Biomedical Materials for Sustainable Wound Care: A Review of Environmental Impact and Clinical Efficacy

Abhishek Saxena[1*], *R J* Anandhi[2], *K* Rashmi[3], *Navdeep* Singh[4], *Dinesh* Kumar Yadav[5], Rahman S. Zabibah[6]

[1]Department of Mechanical Engineering, ABES Engineering College, Ghaziabad-201009, UP, India.
[2]Department of Information Science Engineering, New Horizon College of Engineering, Bangalore, India.
[3]Department of Computer Science and Engineering, Institute of Aeronautical Engineering, Hyderabad, Telangana, India
[4]Lovely Professional University, Phagwara, Punjab, India.
[5]Lloyd Institute of Engineering & Technology, Knowledge Park II, Greater Noida, Uttar Pradesh, India.
[6]Medical Laboratory Technology Department, College of Medical Technology, The Islamic University, Najaf, Iraq.

Abstract. The comparative evaluation offered within the paper aligns with the broader theme of sustainable wound care by means of focusing on the efficacy and environmental concerns of wound dressing technology. The development of advanced biomaterials not most effective for scientific wound control but additionally for environmental sustainability. With the aid of leveraging biocompatible substances and modern technology, such as biodegradable polymers and eco-friendly nanoparticles, researchers goal to create wound care answers that no longer handiest sell green recovery however also limit environmental impact. Via analyzing the benefits, demanding situations, and future directions of hydrogel dressings, electrospun biopolymer nanofibers, and numerous polymeric substances, the study contributes to the discussion on sustainable wound care. It underscores the significance of developing wound care solutions that now not most effective reveal clinical efficacy but also consider their environmental effect. This holistic method resonates with the purpose of exploring the intersection of scientific efficacy and environmental sustainability in the context of biomedical substances for wound care.

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[*] Corresponding Author : abhishek.saxena@abes.ac.in

1 Introduction

Clinical applications of biomaterials in environmental engineering involve making use of biocompatible substances to cope with environmental challenges and enhance human health. The development of advanced biomaterials not most effective for scientific wound control but additionally for environmental sustainability. With the aid of leveraging biocompatible substances and modern technology, such as biodegradable polymers and eco-friendly nanoparticles, researchers goal to create wound care answers that no longer handiest sell green recovery however also limit environmental impact. These substances can be designed to degrade accurately inside the environment after their intended use, reducing the accumulation of non-biodegradable waste. Furthermore, sustainable wound care techniques can also comprise natural, renewable resources as uncooked substances, contributing to a greater environmentally friendly technique. Hence, the convergence of biomedical materials and sustainable practices in wound care aligns with the broader goals of environmental engineering by means of prioritizing both human health and ecological well-being.

1.1 Clinical Applications of Biomaterials

Breaks in the skin or other bodily tissues are referred to as wounds. These consist of skin punctures, scrapes, cuts, and scratches. Wounds are frequently the result of accidents, although they can also result from surgery, sutures, or stitches. Although minor wounds are often not dangerous, it is nonetheless vital to clean them. Whether blunt, sharp, or projectile, there are several ways in which various items can inflict injuries. Depending on what caused them and the injuries they sustained, they are divided into many categories as depicted in Fig. 1: Incised wound, Laceration wound, Abrasion wound.

An incised wound is a clean, linear incision made with a sharp object, such as a knife. It has a tendency bleed a lot since there may be many veins that are severed straight across. Ligaments and tendons, which act as interconnecting structures, might potentially be affected. The research in [1] aims to evaluate the diagnostic potential of SEM (scanning electron microscopy) in determining the direction of a wound. In human skin samples taken from cadavers by S.E.M., we have examined incised wound edges generated by steel blades. A lateral auxiliary tail was discovered to be present in 65% of the entry edges. This result was noted in every instance when the direction of the wound was vertical to Lancer's lines of the skin region where the wound was found. There was no discernible analogous discovery in the exit tails. A lateral auxiliary tail proved to be a more reliable indicator of the direction of the wound than the depth as well as the length of the edges that were wounded. Although murders are the most common kind of sharp-force fatality, suicide deaths with stab or incised wounds are frequently documented. From a forensic standpoint, distinguishing between suicide and homicidal injuries is essential. According to a comprehensive assessment of previous studies in [2], certain criteria' predictive power in classifying a death as either a suicide or a homicide is not always 100% reliable. Vertically oriented chest stabs, defensive injuries, and garment damage are significant indicators of the way of death in homicide. Incised wounds are a prevalent problem, frequently seen in defensive injuries. The study in [3] used five knives and a pivoting arm equipment to examine the features of incised bone wounds. Findings indicated a relationship between force and bone wounds' length, breadth, and depth. The results may help forensic investigators pinpoint the precise knife that was used.

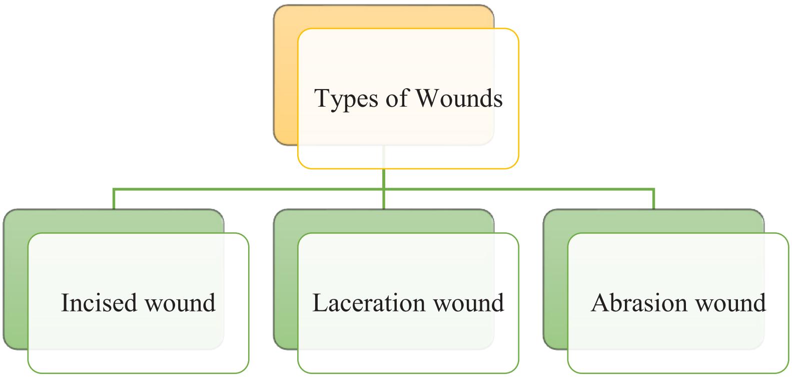

Fig. 1. Types of Wounds

A ripping or crushing force can result in a messy-looking wound known as a laceration wound. Does more harm to the tissue surrounding it than incised wounds, although it doesn't usually bleed as much? On a daily basis, primary care physicians see patients with a variety of diseases. Burns, cuts, hand trauma, and wounds are a few of these frequent appearances; some of them can be treated outpatient by primary care physicians without the need for a specialist's review. In [4] offer evidence-based strategies to help primary care practitioners recognize and handle these presentations more skillfully, as well as provide guidance on how to handle many of these problems on their own. When deciding whether to send a patient to a plastic surgeon or another expert. A recent case brought to light the significance of imaging cuts as, if foreign bodies aren't found before closure, untreated wounds might provide a medicolegal danger [5]. Bony foreign bodies were discovered in the first patient's wound, which might have resulted in problems and medical malpractice. This instance highlights the need of being on the lookout for foreign bodies in cuts and maintaining a high degree of suspicion. Small animal skin wounds need knowledge of wound healing physiology and suitable therapeutic management. In addition to colonizing wounds, bacteria can slow healing, deteriorate cosmetic results, and raise medical expenses. According to research done in [6] at the University of Veterinary Medicine and Pharmacy in Košice, animal bites account for 26.67% of wound cases, making them the most prevalent wound kind. Perforation wounds, cuts, lacerations, degloving wounds, seroma, foreign substances, crushing wounds, contusion and necrosis, dermatitis, and cutting wounds were among the other prevalent wounds. With 31.11% of wounds containing Staphylococcus intermedius, it was the most frequently detected bacterium. According to the study, wound healing in dogs and cats depends on a high-efficacy treatment strategy against Staphylococcus species.

Abrasion wounds are those brought on by friction or a scraping force. Usually not very deep, but frequently contains a lot of foreign objects, including dirt (i.e. after a fall on loose ground). Abrasions are superficial wounds that cause disruptions in tissue continuity on the skin and visceral linings of the body. Generally confined to the skin's surface, these are insignificant cuts that do not generally result in substantial bleeding. The majority of abrasions heal without producing scars. On the other hand, scar tissue may develop throughout the healing process if the abrasion penetrates into the dermis. The most frequent cause of abrasions is friction against the epidermis, which results in the outer layer becoming denuded [7]. Friction and impact are the most frequent processes via which abrasions occur in different types of blunt trauma. Although less common, pressure abrasions might be more important from a medical and legal standpoint, particularly when determining the underlying cause. Globally, corneal injuries and infections are the primary cause of blindness. It is essential to comprehend the mechanisms governing corneal healing in order to design novel treatments. ILCs, or innate lymphoid cells, are involved in tissue and immunological healing [8]. Mice were shown to have a population of cornea-resident group 2 ILCs (ILC2s), which were expressed in T1/ST2, CD90, cKit, and CD127. The corneal wound healing process was partially recovered after the depletion of this cell population, although it was not fully repaired. Dressings are frequently used to promote wound healing, which is essential for preserving the physiological functioning of the skin. Modern dressings that can regulate temperature, relieve pain, and alleviate hypoxic environments—such as hydrogels, hydrocolloids, alginates, foams, and films—are favored since they are biocompatible and biodegradable. These dressings have been shown in clinical trials to be efficacious in vitro, in vivo, and on a variety of wound types [9].

2 Biomaterials in Wound Dressings

Wounds are a leading source of metabolic disorders in the wound microenvironment and are blamed for deaths globally. Hydrogel dressings are a viable way to deal with this problem because of its permeability, biocompatibility, and three-dimensional structure. By providing a moist environment for wound healing, these dressings overcome obstacles and conventional inadequacies [10]. The biggest organ in the human body, the skin, is essential for protecting the body from outside dangers and repairing damaged tissue. Because of their high cost, protracted medical interventions, and ongoing chronic nature, chronic wounds present a serious public health concern. The biomaterials sector has expanded in response to this, concentrating on shortening treatment times and speeding wound healing. Hydrogels, films, foams, membranes, gels, dressings, 3D bioprinting, and combination medicines are examples of common biomaterial forms [11]. Because of their special qualities, ultrafine fibers may be produced effectively by electrospinning, and this approach may find use in wound dressings. The study in [12] examines the structure, properties, characterisation, processing, and applications of electrospun biopolymer nanofibers. It addresses the constraints of technology, research issues, and future developments related to the use of electrospun natural biopolymer fibers in wound dressings. Due to the distinct healing needs of wounds, a variety of wound dressings with particular properties have been developed. Although a single dressing cannot address every common need for wound healing, it can produce the best outcomes when it deviates from a one-size-fits-all strategy. Effective wound dressings should promote wound healing in the least amount of time and money. The study in [13] examines the several polymeric materials—such as foam dressings, hydrocolloids, alginate dressings, synthetic polymer films, and hydrogels—that are used to treat wounds. It also looks at these materials' qualities that meet the criteria for wound healing. The development of hydrogels as a wound dressing is reviewed in [14], with an emphasis on how advantageous they may be compared to conventional gauze and cotton dressings. Hydrogels have a variety of qualities and uses and are created by physical and chemical cross-linking techniques. Good biological activity is exhibited by both natural and synthetic polymers; mixed-use polymers accelerate wound healing. Subsequent investigations will endeavor to create more affordable and varied hydrogel dressings, emphasizing antimicrobial, antioxidant, or slow-release properties. The perfect hydrogel dressing is still lacking, though, especially for chronic wounds. Hydrogel characteristics are further influenced by variables such polymer solubility, processability, and stability. Human health is seriously threatened by bacterial infection and resistance, especially when it comes to wound healing. In order to enhance cell activities and facilitate healing, skin tissue engineering technologies include bioactive components, such as antibacterial agents, into biomaterials. There hasn't, however, been a thorough analysis of antimicrobial wound dressings. The study in [15] examines the latest developments in a variety of antibacterial biomaterials, such as antibiotics, nanoparticles, and cationic chemical compounds. The choice and creation of biomaterials is also covered, including films, hydrogel, sponge, foam, electrospun nanofibers, and 3D printed scaffolds for skin regeneration. New medical biological dressings are being explored using natural biomaterials, which are recognized for their renewable qualities, antibacterial, hemostatic, and biocompatibility qualities. Nanofibers with high specific surface area, porosity, liquid absorption, and semipermeability are created by electrospinning technology and can mimic the composition and biological activities of the extracellular matrix found in nature. Their therapeutic impact and biological activity are inadequate, nonetheless [16]. Researchers need to lower surface tension, enhance mobility in an electric field, and create more effective electrospinning machinery in order to increase mechanical strength and spinnability. These applications can only be expanded with more research.

Table 1. Various Wound Dressing Techniques

Aspect	Hydrogel Dressings	Electrospun Biopolymer Nanofibers	Polymeric Materials	Skin Tissue Engineering Technologies
Main Features	Permeable, biocompatible, 3D structure	High surface area, porosity	Variety (foams, hydrocolloids, alginates)	Incorporation of bioactive components
Benefits	Moist environment for healing, speeds wound healing	Mimics extracellular matrix, liquid absorption	Meet criteria for wound healing, diversity	Enhances cell activities, aids healing
Challenges	High cost, chronic wound specificity	Limited mechanical strength, spinnability	Cannot address all wound needs	Lack of comprehensive analysis for antimicrobial dressings
Research and Development	Focus on antimicrobial, antioxidant properties	Improve mechanical strength, reduce surface tension	Develop dressings for specific wound types	Develop affordable, effective biomaterials with antimicrobial properties
Current Limitations	Inadequate for chronic wounds	Inadequate therapeutic impact	Limited by material properties	Insufficient exploration of natural biomaterials
Future Directions	Develop varied hydrogel dressings	Enhance electrospinning technology	Create more specialized dressings	Expand research on bioactive biomaterials

According to Table 1, Hydrogel dressings provide a moist environment for wound healing and stimulate cell activity. They are produced from electropunched biopolymer nanofibers and polymeric components. They do, however, have drawbacks, including high cost, low mechanical strength, spinnability, chronic wound specificity, and a dearth of thorough antibacterial study. Present study endeavors center around enhancing mechanical strength, diminishing surface tension, and creating cost-efficient, efficient biomaterials possessing antibacterial characteristics. Future initiatives in dressing development include extending research on bioactive biomaterials, improving electrospinning technologies, and producing customized hydrogel dressings.

3 Biomedical Materials for diabetic ulcers

Over 300 million people worldwide suffer from diabetes mellitus, and hyperglycemia hinders the healing of wounds. Chronic diabetic sores, especially diabetic foot ulcers, have increased in number as a result of the growth in diabetes patients [17]. Advanced biomaterials, however, have led to better wound healing results. These adjustable therapeutic approaches reduce inflammation and extracellular matrix enzymatic breakdown while increasing angiogenesis, collagen deposition, cell proliferation, and growth factor concentrations. Patient quality of life will increase when more therapeutic alternatives become accessible as biomaterials for wound healing develop. Millions of people are impacted by the important clinical problem of diabetic ulcer wound healing. Diabetic ulcers can be successfully healed with stem cell treatment, and microcirculation can be enhanced by growth factors [18]. Stem cells, peptides, growth factors, and medications can all be delivered via ulcer wound dressings as medicated systems. Natural, modified, and synthetic polymers are among the latest developments in the application of growth factors, biomaterials, and stem cells in the treatment of diabetic ulcer wounds. Transdermal medication delivery using microneedles is a promising technique, and a novel strategy for diabetic wound healing is introduced. These bioinspired, adaptive indwelling microneedles are intended to aid in tissue regeneration and wound repair in diabetic rat models [19]. They are constructed from PVA hydrogel needle tips that have been packed with mesenchymal stem cell (MSC) exosomes and a 3M medical tape supporting substrate. The PVA hydrogel's mechanical strength is ionically sensitive, enabling the tips to be softened by nitrate ions for tissue adaption and increased by sulfate ions for skin penetration. Diabetic wounds are serious injuries that frequently result in amputations in individuals with diabetes. Present wound dressings are not biocompatible, biodegradable, have poor mechanical characteristics, low antibacterial qualities, and are unable to retain moisture [20-24]. Polymer-based wound dressings that combine synthetic and biopolymers have been developed as a solution to these problems. Therapeutic effects like antioxidant or antibacterial activity can be improved by loading these hybrid scaffolds with medicines or bioactive substances [25]. Diabetes patients are at a higher risk of developing diabetic foot ulcers (DFUs), a serious ailment for whom finding a suitable therapy is difficult because to the intricate pathophysiology of DFU wound settings [26]. Because of their therapeutic release properties, tunability, and convenience of administration, topical biomaterial gels have been created to enhance therapeutic benefits. Preclinical evidence regarding gel therapies in diabetic animal models and clinical applications are reviewed in [27]. Chronic inflammation brought on by diabetes causes wounds to heal more slowly. The distinctions between diabetes-related and native wound healing processes are covered in [28], along with the functions of cytokines and cells in controlling the healing process. MCP-1, or monocyte chemoattractant protein-1, is a pro-inflammatory mediator involved in the healing of diabetic wounds. MCP-1 and related chemokines have been used in recent studies to promote healing and decrease inflammation. Diabetes is frequently associated with wounds that heal slowly, such as diabetic foot ulcers (DFUs). Debridement, off-loading, and amputation are available treatment options [29-32].

4 Biomedical Materials for pressure ulcers

A serious medical problem brought on by the aging population and chronic illnesses, pressure ulcers (PUs) are more expensive to treat and a burden on society [33]. It's alarming that there aren't more sophisticated biological pressure ulcer avoidance solutions, especially in light of developments in other domains. It is essential to comprehend the damage cascade that leads to pressure ulcers (PUs). The damage cascade is cumulative and sequential, emphasizing the significance of early identification [34]. Polymeric membrane dressings that reduce inflammation and subepidermal moisture scanner biocapacitance assessments are examples of current PUP technology [35]. For biomedical engineers, minimizing the impact of pressure ulcers (PUs) is a timely and viable task that involves developing technology-based choices to detect and mitigate PU-specific tissue alterations. Using silver nanoparticles, [36] sought to develop hydrogel pads for the treatment of pressure ulcers and other chronic wounds. The 10:1.2:1.8 PVP/alginate/chitosan ratio demonstrated the qualities needed for an efficient wound dressing [37]. When tested on adult human dermal fibroblasts, L929 mouse fibroblasts, and human keratinocytes, the hydrogel demonstrated no cytotoxicity and antibacterial qualities [38]. The hydrogel outperformed commercial dressings in terms of affordability, non-cytotoxicity, and swelling while lowering bacteria [39-41]. Thus, there is a lot of promise for treating pressure ulcers with the hydrogel based on silver nanoparticles. Bacterial biopolymers, both extracellular and intracellular, contain bacterial cellulose (BC), a common and versatile exopolysaccharide with special properties. A strong basis for creating intricate, multipurpose molecules with conductive, bioactive, and intelligent qualities is offered by BC [42]. In the last 10 years in particular, there has been a great deal of study on the use of BC nanocomposites in medicine, with an emphasis on these materials and devices. BC is beneficial for topical medication administration due to its excellent purity, distinct structural/mechanical properties, skin tolerance, and effectiveness in wound healing [25]. It has been demonstrated that BC is compatible with a range of human cells and can lessen the amount of germs that enter tissue [43]. In blood-brain barrier models, BC-compounds have been employed as a basement membrane, as well as wound dressings, vascular grafts, scaffolds for deficiencies in cartilage, bone, and osteochondral defects.

5 Biomedical Materials for burns

Present wound dressings are limited in mechanical efficacy, have low porosity, and have low antibacterial activity. The porous keratin-chitosan/n-ZnO nanocomposite (KCBZNs) bandage was created by adding nano-ZnO to keratin-chitosan hydrogel. An examination of the bandages was conducted using FT-IR, XRD, SEM-EDX, and TEM-SAD [44]. Using human fibroblast cells as a biocompatibility test, the nanocomposite exhibited increased swelling and bactericidal activity. Increased wound healing, faster skin cell formation, and collagen growth were seen in vivo in SD rats [25]. Several studies have demonstrated the effectiveness of hydrogel nanocomposite in treating burn injuries. Thymol-enhanced bacterial cellulose hydrogel (BCT) was created in this study to treat third-degree burns. As well as demonstrating strong biocidal efficacy against microorganisms specific to burns, BCT appears to promote fibroblast proliferation, demonstrate minimal toxicity, and boost cell viability [46-47]. Studies on in vitro biocompatibility shown the low toxicity and enhanced cell viability of BCT hydrogel. Studies conducted in vivo on female albino Wistar rats treated with BCT hydrogel revealed quicker wound healing, indicating the material's potential use as a natural burn dressing [48]. Evidence suggests that wound healing, an organism's natural defense mechanism against harm, may lead to organ regeneration or scarring [49-52]. In vitro-engineered skin substitutes that resemble human skin have been developed thanks to tissue engineering technologies and are utilized as research models or skin replacements [53]. Skin deficiencies that are full-thickness suggest that autologic skin transplants are necessary [54]. The classification of skin replacements, the forms of their commercial manufacture, therapeutic uses, and the outcomes of using artificial skin are all covered in this review. It also emphasizes recent advancements in cell sources, biomaterials, and growth factors—three essential components of tissue-engineered skin engineering [55]. In the fields of tissue engineering, cell therapy, and biomedical research, the design of created skin replacements is constantly improving [56-58].

Table 2: Comparative analysis of Biomedical materials for chronic Wounds: Implications for Environmental Engineering

Aspect	Diabetic Ulcers	Pressure Ulcers	Burn Injuries
Prevalence	Over 300 million worldwide suffer from diabetes mellitus [17]	Increasing due to aging population and chronic illnesses [59]	Common injuries, particularly in workplaces and households
Impact	Chronic wounds like foot ulcers hinder patient quality of life [17]	Expensive to treat, burdensome to society [60]	Severe pain, risk of infection, scarring, and disability
Biomedical Solutions	Stem cell treatments, growth factors, biomaterial dressings [18]	Polymeric membrane dressings, silver nanoparticle hydrogels [61]	Keratin-chitosan/n-ZnO nanocomposite bandages, thymol-enhanced bacterial cellulose hydrogels [64]
Advancements	Latest developments include microneedle therapies, transdermal drug delivery [19]	Research focuses on improved biocompatibility, antibacterial properties [62]	Nanocomposite bandages, hydrogel dressings [65-67]
Environmental Impact	Reduced need for amputations, less medical waste from improved healing technologies	Potential reduction in healthcare costs, decreased need for long-term care facilities [63]	Biocompatible materials, fewer dressings needed, reduced risk of secondary infections

Table 2 explores the usage of biomedical materials in treating chronic wounds and its implications for environmental engineering. It examines how advancements in wound care technology can effect environmental sustainability, which includes through the development of biodegradable dressings and eco-friendly wound recuperation solutions. Through evaluating the environmental footprint of various biomedical substances and treatments, this analysis pursuits to provide decision-making processes in each healthcare and environmental engineering sectors, promoting the development of greater sustainable practices in wound control.

6 Conclusion

This comparative analysis elucidates the distinct features, advantages, and challenges associated with numerous wound dressing technology, along with hydrogel dressings, electrospun biopolymer nanofibers, and polymeric substances. It underlines the necessity for ongoing research and improvement to address the constraints of cutting-edge wound care answers, mainly for chronic wounds. The future of wound care lies within the innovation of dressings that could cater to specific wound environments while being cost-effective and improving affected person restoration.

- Hydrogel dressings, electrospun nanofibers, and polymeric materials every offer precise benefits in wound control, however also face particular challenges.
- There's a vital want for specialized wound dressings that could deal with the diverse requirements of different wound kinds, particularly persistent wounds.
- Future improvements ought to cognizance on integrating bioactive components to promote healing and fight microbial resistance.
- Cost-effectiveness, more suitable mechanical properties, and targeted healing effects continue to be pivotal desires for next-era wound dressing technology.

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