子灯 | 氙气灯、LED、激光器 | Ti-蓝宝石激光器 | 发光二极管（light-emitting diode，LED）、汞灯 |
| 微生物种类 | 所有类型 | 细菌、真菌等 | 以病毒为主 | 所有类型 |
| 优点 | 快速灭活，灭活范围广；可以长时间在有人员活动的空间中使用，实现宿主无损消毒 | 对组织无害；光源成本低，易于控制；可以长时间在有人员活动的空间中使用，实现宿主无损消毒 | 不产生中间产物，生物安全性高；可以长时间在有人员活动的空间中使用，实现宿主无损消毒 | 快速灭活，灭活范围广；商业产品成熟 |
| 缺点 | 缺少权威标准，光源昂贵，穿透范围有限 | 无法在不添加外源性光敏剂的前提下灭活病毒，不同微生物的内源性光敏剂的类型和吸收峰需要确定 | 消毒需要的时间长，光源价格昂贵，作用机制复杂 | 对宿主细胞有害，对人体有致癌性，穿透范围有限 |
| 应用方向 | 表面近距离消毒、空气净化 | 伤口清创和疾病治疗、农产品采后处理和食品保鲜、空间大范围消毒 | 疫苗生产、血液制品消毒、细胞培养基消毒 | 无人场所的表面近距离消毒、空气净化 |

## 3 研究趋势展望

### 3.1 基于光传输过程的光能-灭活率模型

目前关于光能-灭活率模型的工作主要集中在实验数据拟合上，缺少机理推导方面的研究。在光能方面，相关研究一般使用光源的光功率作为指标[49, 63, 67, 86]。由于光在传播过程中会发生散射和吸收，因此该功率并非最终微生物实际所吸收的功率。大多数基于光照的消毒研究都采用一阶 Chick-Watson 模型[87]描述灭活过程：

$$\lg(N/N_0)=kE. \quad (1)$$

其中：$N/N_0$ 表示灭活率，$N_0$ 为初始微生物数量，$N$ 为该剂量作用后的微生物数量；$k$ 用来衡量微生物对光的敏感性，$cm^2/mJ$；$E$ 为光源的光能密度，$mJ/cm^2$。

一些研究利用更加精确但缺少物理意义的数学模型如 Kamau 模型[88]、修正的 Chick-Watson 模型[89]、Hom 模型[89]、Gompertz 模型[90]、Weibull 模型[91]等拟合实验结果，或者采取数据驱动的方法建立多参数模型[92]。然而，利用上述模型拟合实验结果不具有普遍性，改变实验环境和微生物种类都会改变拟合得到的方程参数。因此，应该充分考虑光能传输过程和灭活过程中所发生的光反应，以微生物实际吸收剂量作为灭活效果的评价标准，建立一个全面的光能-灭活率模型[93]。

### 3.2 最优光能密度和最优灭活波长

对不同微生物灭活时，不同波长光照所需的光能密度不同。在远紫外线消毒过程中，不同微生物的表面微结构及 DNA 或 RNA 排列不同，会影响远紫外线的传输和核酸破坏能力，从而使不同微生物对远紫外线的敏感性出现差异。不同微生物中内源性光敏剂的含量和种类不同[94]，会使多种波长的蓝光均可产生 ROS。最优光能密度的探究目标是针对不同种类细菌和不同波长光照，使用最少的能量实现充分的灭活效果。在最优灭活波长下达到相同的消毒效果所需光能密度是最少的，因此，当应用紫外线和蓝光消毒技术时，应充分考虑每一种微生物对应的最优灭活波长。最优光能密度与最优灭活波长的确定有助于实现宿主无损光照消毒技术的大规模节能应用。

### 3.3 多波长和多模式协同消毒

在未来的实际应用中，应充分考虑不同宿主无损光照消毒技术的优势与不足，在不同场景使用合适的多波长和多模式光照协同消毒，以提高消毒效率和充分性。在多波长方面，文[95]指出，双波长协同照射比单波长照射具有更显著的消毒效果。因此，使用多波长的抗菌蓝光可能是一种更有效的消毒技术。在多模式方面，低功率超短脉冲激光联合抗菌蓝光可以实现蛋白质机械振动和 ROS 破坏细胞器共同作用[96]。此外，间歇远紫外线协同连续抗菌蓝光也是一种可能方案，可以在尽量减少可能的紫外损伤的同时，实现公共空间无菌的目标。

## 4 结 论

宿主无损光照消毒技术能够特异性灭活有害病原体，而不损伤其周围的生物组织，在公共空间消毒、疾病治疗、食品保鲜和生物制品生产等领域具有重要的应用前景。本文综述了 207～222 nm 远紫外线、抗菌蓝光和低功率超短脉冲激光消毒的原理和研究动态，并比较了这 3 种技术的适用场景和优缺点。此外，展望了宿主无损光照消毒技术的研究趋势。在理论方面，应以微生物实际吸收剂量作为灭活效果的评价标准，建立一个全面的光能-灭活率模型；在实际应用方面，有必要确定最优光能密度和最优灭活波长，尝试多波长与多模式协同消毒，促进大规模、高效节能的宿主无损光照消毒技术的应用，阻断病原体的进一步传播。

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# Review of light-based host-nondestructive disinfection

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**Abstract**: [Significance] Pathogens have caused numerous, large, and deadly outbreaks, and various disinfection techniques have been applied to stop the spread of harmful pathogens. These techniques are classified as chemical and physical disinfection based on the principle of inactivation. However, the frequently used disinfection techniques can cause indiscriminate harm to the host. Ultraviolet (UV) light is the most popular light disinfection technique, followed by chemical, thermal, ionizing radiation, and thermal disinfection, which harm the pathogen-containing biological tissues by altering their protein or nucleic acid composition. These technologies are unsuitable for prolonged disinfection in the presence of human activity. Thus, there is a need to explore a disinfection technology that can be safely used on living beings for a prolonged period. The disinfection technique must inactivate the pathogen and protect the host from the pathogen but cause no harm to the host cells. Light-based host-nondestructive disinfection techniques specifically inactivate harmful pathogens without damaging the surrounding tissues and have important applications in space disinfection, disease treatment, food preservation, and biologics production. [Progress] Currently, far-UVC, antibacterial blue light, and low-power ultrashort pulse laser are some of the most widely used nondestructive light disinfection techniques. Far-UVC damages nucleic acids by forming cyclobutane pyrimidine dimers between thymine molecules in DNA/RNA, thereby eliminating the ability of pathogens to replicate and infect. The 207—222 nm far-UVC is considered safe as the short wavelength penetrates only the stratum corneum, the skin's outermost layer, and the outer surface of the eye. However, research on far-UVC is limited because applicable dose standards and inactivation kinetics are lacking. The disinfection ability of antibacterial blue light is due to the presence of certain endogenous photosensitizers inside microorganisms that absorb light energy, such as porphyrins and flavins. These endogenous photosensitizers convert some substances into reactive oxygen species (ROS), which destroy the internal structures, such as organelles, of the microorganism by oxidizing neighboring biomolecules and subsequently inactivating the microorganism. Currently, research on antimicrobial blue light has focused on bacterial and fungal disinfection, with limited research on the inactivation of viruses and protozoans. Because viruses do not have endogenous photosensitizers, antimicrobial blue light requires exogenous photosensitizers to inactivate the virus through the ROS mechanism. Low-power ultrashort pulse laser creates vibrations on the surface of pathogens using femtosecond-level light pulses to induce protein remodeling, which destroys the surface of pathogens and prevents infection. Different proteins differ in densities and vibration durations, so a low-power ultrashort pulse laser selectively inactivates pathogens by varying the pulse frequency without causing damage to other biological tissues. As the inactivation process does not produce unknown intermediates, it is safe to use in the production of vaccines, sterilization of blood products, and disinfection of cell culture medium. [Conclusions and Prospects] Light-based host-nondestructive disinfection techniques should be evaluated using the actual absorbed dose of microorganisms as the criterion for the inactivation effect, and a comprehensive light energy inactivation rate model should be established. It is necessary to explore the optimal light energy density, optimal inactivation wavelength, and multiwavelength and multimodal synergistic disinfection to promote the application of large-scale energy-efficient light inactivation technology to prevent the spread of pathogens.

**Key words**: biological optics; disinfection technology; far-UVC; antibacterial blue light; femtosecond laser

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