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SMART WOUND DRESSING: AN OVERVIEW

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1.ABSTRACT –Wound management remains a major global challenge, placing a significant financial strain on healthcare systems worldwide. Traditional wound dressings such as bandages, hydrogels, and foams offer basic protection and support but fall short in effectively responding to the dynamic process of wound healing. To address these limitations, researchers have explored the development of smart wound dressings that can actively interact with wounds, sense changes in the local environment, and adapt accordingly. By incorporating built-in sensors and advanced materials such as stimuli-responsive and self-healing polymers, these dressings aim to accelerate recovery and improve patient outcomes. Over the past decade, several innovative types of smart wound dressings have emerged, including biomechanical dressings, stimuli-responsive systems, self-healing dressings, self-removable designs, and monitoring-enabled platforms. Despite this progress, a comprehensive review of these advancements is still lacking. This article therefore seeks to provide a structured overview of smart wound dressings, highlighting their current status, recent breakthroughs, ongoing challenges, and future directions, with the goal of offering researchers a clear perspective on the evolution and potential of this rapidly growing field.

Keywords: Bandages, wounds management, sensors, self-healing, smart wound dressing.

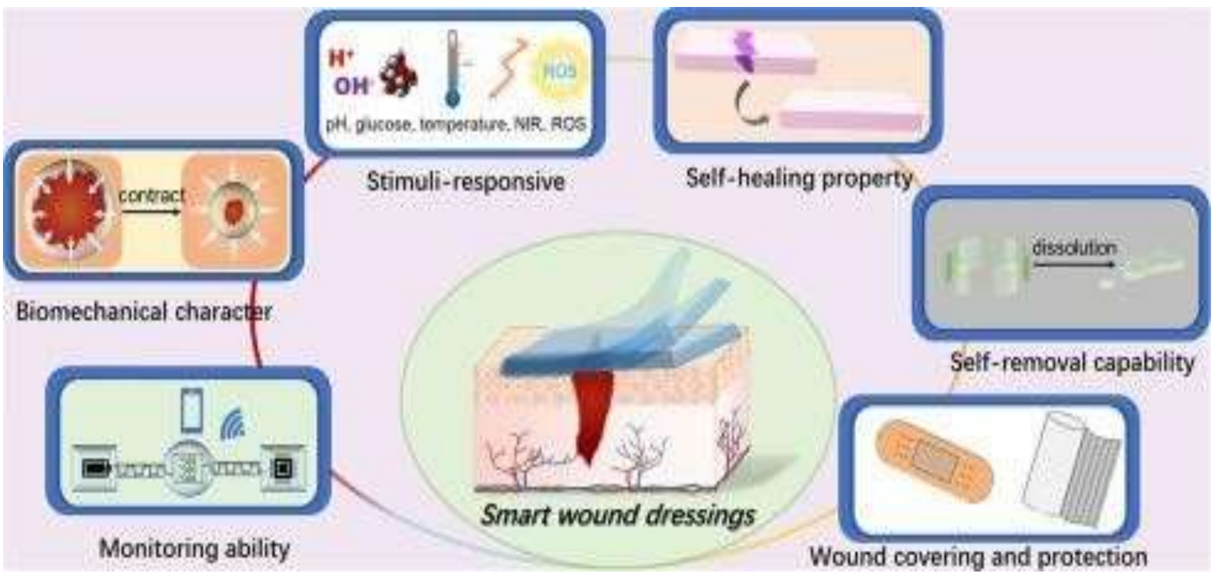

Figure 1: key functions of smart wound dressing

2.INTRODUCTION –

Wound management remains a significant therapeutic and economic challenge, with global expenditures reaching billions annually. Wound dressings function as pharmaceutical adjuncts designed to protect the wound bed, maintain an optimal healing environment, and prevent secondary complications. Despite the availability of numerous formulations, conventional dressings often fail to meet clinical demands. They lack adaptability to dynamic wound physiology, are unsuitable for anatomical regions subjected to mechanical stress (e.g., joints, cervical areas), and frequently cause patient discomfort during dressing changes. These limitations have accelerated the demand for smart wound dressings as advanced drug-delivery and tissue-engineering platforms.

Smart wound dressings represent an innovative strategy in pharmaceutics and biomedical engineering. They are fabricated using stimuli-responsive polymers, bioactive matrices, and integrated biosensors, enabling them to sense local wound conditions and modulate their properties accordingly. Since wound healing progresses through distinct phases such as homeostasis, inflammation, proliferation, and remodeling of smart dressings are designed to interact with each stage, thereby optimizing therapeutic outcomes.

3.CHARACTERISTICS–

Smart wound dressings are advanced bio-interactive therapeutic systems designed to transform wound care by integrating real-time monitoring of critical biomarkers such as pH, temperature, and microbial activity. These dressings function as multifunctional pharmaceutical devices, capable of delivering on-demand, site-specific therapeutics including antimicrobials, growth factors, or anti-inflammatory agents.

Key Characteristics of smart wound dressing:

3.1 Real-time Monitoring & Diagnosis: Sensors embedded within the dressing track wound conditions (e.g., infection, pH, humidity) without removal, providing constant data.

3.2 Stimuli-Responsive Therapy: These dressings respond to local environmental changes (like pH fluctuations or temperature changes) to trigger active, on-demand treatment.

3.3 Controlled Drug Release: Smart dressings can precisely release medication, antibiotics, or growth factors only when needed, minimizing over-medication.

3.4 Accelerated Healing & Protection: They maintain an optimal, moist environment that supports tissue regeneration while offering a robust barrier against bacterial infections.

3.5 Reduced Clinical Intervention: Features like visual indicators for dressing changes reduce the need for manual inspection, minimizing pain and tissue damage.

3.6 Biocompatibility & Safety: Designed to be non-cytotoxic, ensuring they do not irritate the wound or hinder healing.

3.7 Flexible & Wearable Design: Suitable for complex wounds and movement-heavy areas, increasing patient comfort and mobility.

4.CONVENTIONAL TO SMART DRESSING JOURNEY–

The progression from conventional to smart wound dressings signifies a paradigm shift in pharmaceutical wound care technology from passive, static protection to active, intelligent, and patient-specific management. Conventional dressings primarily serve as barrier systems, preventing microbial contamination and maintaining a basic healing environment. In contrast, smart wound dressings integrate biosensors, microelectronics, and therapeutic delivery modules to continuously monitor wound physiology in real time, detect early signs of infection, and, when necessary, administer targeted pharmacological interventions directly at the wound site. This innovation minimizes the need for frequent, painful dressing changes while ensuring personalized, autonomous, and proactive wound therapy, particularly valuable in chronic and complex wound scenarios.

The Evolution of Wound Care:

Conventional Dressings (Passive): Cotton gauze, bandages, and films, which serve to protect against environmental contamination, absorb excess exudate, and keep the wound covered. They are low-cost but require frequent changes and provide no data on the healing process.

Advanced/Active Dressings: Hydrogels, alginates, and foams that maintain a moist environment and actively promote healing by interacting with the wound bed.

Smart Dressings (Intelligent): The latest innovation, which integrates sensors to monitor physiological markers (pH, temperature, moisture, glucose) and sometimes includes microelectronics for on-demand drug delivery or stimulation.

Key technologies of Smart Wound Dressings:

Smart dressings are designed to be multifunctional, combining several key technologies:

Real-time Monitoring (Sensors): Flexible, biocompatible sensors monitor wound parameters like temperature (a rise indicates infection), pH (a rise indicates bacterial infection), oxygenation, and moisture levels.

Colorimetric/Optical Sensors: Some dressings use dyes that change colour in response to pathogenic infections, allowing for easy visual inspection without removing the bandage.

Controlled/On-demand Drug Delivery: These dressings can release antimicrobial agents, drugs, or growth factors directly to the wound site in response to specific triggers like pH changes or infection, or via external control (e.g., via a smartphone).

Wireless Data Transmission: Sensors send real-time data to a smartphone app, providing clinicians with objective data to monitor healing remotely, significantly reducing the need for clinical visits.

Advanced Materials: Hydrogels (e.g., using gelatin methacrylate or GelMA) are often used because of their high absorption capacity, which allows them to effectively manage wound exudate.

5.APPROACHES OF SMART WOUND DRESSINGS-

Smart wound dressings integrate advanced materials and electronics to monitor wound conditions (pH, temperature, moisture, oxygen) in real-time and provide on-demand, targeted therapy. Key approaches include sensor-based monitoring, stimuli-responsive drug delivery, functional, bio-active materials, and AI-driven, smart mobile, or wireless, connectivity to enhance healing rates and reduce infection.

Key Approaches of Smart Wound Dressings:

Sensor-Based Monitoring: These dressings feature built-in miniaturized, flexible sensors to continuously track physiological parameters like pH, temperature, moisture, and reactive oxygen species (ROS).

Stimuli-Responsive Drug Delivery: Advanced materials are designed to release therapeutic agents (antibiotics, growth factors) in response to specific stimuli, such as changes in pH or temperature indicating infection.

Wireless Communication and Data Transmission: Smart, flexible electronics are integrated into dressings to transmit real-time, data to smartphones or external devices, allowing for remote monitoring of the healing process.

Functional Biomaterials: Utilization of bioactive materials and nanotechnology (e.g., electrospun nanofibers, hydrogels) allows the dressing to interact with the wound, enhancing tissue regeneration and providing a, self-degrading, and protective environment.

Closed-Loop Automated Systems: Some dressings combine sensing and drug release into a single, automated, closed-loop system, providing personalized treatment with minimal human intervention.

Active and Intelligent Materials: Use of self-healing, self-degrading, or bioactive materials that promote tissue regeneration and eliminate the need for frequent, painful dressing changes.

Multilayered Functional Scaffolds: Advanced dressings, often created via electrospinning, that combine multiple functions (e.g., rapid clotting, antimicrobial protection, and oxygen permeable barriers) in a single, structured, often bio-based patch.

6.COMPONENTS OF SMART WOUND DRESSINGS-

Smart wound dressings consist of a multi-layered structure combining a biocompatible, moisture-retentive base (hydrogels, alginates) with embedded electronics for real-time sensing (pH, temperature, oxygen) and stimuli-responsive release systems. These, together with wireless communication, allow for monitoring and active, on-demand drug delivery to promote healing.

Key Components of Smart Wound Dressings

6.1 Materials & Functional Matrix:

- Hydrogels: Maintain a moist environment, often made of polyacrylamide, PVA, or carboxymethyl chitosan.
- Alginates: Used for high-drainage wounds, they form gels upon contact with exudate.
- Polymer/Lipid Nanostructures: Offer controlled, stimulus-responsive drug delivery.
- Bioactive Agents: Silver nanoparticles (AgNPs) for antibacterial action, or growth factors.

6.2 Sensing Elements:

- pH Sensors: Monitor changes in acidity indicating infection.
- Temperature Sensors: Detect inflammation.
- Moisture/Exudate Sensors: Measure wound hydration levels.

6.3 Drug Delivery Systems (Stimuli-Responsive):

- Smart polymers that release medication (e.g., antibiotics, growth factors) in response to pH or temperature changes.

6.4 Electronics & Communication:

- Wireless Communication Modules: Bluetooth Low Energy (BLE) to transmit data to smartphones.
- Flexible Circuitry: Microelectronics integrated onto flexible substrates.

6.5 Physical Components:

- Impermeable Outer Layer: Protects against bacterial contamination.
- Absorbing Layers: Specialized sponges or foams (e.g., polyurethane) for exudate management.

Examples are: Gauze, lint, adhesive bandage (plasters), and cotton wool. The main aim is to protect the wound from bacterial contamination. They are also used for secondary dressing. Gauze dressing is made up of woven or non-woven fibres of cotton, rayon, and polyester.

7.PROPERTIES OF SMART WOUND DRESSINGS-

Smart wound dressings are advanced, active, and responsive materials designed to revolutionize chronic wound care by integrating real-time monitoring and therapeutic delivery. Key properties include sensing parameters like pH, temperature, and exudate levels, enabling targeted, stimuli-responsive drug release. These, often biocompatible, dressings improve patient outcomes by reducing the need for frequent, painful dressing changes.

Key properties of smart wound dressings include:

Real-time Monitoring: Built-in microelectronic sensors or colorimetric indicators detect changes in the wound microenvironment, such as pH (infection detection), temperature (inflammation tracking), and moisture levels.

Active Therapy Delivery: These dressings can release antimicrobial agents or growth factors on-demand, triggered by environmental changes (e.g., pH increases) or through external, wireless, or electronic control.

Stimuli-Responsive Behavior: Smart materials (hydrogels, polymers) within the dressing respond to triggers like light, pH, reactive oxygen species (ROS), or temperature to alter their structure, such as becoming self-healing or, in some cases, self-removable.

Diagnostic Capabilities: They can monitor biomarkers (e.g., glucose, lactate, uric acid) that indicate, for example, Diabetic Foot Ulcer (DFU) infection, with data sometimes transmitted via Bluetooth to a smartphone.

Enhanced Healing Environment: They promote accelerated healing by maintaining optimal moisture, preventing infection, and using techniques like, for example, electrostimulation.

Versatility and Comfort: They are often designed as flexible, wearable, and conformable to different body shapes, ensuring close contact with the wound surface, while minimizing damage to new tissue during, say, dressing changes.

8.MECHANISM OF ACTION OF SMART WOUND DRESSINGS-

Smart wound dressings represent a shift from passive coverage to active management, using built-in sensors and smart materials to interact with the wound environment, monitor its status in real-time, and provide targeted, on-demand therapeutic intervention.

The mechanism of action for smart wound dressings involves a "sense-act-respond" cycle, driven by several key components:

8.1 Sensing Mechanisms (Monitoring)

Smart dressings are embedded with miniaturized, flexible sensors that continuously analyze the wound microenvironment to detect changes, specifically in chronic or infected wounds (which are often alkaline, warm, and produce high exudate).

pH Sensors: Chronic/infected wounds show a rise in pH (7–9) compared to healthy skin (pH ~4.5–6). Colorimetric dyes (like bromothymol blue) or electrochemical sensors (using materials like polyaniline) detect this rise to warn of infection.

Temperature Sensors: A sustained increase in local wound temperature (>2°C) is an early indicator of infection. Flexible thermistors or Resistance Temperature Detectors (RTDs) are embedded to monitor this, often reporting data via NFC/Bluetooth to a smartphone.

Moisture Sensors: These manage the "Goldilocks" zone, preventing maceration (too wet) or desiccation (too dry) by measuring moisture levels to signal when a dressing change is needed.

8.2 Stimuli-Responsive Mechanisms (Active Treatment)

Once a change is sensed (e.g., infection, high pH), smart materials (usually hydrogels) change their structure to trigger an action, such as releasing medication.

pH-Responsive Release: The hydrogel swells or degrades in the presence of bacterial byproducts (alkaline conditions) to release loaded antibiotics exactly when and where they are needed.

Temperature-Responsive (Thermo-responsive) Release: These use polymers like PNIPAm that change properties at specific temperatures (e.g., shrinking to expel water/drugs when a wound gets "feverish").

8.3 Therapeutic Actions (Healing and Protection)

On-Demand Drug Delivery: Rather than a constant, passive release, the dressing releases therapeutic agents (antibiotics, growth factors, or anti-inflammatory drugs) only when the sensors detect a need, reducing drug overuse.

Electroactive Stimulation: Conductive hydrogels (using carbon nanotubes, graphene, or silver nanowires) can deliver low-intensity electrical stimulation, which helps to attract cells (galvanotaxis), increase blood flow, destroy biofilms, and accelerate tissue regeneration.

Shape-Memory/Adaptive Structure: These dressings can change shape to conform to deep, irregular wound cavities when triggered by body heat, filling the space and applying gentle pressure for better healing.

Self-Healing Properties: The dressing can repair itself if ruptured, preventing it from splitting apart due to movement at joints.

Oxygen Generation/Supply: Some dressings use H_2O_2-releasing gels to supply oxygen directly to the wound, fighting anaerobic bacteria and promoting tissue repair.

Flow diagram of the "Closed-Loop" Working Process

Infection occurs: Bacteria multiply, and wound pH increases, temperature rises, and exudate increases.

↓

Sensor detects change: The integrated, flexible sensor measures the elevated pH/temp/uric acid.

↓

Data transmission: Information is sent via Bluetooth/NFC to a mobile device.

↓

Actuation: The smart hydrogel responds to the stimulus, releasing antibiotics (if pH/enzyme responsive) or receiving a signal to turn on UV-LEDs (if electronically controlled).

↓

Healing: The infection is treated, and electrical stimulation or active components in the hydrogel promote tissue regeneration.

9.MARKET CAP SIZE OF SMART WOUND DRESSINGS-

Based on market projections, the Smart Wound Care & Bandage Market is expected to be valued at approximately USD 0.89 billion to USD 1.09 billion in 2025. This sector is witnessing rapid growth, driven by the adoption of sensors and AI, with projections suggesting it will grow significantly from 2024 to 2030.

The Indian wound care market, including advanced and smart wound dressings, is valued at approximately USD 1.2–1.5 billion in 2025, with smart wound dressings forming a fast-growing niche segment projected to expand at a double-digit CAGR (12–15%) due to rising diabetes prevalence, chronic wounds, and adoption of sensor-integrated dressings. Asia-Pacific, with India as a key driver, is identified as one of the fastest-growing regions for smart wound care technologies.

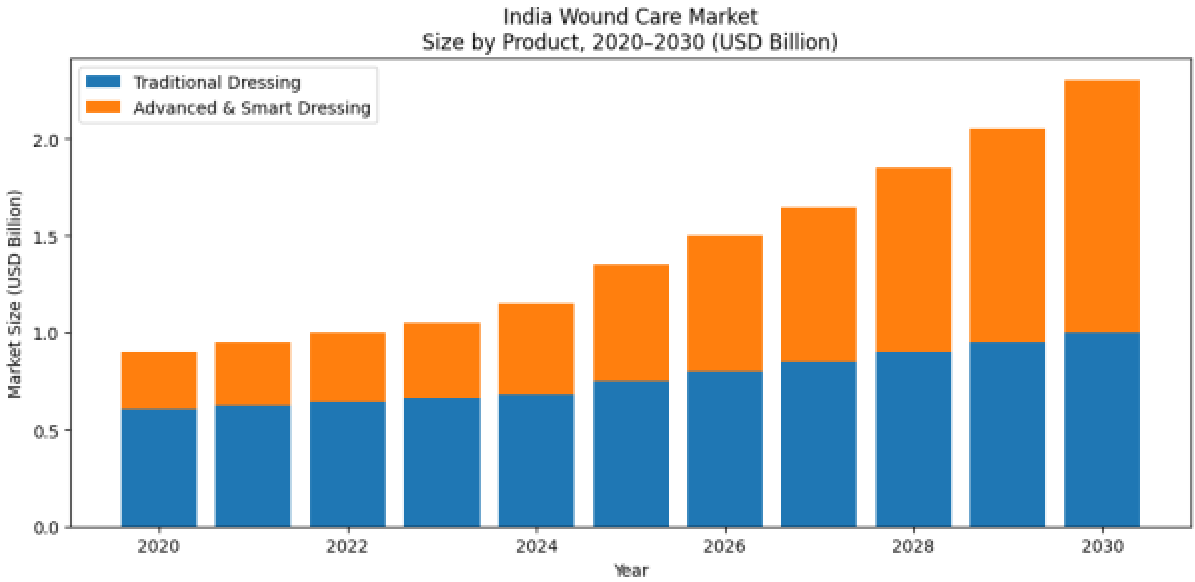

Figure 2: Indian wound care market

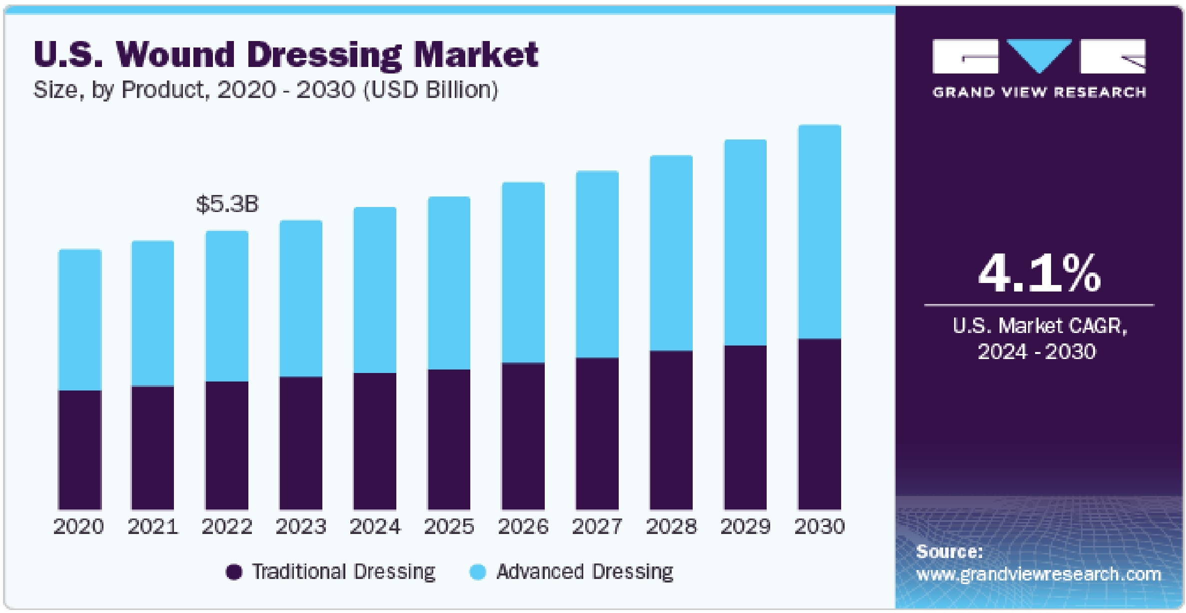

Figure 3: U.S. wound dressing market

10.MARKETED PREPARATIONS-

10.1 Cyber Skin (California Institute of Technology):
This is a next- generation smart bandage that will assist in providing better treatment of chronic wounds. The high-tech bandages can monitor and adjust automatically to the changes within the wounds so that the wound can get even better treatment than it would be able to using normal bandages.

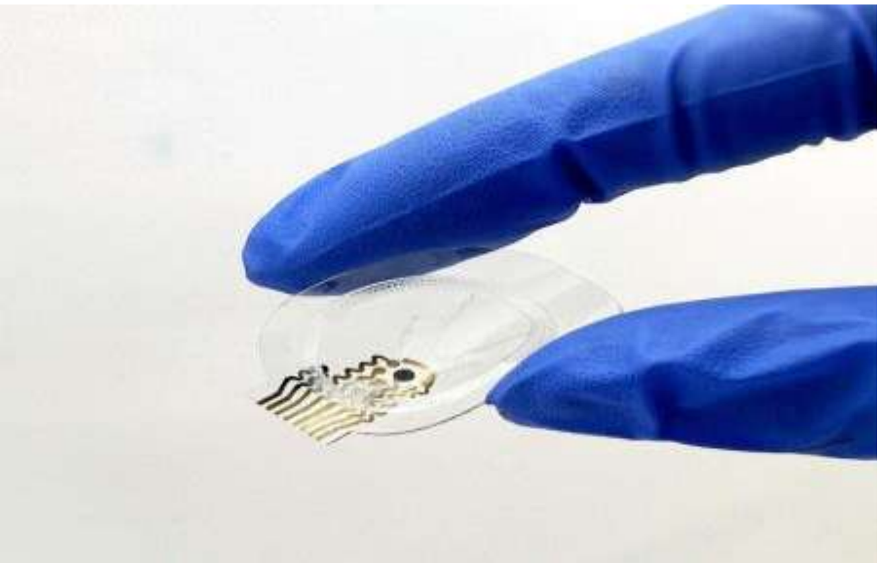

Figure 4: cyber skin

10.2 Water-Powered Electrotherapy Bandage (North Carolina State University):
Uses water to power a battery and electrodes, producing an electric field that speeds up the healing of wounds. It is inexpensive, around $1 per dressing, and does not use electronics.

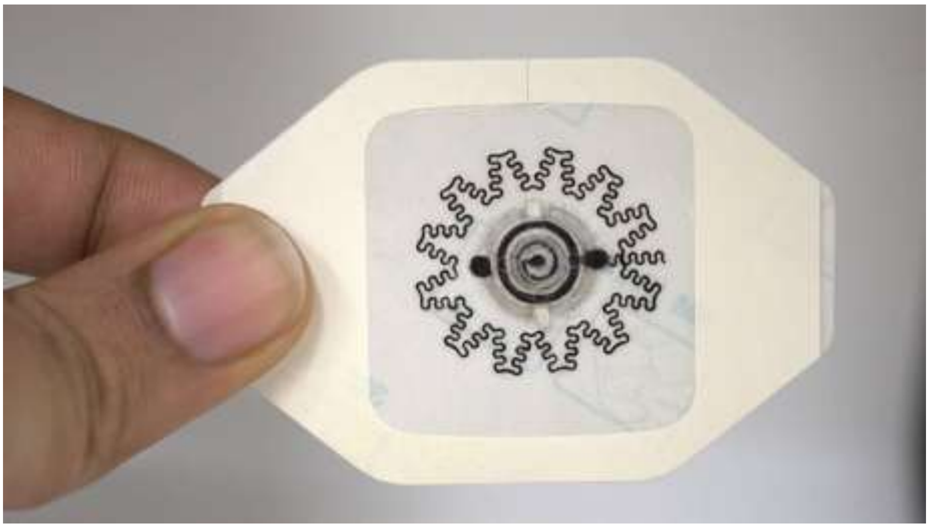

Figure 5: Water-powered Electrotherapy Bandage

10.3 Electrospun Nanodiamond Silk Fibroin Membranes
(Shandong First Medical University & Shandong Academy of Medical Sciences):
Functional membranes include both biosensors and wound healing platforms. They have nano diamonds with nitrogen vacancy centers that allow for temperature sensing to monitor infection or inflammation. The silk fibroin matrix facilitates cell growth and accelerates healing.

Figure 6: Electrospun Nanodiamond Silk Fibroin Membranes

10.4 Collagen-related Theranostic Wound Dressing (University of Leeds):
Integrating a collagen-based wound dressing with a halochromic dye (BTB) that changes colour under alterations of pH, which are associated with infections, produces an advanced dressing for both the healing of wounds and the real-time monitoring of infection. The drop-cast samples retain the dye for several years and have been ascertained to show high bio compatibility.

Figure 7: Collagen-related Theranostic Wound Dressing

10.5 Electrical Stimulation Suture (Donghua University):
A completely biodegradable and self-electrifying material used in sutures, which will aid in the healing of wounds even without employing any additional approaches like using external electric devices.
Electrical Stimulation Sutures developed at Donghua University are bioabsorbable, self-electrifying stitches that use the body's natural movements to generate mild electrical currents, accelerating wound healing and reducing infection risk. They represent a major innovation in surgical wound management.

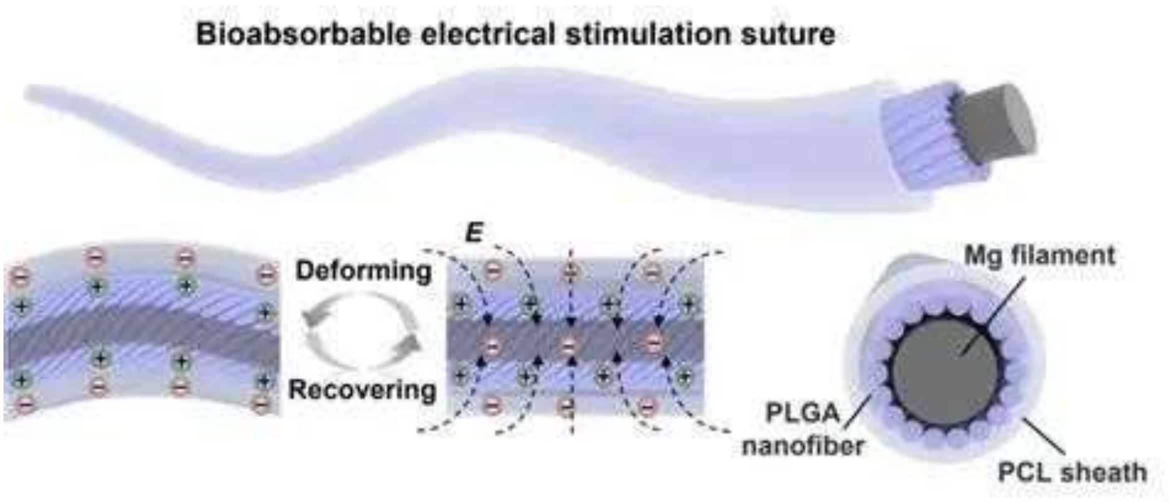

Figure 8: Electrical Stimulation Suture

11.CONCLUSION-

Smart wound dressings have emerged as a revolutionary advancement in wound care, combining biocompatible materials, biosensors, and stimuli-responsive systems to actively monitor and treat wounds. Unlike conventional dressings, they provide real-time data, targeted drug delivery, and adaptive responses to changes in the wound microenvironment.
This innovation not only accelerates healing and reduces infection risks but also minimizes patient discomfort and clinical interventions. With promising applications in chronic wound management and strong market growth projections, smart wound dressings are poised to redefine personalized healthcare. Continued interdisciplinary research and cost-effective development will be essential to translate these technologies into widespread clinical practice.

With rapid market growth and strong research interest, smart wound dressings are poised to become essential tools in personalized medicine, though challenges of cost, scalability, and regulatory approval must still be addressed.

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