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Georgian Biomaterials Journal

News and Views

Photoresponsive hydrogel dressings for controlled drug release in wounds

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ABSTRACT

This study introduces the development of photoresponsive hydrogel dressings designed for controlled drug release in wound care. These hydrogels incorporate photothermal-responsive components enabling drug release to be precisely controlled with near-infrared (NIR) light exposure. Then localized heating triggers the release of therapeutic agents, including anti-inflammatory and antimicrobial drugs, thereby enhancing wound healing by reducing inflammation, encouraging tissue regeneration, and preventing infection. These multifunctional photoresponsive hydrogels represent a promising advancement in smart wound dressings, providing on-demand, spatially and temporally controlled drug delivery to improve healing outcomes in chronic and infected wounds.

Peer review under responsibility of UGPH.

ARTICLE INFORMATION

Article History:
Received 18 February 2025
Received in revised form 20 May 2025
Accepted 25 May 2025

Keywords:
Photoresponsive hydrogel
Wound dressing
Drug delivery
Wound care

Photoresponsive hydrogel dressings offer an advanced method for controlled drug delivery in wound healing [1, 2]. These hydrogels are designed to respond to external light, especially NIR light, allowing precise regulation of when and how much drug is released at the wound site. Photoresponsive hydrogels often incorporate components like polydopamine (PDA), sodium alginate (SA), black phosphorus quantum dots (BPQDs), or reduced graphene oxide (rGO) that confer photothermal properties. Upon NIR light irradiation, these materials convert light into localized heat. This heat generation also enhances the hydrogel's antioxidant properties and tissue adhesion, which benefit wound healing. The PDA/SA hydrogel system showed sustained drug release, effective removal of harmful radicals, and was easy to apply and remove from the skin, making it a promising option for wound dressings that need controlled, on-demand drug delivery [3]. These hydrogels enable sustained and controllable release of drugs such as anti-inflammatory agents such as ibuprofen, growth factors, or antimicrobial compounds [4]. The release can be modulated by adjusting the intensity and duration of light exposure, allowing on-demand dosing that matches the wound healing stages. Some systems also allow visual monitoring of drug release through color changes linked to structural properties, improving treatment precision [5]. Additional innovations include hydrogel dressings embedded with photothermal-responsive microspheres made from materials such as methacrylated hyaluronic acid, silk fibroin, and black phosphorus quantum dots [6]. These microspheres, when exposed to NIR light, undergo stiffness changes that enhance their adhesion and regulate the release of co-loaded therapeutic agents like melittin and vascular endothelial growth factor. The drug release process can also be visually monitored through color changes in the hydrogel, offering an extra layer of control and feedback for wound management. Such multifunctional hydrogels address challenges in chronic wounds, including diabetic ulcers, by improving flexibility, drug delivery accuracy, and healing efficiency [7, 8]. The integration of photothermal effects with drug release in hydrogels provides a dual therapeutic approach: heating under light exposure can directly stop bacterial growth while also triggering the release of anti-inflammatory or regenerative drugs [9]. This dual action speeds up wound healing by lowering infection risk and encouraging tissue regeneration. Additionally, these hydrogels often have other desirable features such as self-healing, skin adhesion, and biocompatibility, which are essential for practical wound care [10].

Moreover, many photoresponsive hydrogels exhibit self-adaptive and removable properties through reversible gel–sol phase transitions, enabling painless dressing changes without damaging new tissue. They also possess antioxidant and anti-inflammatory activities, which help mitigate inflammatory responses and secondary tissue damage[11] . The incorporation of multifunctional components allows these hydrogels to promote collagen deposition, angiogenesis, and overall tissue regeneration, thereby accelerating the healing process [12-14]. Their injectable and rapidly molding nature further enhances clinical applicability for diverse wound types, including infected and chronic wounds [15].

In summary, photoresponsive hydrogel dressings utilize light-triggered mechanisms for controlled and sustained drug release, along with photothermal antibacterial activity and antioxidant effects. These features make them highly effective for treating various wound types, especially chronic and difficult-to-heal wounds, by offering targeted therapy, reducing inflammation, and promoting tissue repair in a controlled and minimally invasive way.

Author Contributions

Naimeh Mahheidari: Conceptualization, Writing – original draft, Writing – review & editing. The author read and approved the final version of manuscript.

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DOI: https://doi.org/....

Declaration of competing interest

The author declares that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

No data is available.

Ethical issues

The author confirms full adherence to all ethical guidelines, including the prevention of plagiarism, data fabrication, and double publication.

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