



HAL
open science

Advancements in Photothermal Materials: Mechanisms, Design, and Sustainable Applications

Sara Falah, Ali Mohammadi Lindi, Mohsen Taghavijeloudar

► **To cite this version:**

Sara Falah, Ali Mohammadi Lindi, Mohsen Taghavijeloudar. Advancements in Photothermal Materials: Mechanisms, Design, and Sustainable Applications. The first international conference New Approaches in Engineering and Basic Science, Jan 2025, Brussel, Belgium. hal-04896384

HAL Id: hal-04896384

<https://hal.science/hal-04896384v1>

Submitted on 19 Jan 2025

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Advancements in Photothermal Materials: Mechanisms, Design, and Sustainable Applications

Sara Falah¹, Ali Mohammadi Lindi², Mohsen Taghavijeloudar^{3*}

1. Department of Chemical Engineering, Babol Noshirvani University of Technology, Babol, Iran; Sarafalah.1375@gmail.com
2. Department of Chemical Engineering, Babol Noshirvani University of Technology, Babol, Iran; Alimohammadilindi@yahoo.com
3. Department of Chemical Engineering, Babol Noshirvani University of Technology, Babol, Iran; mohsen@snu.ac.kr

Abstract

Photothermal materials have emerged as transformative components in sustainable energy technologies due to their ability to efficiently convert solar energy into thermal energy. This review provides an in-depth exploration of the fundamental mechanisms underlying photothermal conversion, emphasizing photoelectron excitation, non-radiative relaxation, and heat transfer. Advancements in the design of photothermal materials, including nanostructured systems, surface engineering, and bioinspired approaches, are discussed to highlight their impact on optimizing performance and addressing scalability challenges. Particular attention is given to polymer coatings, which enhance the stability, functionality, and adaptability of photothermal systems for diverse applications. The integration of photothermal materials into sustainable technologies, such as solar desalination, concentrated solar power (CSP), solar thermal fuels (STFs), and smart textiles, is also examined, showcasing their potential to address global energy and water scarcity challenges. Furthermore, the review identifies critical challenges, such as material cost, stability, and environmental impact, while proposing innovative solutions, including biodegradable polymers, advanced nanotechnology, and interdisciplinary collaborations, to overcome these barriers. By consolidating current knowledge and highlighting opportunities for future research, this paper aims to contribute to the advancement of photothermal materials as key drivers of sustainable energy innovation.

Key words: Photothermal materials, sustainable energy, polymer coatings, solar desalination, concentrated solar power, nanotechnology.

1. Introduction

Solar energy is widely regarded as the most abundant, green, and versatile renewable energy source, delivering approximately 1.8×10^{14} kW of power to the Earth's surface annually. It is one of the clean energy sources with the greatest potential for sustainable high-intensity energy output. The development of solar-related application technologies has been identified as a key solution to critical global challenges, such as the energy crisis and water scarcity. The utilization of solar energy primarily occurs through two pathways: photovoltaic conversion and photothermal conversion. Photovoltaic systems have enabled efficient electricity generation, while photothermal conversion, as one of the most common and promising methods of solar energy utilization, relies on photothermal materials to convert solar radiation into thermal energy. This process takes advantage of the broad solar spectrum, which ranges from 300 nm to 2500 nm and includes three main bands: the ultraviolet band (300–400 nm, ~3% of total energy), the visible band (400–700 nm, ~45% of total energy), and the infrared band (700–2500 nm, ~52% of total energy) [1, 2].

The photothermal effect enables the conversion of electromagnetic (EM) waves into heat, offering a versatile platform for various applications, including solar desalination, concentrated solar power (CSP) systems, photothermal-assisted photocatalysis, smart textiles, and smart windows. Over the past few decades, advancements in material science have significantly improved the efficiency of photothermal materials, progressing from traditional dyes to advanced nanostructured materials and bioinspired designs. In particular, biomimetic photothermal materials have garnered attention for their ability to replicate the energy conversion mechanisms found in nature, further enhancing their performance in energy harvesting and storage [3, 4].

Despite these advancements, solar energy utilization faces inherent challenges, including variability in intensity and availability due to daily and seasonal cycles. To address these limitations, innovative strategies, such as integrating photothermal materials with phase change materials (PCMs), have been developed. PCMs stabilize energy supply by absorbing and releasing thermal energy during phase transitions, maintaining temperatures within a narrow range. When combined with photothermal agents, PCMs improve the heat capacity and thermal stability of the system, thereby enhancing its overall efficiency and reliability. Recent studies have further expanded the scope of photothermal materials by incorporating advanced functionalities such as flame retardancy, optical transparency, and self-healing capabilities, paving the way for their applications in diverse fields [5-7]. Additionally, polymer coatings have emerged as an effective approach to enhance the stability, thermal conductivity, and overall efficiency of photothermal materials by providing protection and improving their interaction with the surrounding environment [8]. The use of polymer materials instead of traditional inorganic materials in solar cells is a new field of development [9]. Compared with silicon and inorganic compound photovoltaic materials, polymer/fullerene solar cells have distinct advantages such as light weight, low cost, excellent power conversion and easy to produce large-area flexible devices [10].

While numerous reviews have focused on individual aspects of photothermal materials and their applications, a comprehensive review addressing their role in sustainable energy technologies is still needed. This paper aims to consolidate the current knowledge on photothermal materials, emphasizing their design, mechanisms, and integration with other technologies to enhance energy conversion and storage. We will explore their potential in solar thermal fuels, thermal management systems, and emerging technologies, highlighting challenges and future directions for advancing this critical field.

2. Fundamentals of Photothermal Materials

Photothermal materials are designed to convert solar energy into thermal energy by exploiting their ability to absorb light across a broad spectrum and efficiently dissipate the absorbed energy as heat. This process is fundamental to a wide range of applications, from energy harvesting to biomedical technologies. The photothermal conversion mechanism can be divided into three primary stages: photoelectron excitation, non-radiative relaxation, and heat transfer. Upon light absorption, electrons in the material are excited to higher energy levels. The relaxation of these electrons through non-radiative pathways generates vibrational energy, which is transferred to the surrounding environment as heat. This sequence of events underscores the unique ability of photothermal materials to directly convert light into thermal energy with minimal energy loss [11, 12].

The efficiency of photothermal conversion depends heavily on the material's optical and thermal properties. Localized Surface Plasmon Resonance (LSPR) is a critical phenomenon observed in plasmonic nanomaterials such as gold and silver nanoparticles. LSPR enhances light absorption by creating strong localized electromagnetic fields at the material's surface. These fields amplify electron oscillations, which in turn increase the rate of energy dissipation as heat. The broad absorption spectrum characteristic of LSPR makes these materials particularly effective in capturing sunlight across the ultraviolet, visible, and infrared regions, thereby maximizing energy conversion efficiency [13-15].

Semiconductors and carbon-based nanomaterials also play a significant role in photothermal applications. In semiconductors, light absorption excites electrons across the band gap, forming electron-hole pairs. The recombination of these pairs through non-radiative processes contributes to heat generation. Carbon-based materials, such as graphene and carbon nanotubes, exhibit unique electronic properties that enable efficient photothermal conversion. Their ability to form delocalized π -electron systems facilitates rapid energy transfer, making them ideal candidates for photothermal applications. Additionally, their high thermal conductivity ensures effective dissipation of the generated heat [16, 17].

Surface modifications and structural engineering of photothermal materials further enhance their performance. The introduction of oxygen vacancies and other defects on the material's surface can significantly increase light absorption and energy conversion efficiency. These defects act as active sites that interact with incident photons, facilitating energy transfer and heat generation. Moreover, the synthesis of heterojunctions, which combine different materials with complementary properties, creates synergies that enhance photothermal efficiency. For instance, integrating plasmonic metals with semiconductors can leverage the

advantages of both systems, leading to improved light harvesting and heat production [18, 19].

Finally, the selection of photothermal materials must account for their stability, scalability, and environmental impact. While metals and semiconductors offer high efficiency, their high cost and potential toxicity pose challenges for widespread adoption. On the other hand, organic materials, including polymers and bioinspired designs, provide a sustainable and cost-effective alternative. These materials can be tailored to exhibit specific optical and thermal properties, ensuring their compatibility with various applications. Understanding and optimizing the fundamental mechanisms of photothermal conversion in these materials are essential for advancing their role in sustainable energy technologies and beyond [20].

3. Design of Photothermal Materials

The design of photothermal materials focuses on optimizing their light absorption, thermal conversion efficiency, and overall stability to meet the demands of various applications. To achieve this, researchers employ advanced strategies that include tailoring material structures, engineering surfaces, and integrating complementary materials into hybrid systems. Each approach plays a critical role in improving the photothermal performance while addressing limitations such as scalability and environmental impact.

Nanostructured materials form the foundation of photothermal design, offering unique optical and thermal properties based on their dimensionalities. For instance, zero-dimensional (0D) nanoparticles like gold and silver leverage localized surface plasmon resonance (LSPR) to enhance light absorption and amplify thermal conversion. However, 1D nanostructures such as nanorods and nanowires provide superior energy transfer capabilities due to their high aspect ratios, making them ideal for applications requiring efficient heat conduction. Two-dimensional (2D) materials, including graphene and transition metal dichalcogenides (TMDs), offer extensive surface areas and excellent thermal conductivity, enabling rapid heat dissipation. Finally, three-dimensional (3D) frameworks such as porous nanostructures enhance light trapping by scattering incident light, thereby boosting energy conversion efficiency. By combining these nanostructures, designers can create optimized photothermal systems tailored for specific applications [13, 21-24].

Surface engineering is another pivotal aspect of photothermal material design. The introduction of surface defects, such as oxygen vacancies or lattice distortions, significantly enhances light absorption and energy conversion by increasing the density of active sites. Functionalizing surfaces with chemical groups further improve the compatibility of photothermal materials with diverse environments, such as biological systems or polymer matrices. For example, attaching hydrophilic groups to the surface of a photothermal material can enhance its performance in aqueous systems, while hydrophobic coatings can improve its stability in air-sensitive applications. These modifications not only enhance photothermal efficiency but also ensure the material's durability under real-world conditions.

Hybrid and composite materials represent a powerful approach to photothermal design, as they combine the strengths of different components to achieve synergistic effects. For example, integrating plasmonic metals with semiconductors creates heterojunctions that facilitate efficient charge separation and energy transfer. This combination is particularly effective for photothermal-assisted photocatalysis, where simultaneous light absorption and catalytic activity are required. Similarly, embedding photothermal nanoparticles into polymer matrices produces composites with enhanced flexibility, mechanical strength, and thermal conductivity. These composites are essential for applications such as wearable devices, flexible solar panels, and thermal management systems in electronics [25-28].

Bioinspired design has emerged as a novel strategy for photothermal material development, drawing inspiration from nature's efficient energy conversion systems. For instance, replicating the hierarchical structures found in butterfly wings or lotus leaves has led to materials with enhanced light absorption, heat transfer, and water repellency. These bioinspired materials often incorporate features such as adaptive optics and hierarchical porosity, which are challenging to achieve through traditional fabrication methods. By mimicking these natural designs, researchers have developed photothermal materials capable of performing efficiently in complex environments, such as water desalination systems or biomedical applications [23,29,30].

The integration of these advanced design strategies ensures that photothermal materials not only achieve high efficiency but also address practical concerns such as scalability, environmental impact, and long-term stability. Future efforts in photothermal material design are likely to focus on developing multifunctional systems that combine photothermal, photocatalytic, and storage capabilities, paving the way for innovative applications in sustainable energy and beyond. By leveraging advances in nanotechnology, surface engineering, and biomimicry, researchers continue to push the boundaries of what photothermal materials can achieve, ensuring their relevance in solving global energy challenges [23].

4. Polymer Coatings for Photothermal Applications

Polymer coatings play a critical role in enhancing the performance of photothermal materials by improving their stability, functionality, and interaction with surrounding environments. These coatings provide a protective layer that shields the photothermal core from degradation due to environmental factors such as oxidation, UV radiation, and thermal cycling. As highlighted in the articles, polymers such as polyaniline (PANI), polypyrrole (PPy), and polyvinyl alcohol (PVA) are frequently employed due to their excellent thermal and chemical stability. These materials not only protect the photothermal agents but also contribute to the overall thermal conductivity and efficiency of the system. The versatility of polymers allows researchers to tailor their properties, including hydrophobicity, adhesion, and mechanical flexibility, to suit specific applications, making them indispensable in

photothermal systems for solar energy, biomedical treatments, and advanced manufacturing processes [31-34].

One of the primary functions of polymer coatings is to enhance the light absorption and thermal conversion capabilities of photothermal materials. By embedding plasmonic nanoparticles such as gold or silver into polymer matrices, researchers can exploit the localized surface plasmon resonance (LSPR) effect to boost light absorption across a broad spectrum. The articles emphasize the use of functionalized polymers to optimize the dispersion and stability of these nanoparticles within the matrix, preventing agglomeration and ensuring consistent performance. Furthermore, the addition of light-absorbing dyes or chromophores to the polymer matrix can further amplify the photothermal response, enabling the development of highly efficient composite coatings [8, 35, 36].

Another significant advantage of polymer coatings lies in their ability to provide responsiveness to external stimuli, such as temperature, pH, and light. Stimuli-responsive polymers enable the creation of smart photothermal systems that adapt their behavior based on environmental changes. For instance, thermoresponsive polymers such as poly(*N*-isopropylacrylamide) (PNIPAM) undergo reversible phase transitions at specific temperatures, which can be utilized for controlled heat release or drug delivery. The articles also discuss the use of pH-responsive polymers for applications in cancer therapy, where the acidic environment of tumors triggers localized photothermal effects. These smart coatings expand the functional capabilities of photothermal systems, making them highly adaptable for diverse applications [37, 38].

The incorporation of polymer coatings into photothermal systems also addresses key challenges related to biocompatibility and environmental sustainability. Traditional photothermal materials, such as metallic nanoparticles, often raise concerns regarding toxicity and environmental impact. The articles highlight the development of bioinspired and biodegradable polymer coatings, such as those derived from natural polymers like chitosan and cellulose. These materials not only reduce the environmental footprint of photothermal systems but also improve their compatibility for biomedical applications. For example, biopolymer coatings enable the safe use of photothermal materials in drug delivery and tissue engineering, where biocompatibility is paramount [39-41].

Despite their numerous advantages, polymer-coated photothermal systems face challenges that require further research and innovation. The articles point out limitations such as the potential degradation of polymer coatings under prolonged exposure to heat and light, which can compromise their protective function. Additionally, achieving uniform coating thickness and optimizing the thermal conductivity of polymer layers remain critical areas for improvement. Future research efforts are directed toward developing advanced fabrication techniques, such as 3D printing and layer-by-layer assembly, to create precisely engineered polymer coatings. By addressing these challenges, researchers can unlock the full potential of polymer coatings in photothermal applications, paving the way for their broader adoption in sustainable energy technologies, healthcare, and beyond [42, 43].

5. Applications in Sustainable Energy Technologies

Photothermal materials have emerged as pivotal components in advancing sustainable energy technologies, leveraging their ability to efficiently convert sunlight into thermal energy. One of the most promising applications lies in solar desalination, where photothermal materials are utilized to evaporate water by converting solar radiation into heat. Advanced designs, such as nanostructured photothermal membranes and coatings, significantly enhance the efficiency of solar-driven evaporation processes. As detailed in the reviewed articles, integrating photothermal materials with phase change systems or porous supports can maximize evaporation rates while minimizing energy losses, offering a sustainable solution to global water scarcity issues. These systems are particularly beneficial for remote and arid regions where conventional water treatment methods are often impractical [44-47].

Another key application of photothermal materials is in concentrated solar power (CSP) systems. CSP technology relies on materials capable of absorbing and retaining heat from concentrated sunlight to produce high-temperature thermal energy. This energy is then converted into electricity through thermodynamic cycles. Recent advancements in photothermal materials, such as the incorporation of plasmonic nanoparticles or bioinspired designs, have drastically improved the thermal storage capacity and stability of these systems. Moreover, the use of polymer-coated photothermal composites provides an additional layer of thermal insulation, reducing energy losses and enhancing overall system efficiency [48-50].

Photothermal materials also find extensive applications in solar thermal fuels (STFs), which are designed to store solar energy in the form of chemical bonds and release it as heat on demand. As discussed in the articles, STFs leverage photothermal conversion mechanisms to achieve reversible heat storage and release cycles. Innovations in material design, such as the integration of molecular photoswitches with photothermal polymers, have enabled the development of STFs with higher energy densities and longer operational lifetimes. These advancements make STFs an attractive alternative for energy storage, particularly in off-grid or decentralized power systems [51-53].

In addition to large-scale energy systems, photothermal materials are increasingly being employed in smart textiles and wearable devices. By embedding photothermal agents into fabrics, these materials can provide temperature regulation, enhance thermal comfort, and even generate power for small electronic devices. The reviewed studies highlight the potential of combining photothermal coatings with flexible substrates to create multifunctional textiles capable of adapting to environmental conditions. Applications range from military clothing and outdoor gear to medical devices that rely on localized heat delivery for therapeutic purposes [54, 55].

Finally, the integration of photothermal materials into building materials and smart windows has gained significant attention for energy-efficient architectural designs. Photothermal coatings applied to window surfaces can selectively absorb sunlight and convert it into heat, reducing reliance on external heating systems. Furthermore, these materials can be

incorporated into walls and roofing systems to improve indoor thermal comfort while lowering energy consumption. The reviewed articles emphasize the potential of these innovations to transform urban environments into energy-efficient ecosystems, addressing the growing demand for sustainable living solutions in densely populated areas [51, 56].

These diverse applications underscore the versatility of photothermal materials in addressing global energy and sustainability challenges. By continuously improving their efficiency, scalability, and integration into various systems, photothermal technologies are poised to play a central role in the transition toward a sustainable energy future [57, 58].

6. Challenges and Opportunities

Despite the significant advancements in photothermal materials, several challenges hinder their widespread adoption and performance optimization. One of the primary challenges is the high cost of raw materials, such as plasmonic metals like gold and silver, which limits scalability and affordability for large-scale applications. Additionally, many photothermal materials, especially those used in harsh environments, suffer from stability issues, including degradation under prolonged exposure to UV light, high temperatures, or reactive chemicals. The environmental impact of synthetic materials, particularly non-biodegradable polymers and toxic metal-based nanoparticles, further complicates their sustainable deployment. Another critical limitation is the efficiency drop in real-world conditions due to factors such as uneven light exposure, heat loss, and fouling in water-based systems, which reduce overall performance compared to ideal laboratory conditions [59, 60].

To address these challenges, researchers are exploring innovative solutions and opportunities for advancing photothermal materials. Developing cost-effective and sustainable alternatives, such as bioinspired and biodegradable polymers, offers a promising pathway to reduce environmental impact and production costs. Advances in nanotechnology and fabrication techniques, including 3D printing and self-assembly, allow for the precise engineering of materials with enhanced performance and tailored functionalities. Moreover, the integration of photothermal materials with complementary technologies, such as phase change materials (PCMs) for thermal storage and nanophotonics for light management, holds immense potential for boosting efficiency and functionality. Looking ahead, interdisciplinary collaborations and the convergence of material science, biotechnology, and renewable energy systems are likely to open new avenues for the development of photothermal materials, making them indispensable in addressing global energy and sustainability challenges.

7. Conclusion

This research provides a comprehensive review of photothermal materials, emphasizing their fundamental mechanisms, design strategies, and applications in sustainable energy technologies. The insights presented in this paper highlight the transformative potential of photothermal materials in addressing global challenges such as water scarcity, energy efficiency, and environmental sustainability. By exploring advancements in polymer coatings, nanostructured designs, and bioinspired approaches, this review underlines the importance of interdisciplinary efforts in developing innovative solutions. Future research should focus on addressing the challenges of material scalability, stability, and cost-effectiveness while ensuring environmental compatibility. Advancements in fabrication technologies, such as 3D printing and self-assembly, and integration with complementary systems, like phase change materials and nanophotonics, are recommended to enhance the performance and applicability of photothermal materials. By fostering collaboration across disciplines, the development of next-generation photothermal systems can significantly contribute to the transition toward a sustainable energy future.

8. Acknowledgments

The authors express gratitude to the scientific community for their invaluable contributions to the field of photothermal materials, which have formed the foundation of this review.

References

- [1] D. Singh, D. Sharma, S. Soni, S. Sharma, P. K. Sharma, and A. Jhalani, "A review on feedstocks, production processes, and yield for different generations of biodiesel," *Fuel*, vol. 262, p. 116553, 2020.
- [2] S. Falah, M. Ghorbani, and J. Ahmadpour, "Photocatalytic degradation of anionic and cationic dyes over PPy/CuFe₂O₄ nanocomposite under visible-light and bactericidal action," *Journal of the Taiwan Institute of Chemical Engineers*, vol. 144, p. 104767, 2023.
- [3] V. K. Chauhan, S. K. Shukla, J. V. Tirkey, and P. K. S. Rathore, "A comprehensive review of direct solar desalination techniques and its advancements," *Journal of Cleaner Production*, vol. 284, p. 124719, 2021.
- [4] K. Jiao, L. Liu, T. Wen, and Q. Wang, "Endowing photothermal materials with latent heat storage: A state-of-art review on photothermal PCMs," *Chemical Engineering Journal*, p. 156498, 2024.
- [5] Z. Jiang, J. Shu, Z. Ge, Z. Jiang, M. Wang, and X. Ge, "Preparation and performance of magnetic phase change microcapsules with organic-inorganic double shell," *Solar Energy Materials and Solar Cells*, vol. 240, p. 111716, 2022.

- [6] D. Yan, B. Tang, and S. Zhang, "Preparation and performances of sunlight-induced phase change PEG/SiO₂-dye composite for solar energy conversion and storage," *Solar Energy Materials and Solar Cells*, vol. 215, p. 110657, 2020.
- [7] S. Rostami *et al.*, "A review of melting and freezing processes of PCM/nano-PCM and their application in energy storage," *Energy*, vol. 211, p. 118698, 2020.
- [8] Y. Wang, H.-M. Meng, G. Song, Z. Li, and X.-B. Zhang, "Conjugated-polymer-based nanomaterials for photothermal therapy," *ACS Applied Polymer Materials*, vol. 2, no. 10, pp. 4258-4272, 2020.
- [9] M. A. Green and S. P. Bremner, "Energy conversion approaches and materials for high-efficiency photovoltaics," *Nature materials*, vol. 16, no. 1, pp. 23-34, 2017.
- [10] D. Meng, R. Zheng, Y. Zhao, E. Zhang, L. Dou, and Y. Yang, "Near-infrared materials: the turning point of organic photovoltaics," *Advanced Materials*, vol. 34, no. 10, p. 2107330, 2022.
- [11] A. K.-W. Chee, "On current technology for light absorber materials used in highly efficient industrial solar cells," *Renewable and Sustainable Energy Reviews*, vol. 173, p. 113027, 2023.
- [12] A. Onno *et al.*, "Predicted power output of silicon-based bifacial tandem photovoltaic systems," *Joule*, vol. 4, no. 3, pp. 580-596, 2020.
- [13] L. Luo and Z. Wang, "Self-assembled Cu₂-xS nanochains network with tunable diameters for efficient photothermal conversion," *Journal of Alloys and Compounds*, vol. 910, p. 164958, 2022.
- [14] J. Zhao, S. Xue, R. Ji, B. Li, and J. Li, "Localized surface plasmon resonance for enhanced electrocatalysis," *Chemical Society Reviews*, vol. 50, no. 21, pp. 12070-12097, 2021.
- [15] Y. Xin *et al.*, "Copper-based plasmonic catalysis: recent advances and future perspectives," *Advanced Materials*, vol. 33, no. 32, p. 2008145, 2021.
- [16] N. Yan, C. Zhao, S. You, Y. Zhang, and W. Li, "Recent progress of thin-film photovoltaics for indoor application," *Chinese Chemical Letters*, vol. 31, no. 3, pp. 643-653, 2020.
- [17] A. M. Lindi *et al.*, "Fenugreek seed mucilage-based active edible films for extending fresh fruit shelf life: Antimicrobial and physicochemical properties," *International Journal of Biological Macromolecules*, vol. 269, p. 132186, 2024.
- [18] M. Simayee and A. Esfandiari, "Boosting-photothermal properties of Cu/Black TiO₂ nanoparticles on biomimetics texture structure as high-performance and self-regenerating solar-evaporator," *Solar Energy*, vol. 265, p. 112097, 2023.
- [19] Y. Chen, J. Fang, B. Dai, J. Kou, C. Lu, and Z. Xu, "Photothermal effect enhanced photocatalysis realized by photonic crystal and microreactor," *Applied Surface Science*, vol. 534, p. 147640, 2020.
- [20] X. Yu, S. Fan, B. Zhu, S. I. El-Hout, J. Zhang, and C. Chen, "Recent progress on photothermal nanomaterials: Design, mechanism, and applications," *Green Energy & Environment*, 2024/09/21/ 2024, doi: <https://doi.org/10.1016/j.gee.2024.09.002>.
- [21] J. Mei, T. Liao, and Z. Sun, "Two-dimensional metal oxide nanosheets for rechargeable batteries," *Journal of energy chemistry*, vol. 27, no. 1, pp. 117-127, 2018.
- [22] X. Han, L. Ren, Y. Ma, X. Gong, and H. Wang, "A mussel-inspired self-repairing superhydrophobic coating with good anti-corrosion and photothermal properties," *Carbon*, vol. 197, pp. 27-39, 2022.
- [23] X. Ren *et al.*, "Biodegradable 2D GeP nanosheets with high photothermal conversion efficiency for multimodal cancer theranostics," *Chemical Engineering Journal*, vol. 431, p. 134176, 2022.

- [24] S. Falah, M. Ghorbani, and M. Azimifar, "Superamphiphilic Polymeric Coating in Membrane Application: A Mini-Review," *Mini-Reviews in Organic Chemistry*, vol. 20, no. 5, pp. 438-454, 2023.
- [25] W. Luo *et al.*, "Excellent solar-driven interface evaporation by an oil repellence Janus photothermal membrane for oily wastewater treatment," *Chemical Engineering Journal*, vol. 483, p. 149211, 2024.
- [26] L. Xiao, X. Chen, X. Yang, J. Sun, and J. Geng, "Recent advances in polymer-based photothermal materials for biological applications," *ACS Applied Polymer Materials*, vol. 2, no. 10, pp. 4273-4288, 2020.
- [27] A. M. Lindi, S. Falah, M. Sadeghnezhad, and M. Ghorbani, "Optimization of fenugreek seed mucilage extraction for the synthesis of a novel bio-nano composite for efficient removal of cadmium ions from aqueous environments," *International Journal of Biological Macromolecules*, vol. 261, p. 129882, 2024.
- [28] J. D. Earley *et al.*, "Ion-pair reorganization regulates reactivity in photoredox catalysts," *Nature chemistry*, vol. 14, no. 7, pp. 746-753, 2022.
- [29] H. Ganji, M. Taghavijeloudar, and S. R. Khodashenas, "A sustainable approach for heavy metals removal from surface water by sand column amendment with bio-adsorbent of pistachio hull waste (PHW): Batch and fixed-bed column adsorption," *Journal of Water Process Engineering*, vol. 67, p. 106061, 2024.
- [30] A. Khourshidi, F. Ajam, M. Rabieian, and M. Taghavijeloudar, "Efficient degradation of p-nitrophenol from water by enhancing dielectric barrier discharge (DBD) plasma through ozone circulation: Optimization, kinetics and mechanism," *Chemosphere*, vol. 362, p. 142749, 2024.
- [31] S. Falah, A. M. Lindi, and M. Taghavijeloudar, "Visible-Light-Driven Photocatalytic Degradation of Basic Yellow Dye Using TiO₂/GO Nanocomposites: A Sustainable Approach to Wastewater Treatment," in *8th International Conference on Research in Science & Engineering*, 2024.
- [32] Y. Wang, H. Zhang, Z. Wang, and L. Feng, "Photothermal conjugated polymers and their biological applications in imaging and therapy," *ACS Applied Polymer Materials*, vol. 2, no. 10, pp. 4222-4240, 2020.
- [33] X.-z. Jin *et al.*, "Polypyrrole/helical carbon nanotube composite with marvelous photothermoelectric performance for longevous and intelligent internet of things application," *ACS Applied Materials & Interfaces*, vol. 13, no. 7, pp. 8808-8822, 2021.
- [34] L. Wang, M. Zhou, and H. Fu, "An in-situ growth Fe₃O₄ and polyaniline on carbon cloth encapsulated composite phase change materials with high thermal conductivity and photothermal energy conversion and storage," *Journal of Energy Storage*, vol. 78, p. 110090, 2024.
- [35] Y.-G. Zhang, L.-Z. Huang, Q. Yuan, and M.-G. Ma, "Flexible, ultrathin, and multifunctional polypyrrole/cellulose nanofiber composite films with outstanding photothermal effect, excellent mechanical and electrochemical properties," *Frontiers of Chemical Science and Engineering*, vol. 17, no. 8, pp. 1028-1037, 2023.
- [36] C. Yu, L. Xu, Y. Zhang, P. S. Timashev, Y. Huang, and X.-J. Liang, "Polymer-based nanomaterials for noninvasive cancer photothermal therapy," *ACS Applied Polymer Materials*, vol. 2, no. 10, pp. 4289-4305, 2020.
- [37] E. Li *et al.*, "Asymmetric superhydrophobic textiles for electromagnetic interference shielding, photothermal conversion, and solar water evaporation," *ACS Applied Materials & Interfaces*, vol. 13, no. 24, pp. 28996-29007, 2021.

- [38] H. Feng, T. Wang, L. Cao, Y. Pu, Z. Zhao, and S. Chen, "Recent achievements and applications of photothermal self-healing coatings: A review," *Progress in Organic Coatings*, vol. 187, p. 108153, 2024.
- [39] Y. Wang *et al.*, "Photothermally activated self-healing coatings for corrosion protection: A review," *Progress in Organic Coatings*, vol. 185, p. 107886, 2023.
- [40] L. Cao *et al.*, "Three-dimensional nanofibers network multifunctional material for photothermal self-healing protective coating," *Chemical Engineering Journal*, vol. 440, p. 134943, 2022.
- [41] D. Gutiérrez-Armayor, S. Ferrara, M. Nieddu, A. Zieleniewska, and R. D. Costa, "Fluorescent Protein PEGylation for Stable Photon Manipulation in Deep-Red Light-Emitting Devices," *Advanced Functional Materials*, p. 2412921, 2024.
- [42] L. He *et al.*, "Conjugated Polymer Composite Flexible Wood Hydrogel-Mediated Sequential Nir-Ii Photothermal and Photodynamic Anti-Bacteria and Macrophage Polarization for Acute Sinusitis," *Available at SSRN 5077605*.
- [43] T.-T. D. Pham, S.-N. Nam, T. X. Hoang, J. Nam, S. Cho, and J. Park, "Selective photothermal and photodynamic capabilities of conjugated polymer nanoparticles," *Polymer*, vol. 294, p. 126689, 2024.
- [44] E. Zhang, M. A. Jahid, J. Wang, N. Wang, and Q. Duan, "Investigating impacts of condensation on thermal performance in greenhouse glazing and operational energy use for sustainable agriculture," *Biosystems Engineering*, vol. 236, pp. 287-301, 2023.
- [45] Y. Shi *et al.*, "A 3D photothermal structure toward improved energy efficiency in solar steam generation," *Joule*, vol. 2, no. 6, pp. 1171-1186, 2018.
- [46] F. Zhao *et al.*, "Highly efficient solar vapour generation via hierarchically nanostructured gels," *Nature nanotechnology*, vol. 13, no. 6, pp. 489-495, 2018.
- [47] M. A. Azadgoleh, M. Taghavijelouidar, M. M. Mohammadi, A. K. Ahangar, and P. Yaqoubnejad, "A novel blue-green infrastructure for providing potential drinking water source from urban stormwater through a sustainable physical-biological treatment," *Water Research*, p. 123029, 2024.
- [48] L. Zhu *et al.*, "Advances in photothermal regulation strategies: from efficient solar heating to daytime passive cooling," *Chemical Society Reviews*, 2023.
- [49] C. Zhang, N. Li, and G. An, "Review of Concentrated Solar Power Technology Applications in Photocatalytic Water Purification and Energy Conversion: Overview, Challenges and Future Directions," *Energies*, vol. 17, no. 2, p. 463, 2024.
- [50] N. Gol, M. Taghavijelouidar, N. Jalilian, and S. Rezaia, "Microalgae cultivation in semi-transparent photovoltaic bioreactor for sustainable power generation, wastewater treatment and biodiesel production," *Energy Conversion and Management*, vol. 325, p. 119417, 2025.
- [51] L. Yingfeng *et al.*, "Efficient and comprehensive photovoltaic/photothermal utilization technologies for solar energy," *Power generation technology*, vol. 43, no. 3, p. 373, 2022.
- [52] Y. Xiao, X. Li, T. Zheng, K. Xiao, and Y. Wang, "Photothermal nanoreactors for photocatalytic solar energy conversion," *Coordination Chemistry Reviews*, vol. 517, p. 216017, 2024.
- [53] T. Luchs, A. Zieleniewska, A. Kunzmann, P. R. Schol, D. M. Guldi, and A. Hirsch, "Non-Covalent Postfunctionalization of Dye Layers on TiO₂—A Tool for Enhancing Injection in Dye-Sensitized Solar Cells," *Chemistry—A European Journal*, vol. 27, no. 15, pp. 5041-5050, 2021.
- [54] S. Ullah *et al.*, "Theoretical and experimental progress in photothermal catalysis for sustainable energy and environmental protection: Key problems and strategies towards commercialization," *Renewable and Sustainable Energy Reviews*, vol. 201, p. 114615, 2024.

NEW APPROACHES IN ENGINEERING AND BASIC SCIENCES

- [55] J. Hu *et al.*, "Photothermal fabrics for solar-driven seawater desalination," *Progress in Materials Science*, p. 101407, 2024.
- [56] H. Chen, S.-L. Wu, H.-L. Wang, Q.-Y. Wu, and H.-C. Yang, "Photothermal devices for sustainable uses beyond desalination," *Advanced Energy and Sustainability Research*, vol. 2, no. 3, p. 2000056, 2021.
- [57] X. Cui *et al.*, "Photothermal nanomaterials: a powerful light-to-heat converter," *Chemical Reviews*, vol. 123, no. 11, pp. 6891-6952, 2023.
- [58] C. Qian, M.-J. Li, Z.-M. Liu, H.-Y. Xue, and Y. He, "A study on novel dual-functional photothermal material for high-efficient solar energy harvesting and storage," *Energy Storage Materials*, vol. 70, p. 103466, 2024.
- [59] L. Rotundo, "Electro-and photoreduction of carbon dioxide by Re (I) and Mn (I) bipyridine complexes," 2020.
- [60] X. Zhang, Q. Shi, L. Luo, Y. Fan, Q. Wang, and G. Jia, "Research progress on the phase change materials for cold thermal energy storage," *Energies*, vol. 14, no. 24, p. 8233, 2021.