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Next-generation advanced wound dressings: A comprehensive review of innovative materials, diagnostic technologies, therapeutics, and future perspectives

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Abstract
Chronic wounds represent a significant healthcare burden globally, often characterized by delayed healing, infection, and high treatment costs. While conventional wound dressings serve primarily as protective barriers, they do not actively support the healing process or adapt to the wound microenvironment. In response to these limitations, recent innovations have led to the development of next-generation wound dressings that incorporate advanced materials, sensor technologies, and drug delivery systems. This review explores the evolving landscape of such technologies, including hydrogel composites, nanotechnology-enhanced materials, biosensor-integrated smart dressings, photodynamic therapy (PDT), and negative pressure wound therapy (NPWT). Special attention is given to their mechanisms of action, therapeutic potential, and translational challenges from laboratory research to clinical implementation. Despite promising advancements, widespread adoption remains constrained by factors such as clinical evidence gaps, regulatory hurdles, cost, and usability. Continued interdisciplinary collaboration, robust clinical trials, and user-centered design will be crucial for the integration of these technologies into routine wound care.

Keywords: Advanced wound care, hydrogel dressings, nanotechnology, biosensors, smart dressings, photodynamic therapy, negative pressure wound therapy, theranostics, chronic wounds, personalized medicine

Introduction
Wound healing is a complex physiological process involving hemostasis, inflammation, proliferation, and remodeling. In certain clinical conditions such as diabetes, vascular diseases, and immobility this process is disrupted, leading to chronic wounds that fail to heal within a typical timeframe. Common examples include diabetic foot ulcers, venous leg ulcers, and pressure ulcers (Guo & DiPietro, 2010) [6].

Traditional wound management strategies often rely on passive dressings like gauze, hydrocolloids, or foams, which primarily serve to protect the wound from external contamination. However, these materials are limited in their ability to interact with the wound environment or promote active healing. The increasing prevalence of chronic wounds and antibiotic-resistant infections has driven the need for advanced solutions that can adapt to changing wound conditions, deliver targeted therapy, and support tissue regeneration.

Recent advances in biomaterials, drug delivery systems, biosensors, and digital health integration have catalyzed the development of multifunctional wound dressings. These next-generation technologies aim to shift wound care from passive to active management, offering capabilities such as infection detection, real-time monitoring, and controlled drug release. This review provides a comprehensive overview of current innovations in wound dressing technologies, their clinical applications, and the challenges hindering their widespread adoption.

Evolution of Wound Dressing Materials
Wound dressing materials have undergone a significant transformation over the past century. The evolution can be broadly categorized into three phases:

Traditional Dressings
These include cotton gauze, bandages, and non-adherent pads. They provide physical protection, absorb exudate, and prevent contamination but offer limited biological activity. Their use is still widespread in low-resource settings due to cost and accessibility.

Moisture-Retentive Dressings
With the discovery that a moist wound environment promotes faster healing, materials such as hydrocolloids, foams, alginates, and films became standard in modern care. They maintain wound hydration, reduce pain, and promote autolytic debridement, but lack the ability to respond to infection or tissue regeneration needs.

Bioactive and Responsive Dressings
Current research focuses on integrating functional elements such as antimicrobials, growth factors, nanomaterials, and sensors into dressings. These dressings aim not only to protect but to actively engage with the wound environment to promote healing, control infection, and provide real-time feedback.

Methodology of Literature Review
A systematic review of literature was conducted using databases such as PubMed, Scopus, Web of Science, and Google Scholar, covering the period from January 2015 to April 2025. The search terms included: "advanced wound dressings", "smart bandages", "hydrogels", "nanoparticles for wound healing", "biosensor-integrated dressings", "photodynamic therapy for wounds", and "negative pressure wound therapy". The number of studies identified, excluded, and included in the final analysis was recorded. Each study was further evaluated to assess evidence quality and risk of bias. Quantitative synthesis of selected data was incorporated wherever available;for instance, silver nanoparticle dressings showed >80% bacterial reduction in five RCTs, and hydrogel-based systems demonstrated 25-30% faster wound closure compared to standard gauze.

Inclusion Criteria
- Experimental or clinical studies on advanced or responsive wound dressings
- Focus on chronic, infected, or complex wounds
- Articles published in peer-reviewed journals

Exclusion Criteria
- Reviews without original data
- Case reports with limited relevance
- Studies focusing exclusively on traditional wound dressing methods

The selected studies were analyzed for dressing type, mechanism of action, antimicrobial properties, clinical performance, and translational challenges (Ahmad *et al.*, 2023; Panáček *et al.*, 2020) [1, 2].

Emerging Technologies in Wound Dressings
Hydrogel-Based and Composite Dressings
Hydrogels are three-dimensional, hydrophilic polymer networks capable of retaining significant amounts of water. They provide a moist healing environment, facilitate gas exchange, and support autolytic debridement.

Advancements
- Composite hydrogels are now being developed by incorporating silver nanoparticles, antimicrobial peptides, growth factors such as vascular endothelial growth factor (VEGF), and biopolymers like chitosan and alginate to enhance therapeutic effects (Zulkifli *et al.*, 2022) [8].
- Hybrid systems improve mechanical strength and sustain drug release.

Clinical Relevance
- Particularly useful for diabetic ulcers, burns, and pressure ulcers.
- Biocompatible and adaptable for controlled drug delivery.

Limitations
- Susceptibility to dehydration
- Limited mechanical integrity in large or heavily exuding wounds

Nanotechnology-Enhanced Dressings
Nanomaterials possess unique physicochemical properties due to their size and surface area, offering enhanced interaction with biological systems.

Common Nanoparticles
- Silver nanoparticles (AgNPs): Disrupt bacterial cell membranes and prevent biofilm formation (Ahmad *et al.*, 2023; Akbarzadeh *et al.*, 2023) [1, 3].
- Zinc oxide (ZnO) and copper oxide (CuO): Exhibit broad-spectrum antimicrobial activity and stimulate fibroblast activity (Phumying & Khwanruthai, 2024) [4].

Benefits
- Targeted delivery and localized antimicrobial effects
- Improved wound healing and reduced need for systemic antibiotics

Concerns
- Potential cytotoxicity and environmental impact (Ahmad *et al.*, 2023; Panáček *et al.*, 2020) [1, 2].
- Risk of resistance development
- Need for long-term safety validation

Smart Dressings with Integrated Biosensors
Smart dressings combine traditional wound care materials with embedded sensors that monitor real-time physiological parameters, such as:
- **pH shifts:** Indicators of infection (Zhang *et al.*, 2022) [14].
- **Temperature changes:** Early signs of inflammation
- **Moisture levels:** To prevent maceration or dryness
- **Bacterial load:** Detected via colorimetric or electrochemical methods (Lee *et al.*, 2021) [7].

Innovations
- Responsive dressings that release antimicrobials or anti-inflammatory drugs based on sensor input (Qiao *et al.*, 2020) [16].
- Integration with mobile apps or wireless systems for remote patient monitoring

Challenges
- Biocompatibility and durability of sensors
- Power supply and miniaturization
- High production costs and limited clinical testing

Photodynamic Therapy (PDT)-Integrated Dressings
Photodynamic therapy involves applying a photosensitizer to the wound and activating it with a specific light wavelength, producing reactive oxygen species (ROS) that kill microorganisms.

Advantages
- Effective against antibiotic-resistant strains like MRSA (Rani Raju *et al.*, 2022) [13].
- Localized action with minimal systemic side effects

Limitations
- Requires specific light sources
- May cause phototoxicity if not properly controlled
- Limited penetration for deeper infections

Negative Pressure Wound Therapy (NPWT)
NPWT uses controlled suction through foam or gauze dressings connected to a vacuum device, promoting wound healing through:
- Enhanced perfusion
- Reduced edema and exudate
- Promotion of granulation tissue

Clinical Applications
- Effective for large, complex wounds, surgical wounds, and pressure ulcers
- Widely used in hospital settings

Barriers
- High cost of equipment
- Requires training and monitoring
- Not ideal for ischemic or necrotic wounds

Theranostic and Multifunctional Platforms
These dressings aim to diagnose wound conditions and treat them simultaneously.

Examples
- Dressings that change color in response to pH or temperature changes (Zhang *et al.*, 2022) [14].
- Systems that release drugs only when infection markers are detected
- Future potential for personalized medicine in wound care

Current Status
- Primarily in experimental and prototype stages
- Require regulatory approval and clinical validation

Mechanistically, these advanced dressings act through cytokine modulation, reactive oxygen species (ROS) scavenging, extracellular matrix (ECM) remodeling, and angiogenesis-related signaling pathways. Material-device interfaces such as elasticity, porosity, and adhesion play a critical role in oxygen permeability, moisture control, and cellular migration.
Emerging technologies include electrospun nanofiber scaffolds, hydroconductive and temperature-responsive polymers, and bioelectrical stimulation dressings. Integration with AI-driven image analysis platforms allows real-time wound assessment and automated healing progression tracking. Distinct wound models diabetic, ischemic, and burn demonstrate variable dressing performance, suggesting the need for model-specific optimization.
Table 1 provides a comparative overview of these advanced wound care technologies, highlighting their mechanistic action, healing efficiency, infection-prevention potential, cost per patient, and clinical readiness.

Table 1: Comparative analysis of advanced wound care technologies

Technology	Approximate Healing Speed*	Infection-Prevention Rate*	Approximate Cost per Dressing / Patient*	Clinical Readiness (Examples)
Hydrogel composites	~25-30% faster vs gauze (12±3 days vs 16±4)	Moderate (moisture control & antimicrobial loaded)	Medium cost	Widely used (Class I device)
Nanoparticle-enhanced dressings (AgNP, ZnO, CuO)	High (multiple small RCTs show significant reduction)	High (biofilm disruption)	Higher cost	Limited clinical (early RCTs)
Smart biosensor dressings	Healing speed still pilot	High (for monitoring / infection detection)	Higher cost + infrastructure	Preclinical & early trials
3D-bioprinted scaffolds	Estimated significant (customized tissue architecture)	Moderate to high (tailored structure)	High cost	Research → early clinical (TRL ≈ 4-6)
Bioelectrical stimulation / Electrospun nanofiber scaffolds	High (accelerates granulation / angiogenesis)	Moderate to high	Medium-High cost	Early clinical / pilot (TRL ≈ 5-7)

Note: Healing-speed and infection-prevention data are approximate, based on representative studies. TRL = Technology Readiness Level.

Mechanistic and Molecular Insights into Healing Enhancement
Reactive oxygen species (ROS) play a dual role in wound healing: at moderate levels they act as signaling molecules to stimulate fibroblast and keratinocyte migration, angiogenesis (via VEGF, FGF), and extracellular matrix (ECM) deposition. However, Excessive ROS induce oxidative stress, suppress angiogenesis, upregulate matrix metalloproteinases (MMPs), degrade ECM components such as collagen I and III, and consequently stall healing.
Advanced wound dressings especially nanomaterial and hydrogel-based systems help restore redox balance by scavenging ROS through catalytic nanoparticles (e.g., cerium oxide, silver, or ZnO) or antioxidant-loaded matrices. This modulation reduces inflammation and supports collagen synthesis and granulation tissue formation.
These materials also influence cytokine signaling (e.g., upregulating TGF-β, IL-10, and VEGF) and ECM gene expression, directly enhancing tissue regeneration. Material

parameters such as elasticity (matching dermal modulus 10-40 kPa), porosity (allowing oxygen/nutrient exchange), and surface charge also play key roles in cellular adhesion and migration.

Collectively, these mechanisms explain how smart or bioactive dressings accelerate wound closure, reduce infection, and promote angiogenic and epithelial tissue recovery.

Biocompatibility, Toxicity, and Long-Term Safety of Advanced Wound Dressings

Recent literature regarding toxicity, biocompatibility, and long term safety of advanced dressing materials:

- Silver nanoparticle based dressings show antimicrobial and healing benefits, but also mild adverse effects. Possible issues include cytotoxic effects on skin cells (keratinocytes, fibroblasts), induction of reactive oxygen species (ROS), mitochondrial damage, lipid peroxidation, genetic toxicity, and interference with cell migration (Ahmad *et al.*, 2023; Akbarzadeh *et al.*, 2023) [1, 3].
- The "Silver nanoparticle-based dressings" review noted that while benefits are substantial, the evidence base for long term systemic accumulation or delayed effects remains limited (Ahmad *et al.*, 2023) [1].
- Studies on zinc oxide nanoparticles (ZnO NPs) also show effective antibiofilm and antimicrobial action, but some *in vitro* studies demonstrate that high doses may impair cell viability or induce oxidative stress (Phumying & Khwanruthai, 2024) [4].
- Material biodegradation: For dressings meant to degrade or be absorbable (natural polymers / collagen / chitosan, etc.), there are reports of inflammation or foreign body response, especially where degradation products or crosslinkers are not fully biocompatible. While many preclinical models indicate acceptable biocompatibility, long term human data are often lacking (Haque *et al.*, 2022; Srivastava *et al.*, 2024) [5, 11].
- Sustainability and environmental safety aspects, such as nanoparticle disposal and polymer biodegradability, should also be incorporated into safety assessments to align with evolving regulatory expectations.

Table 2: Comparative Summary of Technologies

Technology	Healing Acceleration	Infection Control	Monitoring Capability	Clinical Use Stage	Technology
Hydrogel Composites	High	Moderate	None	Clinical	Hydrogel Composites
Nanoparticle Dressings	High	High	None	Limited clinical	Nanoparticle Dressings
Smart Biosensor Dressings	High	High	High	Preclinical	Smart Biosensor Dressings
PDT Dressings	Moderate	High	Limited	Pilot Studies	PDT Dressings
NPWT Systems	High	High	Moderate	Widely Used	NPWT Systems
Theranostic Platforms	Moderate	Moderate	High	Experimental	Theranostic Platforms

Table 3: Current Clinical Trials and Marketed Advanced Wound Dressings

Name / Product	Technology Type	Clinical Trial(s) or Approval Status	Key Findings / Use
Silver Nanoparticle Dressings	Nanoparticle-enhanced antimicrobial	Multiple small clinical studies; reviews summarizing trials in burns, ulcers, and dental wounds.	Shown to reduce infection, improve healing; some mild adverse effects but generally well tolerated.
FDA-Classified Hydrogel Wound Dressings (Without Drug/Biologic)	Hydrogels (passive)	Device Code NAE; "Hydrogel Without Drug And/Or Biologic" classified as Class I device under FDA regulation 878.4022.	These dressings are cleared via relatively simple regulatory pathways; provide moisture retention, protection, though no active or sensor functions.
Wound Dressings with Drugs / Antimicrobials (FRO product code)	Drug-containing dressings	FDA's product code "FRO"; many devices have been cleared through 510(k) showing substantial equivalence.	Allow claims of antimicrobial action; used in various clinical settings. Their safety/efficacy depend on drug load, release kinetics, and patient wound type.
Nanoparticle Smart Dressings in Trials / Pre-clinical to Early Clinical	Sensor + NP + smart release	Recent studies on dressings detecting bacterial load or infection indicators with nanoparticle agents and releasing antimicrobials accordingly. (No large phase III trials identified yet.	Promising for precise treatment; the transition to human clinical trials shows future potential but more safety and efficacy data needed.

Table 4: Regulatory Classification and Approval Pathways in Key Markets

Market / Region	Regulatory Authority	Classification Classes & Criteria Relevant to Advanced Dressings
USA (FDA)	CDRH - Center for Devices and Radiological Health	Dressings without drug/ biologic or sensor = Class I (general controls) if low risk. Dressings containing drugs, antimicrobials, or novel sensors may require 510(k) or Premarket Approval (PMA). The FDA has proposed, but not yet finalized, reclassification of certain antimicrobial wound dressings/washes into higher-risk categories (potential Class III) due to antimicrobial resistance concerns.
European Union	European Medical Device Regulation (MDR 2017/745)	Devices classified in Class I, IIa, IIb, or III depending on risk, invasiveness, duration of contact, nature of active elements. Under MDR, dressings for simple wound coverage often class I; dressings with active components or sensors (especially if for serious wounds) may be class IIb or III.
India	CDSCO (Central Drugs Standard Control Organization)	Classification of devices based on risk; non-sterile or non-measuring simple dressings may come under lower class (Class A in India), higher risk sensor- or drug-containing devices under higher classes. Licensing requirements differ (import/manufacturing).
Other Jurisdictions (e.g., Thailand)	National medical device regulatory bodies	Often adopt risk-based classification: simple dressings vs. dressings with pharmacological or sensor contribution, duration of contact, etc.

Challenges in Clinical Translation
Despite technological maturity in laboratories, several obstacles limit clinical adoption:

Clinical Evidence Gaps
- Limited randomized controlled trials (RCTs)
- Small sample sizes and short follow-up durations

Regulatory Complexities
- Lack of standardized regulatory pathways for smart materials and biosensors
- Varying global approval requirements

Cost and Accessibility
- High manufacturing costs
- Limited availability in resource-constrained settings
- Unclear reimbursement policies

Usability and Integration
- Need for user-friendly, wearable designs
- Training requirements for healthcare providers
- Compatibility with existing digital health systems

Current translational limitations also include a lack of unified international regulatory pathways for smart biosensor-based devices and inadequate standardization of performance metrics. Incorporation of human-factor design principles and structured user feedback loops is recommended to enhance device usability and adoption in clinical practice.

Future Perspectives
Ethical Considerations, User Training, and Patient-Centered Design: As next-generation wound dressings increasingly incorporate sensing, data gathering, and possibly remote monitoring or connectivity, ethical issues such as patient privacy**,** data security, and informed consent become central. Patients should be made aware of what physiological data is collected (e.g., pH, bacterial load, temperature), how it is used, stored, and who has access. Additionally, user training for both healthcare providers and patients is essential to ensure proper application, monitoring, and interpretation of smart functionalities; poorly trained use can lead to misuse or misinterpretation of sensor signals. Patient-centered design should also address comfort, ease of use (e.g., changing dressings, visibility of sensors), pain risk during application/removal, and aesthetic considerations. Special attention should be paid to vulnerable populations (elderly, children, those with limited mobility or cognitive impairments), so homes or low-resource settings are considered in design and instructions. Ethical review should also consider equitable access to ensure that advanced dressings do not exacerbate healthcare disparities.
To address existing barriers and maximize impact, the following areas require focus:
- **Large-scale multicenter clinical trials** to establish safety and efficacy
- **Cost-reduction strategies** for scalable manufacturing
- **Policy support** for integration into public healthcare systems
- **Interdisciplinary collaboration** between engineers, clinicians, and regulatory experts
- **Design optimization** for wearability, durability, and ease of use
- **Emphasis on patient-centric approaches** to personalize wound care

Mapping of each technology to its Technology Readiness Level (TRL) provides a clearer translational roadmap—from TRL 4 (preclinical smart dressings) to TRL 7 (pilot clinical hydrogels). These TRL values are approximate estimates based on published preclinical and early clinical studies, and do not represent formal TRL certifications. Additionally, sustainability and eco-safety should guide future material design. Integration of digital wound-care ecosystems with electronic health records (EHR) and AI-based decision support systems can enable data-driven personalized care.

Conclusion
Next-generation wound dressings represent a transformative shift in wound care, moving from passive protective materials toward intelligent, bioactive, and responsive systems. Advanced technologies including hydrogel composites, nanoparticle-enhanced dressings, biosensor-integrated platforms, 3D-bioprinted scaffolds, and electrospun nanofiber systems demonstrate the ability to accelerate healing, reduce infection risk, and support tissue regeneration through precise modulation of reactive oxygen species, cytokine signaling, extracellular matrix deposition, and angiogenesis. By leveraging tailored mechanical properties, porosity, and bioactive surface cues, these dressings create microenvironments that actively promote cellular migration, proliferation, and granulation tissue formation, offering a mechanistic basis for their clinical benefits.
Despite these promising features, translation into routine clinical practice remains constrained by limited large-scale clinical trials, variability in regulatory pathways, high production costs, and usability challenges. The incorporation of sensing and data-driven capabilities introduces additional considerations, including patient privacy, data security, informed consent, and the need for structured training for both healthcare providers and patients. Addressing these challenges requires an integrated strategy combining interdisciplinary research, patient-centered design, cost-effective manufacturing, and regulatory harmonization.
Looking forward, the convergence of bioactive dressings with digital health ecosystems, AI-enabled decision support, and personalized medicine approaches has the potential to redefine wound management. Ethical deployment, equitable access, and sustainability considerations must remain central to the development of next-generation products. With continued innovation, robust clinical validation, and thoughtful integration into healthcare systems, advanced wound dressings could substantially improve patient outcomes, reduce healthcare burden, and set new standards for precision wound care globally.

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