# Review on Emerging Photothermal Cancer Therapy Using Two-Dimensional MXene Nanomaterials

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**ABSTRACT**

Nanomaterial-assisted photothermal therapy (PTT) as a non-invasive cancer treatment has emerged as a promising strategy for the localized ablation of tumors while minimizing systemic toxicity. Among the various nanomaterials developed for this purpose, MXenes a class of two-dimensional transition metal carbides and nitrides have gained significant attention due to their strong light absorption, high photothermal energy conversion efficiency, low infrared emissivity, and surface tunability. These properties enable MXenes to serve as efficient photothermal agents capable of generating localized hyperthermia under near-infrared (NIR) light irradiation. This review provides a brief overview of the molecular structure and photothermal properties of MXenes and explains the mechanisms underlying their advantageous photothermal performance compared to other competing materials. It further discusses recent in vivo studies demonstrating complete tumor eradication through MXene-assisted PTT. Finally, future research directions are proposed to address current challenges and advance MXenes as platforms for safe, effective, and non-invasive cancer treatment.

*Keywords:* photothermal therapy; non-invasive cancer treatment; MXene; two-dimensional nanomaterials.

## INTRODUCTION

Photothermal therapy (PTT) has gained recent attention as a non-invasive cancer treatment strategy [1]. PTT utilizes light-absorbing agents to convert near-infrared (NIR) light into heat, inducing localized hyperthermia that selectively destroys cancer cells. This spatial selectivity minimizes damage to surrounding healthy tissue and allows PTT to be combined with other therapeutic approaches, such as chemotherapy or immunotherapy, without increasing systemic toxicity [2].

Because photothermal energy conversion is central to PTT, the selection of an efficient photothermal agent is critical to the therapy's success. An ideal photothermal agent must exhibit high photothermal conversion efficiency in the NIR region, along with excellent biocompatibility [3].

MXenes, a novel class of two-dimensional transition metal carbides and nitrides, have recently emerged as promising nanomaterials for photothermal applications. They possess strong NIR light absorption, efficient photothermal conversion, and versatile surface chemistry that enables functionalization to enhance biocompatibility [4]. These characteristics place MXenes at the forefront of research in non-invasive cancer therapy, and a growing number of studies are investigating their potential in photothermal-based treatments.

This review provides an overview of the photothermal properties and underlying mechanisms of MXenes, followed by a discussion of their recent applications in photothermal cancer therapy.
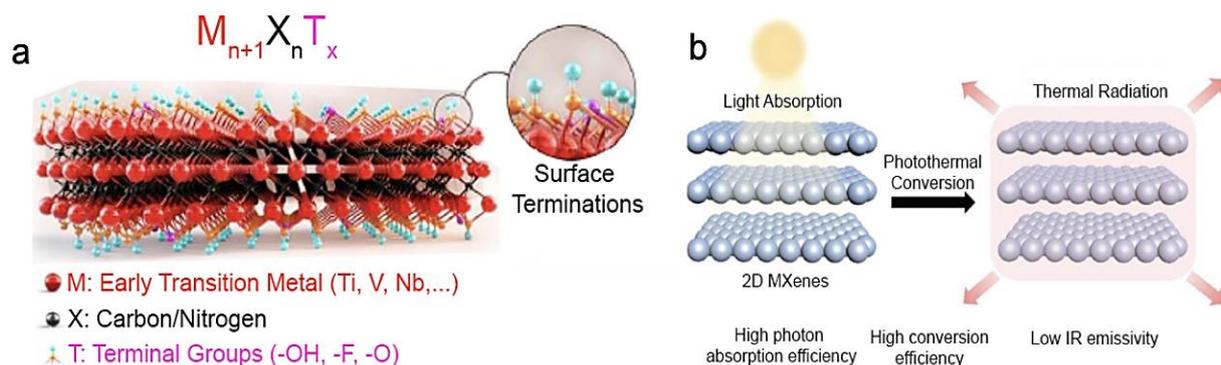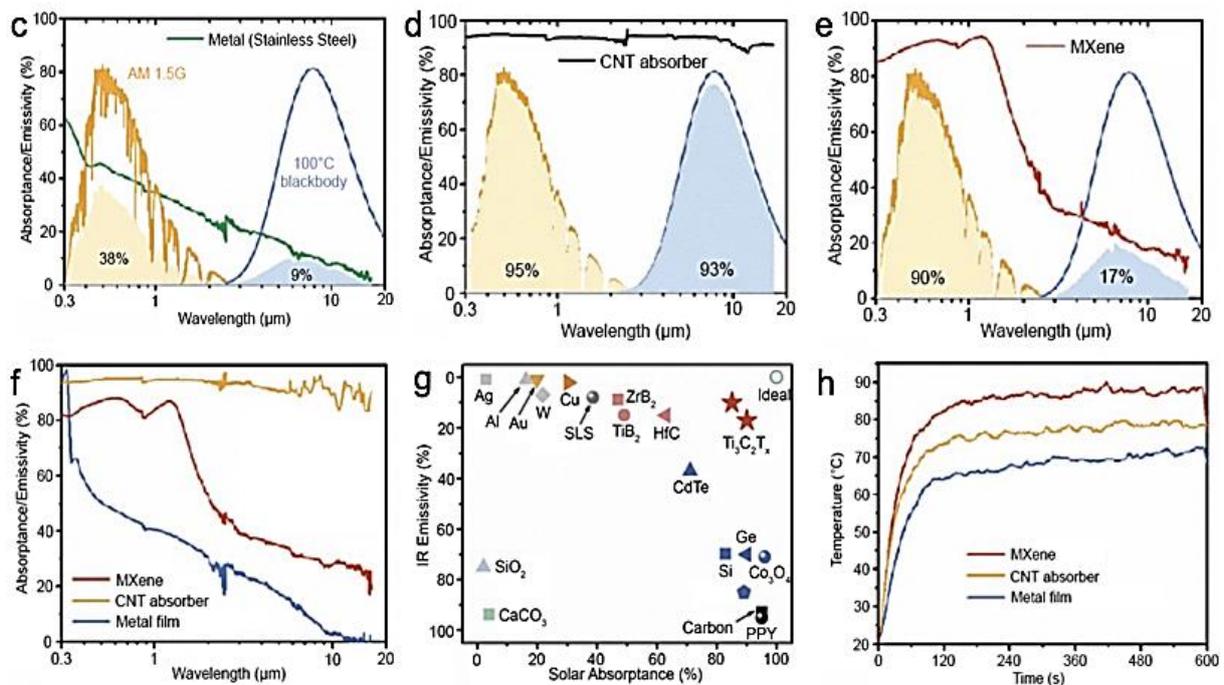
**FIGURE 1:** (a) Schematic illustration of the molecular structure of two-dimensional MXene nanomaterial [5]. Reproduced with permission from AAAS. (b) Schematic illustration of photothermal conversion in 2D MXenes, highlighting their high photon absorptance, efficient photothermal energy conversion, and low infrared emissivity [2]. (c-e) Absorptance spectra, AM 1.5G solar absorption spectrum, and radiation spectrum at 100 °C of (c) a polished stainless-steel (SLS) metal sheet, (d) a carbon nanotube (CNT) black absorber, and (e) a MXene film [6]. (f) Wavelength-dependent absorptance/emissivity spectra of $Ti_3C_2T_x$ MXene film, CNT absorber, and metal film [6]. (g) Comparison of solar absorptance and IR emissivity performance of MXenes with other representative photothermal materials [6]. (h) Time-dependent temperature profiles of $Ti_3C_2T_x$ MXene, CNT absorber, and metal film under continuous light exposure [6]. Reproduced with permission from Wiley.

## Molecular Structure and Photothermal Properties of Two-Dimensional MXenes

As illustrated in Figure 1a, MXenes represent a large family of two-dimensional transition metal carbides or carbonitrides, or nitrides, nanomaterials with the general molecular formula $M_{n+1}X_nT_x$ . In this formula, M represents an early transition metal such as titanium, vanadium, or niobium, while X denotes carbon and/or nitrogen. The variable n represents an integer, typically ranging from 1 to 5. The $T_x$ component refers to surface terminations, such a hydroxyl (–OH), oxygen (–O), and fluoride (–F), which decorate the outer surfaces of the MXene sheets [5].

MXenes are commonly synthesized by selectively etching the A-layer, usually aluminum, from precursor MAX phases using fluoride-containing solutions such as hydrofluoric acid (HF) or ammonium bifluoride ($NH_4HF_2$) [1]. This process produces ultrathin 2D nanosheets that retain the layered structure of MAX phases, exhibit hydrophilic surfaces, and contain abundant surface terminations.

Photothermal conversion is the process by which absorbed light energy is transformed into thermal energy. When photons are absorbed by a material, their energy excites electrons to higher energy states. As the electrons relax back to their ground state, the absorbed energy is released either as light through radiative decay or as heat through non-radiative decay. The ability for materials to generate heat from light defines its photothermal properties.

Efficient photothermal heating requires high photon absorptivity, high photothermal conversion efficiency, and low infrared (IR) emissivity (Figure 1b). This allows materials to absorb light effectively, convert that light into heat, and retain the generated heat locally to maintain elevated temperatures [6].

MXenes exhibit particularly strong photothermal properties, including efficient light absorption, especially in the NIR region, and high photothermal conversion efficiency. For example, $Ti_3C_2T_x$ MXene demonstrates approximately 100% internal conversion efficiency when exposed to an NIR laser [7]. Additionally, MXenes possess low IR emissivity, which minimizes thermal radiation loss and helps retain heat in the targeted area. This combination enables MXenes to achieve rapid and substantial temperature increases under NIR irradiation, a prerequisite for effective tumor ablation in PTT.

To evaluate the photothermal performance of MXenes relative to other competing materials, their absorptance and emissivity spectra have been systematically measured and analyzed. Figures 1c to 1e present the absorptance spectra, solar absorption spectrum, and infrared radiation spectrum for a polished stainless-steel (SLS) metal sheet, a carbon nanotube (CNT) absorber, and a $Ti_3C_2T_x$ MXene film [6]. Figure 1f compares the absorptance spectra of three materials. The metal sheet exhibits low light absorptance at around 30-40% across most wavelengths. In contrast, both the CNT absorber and

the MXene film display extremely high absorptance in the UV to NIR range, exceeding 90% absorptance. This high absorptance is especially relevant in the NIR window, spanning wavelengths from 0.7 to 1.7 μm, where biological tissues are most transparent to light.

The yellow and orange regions of the spectra in Figures 1c to 1e represent the materials' absorptance under Air Mass 1.5 Global (AM 1.5G) solar conditions, simulating sunlight on Earth's surface. Both the CNT absorber and $Ti_3C_2T_x$ MXene film demonstrate very high solar absorption around 90 to 95% whereas the metal film absorbs only around 38%. The blue regions in Figures 1c to 1e represent the IR emissivity of the materials when heated to 100 °C. An ideal blackbody curve, depicted as a dark blue line, serves as the theoretical maximum emitter of IR radiation at this temperature. The CNT absorber nearly reaches this maximum with a high emissivity of 93%, indicating that it radiates most of the heat it absorbs. In contrast, the $Ti_3C_2T_x$ MXene film retains heat more effectively due to its low emissivity of just 17%, enabling sustained and localized hyperthermia during treatment. Thus, MXenes have the optimal combination of high light absorption and low IR emissivity, enabling efficient heat generation and retention.

Figure 1g further compares the photothermal properties of MXenes with those of other competing materials. MXenes uniquely combine IR emissivity below 20% with solar absorptance exceeding 80%, clearly outperforming other materials.

The practical implications of these properties are further confirmed by experimental photothermal heating tests. As shown in Figure 1h, when subjected to 1 sun solar irradiation for 10 minutes, a $Ti_3C_2T_x$ MXene film rapidly reached temperatures of approximately 89 °C [6]. In comparison, a metal film and CNT absorber reached only 72 °C and 80 °C, respectively, under the same conditions. This rapid temperature rise confirms MXenes' superior ability to convert light into heat.

MXenes' strong NIR absorption, efficient photothermal conversion, and low IR emissivity in comparison to other materials allow for rapid heating under NIR irradiation. These attributes position MXenes as highly promising candidates for photothermal therapy applications.
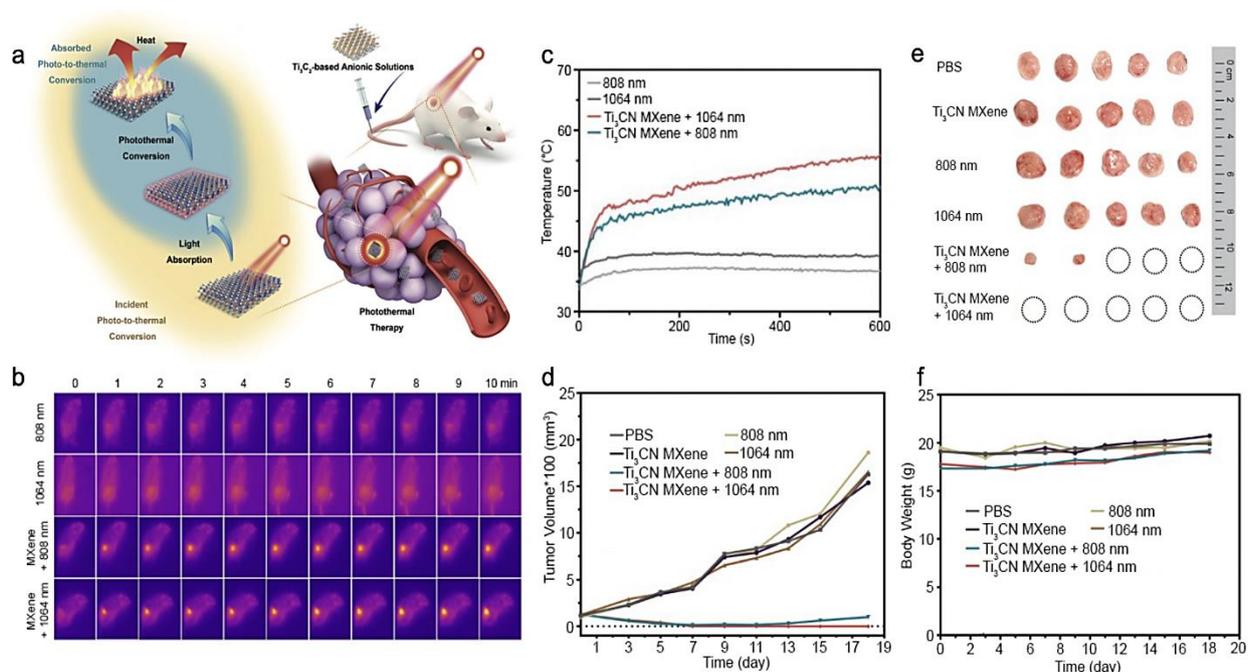


**FIGURE 2:** (a) Schematic illustration of MXene-assisted photothermal therapy for in vivo photothermal tumor ablation [8]. (b) Infrared thermal images of tumor-bearing mice with or without receiving the intravenous injection of d-$Ti_3CN$-BSA MXene under 808 nm or 1064 nm laser irradiation (1.5 W/cm$^2$) at various time intervals [9]. (c) Time-dependent temperature profiles at the sites of 4T1 tumor-bearing mice, treated with 808 nm laser, 1064 nm laser, d-$Ti_3CN$-BSA + 808 nm laser, and d-$Ti_3CN$-BSA + 1064 nm laser [9]. (d) 4T1 tumor volume change in mice over time (PBS, d-$Ti_3CN$-BSA only, 808 nm, 1064 nm, d-$Ti_3CN$-BSA + 808 nm, and d-$Ti_3CN$-BSA + 1064 nm) [9]. (e) Photographs illustrating tumor volume change in mice after 18 days [9]. (f) Body-weight of mice over time (PBS, d-$Ti_3CN$-BSA only, 808 nm, 1064 nm, d-$Ti_3CN$-BSA + 808 nm, and d-$Ti_3CN$-BSA + 1064 nm) [9]. Reproduced with permission from Wiley.

**MXenes in Photothermal Therapy**
In a typical PTT procedure, photothermal agents are first administered into the bloodstream. Once localized at the tumor, external light is applied to the targeted area to initiate the photothermal conversion process (Figure 2a) [1]. A critical factor in photothermal therapy is the penetration depth of the incident light.

Most wavelengths in the visible or ultraviolet range are rapidly scattered or absorbed by biological tissues, limiting their effectiveness for treating deep-seated tumors. To overcome this limitation, NIR light is used due to its superior tissue penetration, which results from reduced scattering and lower absorption by water and biological chromophores.

NIR-I light (700–900 nm) is commonly used, while NIR-II light (1000–1700 nm) can penetrate even deeper into tissue [4]. Although NIR-II light has lower photon energy than NIR-I due to its longer wavelength, its enhanced tissue penetration makes it particularly suitable for treating deeply embedded tumors.

For instance, an in vivo experiment using 4T1 tumor-bearing mice was conducted to evaluate the effectiveness of MXenes as photothermal agents in PTT (Figure 2b-f) [9]. The mice, each bearing tumors approximately 120 mm$^3$ in volume, were randomly divided into six groups of five mice each. The first group served as a control and was administered a phosphate-buffered saline (PBS) solution to maintain pH balance. The second and third groups were treated with an 808 nm laser and a 1064 nm laser, respectively. The fourth group received an intravenous injection of delaminated $Ti_3CN$ MXene with a bovine serum albumin (BSA) attachment to improve the dispersibility and stability in the physiological environments (d-$Ti_3CN$-BSA). The fifth group was injected with d-$Ti_3CN$-BSA photothermal agent and treated with an 808 nm laser, representing photothermal therapy with a NIR-I laser. The sixth group was injected with d-$Ti_3CN$-BSA and treated with a 1064 nm laser, representing PTT with a NIR-II laser.

Treatments were initiated by injecting the mice with the $Ti_3CN$ MXene agent through the tail vein, then irradiating them with a NIR laser (1.00 W/cm$^2$). Infrared thermal images were taken of the mice at one-minute intervals during treatment, as shown in Figure 2b, with corresponding temperature profiles presented in Figure 2c. The tumors on the mice injected with the MXene had a far greater temperature increase than the mice without the MXene, increasing from 35℃ to 50-55℃. Notably, the 1064 nm laser proved more effective than the 808 nm laser, raising the temperature to 55 °C compared to 50 °C, highlighting the strong photothermal response of MXenes under NIR-II irradiation.

The tumor volumes were measured at two-day intervals over 18 days, as presented in Figure 2d and 2e. A marked difference was observed between the PTT-treated groups and the controls. In the PBS, d-$Ti_3CN$-BSA only, 808 nm only, and 1064 nm only groups, tumor volumes increased dramatically to around 1500 mm$^3$ after 18 days. In contrast, the d-$Ti_3CN$-BSA + 808 nm laser group exhibited a significant reduction in tumor volume, while the d-$Ti_3CN$-BSA + 1064 nm laser group successfully eradicated the tumors. These results indicate that the combination of $Ti_3CN$-BSA MXene with NIR laser irradiation resulted in complete tumor ablation, while neither the MXene alone nor the NIR laser alone affected the tumor's growth in any meaningful way. Bodyweight monitoring was conducted throughout the study to evaluate treatment safety. As shown in Figure 2f, all groups maintained stable body weights, indicating that the treatments did not induce significant systemic side effects or adverse reactions. This favorable outcome is attributed to the hydrophilic surface characteristics of MXenes, which result in excellent biocompatibility.

These results demonstrate that the $Ti_3CN$-BSA MXene exhibits excellent cancer treatment performance in photothermal therapy under NIR-II laser irradiation, enabling effective tumor ablation without any detectable cytotoxicity.

## CONCLUSION AND PERSPECTIVES

MXenes have emerged as promising nanomaterials for non-invasive photothermal cancer therapy. Their unique combination of strong near-infrared absorptivity, high photothermal conversion efficiency, and low infrared emissivity positions them as ideal candidates for photothermal cancer therapy. These properties enable MXenes to rapidly generate localized heat under NIR light exposure while minimizing heat dissipation, allowing for the thermal ablation of tumor tissues.

In vivo studies have clearly demonstrated the efficacy of MXene-mediated PTT. Animal experiments confirmed that MXene-assisted PTT can achieve complete tumor ablation without observable side effects. These results highlight the advantages of MXenes over conventional invasive cancer therapies by providing a localized, controllable, and minimally toxic therapeutic approach.

Despite these advancements, several research areas can be further developed. To date, most studies have focused on titanium-based MXenes, but exploring MXenes composed of alternative transition metals such as vanadium, molybdenum, or niobium may provide additional functionalities. In particular, biodegradability is critical for clinical use, and non-titanium MXenes have shown potential for enhanced degradability in physiological environments. Further studies are needed to optimize MXene compositions for controlled degradation without compromising therapeutic efficacy.

Currently, MXenes hold significant potential as next-generation nanoplatforms for effective photothermal therapy. Continued interdisciplinary research efforts will be essential to overcome present limitations and accelerate the development of MXene-based photothermal agents for safe and effective clinical applications in non-invasive cancer treatment.

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