



界面光热绿色蒸汽驱动低碳创新

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摘要 太阳能界面蒸发, 通过将太阳能光热转换限域在气液界面实现高效水蒸发, 已成为太阳能利用的重要路径之一. 其产生的“绿色蒸汽”以太阳能为唯一驱动力, 具备低成本、高效率和环境友好等优势, 在水资源利用、清洁能源生产、环境保护以及医疗健康等领域发挥重要作用. 绿色蒸汽驱动的低碳创新, 不仅为我国实现“双碳”目标提供了坚实支撑, 也为推动绿色经济转型和培育新质生产力奠定了技术基础. 本文系统总结了界面光热绿色蒸汽在能源、资源、农业、环境、健康等领域的最新进展, 深入探讨了材料设计、器件构筑与系统集成创新策略, 并评估其产能潜力、应用可行性及发展挑战. 最后, 本文展望了基于绿色蒸汽的全光谱太阳能利用及多产品联产, 旨在进一步提升太阳能综合利用效率, 为我国绿色低碳产业发展和循环经济体系建设开辟新路径.

关键词 绿色蒸汽, 界面蒸发, 微纳结构, 光热转换, 低碳技术

太阳能界面蒸发技术通过微纳结构设计和光热协同调控, 将能量转换过程局域于气-液界面, 突破了传统体相加热模式光吸收差、热损耗大的瓶颈, 为能源转型、环境治理及资源开发提供了变革性解决方案^[1-10]. 在无聚焦、非绝热条件下, 太阳能界面蒸发可实现接近热力学极限的太阳能利用效率(92.5%^[5]), 已成为我国实现“双碳”目标的重要路径之一.

太阳能界面蒸发生成的蒸汽是理想的能源和资源载体, 与依赖化石燃料的传统蒸汽生产方式相比, 其仅靠太阳能驱动, 因此被称为“绿色蒸汽”(图1). 凭借低成本、高效率和环境友好等优势, 绿色蒸汽已形成资源、能源、环境、健康协同发展的多维应用体系(图1)^[5,11-14]. 在环境与水资源领域, 太阳能界面蒸发能够高效净化苦咸水^[15]、海水^[4]及工业废水^[16], 回收水资源并产出高纯度盐产品^[17]. 在能源领域, 通过耦合界面蒸发与光伏系统^[18], 绿色蒸汽不仅能增强光伏板散热

(降温11°C), 提升光电转换效率(提高7.9%), 还可冷凝生成饮用水(0.8 L m⁻² h⁻¹), 实现水电联产. 在医疗健康领域, 绿色蒸汽的高温特性(>120°C)可有效杀灭细菌^[19,20], 突破传统医疗灭菌设施对电网的依赖, 为离网医疗设备提供了新方向. 在资源开发领域, 绿色蒸汽能够驱动纳滤^[10]、吸附^[21]等过程, 为盐湖提锂、海水提铀等提供绿色解决方案. 在农业生态领域, 基于绿色蒸汽的“海水-蒸汽-灌溉水”循环系统, 实现了可持续灌溉与盐碱土壤改良^[22-24], 助力农业可持续发展. 尽管已取得诸多突破, 太阳能界面蒸发在机制探究、材料创新和器件开发等方面仍有广阔的研究空间, 持续创新将推动这一新兴领域为全球能源、资源与环境挑战提供可持续的解决方案.

基于此, 本文系统总结了绿色蒸汽驱动的低碳技术在能源、资源、农业、环境和健康等领域的最新进展, 探讨了其在材料、器件与系统层面的设计策略, 评

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图1 (网络版彩色)界面光热绿色蒸汽已形成资源、能源、环境、健康协同发展的多维应用体系

Figure 1 (Color online) Green steam, generated via interfacial photothermal conversion, supports a multidimensional application framework spanning resources, energy, environment, and health

估了其产能潜力、实用性及未来发展面临的挑战。最后, 本文展望了基于绿色蒸汽的全光谱太阳能利用及多产品联产, 为提高太阳能综合利用效率提供了新思路。

1 绿色蒸汽的界面蒸发生成机制

绿色蒸汽通过太阳能界面蒸发高效产生, 其核心机制是将太阳能光热转换局域在气-液界面, 从而降低热损耗并提升能量转换效率(图1)。该过程包括三个关键步骤: 首先, 界面蒸发材料吸收太阳辐射并将其转化为热能; 其次, 热量通过材料传导至水体表面; 最后, 水体在气液界面吸收热量并发生蒸发。该过程涉及光吸收、热传导、热辐射与热对流等多种能量转换与传递机制。根据能量守恒原理, 绿色蒸汽的通量可由式(1)描述:

$$\dot{m}h_{\text{fg}} = A\alpha q_{\text{solar}} - A\varepsilon\sigma(T^4 - T_{\infty}^4) - Ah(T - T_{\infty}) - Aq_{\text{water}}, \quad (1)$$

其中, $\dot{m}$ 为绿色蒸汽通量, T 为蒸发材料表面温度, h_{fg} 为水在温度 T 下的气液相变潜热, A 为界面蒸发材料的受光面积, α 为界面蒸发材料光吸收率, q_{solar} 为太阳辐射功率, ε 为界面蒸发材料表面发射率, σ 为玻尔兹曼常数, T_{∞} 为环境温度, h 为热对流系数, q_{water} 为吸收体对

水体的热传导和热辐射的等效热流密度。

基于太阳能界面蒸发生成绿色蒸汽的能量转换效率(η)定义为水蒸发吸收的热量与入射太阳辐射总能量的比值:

$$\eta = \frac{\dot{m}h_{\text{LV}}}{Aq_{\text{solar}}}, \quad (2)$$

其中, h_{LV} 为包括显热和相变潜热在内的总蒸发焓变, A 为界面蒸发材料的受光面积, q_{solar} 为太阳辐射功率。

由式(1)和(2)可以看出, 在恒定太阳辐射条件下, 界面蒸发材料的光吸收能力决定了系统的能量输入, 而热损失(包括热传导、热辐射和热对流)显著影响绿色蒸汽的通量与能量转换效率。此外, 持续稳定地向蒸发界面供水也是实现高通量与高效率绿色蒸汽生成的关键^[2,9]。

目前, 已有多篇综述系统总结了界面蒸发材料的结构设计与功能构效关系^[2,9,11,14], 以优化绿色蒸汽的产量与能效。本文不再赘述材料设计的综述内容, 而是聚焦于以绿色蒸汽为核心的太阳能界面蒸发技术应用, 系统探讨其在纯净水制备、关键资源提取、农业灌溉和生产绿电等方向近零碳排放的发展路径与应用潜力。

2 绿色蒸汽生产饮用水

绿色蒸汽可用于生产高质量饮用水。研究表明, 以绿色蒸汽制得的蒸馏水, 其离子浓度等指标均符合世界卫生组织饮用水标准^[4,25~27]。据估算, 绿色蒸汽产水的成本约为0.4~2.2美元/吨^[28~32], 远低于小型反渗透系统的5~10美元/吨^[33], 接近大型集中式水处理设施的0.9~1.4美元/吨^[34]。目前, 基于绿色蒸汽的水净化技术已发展出多种运行模式, 如蒸发-冷凝串联、太阳能蒸汽驱动膜分离等。以下将系统介绍绿色蒸汽生产饮用水的主要技术路线。

2.1 蒸发-冷凝净水器

常见的绿色蒸汽净水装置由太阳能界面蒸发单元与冷凝单元串联组成。蒸发单元通常采用碳材料或金属等离激元材料, 通过电子激发-弛豫过程^[35,36]或者局域表面等离激元共振效应^[4,37], 高效吸收太阳辐射并将其转化为热能。同时, 结合微纳结构设计^[38,39]与光学、热学协同调控, 热量被局域在气-液界面, 产生局部高温, 进而促进液态水快速汽化。生成的水蒸气在蒸汽压梯度驱动下扩散至冷凝界面, 凝结成微液滴, 最终在重力作用下汇聚为液态水^[38,39]。

目前,该类系统的蒸发效率已突破90%^[40,41],但冷凝单元的传热、传质瓶颈仍限制整体产水效率^[42].传统冷凝单元多采用透明盖板结构,常用材料包括聚甲基丙烯酸甲酯(PMMA)、聚对苯二甲酸乙二醇酯(PET)和玻璃等,主要依靠盖板与蒸汽间的温差驱动冷凝^[21,43](图2(a)).尽管结构简单、价格便宜,该方案仍面临三方面挑战:(1) 冷凝液滴易引发多重散射,造成高达35%的入射光能量损失^[42,44];(2) 盖板材料导热性差(导热系数 $<5\text{ W m}^{-1}\text{ K}^{-1}$ ^[42,45]),造成热阻累积,削弱冷凝效率^[46];(3) 封闭结构易形成非冷凝气体层,进一步增加热阻并抑制冷凝^[47].

为解决液滴折射引起的光损失问题, Zhu等人^[42]提出了倒置式界面蒸发-冷凝产水结构(图2(b)).该结构通过将冷凝单元置于蒸发单元下方,实现了光热蒸发与蒸汽冷凝过程的空间解耦.在倒置式结构中,冷凝界面无需透光,因此可选用导热性能优异的金属材料,如

铜^[42]、铝^[48](导热系数 $>400\text{ W m}^{-1}\text{ K}^{-1}$),显著增强冷凝产水性能.实验结果表明,倒置式蒸发-冷凝净水器的能量转换效率高达70%^[42],显著优于传统结构的~35%^[42,46].

为加快蒸汽扩散,研究者提出利用气流增强蒸汽流动的策略. Deng等人^[47]开发了一种集成振动悬臂梁的太阳能界面蒸发净水器,利用水波驱动悬臂梁振动,促进蒸汽迁移(图2(c)).该系统在封闭环境下实现了 $1.9\text{ kg m}^{-2}\text{ h}^{-1}$ 的蒸发速率,并在户外湖面测试中维持了 $1.8\text{ kg m}^{-2}\text{ h}^{-1}$ 的平均产水速率,冷凝水盐度仅为34 ppm,符合饮用水标准.与依赖风扇或泵的强制对流方式相比,该策略借助自然水体的扰动调控气流,无需外接电源或复杂控制系统,结构简单,适应性强,为绿色净水提供了新思路.

为突破单级系统的热力学限制,研究者提出了多级联用系统(图2(d)),通过回收冷凝潜热,提高能量利

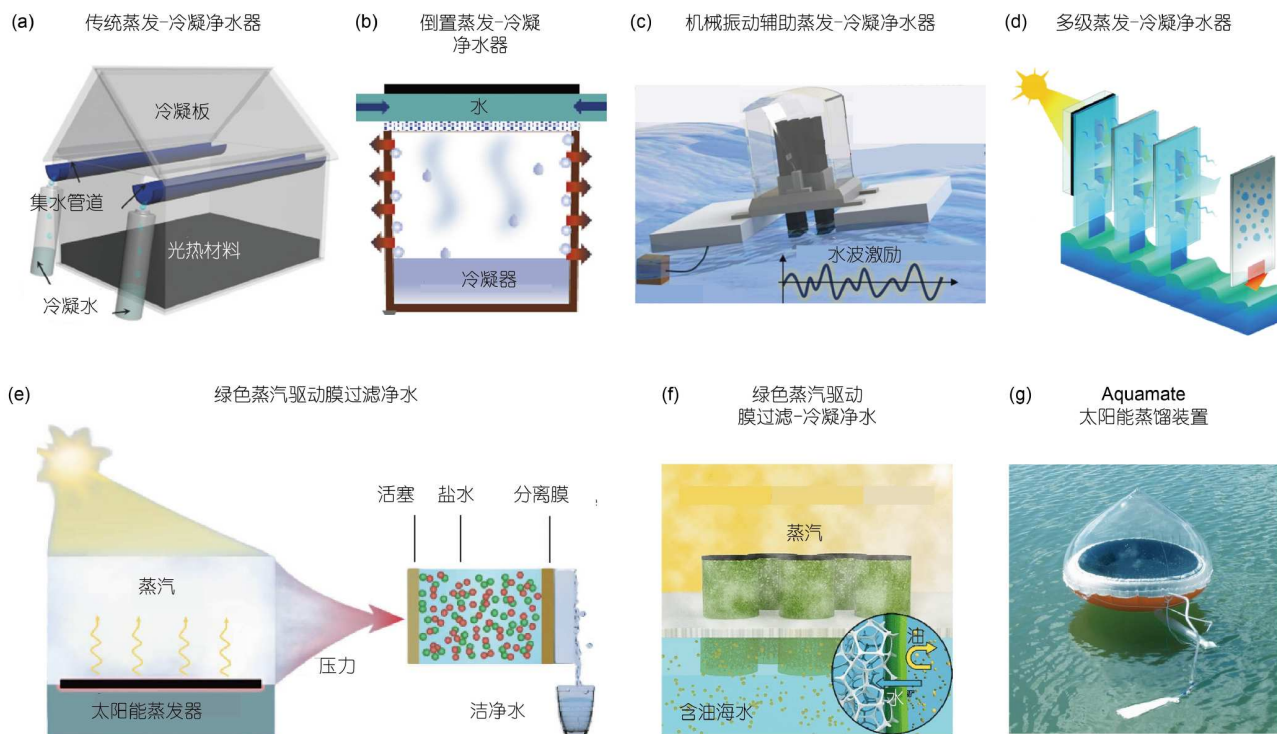


图2 (网络版彩色)绿色蒸汽生产饮用水. (a) 传统蒸发-冷凝净水器示意图, 多采用透明盖板结构, 依靠盖板与蒸汽间的温差驱动冷凝^[43]; (b) 倒置蒸发-冷凝净水器示意图^[42]; (c) 机械振动辅助蒸发-冷凝净水器示意图^[47]; (d) 多级蒸发-冷凝净水器示意图^[48]; (e) 绿色蒸汽驱动膜过滤净水^[50]; (f) 绿色蒸汽驱动膜过滤-冷凝净水^[51]; (g) Aquamate Systems公司开发的太阳能蒸馏装置(Aquamate Solar Still)

Figure 2 (Color online) Green steam-based potable water production. (a) Schematic diagram of conventional evaporation-condensation purifier, which adopts a transparent cover and relies on the temperature difference between the cover and steam to drive condensation^[43]; (b) schematic diagram of inverted evaporation-condensation purifier^[42]; (c) schematic diagram of mechanically vibrated evaporation-condensation purifier^[47]; (d) schematic diagram of multi-stage evaporation-condensation purifier^[48]; (e) green steam-driven membrane filtration for water purification^[50]; (f) green steam-driven membrane filtration and condensation for water purification^[51]; (g) the solar distillation device developed by Aquamate Systems (Aquamate Solar Still)

用效率^[48,49]。其原理是构建多级蒸发-冷凝结构,回收前一级的冷凝潜热为后一级的蒸发提供能量,从而提升整体能效。Xu等人^[48]开发了一种热局域多级太阳能蒸馏系统。该系统中冷凝器既是前一级的产水界面,又是后一级的加热源,实现了冷凝潜热的再利用。通过优化空气间隙、蒸发器尺寸和级数,并引入隔热材料,该研究构建了10级蒸发-冷凝净水系统。在标准太阳光照下(1 kW m^{-2}),该系统的产水速率达到 $5.78 \text{ L m}^{-2} \text{ h}^{-1}$,太阳能-蒸汽转化效率达到385%,约为单级装置的五倍。

2.2 绿色蒸汽驱动膜过滤产水

绿色蒸汽不仅可高效驱动蒸发冷凝产水,也可与膜分离技术耦合,实现从复杂水源中获取纯净水。根据耦合方式的不同,当前研究主要发展出两类策略:一类是以绿色蒸汽作为驱动力,推动盐水通过反渗透或纳滤膜实现脱盐产水^[50];另一类是结合膜过滤单元和界面蒸发过程,提升处理含油废水的稳定性与水质安全性^[51-53]。

绿色蒸汽具有高压特性,能够驱动盐水通过低能耗的反渗透膜或纳滤膜过滤,生产纯净水(图2(e))^[50]。Wang等人^[50]开发了一种太阳能蒸汽驱动的反渗透/纳滤装置,采用碳泡沫/碳纳米管复合光热材料高效吸收太阳能,加热乙醇生成高压乙醇蒸汽,推动海水通过分离膜。在12倍太阳光强下(12 kW m^{-2}),该装置产水速率达到 $81 \text{ kg m}^{-2} \text{ h}^{-1}$,显著优于传统蒸发-冷凝产水装置的 $0.4\sim 5.3 \text{ kg m}^{-2} \text{ h}^{-1}$ 。

在含油废水处理中,传统界面蒸发法存在油乳液堵塞通道和挥发性有机物污染冷凝水的问题。为此,研究者将膜过滤单元引入界面蒸发系统,利用膜选择性地透过水分子,阻挡油污,实现更清洁的产水过程。Wu等人^[51]开发了一种仿植物根结构的薄膜复合(TFC)蒸发器,结合超疏油海藻酸钙水凝胶的选择屏障作用与多孔海绵骨架的快速输水能力,构建出高效的膜过滤-蒸发-冷凝耦合系统(图2(f))。该器件由三部分组成:外层水凝胶膜阻挡油乳液,仅允许水分子透过;中间海绵层提供高通量水传输;顶部碳墨光热层高效吸收太阳能,驱动蒸发。在标准太阳光照下,阵列式TFC蒸发器蒸发速率达 $3.10 \text{ kg m}^{-2} \text{ h}^{-1}$,对多种油乳液的去除率超过99.9%,且在处理10 wt%高浓度乳液连续运行8小时后仍保持稳定性能。

2.3 绿色蒸汽净水技术的应用前景与挑战

绿色蒸汽净水技术已取得显著进展。表S1总结了

不同绿色蒸汽驱动水净化技术的产水性能。倒置蒸发-冷凝净水器的产水速率可达 $1.0 \text{ kg m}^{-2} \text{ h}^{-1}$,蒸发-膜过滤净水器在12倍太阳光强下,产水速率可达到 $81 \text{ kg m}^{-2} \text{ h}^{-1}$ 。这些结果展示了绿色蒸汽技术在净化多种水源并获得饮用水方面的潜力,特别是在脱盐和废水处理领域的广泛应用前景。

目前,绿色蒸汽净水技术已初步实现商业化。如图2(g)所示,Aquamate Systems公司开发的太阳能蒸馏装置(Aquamate Solar Still)已用于海水淡化。该装置由透明顶盖和光热蒸发材料组成,蒸发材料吸收太阳光并将其转化为热能,加热海水生成水蒸气,水蒸气在透明顶盖表面冷却为水滴,收集获得饮用水。

然而,现有技术在大规模应用中仍面临挑战。首先,技术的大规模应用稳定性仍需进一步验证;其次,现有测试多基于稳定光照或理想环境条件^[13],与实际环境(如光照波动和水质变化)存在显著差异。因此,未来需通过技术优化,开展长期实地测试,提升系统的稳定性。同时,必须持续监测水质安全和运行维护成本,确保技术的可行性与可持续性。

3 绿色蒸汽实现可持续农业

全球水资源短缺日益加剧^[54],农业作为全球用水消耗的主要领域(约占80%)^[55],其低碳可持续用水策略亟需突破。绿色蒸汽技术通过太阳能驱动海水淡化,可高效产出适用于农业灌溉的纯净水源^[23,56-61]。相比依赖集中式海水淡化设施的传统海洋农业模式^[62,63],该技术大幅降低了水资源获取的成本和碳排放^[64-66]。此外,所产淡水还可用于土壤修复^[24]和盐碱地治理^[22],为海上漂浮农场^[23]等新型农业场景提供了可行路径。

农业用水与饮用水在水质要求上存在本质差异。饮用水需满足严格的卫生与安全标准,限制微生物、重金属及有机污染物浓度,以保障人体健康;而农业灌溉更关注水对作物生长和土壤结构的适应性,容许一定量的盐分和杂质存在。例如,总溶解固体在饮用水中建议不超过 $500\sim 1000 \text{ mg L}^{-1}$,而农业灌溉水则可容忍高达 2000 mg L^{-1} ,部分耐盐作物甚至可承受更高浓度。同时,农业用水中允许较高浓度的钠、氯、硼等离子,只要不对作物和土壤造成损害。这一差异使界面光热蒸发技术无需过度净化,即可满足农业灌溉需求,具备更大的应用潜力。另一方面,农业系统设计还需统筹考虑太阳光谱能量的合理分配。植物的光合作用依赖于特定波段的可见光,而光热蒸发同样依赖太阳能驱动,

二者在有限光照资源下存在能量竞争. 如何优化光能在蒸发产水与作物光合之间的分配, 是提升系统整体效率与作物产量的关键. 此外, 土地与空间利用效率亦是农业应用中必须权衡的重要因素. 本节将重点综述太阳能蒸发器件在农业灌溉与土地修复领域的优化设计与研究进展.

3.1 界面蒸发技术在农业灌溉中的应用

界面蒸发海洋农业系统通常采用双腔室结构(图3(a)), 包括太阳能海水淡化腔室和农业种植腔室, 通过管道输送淡水. 例如, Zou等人^[57]开发了一种基于3D桥拱界面蒸发器的太阳能海水淡化-种植集成系统. 在海水淡化腔室中, 仿生桥拱结构通过诱导Marangoni流动, 实现稳定的海水蒸发(10 wt%的盐水连续运行200小时). 冷凝收集的淡水供给种植腔室中的作物生长. 实

验表明, 使用脱盐水灌溉, 麦苗的生长速率达到 18 g d^{-1} , 与地下水灌溉相当, 验证了界面蒸发技术在海洋农业中的可行性. 然而, 双腔室设计由于功能模块分离, 占用较大空间, 限制了单位面积的资源产出效率.

为提升单位面积资源产出效率, Wu等人^[60]提出了一种叠层海水淡化-作物种植设计方案(图3(b)). 他们开发了一种双层垂直太阳能海上农场, 底层利用太阳能界面蒸发技术蒸发海水生成清洁水, 顶层用于植物种植; 并利用毛细管将底层淡水输送至上层土壤, 实现自动灌溉. 该系统海水蒸发速率达到 $1.29\text{ kg m}^{-2}\text{ h}^{-1}$, 能够支持西蓝花、生菜、小白菜等多种蔬菜的生长.

现有海水淡化-作物种植系统普遍存在太阳能利用率低的问题: 作物只能吸收光合有效辐射波段(主要是 $400\sim 700\text{ nm}$, 可拓展至 $300\sim 800\text{ nm}$)进行光合作用^[67-69], 大量红外光未被利用. 为提高光能利用效率,

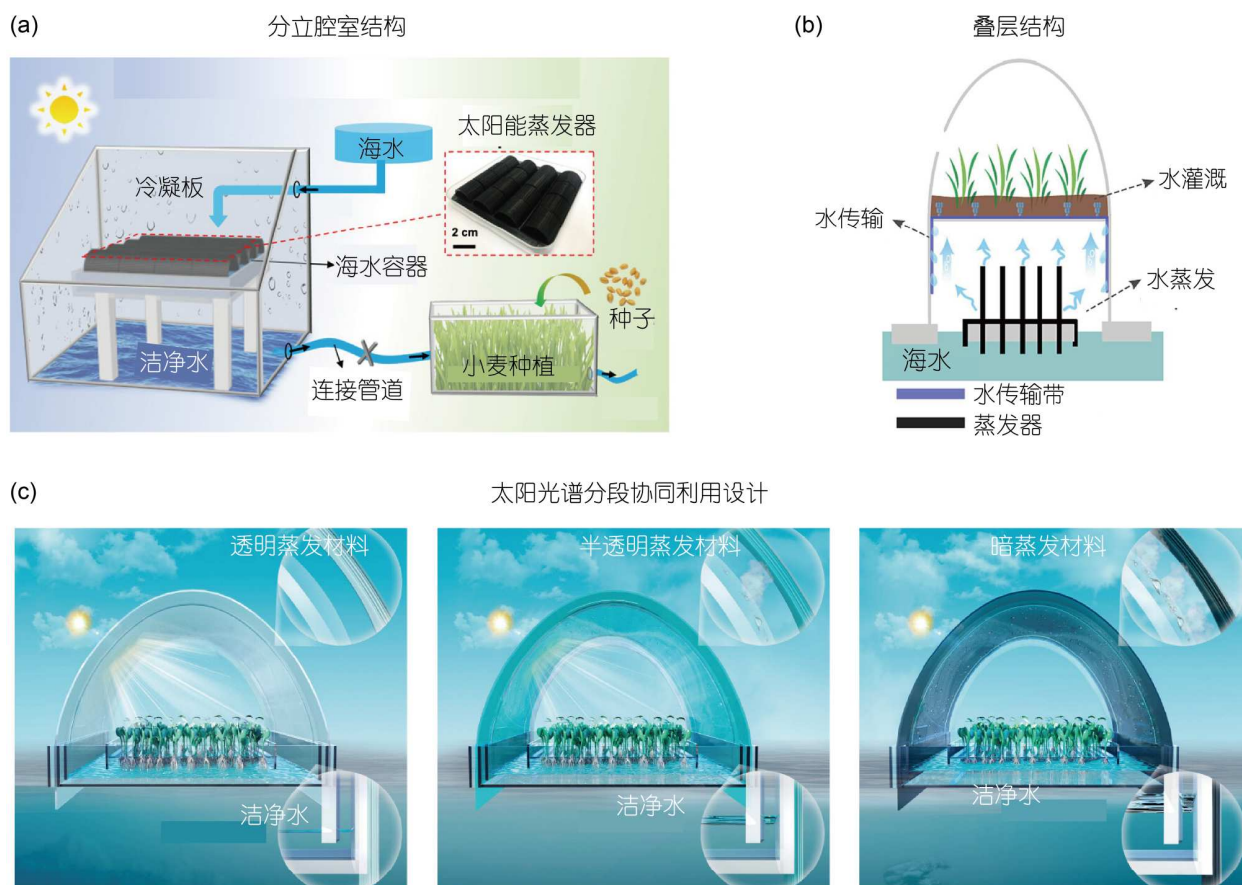


图3 (网络版彩色)界面蒸发技术在农业灌溉中的应用. (a) 分立腔室结构的太阳能海水淡化-种植系统^[57]; (b) 叠层太阳能海水淡化-种植系统^[60]; (c) 太阳光谱分段协同利用提升界面蒸发-农业系统效率^[23]

Figure 3 (Color online) Application of interfacial evaporation technology in agricultural irrigation. (a) Solar desalination-planting system with separate chamber structure^[57]; (b) stacked solar desalination-planting system^[60]; (c) synergistic utilization of solar spectrum segmentation to enhance the efficiency of interfacial evaporation-agriculture system^[23]

Bian等人^[23]提出了太阳光谱分波段协同利用策略(图3(c)). 他们设计了一种可调透光率的木质圆顶, 使可见光和部分紫外光(300~800 nm)透过圆顶供植物光合作用, 同时吸收800 nm以上的红外光驱动海水淡化. 此外, 他们引入动态光-水调控策略, 根据作物生长阶段调整光照与水资源配比. 例如, 在萌芽期使用全吸光材料以提供充足水分; 生长期则切换至半透明圆顶, 兼顾光照和灌溉需求. 该策略显著提升了太阳能和土地利用效率, 为海洋农业可持续发展提供了新路径.

在水-食物联产基础上, Wang等人^[70]将盐度梯度发

电技术与界面蒸发海洋农场相结合, 构建了“水-电-食物联产”一体化系统(图4(a)). 该系统采用石墨烯-三聚氰胺气凝胶作为界面蒸发材料, 实现高效太阳能海水淡化, 蒸发速率达到 $1.42 \text{ kg m}^{-2} \text{ h}^{-1}$, 光热转换效率达到89.4%. 在海水淡化过程中, 系统利用浓缩海水与淡水之间的盐差发电, 峰值功率密度达 $\sim 0.25 \text{ W m}^{-2}$. 生成的淡水则用于小麦灌溉, 7天内幼苗高度达到85 mm, 与地表水灌溉效果相当. 该系统仅靠太阳能输入, 能够同时实现淡水生产、盐差发电和作物灌溉, 为解决水、能源、粮食危机提供了创新方案.

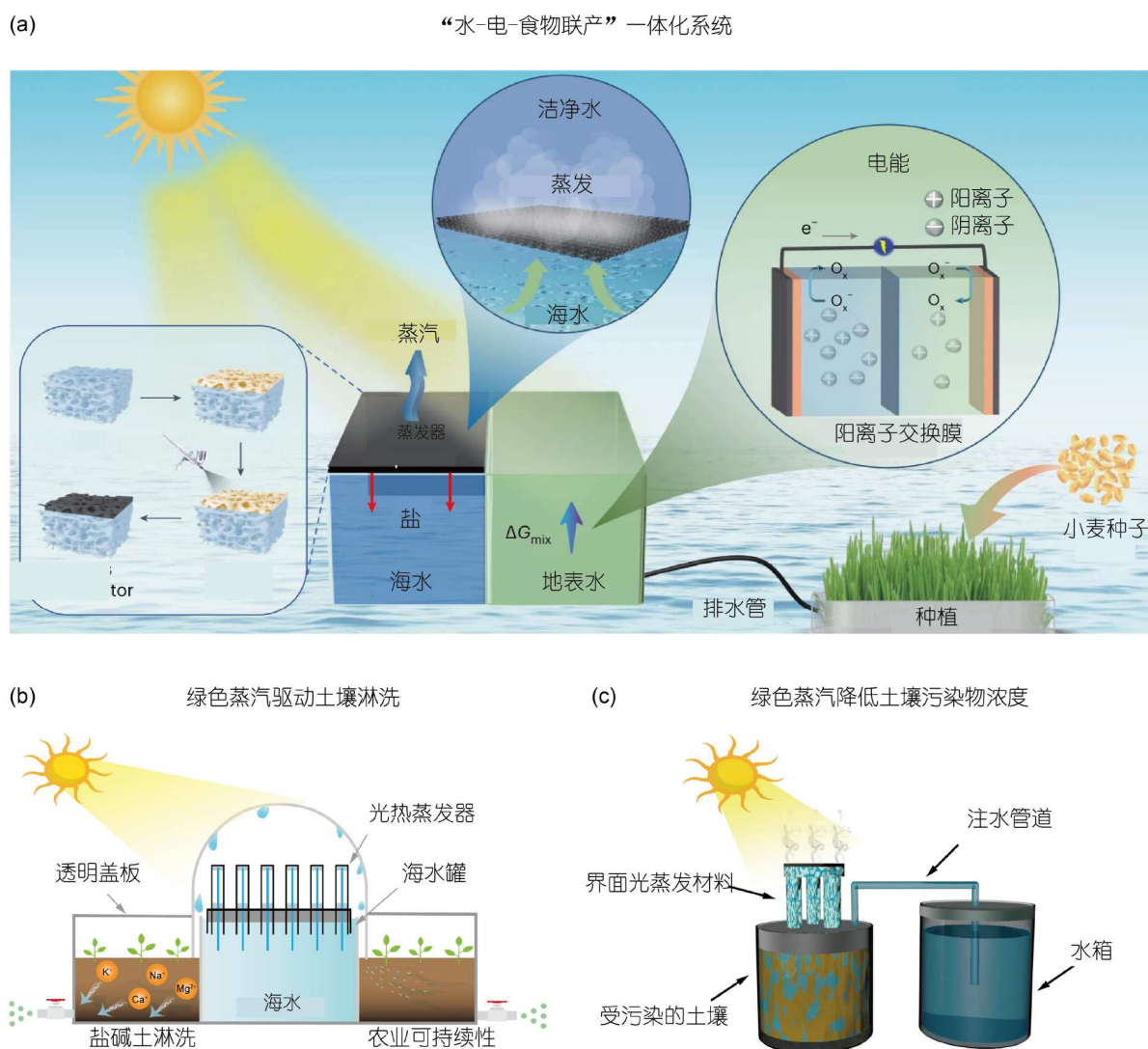


图4 (网络版彩色)界面蒸发技术在农业灌溉与土壤修复中的应用. (a)“水-电-食物联产”一体化系统^[70]; (b)绿色蒸汽驱动土壤淋洗^[22]; (c)绿色蒸汽降低土壤污染物浓度^[24]

Figure 4 (Color online) Application of interfacial evaporation technology in agricultural irrigation and soil remediation. (a) An integrated water-electricity-food co-production system^[70]; (b) green steam-driven soil leaching^[22]; (c) green steam-driven reduction of soil pollutant concentration^[24]

3.2 绿色蒸汽驱动土壤修复

绿色蒸汽在土壤修复领域展现出显著的应用潜力^[22,71~73],其修复机制包括淋洗脱盐^[22]和仿生植物修复^[24,71~73]等.修复后的土壤符合农业用地标准,可实现资源再利用(表S2).

绿色蒸汽可与土壤淋洗技术结合,修复盐碱地(图4(b)).Wu等人^[22]开发了一种太阳能驱动的土壤淋洗装置,其利用太阳能界面光热材料驱动海水蒸发,原位生成淡水,实现盐碱土壤的淋洗与可持续灌溉.该系统采用三维界面蒸发材料,每日可产淡水 10.95 kg m^{-2} ,淋洗效率是传统自然蒸发的3倍.处理后,土壤电导率从 6.72 mS cm^{-1} 降至 0.14 mS cm^{-1} ,植物发芽率从0%提升至65%.这一方法为海岛盐碱地区提供了绿色的水土资源治理方案.

绿色蒸汽还可与仿生蒸腾材料结合,降低土壤中重金属污染物浓度^[73](图4(c)).该技术通过仿生植物蒸腾结构,在材料表面构建污染物吸附位点,有效捕获土壤中的重金属离子^[24,72].Wu等人^[24]开发了一种太阳能驱动的光热蒸发土壤修复装置,利用氧化石墨烯基光热材料增强水蒸发并加快重金属吸附.两周内,土壤铅含量从 359 mg kg^{-1} 降至 221 mg kg^{-1} ,且无营养流失或二次污染.与传统植物修复相比,该方法处理速度快4.6倍,植物毒性显著降低,处理后生菜根部铅含量减少47.9%.

4 绿色蒸汽生产绿电

绿色蒸汽可通过热电^[74]、热电化学^[75]、盐度梯度发电^[76]等技术,将内能高效转化为电能,提供多元化的清洁能源生产路径.此外,将太阳能界面蒸发系统与光伏电池结合^[18],可实现水电联产,为偏远地区提供离网式清洁能源和资源解决方案.

4.1 热梯度发电

绿色蒸汽的内能可以通过热电技术转化为电能.Li等人^[74]开发了一种集成绿色蒸汽与热电转换的装置,能够同时生产清洁水和电能.如图5(a)所示,该装置以自然水源为原料,通过太阳能界面蒸发技术生成高温蒸汽.蒸汽随后被输送至储热模块,通过热交换储存热量,并在冷却过程中凝结成水滴,提供洁净水.储存的热量则通过热电模块转化为电能.在30倍太阳辐照下(30 kW m^{-2}),系统的功率输出可达 292.9 W m^{-2} ^[74].

另一种将绿色蒸汽内能转化为电能的方式是热电化学发电.Zhao等人^[75]将绿色蒸汽与热电化学电池结合,回收蒸汽冷凝潜热发电(图5(b)).该系统由光热蒸发和热电化学两部分组成:光热蒸发单元采用还原氧化石墨烯/竹纸作为蒸发层,侧面覆盖聚苯乙烯泡沫以减少热损失,实现高效蒸发;热电化学模块使用 $\text{Fe}(\text{CN})_6^{3-/4-}$ 电解质,利用温差推动 $\text{Fe}(\text{CN})_6^{3-}$ 在热端氧化, $\text{Fe}(\text{CN})_6^{4-}$ 在冷端还原,将冷凝潜热转化为电能.户外测试中,该装置能够产生 $10\sim 15.2^\circ\text{C}$ 温差,最大开路电压 248 mV ,最大短路电流 $87\text{ }\mu\text{A}$.其功率密度仍低于传统高温热电材料,需进一步提升氧化还原对的扩散效率以增强性能.

热释电技术利用温度波动进行发电,是一种新兴的绿色发电方式.Jiang等人^[77]结合太阳能界面蒸发技术与热释电发电技术,通过温度周期性变化将热能转化为电能(图5(c)).该系统由钨掺杂二氧化钒(W-doped VO_2)和聚偏二氟乙烯(PVDF)复合薄膜构成.在太阳辐照下,W-doped VO_2 通过可逆固-固相变产生温度波动,激活PVDF的热释电效应,实现光热转换和电能输出.在 1.1 kW m^{-2} 下,最大功率密度可达 $104\text{ }\mu\text{W m}^{-2}$,同时保持71.43%的水蒸发效率.该系统集成热管理、水蒸发与发电功能,利用温度时间变化发电,突破了传统技术对空间温差的依赖.

4.2 盐度梯度发电

绿色蒸汽的快速生成在溶液中形成高盐度区域,与未蒸发的低盐度水体之间形成盐度梯度,可用于发电^[78,79].基于此原理,Yang等人^[76]开发了一种基于离子选择性分离膜的蒸发-发电系统(图5(d)).该系统包括碳纳米管改性滤纸、Nafion膜和Ag/AgCl电极.运行时,碳纳米管改性滤纸吸收太阳能并促使水分快速蒸发,形成高盐区(6 mol L^{-1}),与主体海水(0.6 mol L^{-1})形成盐度梯度.在该梯度驱动下,离子通过Nafion膜扩散,产生电流.实验表明,在标准太阳辐照下,系统的蒸发速率可达 $1.15\text{ kg m}^{-2}\text{ h}^{-1}$,电能输出功率约为 1 W m^{-2} ,能量密度高于传统河水-海水混合盐差发电.然而,该方案在长期运行中可能面临盐分积累、电极催化活性下降、膜稳定性不足等问题,仍需进一步优化.

为提升稳定性,Long等人^[78]提出翻转式蒸发-发电耦合策略(图5(e)).该系统由聚苯胺-氧化石墨烯-二氧化锰复合电极和阴离子交换膜两部分组成.一方面,阴离子交换膜产生的Donnan势与电极电化学反应叠加,

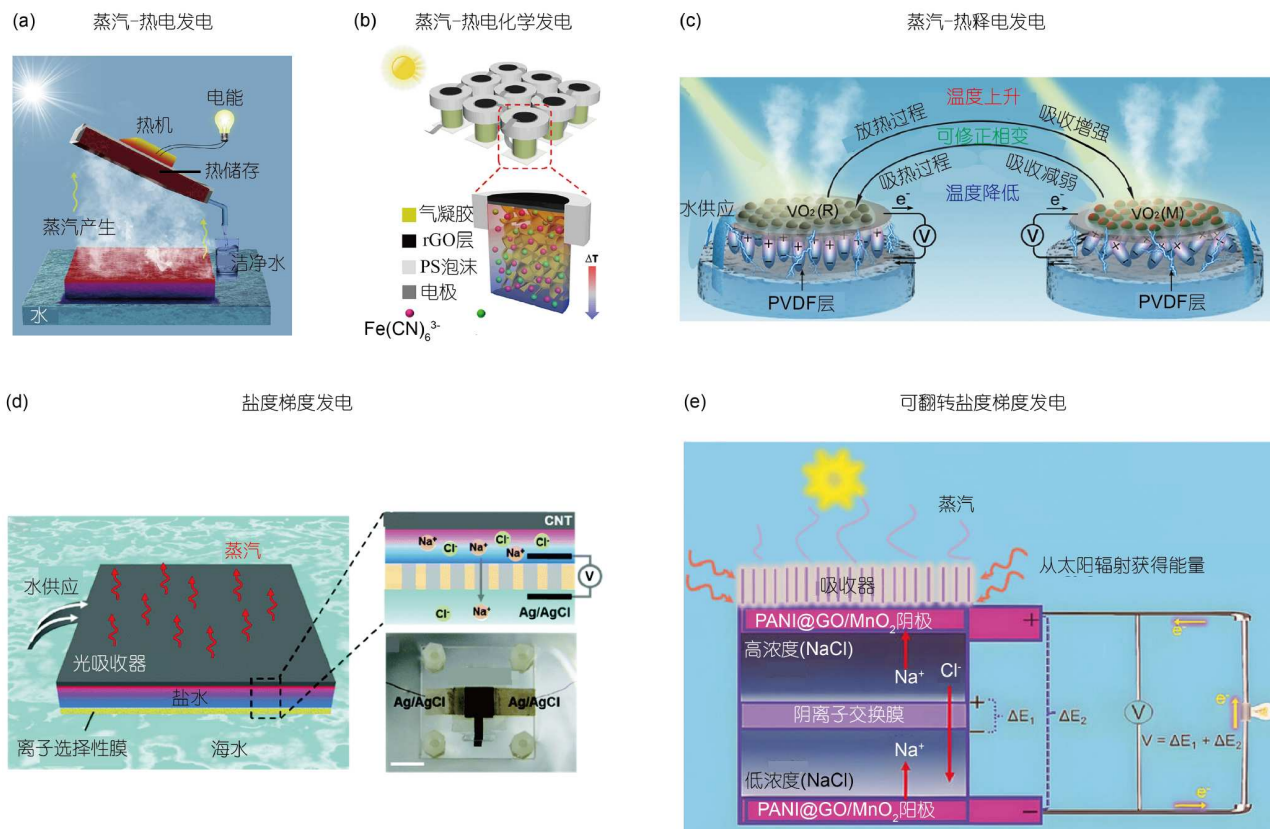


图5 (网络版彩色)绿色蒸汽驱动热梯度发电和盐梯度发电。(a) 热电发电^[74]; (b) 热电化学发电^[75]; (c) 热释电发电^[77]; (d) 基于离子选择膜的盐度梯度发电^[76]; (e) 可翻转盐度梯度发电^[78]

Figure 5 (Color online) Green steam-driven thermal-gradient power generation and salinity-gradient power generation. (a) Thermoelectric power generation^[74]; (b) thermoelectrochemical power generation^[75]; (c) pyroelectric power generation^[77]; (d) salinity-gradient power generation with ion-selective membranes^[76]; (e) reversible salinity-gradient power generation^[78]

提升了系统的开路电压, 最高可达0.31 V; 另一方面, 周期性翻转策略(上下电极对调)能够有效抑制盐分累积, 提升系统稳定性。在标准太阳辐照下(1 kW m^{-2}), 该系统实现了 1.1 W m^{-2} 的功率密度和 $1.25 \text{ kg m}^{-2} \text{ h}^{-1}$ 的淡水产量, 并且能够稳定运行240小时。通过优化阴离子交换膜厚度和补水速率, 系统的盐梯度能量转化效率可达5.5%, 为海洋环境下淡水和电能协同供应提供了可靠和高效的技术方案。

4.3 光伏-蒸发协同水电联产

将太阳能界面蒸发与光伏发电耦合, 可提升光伏组件的发电效率和太阳能综合利用率, 实现“水电联产”^[18,80](图6)。Xu等人^[18]开发了一种光伏-蒸发集成系统, 包含红外透明硅光伏电池、热互连层和界面光热净水装置三部分。运行时, 顶部光伏电池利用高能光子发电, 中间热互连层将光伏余热传递至底部净水装置,

底部净水器则利用低能光子和光伏余热增强蒸发。净水器的蒸发冷却作用可使光伏组件温度降低 $11 \sim 8^\circ\text{C}$, 发电效率提升7.9%~2.2%。通过光子分配与热管理设计, 在标准太阳辐照下, 该系统实现了74.6%的太阳能综合利用效率, 光伏发电效率达到20.4%, 净水产率为 $0.80 \text{ kg m}^{-2} \text{ h}^{-1}$, 为分布式能源和水资源供应提供了高效解决方案。

4.4 绿色蒸汽生产清洁能源的应用前景与挑战

太阳能界面蒸发技术在分布式能源供给领域展现出独特优势。其具备轻量化、经济性和离网运行的特点, 功率密度可达 $1 \sim 10 \text{ W m}^{-2}$ (表S3), 能够满足物联网终端、环境监测传感器等低功耗设备的能源需求。然而, 该技术仍处于发展阶段, 材料和系统层面有较大优化空间。实际应用中, 需解决材料耐久性、稳定性和成本效益等关键问题, 并进行全面评估和优化。未来研究

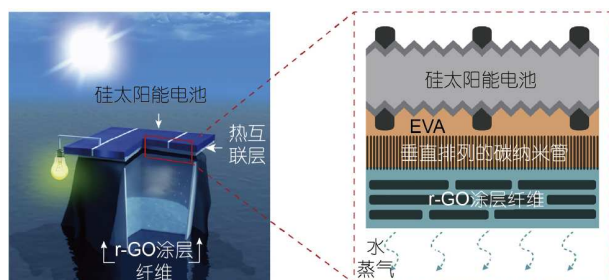


图6 (网络版彩色) 光伏-蒸发协同水电联产^[18]

Figure 6 (Color online) Photovoltaic-evaporation synergistic water and electricity co-generation^[18]

应重点关注技术可行性与经济性的平衡, 推动其从实验室向实际应用转化。

5 绿色蒸汽灭菌

绿色蒸汽凭借其高温特性($>120^{\circ}\text{C}$), 可实现高效灭菌, 甚至达到医疗级灭菌标准($\text{SAL} = 10^{-6}$), 即每一百万个灭菌物品中, 最多有一个未被灭菌^[19,81]。得益于其分散部署和低成本优势, 绿色蒸汽为资源匮乏地区提供了可持续的医疗及生活用品灭菌方案。

5.1 高温蒸汽灭菌

绿色蒸汽灭菌原理是通过高温蒸汽破坏细菌的细胞壁和DNA结构, 从而杀灭细菌(图7(a))。相较于传统整体加热的太阳能灭菌装置, 绿色蒸汽采用界面加热技术, 将太阳能光热转换局限在界面超薄水层, 显著减少热损失, 并提升蒸汽温度。例如, Li等人^[19]开发了一种生物炭基界面光热灭菌装置, 利用界面加热, 仅需122 s即可产生 121°C 蒸汽, 单次灭菌时长缩短至8.4 min, 能耗降至 100 J mL^{-1} 。单次灭菌成本仅为0.25美分, 远低于商业设备。然而, 该系统仍需依赖聚光镜和高压釜生成高温高压蒸汽。

为了避免使用高压釜, Wang等人^[20]提出了一种热集中高温蒸汽灭菌器(图7(b))。该装置包含三部分: 管翅式太阳能集热管、透明气凝胶隔热层以及复合抛物面聚光器。集热管通过选择性涂层实现高效光热转换, 并将热量传导到翅片根部形成高温区, 中间气凝胶隔热层有效减少热损失, 聚光器则通过2倍几何聚光增强光强。实验表明, 该系统在常压下可生成 132°C 蒸汽, 为无燃料医疗灭菌提供了可行方案。

为简化聚光系统并提升低光照条件下的灭菌效果, Chang等人^[82]构建了真空管高温蒸汽灭菌装置(图7(c))。

该装置由真空管、储水区、蒸发区和加热区四部分组成: 真空管为内涂 TiNO_x 的双层硼硅玻璃管, 利用其高吸收率和低热发射率特性, 最大化吸光加热并减少热损失; 储水区位于真空管的底部; 蒸发区居中, 由铜网、亲水纤维和聚氨酯棒组成, 聚氨酯棒提供支撑, 亲水纤维通过毛细作用供水, 铜网传导真空管热量驱动界面蒸发; 加热区位于蒸发区上方, 由多层铜网换热器组成, 利用真空管热量将绿色蒸汽进一步加热为过热蒸汽, 用于灭菌。在 600 W m^{-2} 太阳辐照下, 装置可稳定输出 123°C 蒸汽, 有效杀灭嗜热脂肪的芽孢杆菌和大肠杆菌。该设计结合真空管隔热与界面蒸发的协同作用, 无需昂贵的聚光器或加压装置即可产生高温蒸汽, 为偏远地区提供经济、可持续的灭菌解决方案。

5.2 基于绿色蒸汽的协同灭菌方案

为提升灭菌效果, 研究人员开发了协同杀菌策略, 常见方法包括光热-光催化协同灭菌^[83,85]和光热-金属离子协同灭菌^[86,87]。

光热-光催化协同灭菌结合了物理热损伤和化学氧化损伤的双重机制, 增强灭菌效果(图7(d))。一方面, 光催化材料吸收太阳辐射, 产生活性氧, 如羟基自由基、过氧化氢和超氧阴离子等。这些氧化剂能够破坏细菌的细胞膜、蛋白质和DNA等, 导致细胞代谢紊乱, 进而杀灭细菌^[84]。另一方面, 光热效应能够破坏细菌细胞膜, 促进活性氧进入细菌内部, 进一步增强杀菌效果。Fang等人^[83]开发了一种 $\text{Au@ZIF-8/Ti}_3\text{C}_2\text{T}_x$ 纳米复合水凝胶, 用于光热-光催化协同灭菌。光照下, 金纳米颗粒通过局部表面等离子共振增强光吸收, 实现光热杀菌; ZIF-8与 $\text{Ti}_3\text{C}_2\text{T}_x$ 则形成肖特基结, 促进活性氧生成, 实现化学氧化杀菌。该水凝胶在太阳光照条件下对大肠杆菌和金黄色葡萄球菌表现出100%的蒸汽灭菌效率, 表明其在光热-光催化协同灭菌中的优异性能。

光热-金属离子协同杀菌则通过物理热损伤与化学代谢干扰双重机制, 提升灭菌效果(图7(e))。一方面, 金属离子可穿透细胞膜, 与细菌内部的核酸、蛋白质等作用, 破坏细胞代谢, 从而杀灭细菌^[84,87]。另一方面, 光热效应能够提高细胞膜通透性, 加速金属离子穿透细胞并干扰其内部代谢, 进一步增强杀菌效果。例如, Cao等人^[86]设计了一种碳化花生壳负载 CuO 纳米颗粒的生物质光热蒸发灭菌器。在标准太阳光强下, 材料表面温度达到 83°C , 显著加快 Cu^{2+} 释放杀菌, 对大肠杆菌和金黄色葡萄球菌的杀菌率均超过99.9%。

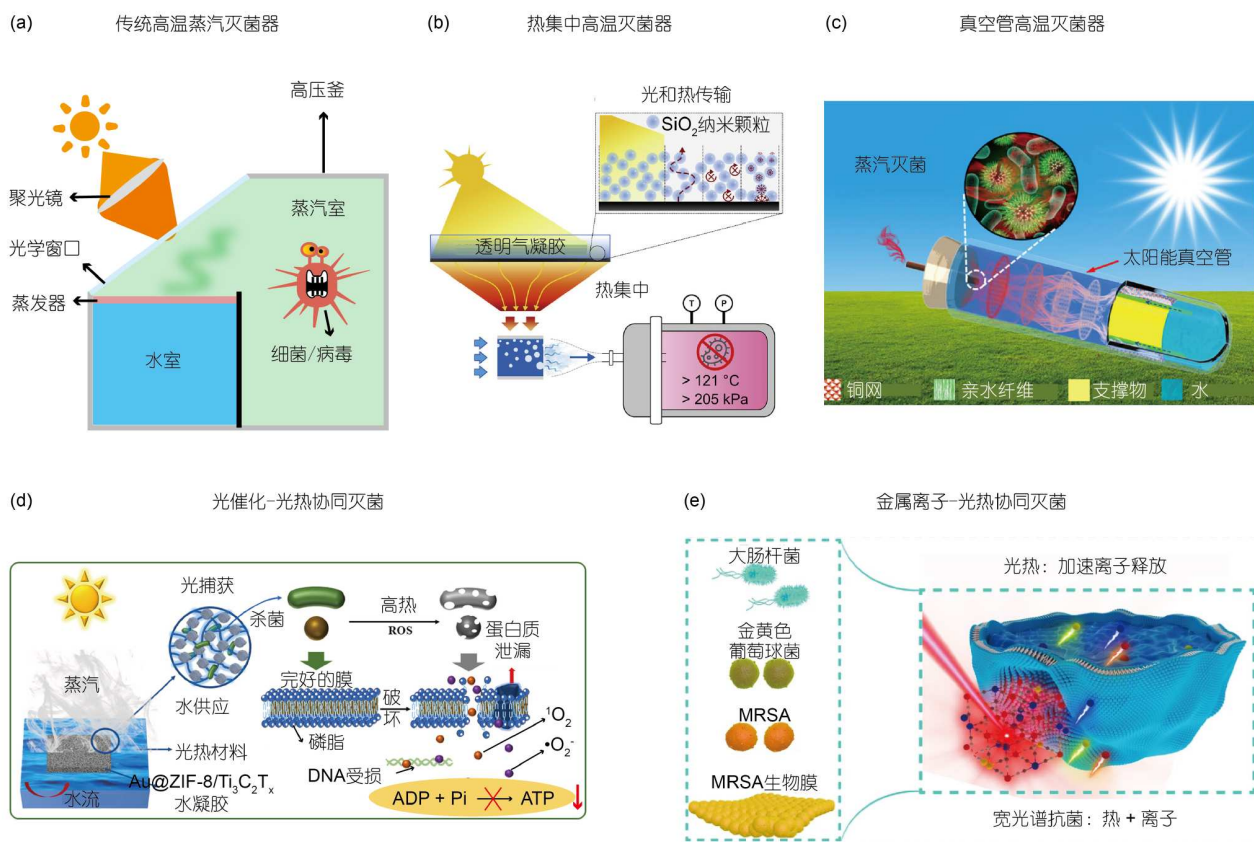


图 7 (网络版彩色)基于绿色蒸汽的灭菌。(a) 传统高温蒸汽灭菌器; (b) 热集中高温蒸汽灭菌器^[20]; (c) 真空管高温灭菌器^[82]; (d) 光催化-光热协同灭菌^[83]; (e) 金属离子-光热协同灭菌^[84]

Figure 7 (Color online) Green steam-based sterilization. (a) Traditional high-temperature steam sterilizer; (b) thermal concentrated high-temperature steam sterilizer^[20]; (c) vacuum tube high-temperature sterilizer^[82]; (d) photocatalytic-photothermal synergistic sterilization^[83]; (e) metal ion-photothermal synergistic sterilization^[84]

5.3 绿色蒸汽灭菌应用前景与挑战

绿色蒸汽灭菌技术融合光热转化、光催化及金属离子释放灭菌等机制, 具备经济性、离网运行和多场景适应等优势, 适用于医疗器械、食品加工等领域, 实现低成本、高效灭菌。如表S4所示, 绿色蒸汽灭菌技术在不同条件下可有效灭菌多种病原体, 包括大肠杆菌、金黄色葡萄球菌、耐甲氧西林金黄色葡萄球菌等, 灭菌效率可达99.999999%。此外, 光催化-光热协同灭菌技术在标准太阳光照下对*E. coli*和*S. aureus*的灭菌效率可达到100%。

未来研究将聚焦开发低能耗、高效能的协同灭菌技术, 以应对多样化病原体的挑战。此外, 在反应器设计方面, 应重视运行稳定性。例如, 可通过仿生结构提升抗污染能力, 或构建模块化系统, 增强系统可维护性。为推动技术落地, 未来需依托大规模示范项目验证其

可行性和经济性, 并促进其在偏远地区的广泛应用与推广。

6 绿色蒸汽提取关键资源

绿色蒸汽能够驱动纳滤、吸附等过程, 高效提取锂、铀等战略资源^[10,17,21,88~97], 并可结合光催化、电解等技术制备氢气等清洁能源^[98~111]。本节将系统介绍绿色蒸汽在资源提取中的研究进展。

6.1 绿色金属资源

Song等人^[10]利用界面蒸发产生的毛细压强驱动膜分离, 实现了绿色盐湖锂资源提取。绿色蒸汽盐湖提锂装置包含三部分(图8(a)): 顶层为光热蒸发层, 作为绿色高压泵, 产生约18个大气压的毛细压强; 中间为锂存储层, 传导压强并存储提取的锂盐; 底层为锂离子选择性

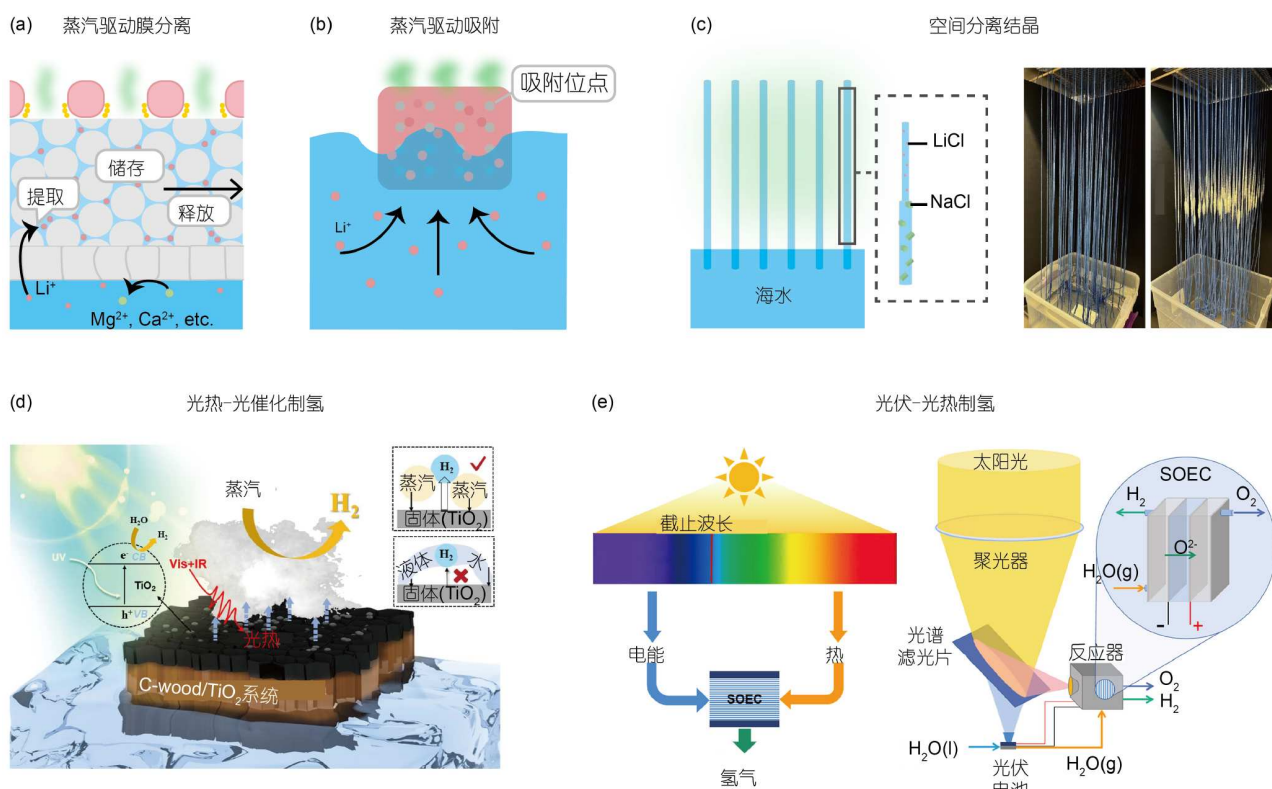


图 8 (网络版彩色)绿色蒸汽提取绿色资源. (a) 蒸汽驱动膜分离^[10]; (b) 蒸汽驱动吸附^[21]; (c) 绿色蒸汽驱动空间分离结晶, 提取盐湖锂资源^[90]; (d) 光热-光催化制氢^[108]; (e) 光伏-光热制氢^[110]

Figure 8 (Color online) Sustainable resource extraction via green steam. (a) Steam-driven membrane separation^[10]; (b) steam-driven adsorption^[21]; (c) green steam-driven spatially separated crystallization for extracting lithium resources from salt lakes^[90]; (d) photothermal-photocatalytic hydrogen generation^[108]; (e) photovoltaic-photothermal hydrogen generation^[110]

膜, 选择性传输 Li^+ , 阻隔 Ca^{2+} 、 Mg^{2+} 等杂质离子. 工作时, 该器件漂浮于盐湖表面, 在光热蒸腾压驱动下, 锂盐穿过离子筛分层进入存储层, 并通过水循环系统收集, 最终实现了近零能耗、高选择性和高锂利用率的太阳能盐湖提锂.

绿色蒸汽还可增强选择性吸附材料的吸附动力学^[112]和容量^[113], 增强资源提取性能(图8(b))^[21,92,97]. Chen等人^[21]研发了太阳能界面蒸发驱动的锂吸附毡, 由负载 $\text{Li}_{1.6}\text{Mn}_{1.6}\text{O}_4$ 吸附剂的聚丙烯/聚乙烯纤维制成. 工作时, 该材料通过界面光热效应升温至 40°C , 显著提升锂离子吸附速率和容量. 在2倍标准太阳光照下 (2 kW m^{-2}), 锂吸附速率可达 $9.4\text{ mg g}^{-1}\text{ h}^{-1}$.

此外, 绿色蒸汽可通过不同盐的选择性结晶分离提取卤水中的关键资源^[17,90]. 例如, Chen等人^[90]提出了一种由天然棉纤维编织而成的绳状结晶器, 用于提取盐湖锂资源(图8(c)). 该蒸发器利用毛细作用将盐水提升至 0.6 m , 并通过增加水-空气界面的面积提高蒸发

速率, 达到传统太阳能蒸发池的27倍. 在蒸发过程中, 钠盐首先结晶, 锂盐随后结晶, 从而实现沿结晶器高度的分区结晶分离. 在模拟盐湖和海水条件下, 该结晶器分别能选择性浓缩锂达39倍和675倍. 实验还表明, 构建纤维结晶器阵列可节省90%以上的占地, 且提高生产力一个数量级, 展现出显著的应用潜力.

6.2 绿色蒸汽制备清洁燃料

绿色蒸汽结合光催化、电解等技术, 可高效制备氢气等清洁燃料, 已成为海水制氢的重要方向^[98~100,102~109]. 其优势包括: (1) 水质净化, 蒸发过程可原位净化海水, 避免了大规模海水淡化设施和耐腐蚀电极的需求^[114]; (2) 快速气相分离, 气液界面加快氢气和氧气分离, 促进催化反应向产物生成方向进行^[98,106,108]; (3) 低能耗, 气相光催化水分解反应的吉布斯自由能低于液态水光催化分解反应, 降低能耗^[115].

Han等人^[108]开发了一种表面碳化木材负载 TiO_2 的

光热-光催化复合产氢材料(图8(d)). 光照下, 碳化木材通过光热效应蒸发水分, 水蒸气则在 TiO_2 表面光催化分解产氢. 与液态水分解产氢相比, 蒸汽分解产氢反应的吉布斯自由能从 237 kJ mol^{-1} 降至 227 kJ mol^{-1} , 同时, 氢气传输阻力降低. 该材料在纯水中的产氢速率达到 $487.4 \mu\text{mol m}^{-2} \text{ h}^{-1}$, 在海水中仍可保持 $248.1 \mu\text{mol m}^{-2} \text{ h}^{-1}$, 是单纯 TiO_2 光催化材料的3.2倍. 经过5次循环, 材料仍保持82.9%的初始活性, 展现出优异的稳定性.

基于类似原理, Ma等人^[104]开发了光热-光催化复合气凝胶材料. 材料上层为负载 SrTiO_3 光催化剂的聚乙烯醇凝胶, 下层为还原氧化石墨烯光热材料. 光照下, 光热层吸收可见-红外光产生水蒸气, 水蒸气向上扩散至光催化层分解产氢. 该设计通过气-固相反应避免了光催化剂与海水接触, 有效抑制了光催化剂的离子腐蚀问题. 该材料的产氢速率达到了 $17.94 \text{ mmol m}^{-2} \text{ h}^{-1}$, 淡水产量达到 $0.92 \text{ kg m}^{-2} \text{ h}^{-1}$, 综合太阳能转化效率可达62.3%.

绿色蒸汽还可与光伏电解装置结合, 协同制氢^[109,110]. Liu等人^[110]提出了一种全光谱利用的太阳能光伏-光热蒸发制氢系统(图8(e)). 具体原理如下: 短波长太阳光被光伏组件吸收并转化为电能驱动水电解, 同时光伏电池的废热被用于预热水体; 长波长太阳光则转化为热能, 加热水体, 促进水分解反应. 在最优条件下, 太阳能-氢能转化效率达39.0%, 比传统光伏电解水制氢和热化学循环分解水制氢分别提高19.0%和21.6%, 显著提升太阳能制氢效率.

6.3 绿色蒸汽提取关键资源的应用前景与挑战

绿色蒸汽在资源提取和循环经济中具有重要应用潜力. 表S5汇总了绿色蒸汽提取关键资源性能. 目前的技术主要集中在单一元素的提取, 忽视其他高附加值元素的回收. 未来应构建多产品协同回收体系, 提高工艺的经济性. 此外, 绿色蒸汽资源提取技术在规模化应用方面仍面临挑战, 尤其是处理大量盐水, 虽然实验室研究提供了参考, 但仍需通过大规模示范项目来验证其可行性.

7 总结与展望

太阳能界面蒸发技术通过高效利用太阳能生成绿色蒸汽, 为水处理、资源提取、粮食生产及医疗健康等关键领域提供了极具前景的可持续解决方案. 作为一项接近零碳排放的低碳技术, 其在构建环境友好型能源体系中的价值日益凸显. 近年来, 随着新型光热材料的开发、结构设计的优化以及系统集成技术的持续创新, 太阳能界面蒸发的蒸发速率、光利用效率与长期运行稳定性均实现了显著提升, 为解决全球日益严峻的食物、能源与水等资源短缺问题提供了新思路.

然而, 目前绿色蒸汽驱动下的资源获取系统多以“单一功能”方式运行, 即食物、能源与水资源往往在空间上相互独立, 导致系统能效低、空间利用率不高、基础设施成本高昂, 难以满足可持续发展的综合需求. 因此, 亟需打破传统边界, 探索“绿色蒸汽+”的多能协同路径——将太阳能界面蒸发技术与光伏发电^[18]、风能转换^[116]、能量存储^[117]、碳捕获^[118]等多元化技术^[119,120]有机结合. 这一协同策略, 一方面能通过优化热管理、减少能量浪费, 显著增强净水过程的能量利用效率; 另一方面, 更可驱动构建集淡水生产、清洁能源输出、农作物培育甚至化工原料提取于一体的综合联产系统, 实现资源在时空维度上的高效整合与循环利用.

在联产系统的设计中, 太阳能全光谱的高效利用是核心关键. 太阳光谱范围覆盖约200~2500 nm, 其中光伏和光催化技术主要吸收利用可见光至近红外波段, 而界面太阳能蒸发技术则几乎可覆盖整个太阳光谱. 因此, 通过合理配置各技术对不同波段太阳光的选择性吸收与利用, 可构建协同作用最大化的光谱分配系统, 最大化太阳能的综合利用效率, 减少能量浪费.

展望未来, 太阳能界面蒸发技术有望与多功能联产系统深度融合, 形成集淡水获取、农业灌溉、清洁能源生产和环境修复于一体的复合平台. 这将显著提升资源利用效率, 推动资源循环与碳中和目标的实现. 作为应对全球水、能源与粮食等资源危机的关键路径, 太阳能界面蒸发技术将为绿色低碳转型和可持续发展提供创新路径与解决方案.

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补充材料

- 表S1 绿色蒸汽生产饮用水性能汇总
- 表S2 绿色蒸汽用于农业灌溉性能汇总
- 表S3 绿色蒸汽生产绿电性能汇总
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- 表S5 绿色蒸汽提取关键资源性能汇总

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Summary for “界面光热绿色蒸汽驱动低碳创新”

Green steam from sunlight: interfacial evaporation enabling low-carbon solutions

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Interfacial solar evaporation is an emerging technology that enables efficient water evaporation by converting solar energy into localized heat at the water-air interface. This technology utilizes solar-driven interface evaporators deployed on the water surface, requiring no external energy input while achieving high-efficiency steam generation. The core of this process lies in the use of highly efficient photothermal conversion materials that effectively capture solar radiation and localize the absorbed energy, directly transforming sunlight into heat to drive water evaporation. Because this method relies solely on solar energy, the generated steam is considered “green steam”, as the entire process operates with near-zero carbon emissions. This sustainable approach holds great potential in seawater desalination, wastewater treatment, and steam-driven power generation. Particularly in remote and resource-scarce regions, interfacial solar evaporation offers a sustainable and cost-effective solution for resource acquisition, providing new hope for addressing global water shortages.

Green steam generated through interfacial solar evaporation has a broad range of applications. One of the most significant uses is in clean water production, where it can efficiently extract fresh water from various sources, including seawater, brackish water, and industrial wastewater. This makes it an ideal solution for household water supply, agricultural irrigation, and emergency drinking water production in disaster-stricken areas. In addition, interfacial solar evaporation is highly effective in wastewater treatment. It enables the purification of municipal sewage and industrial effluents from sectors such as textile manufacturing, thermal power plants, and the pharmaceutical industry, achieving zero liquid discharge by fully separating water from contaminants. Beyond water purification, this technology has demonstrated excellent performance in sterilization and disinfection, making it useful in healthcare, sanitation, and food safety applications. Furthermore, green steam generation through interfacial solar evaporation can be integrated with renewable energy technologies for electricity production, increasing its practicality and expanding its impact in sustainable energy systems.

Over the past decade, significant advancements have been made in interfacial solar evaporation, pushing the technology close to its thermodynamic efficiency limit. Under concentrated solar illumination, freshwater production rates have exceeded $80 \text{ L m}^{-2} \text{ h}^{-1}$, with stable operation extending beyond 600 hours. These improvements have positioned interfacial solar evaporation as a highly promising clean energy solution. However, despite these impressive laboratory achievements, several critical challenges remain for large-scale deployment. One major obstacle is maintaining high efficiency and stability in real-world conditions, as external factors such as contamination, environmental fluctuations, and long-term durability must be considered. Additionally, reducing the cost of photothermal materials and evaporation devices is crucial to making this technology economically viable for widespread adoption. Addressing these challenges requires further research and innovation in material design, system engineering, and large-scale implementation strategies.

This review systematically summarizes the latest advancements in interfacial photothermal green steam across energy, resources, agriculture, environment, and health sectors. It thoroughly explores innovative strategies in material design, device construction, and system integration, while evaluating production potential, application feasibility, and developmental challenges. Finally, it envisions full-spectrum solar utilization and multi-product co-production based on green steam, aiming to enhance comprehensive solar energy efficiency and pave new pathways for China’s green, low-carbon industrial development and circular economy system.

green steam, interfacial evaporation, micro-nanostructures, solar-to-heat conversion, low-carbon technology

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