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A Current Perspective on Wound Dressings

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ABSTRACT

Wound care is a crucial procedure aimed at facilitating healing, minimizing infection risks, and restoring the natural barrier function of the skin. Chronic wounds can lead to significant health complications and negatively impact quality of life. Effective wound care involves maintaining a moist environment, providing thermal insulation, and ensuring proper protection of the wound. Consequently, wound dressings are developed to enhance and protect the microenvironment of the wounds. Modern wound dressings, incorporating nanoparticles, synthetic polymers, and smart systems, have emerged as replacements for traditional bandages. These advancements offer the potential for more rapid and effective treatment options in wound care. This review highlights the importance of innovative wound dressings to meet the evolving needs of wound care. Progress in this area is vital for addressing the unmet medical needs associated with wound management.

Keywords: Wound Care, skin, wound dressing, nanocarriers

Yara Pansumanlarına Güncel Bir Bakış

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ÖZET

Yara bakımı, iyileşmeyi kolaylaştırmayı, enfeksiyon risklerini en aza indirmeyi ve cildin doğal bariyer fonksiyonunu geri kazandırmayı amaçlayan önemli bir prosedürdür. Kronik yaralar önemli sağlık komplikasyonlarına yol açabilir ve yaşam kalitesini olumsuz etkileyebilir. Etkili yara bakımı, nemli bir ortamın korunmasını, termal izolasyonun sağlanmasını ve yaranın uygun şekilde korunmasını içerir. Sonuç olarak, yara pansumanları yaraların mikro ortamını iyileştirmek ve korumak için geliştirilir. Nanopartiküller, sentetik polimerler ve akıllı sistemler içeren modern yara pansumanları, geleneksel bandajların yerine geçmek üzere ortaya çıkmıştır. Bu gelişmeler, yara bakımında daha hızlı ve etkili tedavi seçenekleri için potansiyel sunmaktadır. Bu inceleme, yara bakımının gelişen ihtiyaçlarını karşılamak için yenilikçi yara pansumanlarının önemini vurgulamaktadır. Bu alandaki ilerleme, yara yönetimiyle ilişkili karşılanmamış tıbbi ihtiyaçları ele almak için hayati önem taşımaktadır.

Anahtar Kelimeler: Yara bakımı, cilt, yara örtüsü, nanotaşıyıcılar

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Introduction

Wounds can occur due to a variety of factors, including mechanical trauma, diabetes, burns, genetic disorders, or surgeries, leading to disruptions in the integrity and function of healthy skin [1]. As age progresses, the healing process slows down, and changes that damage the epidermis and dermis are observed. This makes the skin more susceptible to injuries, particularly in older adults. Non-healing wounds can result in decreased mobility, difficulties in daily activities, loss of productivity, and a lower quality of life [2]. While there are several approaches for wound treatment, including infection control, wound cleansing, transplantation, cell therapy, and dressings, there is still no perfect or flawless treatment method [3].

Innovative technologies employed in wound care and treatment are consistently advancing to expedite the healing process and enhance quality of life. Advanced wound dressings, equipped with sensors that detect the wound condition and materials responsive to stimuli, optimize the healing process, while nanoparticles enhance drug efficacy and reduce side effects. Nanoparticles, with their antibacterial properties, support wound healing and have yielded significant results in various biomedical applications [4-6]. These developments increase the potential for rapid and more effective treatment options in wound care. This article reviews the studies conducted on wound dressings and current treatment approaches. Additionally, it provides insights into future developments in wound dressings.

Wound Types

Wounds are generally classified by their structure as either open or closed, and clinically as acute or chronic [1].

Acute wounds occur due to external damage to the skin and can arise from various causes such as bites, burns, minor cuts, abrasions, crush injuries, surgical interventions, or gunshot wounds [7]. Additionally, factors like radiation, extreme temperature changes, or exposure to chemicals can also trigger such wounds. Acute wounds typically heal on their own within 8 to 12 weeks [1].

Chronic wounds, on the other hand, take a long time to heal due to prolonged inflammation and are generally more complex. The most prevalent types are diabetic ulcers, pressure ulcers, arterial ulcers and venous ulcers [8]. Venous ulcers, often a sign of chronic venous insufficiency, typically occur on the legs. These wounds may begin superficially but have the potential to deepen; the surrounding skin is often erythematous or hyper-pigmented, and risk factors such as age, obesity, and leg injuries can impact the healing process [9,10]. Arterial ulcers, typically found on distal extremities, can be deep, with well-defined wound edges and eschar formation. Diabetic ulcers typically develop on the plantar surface of the foot and are primarily attributable to neuropathy, peripheral artery disease, and structural deformities. These ulcers can progress from superficial to deep and may result in dry, easily reinjured tissue [9]. Pressure ulcers result from prolonged contact with hard surfaces, are located over bony prominences, and carry a high risk of compression. Factors such as smoking, diabetes, vascular disease, and poor skin hygiene contribute to the formation of these wounds [8,11].

Open wounds can result from lacerations, punctures, surgical wounds, insect bites, or radionecrosis. These wounds expose the skin and require various treatment methods. Closed wounds, however, involve damage without an open cut or injury on the surface of the skin. These encompass contusions, hematomas, and injuries to soft tissues, small blood vessels, or deeper tissue layers [1].

Wound Healing

Wound healing is a multifaceted process involving four primary phases: haemostasis, inflammation, proliferation, and remodelling [12]. Initially, in the haemostasis phase, blood vessels constrict following injury, and a temporary platelet plug forms. This plug transforms into a more durable fibrin clot within a few hours. During the inflammation phase, white blood cells clear away dead tissue, debris, and bacteria, while chemical messengers that initiate the healing process are released. The proliferative phase is characterized by the development of granulation tissue and the formation of epithelial tissue. Granulation tissue includes the proliferation of fibroblasts, collagen deposition, and the development of new blood vessels. This process begins within the first 12-48 hours of wound healing and can continue for several months in full-thickness wounds. Epithelialization starts after the wound surface is covered with new tissue and usually completes within 3-4 weeks. The remodelling phase can last up to two years, during which collagen deposits form to increase the strength of the new tissue and enhance the wound's tensile strength. However, the healed wound often does not regain its original strength fully, recovering only a significant portion [13].

Wound healing can be categorized into three types: primary, secondary, and tertiary healing. Primary healing involves the healing of clean wounds, typically closed with surgical sutures, and is the least complex. Secondary healing is a more complex process, typically for wounds with significant tissue loss or large wounds, and usually takes longer to heal. Tertiary healing is used for wounds with extensive tissue damage and significant bacterial contamination; it allows time for the inflammatory process before the wound is closed.

The wound healing process can be negatively affected by nicotine and carbon monoxide. Nicotine reduces blood flow, while carbon monoxide impairs oxygen transport. Metabolic disorders, aging, and certain diseases also diminish healing capacity. In older adults, factors such as a decrease in fibroblasts, reduced nutritional and fluid intake, and other health issues can delay healing. Surgical anesthetics can impact healing by affecting thermoregulation, and alcohol consumption can complicate tissue repair. Therefore, the wound healing process requires careful management [12].

Ideal wound care technology facilitates healing by maintaining a moist, clean, and warm environment. It should protect the wound bed from mechanical injury and bacterial contamination, control exudate levels, permit gas exchange, and provide thermal insulation. Additionally, it should offer therapeutic components that are non-toxic, non-allergenic, and provide an optimal temporary profile [14]. Wound treatment strategies can differ based on the hospital, clinician, and healthcare staff involved. Currently, advanced

wound dressings are often favored and come in various designs to provide a range of features.

Wound Dressings and Nanotechnology

Wound dressings provide ideal conditions for healing by protecting the wound from trauma and pathogens while coming into direct contact with it [15]. Historically, wound treatment commonly involved traditional dressings such as absorbent natural and synthetic bandages, cotton wool, lint, and gauze. These dressings kept the wound dry, allowed exudate to evaporate, and prevented bacteria from entering the wound [16]. However, because traditional dressings were often inadequate in facilitating proper drainage, modern wound dressings have since replaced them. Modern dressings, with their semi-permeable properties and high absorbency, promote the development of granulation tissue and support the migration of epithelial cells from the wound edges towards the center [17]. Today, wound dressings are commonly made from synthetic or natural polymers. Natural polymers include dextran, chitosan, elastin, cellulose, and alginate; however, these materials typically exhibit limited mechanical strength. This limitation can be mitigated by employing synthetic polymers such as poly(α-esters), poly(lactic acid) (PLA), and poly(glycolic acid) (PGA). Since the mid-1990s, a range of advanced wound dressings has been introduced, including hydrogels, hydrocolloids, alginates, synthetic foam dressings, adhesives, vapor-permeable films, silver/collagen-containing dressings, and nanofibers [15,18].

Wound dressings support the healing process through their various properties and functions. Films are transparent, self-adhesive polyurethane sheets that permit the passage of gases and water vapor while providing a barrier against liquids and bacteria. Film dressings, which need to be changed several times a week, are suitable for intravenous access covers, donor sites of small skin grafts, or superficial lacerations [19]. Hydrocolloids, made from gel-forming substances combined with elastomers and adhesives, can adhere to both dry and moist areas and can be effective on wounds with mild to moderate exudate, such as traumatic injuries, minor burns and pressure ulcers [16]. Hydrogel dressings, due to their high water content, create a moist environment that facilitates the granulation process and are especially suitable for burns, pressure ulcers, chronic wounds and necrotic wounds [20]. Alginate dressings, known for their high absorbency capacity, help limit wound exudates and minimize bacterial contamination; their gel-forming properties activate upon contact with wound fluids. Foam dressings, made from porous polyurethane materials, are particularly suitable for bony prominences or exudative cavities. They need to be replaced daily or several times a week when saturated with exudate, and the type of dressing should be adjusted as the wound progresses [19].

Although a range of wound dressings has been developed for chronic wounds, they do have certain limitations. Smart wound dressings, which incorporate embedded sensors and stimuli-responsive materials, can detect and adapt to alterations in the wound environment [14]. In recent years, research has focused on smart wound dressings that are biomechanically responsive, stimuli-sensitive, and self-healing [21]. For instance, Li et al. [22] synthesized shape-memory polymers incorporating dihydroxypropyl methacrylate, which have been demonstrated to support wound healing Additionally, thermosensitive N-isopropylacrylamide (NIPAM)-based hydrogel dressings have been designed with integrated heating elements for drug delivery [23]. In another study, membranes were developed using pH-responsive nanomaterials to deliver antibiotics; these membranes can offer targeted antibiotic treatment according to the pH of the wound environment. These smart wound dressings offer significant potential for conditions such as chronic wounds and burns [24-26].

Nanoparticles

Delivering drugs effectively to the target area is challenging because most drugs disperse throughout the body, resulting in only a small dose reaching the intended site. This reduces the drug's efficacy while increasing side effects. To address this issue, nanoparticles have been developed. Nanoparticles encapsulate, absorb, or chemically bind drugs, thereby protecting the drug from chemical and enzymatic degradation. They assist in the efficient delivery of drugs to target areas and are, therefore, a fundamental component of modern nanotechnology [27].

The use of nanoparticles in drug delivery systems offers several advantages. First, they enable the controlled and sustained release of drugs to target areas, which enhances the efficacy of the drugs and reduces their side effects. Additionally, nanoparticles extend the systemic circulation life of drugs and reduce immunogenicity, thereby improving therapeutic effectiveness. Nanoparticles can also enhance the solubility of drugs and improve bioavailability by preventing drug waste [28].

Research conducted over the past five years has demonstrated the effectiveness of nanoparticles in healthcare and the benefits they provide. For example, titanium dioxide nanoparticles support wound healing by offering antibacterial properties, while zinc oxide nanoparticles enhance the water vapour permeability and antibacterial efficacy of wound dressings [29-31]. Copper oxide nanoparticles, on the other hand, provide antimicrobial effects and accelerate the healing of diabetic foot ulcers [32,33].

Silver nanoparticles are extensively utilized in wound dressings because of their significant antibacterial properties and their demonstrated ability to enhance the wound healing process [34-37]. Additionally, selenium and sulphur nanoparticles are noted for their antibacterial properties and wound-healing support [38-40]. Gold nanoparticles stand out for their high biocompatibility and antibacterial activity [41,42].

Insulin-loaded chitosan nanoparticles optimize the healing environment by accelerating the wound healing process. These nanoparticles, when coated onto wound dressings, facilitate more effective healing [43]. Overall, nanoparticles allow for significant advancements in

biomedical applications by providing advantages in drug delivery systems. The recent studies of wound dressings containing nanoparticles were summarized in Table 1.

Table 1. The Recent Studies On Nanoparticle Wound Dressings

Wound dressing type	Drug/Agent	Wound type/Purpose	Results	Referance
GA-PVA-PCL wound dressing with live *Lactobacillus*-Zinc oxide (ZnO) nanoparticles	Zinc oxide	Wound healing	• ZnO nanoparticles which were biologically synthesized using *L. plantarum* and *L. acidophilus* • Addition of nanoparticles to GA-PVA-PCL structured matrix • Matrix and ZnO NP with low cytotoxicity • GA-PVA-PCL with *Lactobacillus*-ZnO nanoparticles, which is a safe and promising material for wound dressing	[44]
Heparinized PVA/chitosan hydrogel containing zinc oxide nanoparticles	Zinc oxide	Wound healing	• Increased heparin release rate by addition of ZnO nanoparticles to PVA/chitosan hydrogel • Strong mechanical properties with the hydrogel in both dry and wet conditions • Improved water vapor permeability and swelling properties, and increased the number of pores in the hydrogel structure by incorporation of nZnO • High cell viability above 70% and 80% after 24 and 48 hours, respectively • Having antibacterial effect exceeding 70% against *Escherichia coli* and *Staphylococcus aureus* after including nZnO to the hydrogels	[31]
PVA/agar hydrogel wound dressing containing zinc oxide nanoparticles	Zinc oxide	Wound healing	• A decrease in viscosity and elastic modulus with increasing amounts of zinc oxide nanoparticles • Hydrogel swelling rate measurements in the range of 70% and 138% • Effective swelling behavior in both acidic and alkaline environments with hydrogel, making it suitable for all phases of the healing process • Resistance to Gram-positive *B. subtilis* bacteria	[45]
PCL wound dressing containing copper oxide nanoparticles (CuONP)	Copper oxide	Diabetic foot ulcers	• Hemocompatible PCL films containing CuONP at 0.07% concentration • Stable thermal properties • Inhibition of MRSA growth • Treated HFF-1 cells exhibited over 80% viability without DNA damage • Films with no more than 5% broken red blood cells	[33]
Magnesium hydroxide nanoparticle/chitosan hydrogel wound dressing	Magnesium hydroxide	Wound healing	• High biocompatibility and enhanced broad-spectrum antibacterial activity • Greater healing efficacy compared to sterile gauze • Contribution to the development of next-generation antibacterial materials	[46]
Titanium dioxide nanoparticulate wound dressing	Titanium dioxide	Excision wound	• Antibacterial activity with titanium dioxide nanoparticle addition • Biofilm with high swelling ability	[30]

containing gellan gum biofilm			• Better re-epithelialization without scarring • Wound treatment within 14 days • Great potential as a wound dressing material	
Carrageenan-based hydrogel film incorporated with sulfur nanoparticles and grape fruit seed extract	Sulfur/grape fruit seed extract	Full thickness wound	• Increased water vapor permeability, swelling ratio, and porosity by addition of sulfur nanoparticles and grape fruit seed extract • Enhanced biocompatibility for the L929 cell line with a chitosan coating • Strong antibacterial activity against *Staphylococcus epidermidis* and *Escherichia coli* • Decrease in wound size to 31% in the control group and 1.3% in the group treated with the hydrogel film after 2 weeks	[40]
Collagen- alginate doped PVP coated wound dressing containing silver nanoparticles	Silver	Wound healing	• Silver nanoparticles prepared with PVP as stabilizing agent and NaBH4 as reducing agent • Significant antimicrobial activity against both *Escherichia coli* and *Staphylococcus aureus*	[47]
TEMPO oxidized bacterial cellulose membrane wound dressing with silver nanoparticles	Silver	Wound healing	• Sustained silver release from nanoparticles at 12.2% / day for 3 days at 37°C • Significant antibacterial activity against *Escherichia coli* and *Staphylococcus aureus*, 100% and 92%, respectively	[35]
Keratin wound dressing containing silver nanoparticles	Silver	Allogeneic full-thickness surgical wound	• Significant acceleration in wound closure and epithelialization on the 5th and 8th days compared to the control group • Inhibition of growth of *Escherichia coli* and *Staphylococcus aureus* • No inhibition of fibroblast growth and no cause of hemolysis	[48]
Silver-loaded PVA/SA/CMCS hydrogel wound dressing	Silver	Wound healing	• Superior mechanical properties compared to silver-free hydrogels • Maintainining a consistently moist environment for the wound, with excellent water absorption and retention • High biocompatibility • Increased antibacterial performance and long-lasting effect • Promoting cell proliferation and meeting ideal wound dressing requirements	[36]
Bacterial cellulose-based wound dressing loaded with silver nanoparticles	Silver	Chronic wound	• Antimicrobial activity against *Staphylococcus aureus, Pseudomonas aeruginosa* and *Candida auris* • Cytocompatibility • Antioxidant properties • High moisture content and good transparency	[49]

Wound dressing coated with silver nanoparticles, sodium alginate and essential oils	Silver	Wound healing	• Increase in antimicrobial and antibiofilm potential with the addition of silver nanoparticles • Enabling the development of ideal wound dressings with silver nanoparticles	[50]
Wound dressing with silver nanoparticles	Silver	Diabetic foot ulcers	• 80 patients in two groups with diabetic foot ulcers • Group A; wound dressing containing silver nanoparticles • Group B; traditional wound dressing • Complete recovery in 29 (72.5%), 34 (85%) and 36 (90%) patients in group A at weeks 8, 10 and 12, respectively • More effectively wound healing with wound dressings containing silver nanoparticles than conventional wound dressings	[37]
Chitosan-based gelatin/polyvinyl pyrrolidone wound dressing loaded with silver nanoparticles	Silver	Wound healing	• Chitosan for drug loading, gelatin for wound healing, polyvinyl pyrrolidone as a synthetic polymer, and AgNPs for elasticity and antibacterial action • Enhanced mechanical performance with high thermal and hydrolytic stability	[51]
Chitosan/PVA-based wound dressing containing selenium nanoparticles	Selenium	Wound healing	• Ability to kill pathogenic *Escherichia coli* and *Staphylococcus aureus* bacteria and inhibit their growth	[38]
Wound dressing prepared using silk fabric containing gold nanoparticles (AuNPs)	Gold	Wound healing	• Antibacterial wound dressing prepared using woven silk fabrics • Incorporation of AuNPs into silk fabric • Significant reduction in antibiotic dosage and avoidance of overuse of antibiotics in dressings with the addition of AuNP	[52]
NRL-structured wound dressing containing metronidazole-loaded gold nanoparticles	Metronidazole	Wound healing	• Biocompatible wound dressing in addition to fibroblast proliferation in hemolytic analysis • A promising approach for dermal applications with the developed wound dressing	[42]
PNIPAM/PVA/MO nanoparticles wound dressing	Silver sulfadiazine	Wound healing	• Wound dressing designed with drug-loaded polymeric biomaterials • Release of silver sulfadiazine first from the support membrane and then from the medium • Antibacterial activity • Biocompatibility on human dermal fibroblasts	[53]
PCL/COLL wound dressing coated with insulin-loaded chitosan nanoparticles	Insulin	Full-thickness excisional wound	• Production of insulin-loaded chitosan nanoparticles by ionic gelation process • Increase in PCL/COLL hydrophilicity, water uptake and blood compatibility by addition of chitosan nanoparticles • At the end of 14 days, 45% reduction in wound size with sterile gauze, while complete closure with PCL/COLL/Cs-Ins wound dressing	[43]

Nanofibers

Nanofibers are defined as fibers with diameters less than one micron, and their micro- and nanoscale structural properties enable the development of specialized materials. In recent years, these structures have become a significant research topic in various biomedical applications [54]. Nanofibers can be fabricated using various techniques, including electrospinning, wet spinning, microfluidics, self-assembly and rotary spinning [55]. Their small size and large surface area are advantageous for enhancing the sensitivity and speed of biosensors [56]. Nanofibers can be used as temporary tissue scaffolds, drug carriers, and drug delivery systems. The porous structure of electrospun nanofibers supports cellular respiration and promotes wound healing [57]. Additionally, these fibers are used to create wound dressings that prevent scarring and provide protection against bacteria [54].

Nanofibers produced by electrospinning are employed as dressing materials that support wound healing. These nanofibers come in various sizes and feature high porosity and surface-to-volume ratios. Polymer nanofibers can be combined with additives or bioactive plant extracts for enhanced functionality [58]. For instance, a 2019 study examined the responses of *Saccharomyces cerevisiae* and *Candida albicans* yeasts to polyacrylonitrile (PAN) nanofiber mats and found that PAN nanofibers exhibited natural antifungal properties against these yeasts [59].

Phloridzin, a flavonoid with antioxidant and antibacterial properties, has been reported to provide good mechanical properties and wound healing when used in nanofiber wound dressings loaded with silk protein and polyvinylpyrrolidone (SF/PVP) [60,61]. Hesperidin, another flavonoid found in citrus fruits such as lemons and oranges, is known for its wound-healing properties. Studies have shown that hesperidin-loaded nanofibers more effectively support skin regeneration [60].

Non-antibiotic nanofibers are also gaining interest in wound healing. Honey, a natural wound-healing agent due to its antioxidant and antibacterial properties, has been added to ethylcellulose/mastic gum nanofiber mats, resulting in increased fiber diameter and enhanced antioxidant and antibacterial activities [62]. Moreover, cellulose acetate (CA) nanofiber mats containing Manuka honey have demonstrated biocompatibility and good cell proliferation [63].

Plant extracts are also used for their antimicrobial and wound-healing properties. For example, nanofiber wound dressings containing *Malva sylvestris* extract have shown high antibacterial activity. Biocompatible nanofibers effective against *E. coli* were produced from natural materials, providing good cell adhesion and high absorbency [64]. Additionally, antimicrobial peptides integrated into electrospun nanofiber mats offer low toxicity and broad-spectrum antibacterial properties [65].

Nanofibers, when combined with various materials, are emerging as biomedical products that accelerate wound healing, offer antibacterial properties, and provide biocompatibility. These products hold a significant place due to the advantages they offer in different application areas. The recent studies of wound dressings of nanofibers were summarized in Table 2.

Table 2. The Recent Studies on Nanofiber Wound Dressings

Wound dressing type	Drug/Agent	Wound type/Purpose	Results	Referances
Polyacrylonitrile-based nanofiber wound dressing	-	Wound healing	• First-time exposure of *Saccharomyces cerevisiae* and *Candida albicans* to PAN nanofiber mat • More inhibition on the growth of *C. albicans* with PAN nanofiber mat	[59]
Polyurethane/polyacrylic acid/poloxamer nanofiber wound dressing	-	Wound healing	• Addition of poloxamer at concentrations of 5%, 10%, 15% • Increase in nanofiber diameter, wettability, swelling ratio and degradation degree with increasing amount of poloxamer • Non-toxic nanofibers	[66]
Fluorizin-loaded silk protein/PVP composite nanofiber wound dressing	Florizin	Full-thickness wound	• Appropriate permeability and hydrophilicity with composite nanofiber • High porosity • Good bactericidal activity against both Gram-positive and Gram-negative bacteria	[61]
Hesperidin-containing polyacrylonitrile/polyethylene	Hesperidin	Excisional wound	• Sustained release after initial burst release with hesperidin-loaded nanofibers	[60]

oxide nanofiber wound dressing			• Significant increase in swelling percentage and release rate by increasing the amount of PEO from 20% to 40% • High wound healing rate • More effective promotion of skin regeneration compared to hesperidin-free nanofibers	
Wound dressing containing TPP/honey/chitosan nanofibers loaded with capsaicin and gold particles	Capsaicin-gold nanoparticles	Chronic wound	• Nanofibers prepared by electrospinning • Antibacterial properties as well as significant and rapid wound closure capacity • Significant reduction in viscosity • Inhibition of bacterial growth by chitosan-capsaicin and chitosan-gold particles	[67]
Honey-loaded PVA nanofiber wound dressing	Honey	Wound healing	• Minimal weight loss in fibrous membranes for 10 days • Significant swelling • Maximum re-epithelialization with a specific honey loading (0.5%) • Reduction in biofilm formation	[68]
Honey-loaded sodium alginate/PVA nanofiber wound dressing	Honey	Wound healing	• Fabrication of honey/SA/PVA nanofiber membranes by fully aqueous electrospinning • Good biocompatibility • Enhanced antioxidant activity of nanofiber membranes with increased honey content • Proven antibacterial activity against *Staphylococcus aureus* and *Escherichia coli*	[69]
Wound dressing containing honey-loaded ethylcellulose/citre gum nanofiber	Honey	Wound healing	• High swelling of nanofibers with 5% honey content, low swelling of nanofibers with 20% honey content • Enhanced antioxidant and antibacterial activity, improved mechanical properties, favorable cell growth and proliferation in nanofibers with high honey content • Lack of cytotoxicity, excellent degradability • Use in tissue engineering and wound healing due to good biocompatibility	[62]
Cellulose acetate (CA) nanofiber wound dressing containing Manuka honey	Manuka honey	Wound healing	• CA nanofiber mats containing different amounts of Manuka honey • Decrease in mat surface area due to increase in nanofiber diameter with the addition of honey • High porosity • Biocompatibility	[63]

			• Excellent cell proliferation and growth against the NIH 3T3 fibroblast cell line	
PCL nanofiber wound dressing containing *Tridax procumbens* extract	*Tridax procumbens* extract	Wound healing	• High antibacterial activity for both Gram positive and Gram negative bacteria • Wound healing enhancement and therapeutic effects on surfaces containing pathogenic microorganisms, especially in the hospital environment	[70]
Polycaprolactone/gelatin nanofiber wound dressing containing *Calendula officinalis* extract	*Calendula officinalis*	Wound healing	• Acceptable size, shape, porosity and surface roughness with the nanofibers • Favorable chemical composition and hydrophobicity • Potential use as a wound dressing after testing with *in vitro* and *in vivo* studies	[71]
Polyurethane/CMC nanofiber wound dressing containing *Malva sylvestris* extract	*Malva sylvestris* extract	Diabetic wound	• CMC added in different amounts • Antibacterial activity against *E. coli* and *S. aureus* bacteria • Increased wound healing rate in extract-containing dressings • Improvement in mechanical and thermal properties of nanofibers by adding the extract to the polymer matrix	[64]
Aloe vera extract nanofiber wound dressing	*Aloe vera,* pullulan	Wound healing	• Nanofiber membranes produced by Forcespinning® method • Ability to support cell growth and antibacterial activity • Porous and high surface area • Non-cytotoxic to NIH 3T3 fibroblast cells and allow efficient fibroblast cell attachment as well as inter-layer cell growth	[65]
Hydrogel sheeting based on TEMPO-oxidized ginger nanofibers	Ginger essential oil	Wound healing	• Hydrogel production by vacuum assisted filtration without crosslinker • Good tensile strength and elastic modulus • Highest water absorption with 62 times the initial weight • Absence of *S. aureus* and *E. coli* growth, bactericidal effect	[72]
Hyaluronic acid nanofiber wound dressing	ε-poly l-lysine (EPL)	Chronic wound	• Nanofiber mats with hyaluronic acid containing antimicrobial peptide (ε-poly l-lysine) • Nanofibers with high absorbency and durability as well as antibacterial activity and biocompatibility • Performance comparison with a starch substitute as a wound dressing	[73]

			• Hyaluronic acid mantle degradation and releasing antimicrobial peptide faster	
PVA/CS nanofiber wound dressing containing sericin	Sericin-tetracycline	Healing soft tissue infection	• Decrease in fiber diameter and mechanical strength, increase in hydrophilicity and elongation at break with the addition of sericin • Increased re-epithelialization compared to sericin-free wound dressing • Inhibition of *Escherichia coli* and *Staphylococcus aureus* growth with high sericin and tetracycline • Ability to promote cell proliferation and biocompatibility	[74]
PVA/PAN structured wound dressings containing core-shell nanofibers	Diclofenac sodium-gentamicin sulfate	Wound healing	• Core-shell nanofibers showing excellent biocompatibility in addition to dual drug release • Controllable drug release behavior • Tremendous potential for diverse fields such as protein release, sensors, photocatalysis and tissue engineering • Sufficient profile to be used as a wound dressing	[75]
PAN nanofiber wound dressing loaded with diclofenac sodium salt	Diclofenac sodium	Acute wound	• Providing adequate antibacterial barrier and prolonged drug release for acute wounds (maximum ~40% release over 72 hours) • Stronger cell-cell interaction than cell-material interaction due to the inherent hydrophobic nature of PAN nanofibers • Inhibition of bacterial growth of both *E. coli* and S*. aureus*	[76]
Melatonin-loaded CTS/Coll-based nanofiber wound dressing	Melatonin	Wound healing	• Addition of different doses of melatonin • Marked cell viability enhancement in human epidermal keratinocytes, dermal fibroblasts and reference melanoma cells • Increased re-epithelialization	[77]
Melatonin-loaded trilayer nanofiber wound dressing	Melatonin	Full-thickness excisional wound	• Trilayer (Cs-PCL/PVA-melatonin/Cs-PCL) cover produced by electrospinning • Sustained release of melatonin • Low spoilage rate and high water uptake • Hydrophilic effect that promotes cell attachment • Completely regenerated epithelial layer, reduction in inflammatory cells	[78]

Conclusion and Future Prospects

Wounds result from the damage caused by various agents, leading to a disruption of tissue integrity in the body. Multiple factors contribute to the formation of wounds, which can influence the development of different types of wounds, such as open, closed, acute, and chronic wounds. Understanding the structure and function of the skin is crucial for managing the wound healing process and selecting appropriate treatment methods. Wound healing is a multifaceted process that involves inflammation, proliferation, and remodeling phases. The severity of tissue damage influences both the duration of healing and the mechanisms of wound closure. Additionally, metabolic disorders such as diabetes and cardiovascular diseases, smoking, stress, advanced age, and certain anesthetic agents can delay wound healing. This review has discussed the recent studies on wound dressings, which play a significant role in wound care, current treatment approaches, and provides information on future formulations to be developed.

Conventional wound dressings, including natural or synthetic bandages, cotton wool, and sterile gauze, have been superseded by advanced materials such as hydrogels, hydrocolloids, alginates, films, synthetic foam dressings, and dressings incorporating nanoparticles and nanofibers [14]. However, natural polymers like chitosan, alginate, cellulose, chitin, and elastin can weaken the mechanical properties of these dressings. To address this issue, synthetic polymers such as poly(α-esters), PLA, and PGA are incorporated. With the advancement of nanotechnology, antimicrobial agents have also been added to wound dressings as nanoparticles and nanofibers. Along with polymers, various compounds such as protein (e.g. sericin), glycoside obtained from fruits (e.g. hesperidin), honey (e.g. Manuka honey), plant extract (*Malva sylvestris*, *Aloe vera*), drug (metronidazole, diclofenac), metal oxide (ZnO, TiO_2) and metals such as silver and gold have been incorporated into wound dressings and investigated for their activities to be used in wound care/treatment [79].

To accelerate decision-making in wound care and provide critical information, smart systems are being developed. Sensors integrated into wound dressings to monitor pH, temperature, oxygen and humidity can detect and respond to changes in the wound environment. These sensors are particularly valuable for addressing challenges associated with chronic wound healing and can be integrated with active drug delivery systems [80].

Current approaches focus on studies emerging with personalized medicine in addition to sensor wound dressings using nanotechnology. The development of tools for the diagnosis, treatment and prevention of diseases, rather than a single type, for individuals with similar genetics, environment and lifestyle, falls within the scope of personalized medicine. In this way, it has been shown that wound dressings can be produced using 3D printers in customizable shapes and containing different doses of drugs required for wound healing. These promising studies, which lead to the future, will remove the limitations related to wound care and also provide a more rapid and accurate treatment choice.

Conflicts of interest:

There are no conflicts of interest in this work.

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Ethical Approval Statement

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