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Exploring the Impact of Ceramic Reinforcements on the Mechanical Properties of Wound Dressings and Drug Release

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ABSTRACT

Wound dressings play a vital role in facilitating wound healing by maintaining a moist environment at the wound site to promote cellular migration and proliferation. Traditional wound dressings are often limited by shortcomings such as insufficient moisture retention, lack of antimicrobial activity and low mechanical strength. In recent years, ceramic reinforced composite wound dressings have gained attention due to their ability to overcome these limitations. Ceramic reinforcing phases like hydroxyapatite (HA), aluminium oxide (Al_2O_3) and zinc oxide (ZnO) in polymer matrices enhance moisture absorption, provide antimicrobial activity and improve mechanical properties. This article aims to provide a comprehensive review on ceramic reinforced composite wound dressings, with a focus on investigating their effect on wound healing, drug release behaviour and mechanical properties. Firstly, an overview of the wound healing process and requirements of an ideal wound dressing are presented. Factors affecting moisture absorption, drug release and mechanical properties of wound dressings are then discussed. Recent advances in HA, Al_2O_3 and ZnO reinforced composite dressings are reviewed, and their wound healing, drug release and mechanical performances are analysed and compared. Finally, the current challenges and future prospects of ceramic reinforced wound dressings are outlined. Through this systematic analysis, important insights on materials selection, fabrication techniques and structure-property relationships of advanced wound dressings are provided.

1. Introduction

The skin forms the first line of defence against external pathogens and helps prevent dehydration of the body by regulating water loss. However, wounds or disruptions to the skin barrier compromise this protective function. Approximately 7 million people suffer from chronic wounds globally due to complications from illnesses like diabetes or pressure sores [1]. Wound healing is a complex process involving inflammation, proliferation and remodeling stages to restore tissue integrity [2]. Traditional wound dressings play a vital role in facilitating healing by maintaining a moist environment conducive to cellular migration, proliferation and tissue synthesis [3]. However, common dressings often encounter limitations such as insufficient moisture retention, lack of antimicrobial activity and low mechanical strength. In the past decade, ceramic particle reinforced polymer composite wound dressings have gained attention as a promising alternative with several advantages over traditional dressings [4-6]. Ceramic fillers like hydroxyapatite (HA), aluminium oxide (Al_2O_3) and zinc oxide (ZnO) incorporated into polymer matrices yield dressings with enhanced properties. These ceramics provide reinforcement to polymer matrices, leading to improved moisture management ability, antimicrobial efficacy and mechanical strengths of the resulting composites [7-9]. Specifically, HA is a naturally occurring mineral phase present in bone and teeth, offering similarities to the inorganic components of skin that promote wound healing [10]. Al_2O_3 and ZnO are versatile biomaterials used widely as reinforcement agents due to their hardness, thermal stability, and biocompatibility. When incorporated into synthetic polymer matrices, HA, Al_2O_3 and ZnO nano/microparticles are postulated to facilitate wound repair by absorbing exudate, releasing antimicrobial ions, and imparting structural integrity to the dressings. This reduces the need for frequent dressing changes and provides a stable environment conducive for healing at the wound-dressing interface [13-15]. However, although significant advances have been made in fabricating ceramic reinforced wound dressings, the influence of different ceramics, particle sizes and processing techniques on critical wound healing parameters like moisture retention, drug elution and mechanical performance requires systematic investigation. This comprehensive literature review aims to provide an overview of recent developments in HA, Al_2O_3 and ZnO reinforced wound dressings, evaluating their impact on key wound healing parameters through critical analysis of reported data. This article aims to explore the impact of ceramic reinforcements, including hydroxyapatite (HA), Al_2O_3, and zinc oxide (ZnO), on the mechanical properties of wound dressings and their influence on wound healing and drug release. Traditional wound dressings often have limitations such as inadequate moisture retention, lack of antimicrobial activity, and low mechanical strength. In recent years, ceramic reinforced composite wound dressings have emerged as a promising solution to overcome these limitations. By incorporating ceramic reinforcing phases into polymer matrices, these dressings enhance moisture absorption, provide antimicrobial activity, and improve mechanical properties. This comprehensive review provides an overview of the wound healing process, the requirements of an ideal wound dressing, and the factors influencing moisture absorption, drug release, and mechanical properties of wound dressings. It further examines recent advances in HA, Al_2O_3, and ZnO reinforced composite dressings, analyzing their wound healing, drug release, and mechanical performances. The article also highlights the challenges and future prospects of ceramic reinforced wound dressings, offering valuable insights into materials selection, fabrication techniques, and structure-property relationships in the development of advanced wound dressings.

2. An Overview of the Wound Healing Process

Wound healing is a dynamic and complex process involving overlapping phases of inflammation, proliferation and remodeling [2,16]. The process of wound healing is shown in Figure 1. Upon injury, hemostasis commences immediately to stop bleeding through formation of a fibrin clot from coagulation of plasma proteins [16,17]. Platelets embedded in the clot release growth factors that initiate the inflammatory phase lasting 3-5 days [2,17,18]. Vasodilation and increased capillary permeability aid immune cell migration and release of pro-inflammatory cytokines that prepare the wound site for healing. Concurrent with inflammation, proliferation starts within 24 hours as new blood vessels form (angiogenesis) and fibroblasts synthesize collagen [2,16-18]. Epithelial and connective tissue regenerate to close the wound gap [2,17,18]. Throughout the 2-4 week proliferation stage, the wound exponentially gains strength through collagen deposition and epithelialization [2,17]. Finally, the remodeling phase lasting from 4 weeks to 2 years involves collagen cross-linking and scar tissue organization to attain 80% of wound breaking strength [2,17,20]. Throughout healing, matrix metalloproteinases breakdown and remodel the extracellular matrix while their inhibitors regulate protease activity [21]. Growth factors like transforming growth factor-β, vascular endothelial growth factor, fibroblast growth factors and platelet-derived growth factor stimulate each repair phase [2,21-23]. Insufficient fluid at the wound impedes hemostasis, delays inflammation and hinders cellular migration, emphasizing the role of dressings in maintaining a moist environment [24,25]. Ideally, an optimal wound dressing promotes hemostasis, absorbs exudate to prevent infection while retaining a moist microenvironment favorable for proliferation and remodeling [25,26].

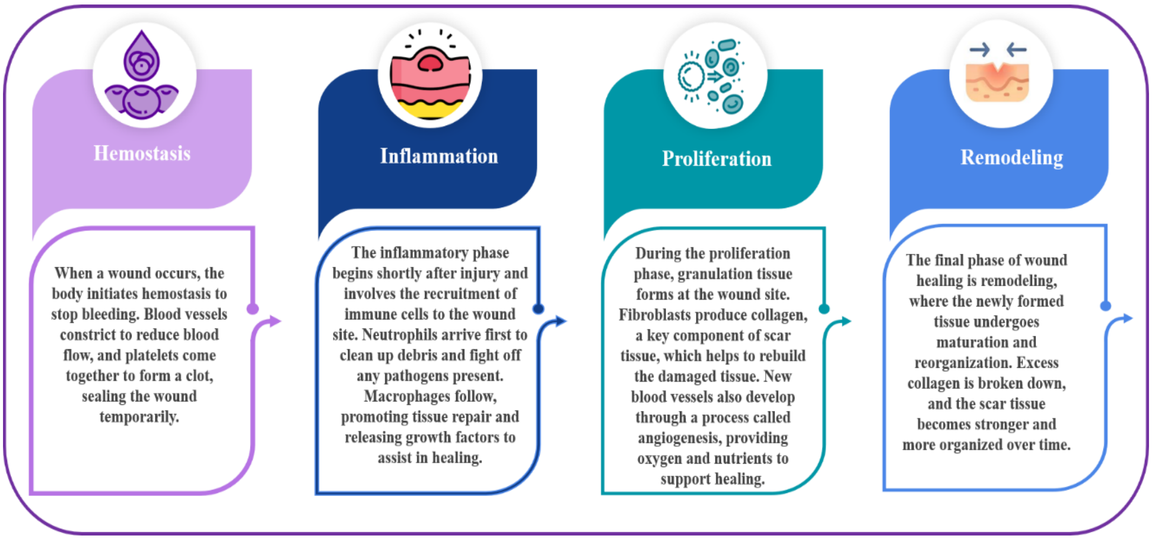

Fig.1. The process of wound healing

3. Requirements for an Ideal Wound Dressing

Wound dressings are essential in the management of both acute and chronic wounds, but traditional materials often fail to meet the multifaceted needs of wound care. To address these limitations, advanced wound dressings incorporating ceramic reinforcements have emerged as a promising solution. This review article aims to comprehensively analyze the impact of ceramic reinforcements, including hydroxyapatite (HA), Al_2O_3, and zinc oxide (ZnO), on the mechanical properties of wound dressings and their influence on wound healing and drug release. Moisture management is a crucial aspect of wound healing, as a moist environment promotes cellular migration, proliferation, and tissue synthesis. However, traditional dressings often struggle to maintain adequate moisture levels, leading to delayed healing and increased infection risk. Ceramic reinforcements have been found to enhance the moisture absorption capabilities of wound dressings. By incorporating ceramic fillers into polymer matrices, advanced dressings can effectively absorb exudate and maintain an optimal moisture balance at the wound site. Hydroxyapatite, Al_2O_3, and ZnO have demonstrated improved moisture management abilities, facilitating a conducive environment for wound healing. Antimicrobial activity is another critical requirement for wound dressings, as infections can significantly impede the healing process. Traditional dressings often lack inherent antimicrobial properties, making them less effective in preventing and combating infections. However, ceramic reinforcements offer the potential for antimicrobial efficacy. Through the release of antimicrobial ions, ceramic particles such as ZnO can provide an additional layer of protection against microbial colonization and infection. By incorporating ceramic reinforcements into the polymer matrix, advanced dressings can enhance their antimicrobial activity and contribute to improved wound healing outcomes. In addition to moisture retention and antimicrobial activity, the mechanical properties of wound dressings play a vital role in their effectiveness. Traditional dressings often lack sufficient mechanical strength, leading to poor conformability, inadequate protection, and discomfort for patients. Ceramic reinforcements can enhance the mechanical properties of dressings, providing improved structural integrity and durability. Hydroxyapatite, which shares similarities with the inorganic components of skin, has been shown to enhance the mechanical strength of composite dressings. Similarly, Al_2O_3 offers excellent hardness and thermal stability, contributing to the mechanical robustness of wound dressings. This review article will provide a comprehensive analysis of ceramic reinforced composite wound dressings, with a focus on their impact on wound healing, drug release behavior, and mechanical properties. It will present an overview of the wound healing process and the requirements of an ideal wound dressing. Factors influencing moisture absorption, drug release, and mechanical properties will be discussed in detail. The review will also delve into recent advancements in the field, specifically examining the performance of HA, Al_2O_3, and ZnO reinforced composite dressings. By critically analyzing and comparing the reported data, the article will provide valuable insights into the potential of ceramic reinforced wound dressings to improve wound healing outcomes. Furthermore, the review will address the current challenges and future prospects of ceramic reinforced wound dressings. It will shed light on the materials selection process, fabrication techniques, and structure-property relationships involved in developing advanced wound dressings. By identifying gaps in knowledge and highlighting potential areas for further research, this article aims to contribute to the advancement of ceramic reinforced wound dressings and ultimately improve patient outcomes in wound care.

3.1 Moisture Management

Wound dressings play a crucial role in wound care by providing a protective barrier and facilitating the healing process. One of the key requirements for an effective wound dressing is the ability to absorb and retain exudate while maintaining a moist wound bed. Proper fluid handling is essential to prevent desiccation and scabbing, which can impede the healing process, while also avoiding excessive fluid accumulation that can lead to maceration. In the initial stages of wound healing, the formation of a moist environment is critical for promoting cellular migration, angiogenesis, and collagen deposition. A moist wound bed supports the migration of various cells, including fibroblasts and epithelial cells, which are essential for tissue repair and regeneration. It also facilitates the formation of new blood vessels (angiogenesis) and the synthesis of collagen, promoting the remodeling phase of wound healing. Traditional wound dressings often fall short in maintaining optimal moisture levels, leading to delayed healing and increased risk of infection. To address these challenges, advanced wound dressings have been developed with improved fluid handling capabilities. Ceramic reinforced composite dressings have shown promise in enhancing moisture absorption and retention. By incorporating ceramic fillers, such as hydroxyapatite (HA), Al_2O_3, and zinc oxide (ZnO), into the polymer matrix, these dressings can effectively absorb and manage exudate while maintaining a moist wound environment. The ceramic reinforcements provide additional surface area and capillary action, facilitating the absorption and retention of fluid within the dressing. This helps to create an optimal environment that supports the various stages of wound healing. In addition to moisture management, advanced wound dressings need to provide an appropriate balance of gas permeability and moisture vapor transmission. This allows for adequate oxygenation and moisture evaporation, preventing the accumulation of excessive moisture that can lead to maceration. Ceramic reinforced composite dressings have shown the potential to balance these requirements. The incorporation of ceramic fillers can enhance the gas permeability and moisture vapor transmission rate of the dressings, allowing for proper gas exchange and moisture control.

3.2 Barrier Function

Wound dressings play a crucial role in wound care by forming a protective barrier that seals the wound from external contaminants, regulates water vapor transfer, and facilitates autolytic debridement. This protective barrier is essential for creating an optimal environment that supports the healing process. One of the key functions of wound dressings is to prevent the entry of external contaminants into the wound site. By forming a physical barrier, dressings help to shield the wound from bacteria, dirt, and other potential sources of infection. This is particularly important for open wounds or surgical incisions where the risk of infection is high. By effectively sealing the wound, dressings minimize the chances of contamination and create a clean and protected environment that promotes healing. In addition to protecting the wound from external contaminants, dressings also play a role in regulating water vapor transfer. This is important for maintaining an appropriate moisture balance at the wound site. Too much moisture can lead to maceration, where the skin becomes excessively softened due to prolonged exposure to moisture. On the other hand, excessive dryness can hinder the healing process. Dressings with semi-permeable qualities strike a balance by allowing some moisture to escape through evaporation while preventing excessive dehydration. This helps to create a moist wound environment that is conducive to healing while avoiding complications related to excessive moisture or dryness. Furthermore, dressings facilitate autolytic debridement, which is the natural process of removing necrotic or dead tissue from the wound. Autolytic debridement occurs when the body's enzymes break down and liquefy necrotic tissue, allowing it to be removed naturally. Dressings can support this process by creating an ideal environment for enzyme activity and the gradual breakdown of necrotic tissue. By maintaining a moist environment, dressings promote the activity of enzymes and enhance the autolytic debridement process. This helps to remove non-viable tissue and create a clean wound bed, which is essential for proper wound healing. Additionally, dressings with semi-permeable qualities allow for gaseous diffusion. This enables the exchange of oxygen and carbon dioxide between the wound and the surrounding environment. Adequate oxygenation is crucial for supporting cellular metabolism and promoting the growth of new tissue. By allowing oxygen to reach the wound site, dressings with semi-permeable properties contribute to an oxygen-rich environment that supports healing.

3.3 Absorbency

Highly absorbent dressings play a crucial role in wound care, particularly during the inflammatory stage, by effectively drawing exudate away from wound interfaces. Exudate, the fluid that accumulates in wounds as a result of inflammation, contains various substances such as plasma proteins, inflammatory cells, and cellular debris that can hinder the healing process if not managed properly. By rapidly absorbing and containing exudate, these dressings help create a clean and moist wound environment that is conducive to healing. The absorption capacity of dressings is a key factor that influences the integrity of the dressing and reduces the frequency of changes required. Dressings with high absorbency are designed to efficiently manage exudate, preventing it from pooling at the wound site and potentially causing maceration or infection. This is particularly important during the inflammatory stage when exudate production is typically at its peak. By effectively drawing exudate away from the wound interface, these dressings minimize the risk of complications and promote optimal wound healing. In addition to managing exudate, the absorption capacity of dressings also plays a role in maintaining the integrity of the dressing itself. When a dressing reaches its saturation point and can no longer absorb exudate effectively, it may become saturated and lose its ability to provide a barrier against external contaminants. This can compromise the wound healing process and increase the risk of infection. Highly absorbent dressings with a greater absorption capacity can maintain their integrity for a longer duration, reducing the need for frequent dressing changes and minimizing disruption to the wound bed. This not only improves patient comfort but also contributes to cost-effectiveness in wound management. Moreover, the choice of dressing with appropriate absorption capacity is influenced by various factors, such as the type and severity of the wound, the amount of exudate produced, and the patient's overall condition. For wounds with high exudate levels, such as chronic ulcers or heavily exuding acute wounds, dressings with a higher absorption capacity are typically preferred. These dressings can effectively manage the excess exudate and prevent maceration, promoting a moist wound environment that supports healing. On the other hand, for wounds with lower exudate levels, dressings with a lower absorption capacity may be more appropriate to avoid excessive dryness and promote autolytic debridement. It is worth noting that while highly absorbent dressings offer advantages in managing exudate, proper selection and monitoring are essential to ensure optimal outcomes. Dressings should be chosen based on the individual characteristics of the wound and regularly assessed to determine if they are meeting the absorption needs. In some cases, a combination of dressings with different absorption capacities may be used to address varying exudate levels at different stages of wound healing.

3.4 Conformability

conformability is a vital characteristic of ideal wound dressings, ensuring effective wound care by minimizing dead space, maintaining optimal moisture levels, and promoting a secure barrier against external contaminants. Figure 2 .Dressings play a crucial role in wound care by closely conforming to the irregular topography of wounds without causing additional trauma, thereby reducing dead space and facilitating the healing process. The ability of dressings to conform to the contours and irregularities of wounds is essential for several reasons. Firstly, close conformity helps to establish intimate contact between the dressing and the wound bed, promoting a secure and effective barrier against external contaminants. Irregular wound topographies, such as uneven surfaces or crevices, can create spaces where bacteria, debris, or foreign particles can accumulate, increasing the risk of infection and hindering the healing process. By closely adhering to the wound surface, dressings minimize dead space, leaving no room for pockets of fluid or materials that could impede healing or serve as a breeding ground for microorganisms. Secondly, close conformity of dressings helps to maintain the optimal moist wound environment. Moisture is a critical factor in wound healing, as it supports cellular migration, angiogenesis, and collagen synthesis. When dressings conform closely to the wound surface, they create a microenvironment that retains moisture, preventing excessive drying or excessive moisture accumulation. This balanced moisture environment promotes the migration of essential cells, such as fibroblasts and epithelial cells, which are crucial for tissue repair and regeneration. It also facilitates the formation of new blood vessels (angiogenesis) and the synthesis of collagen, key processes in the proliferation and remodelling phases of wound healing.

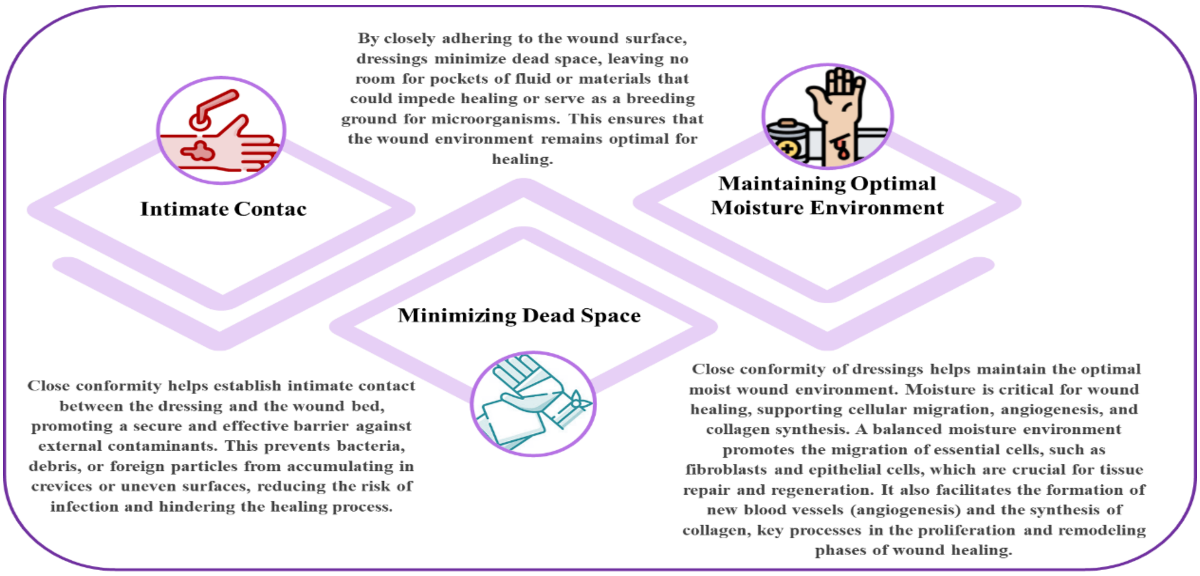

Fig.2. Compatibility of ideal wound dressings

3.5 Fluid Retention

Ideally, in wound care, dressings should not only absorb fluid effectively but also retain the absorbed fluid within the dressing to maintain a moist wound surface and minimize repeated adsorption cycles. The ability of dressings to retain absorbed fluid is crucial for several reasons. Maintaining a moist wound surface is widely recognized as a key factor in supporting the healing process. A moist wound environment promotes cellular migration, angiogenesis, and the synthesis of collagen, all of which are essential for effective wound healing. By retaining absorbed fluid within the dressing, dressings help create and maintain this optimal moisture balance [17-21]. The retained fluid continuously hydrates the wound bed, keeping it moist and promoting the proliferation of essential cells involved in tissue repair and regeneration. Retaining the absorbed fluid within the dressing also reduces the frequency of dressing changes, minimizing disruption to the wound bed and improving patient comfort. Frequent dressing changes not only increase the risk of wound contamination and trauma but also add to the overall burden and cost of wound management. By effectively retaining the absorbed fluid, dressings can maintain their integrity and absorption capacity for an extended period, reducing the need for frequent changes [22-24]. Furthermore, the retention of absorbed fluid within the dressing contributes to a more efficient wound healing process. When the absorbed fluid remains within the dressing, it creates a microenvironment that supports autolytic debridement, the natural process of removing necrotic or dead tissue from the wound. The moist environment softens and loosens the non-viable tissue, making it easier to remove during dressing changes. This promotes a cleaner wound bed and facilitates the growth of healthy granulation tissue, which is essential for wound healing. In order to retain absorbed fluid effectively, dressings are designed with various features and materials. Dressings with high absorbency, such as foam or alginate dressings, are often used to effectively absorb and retain fluid. These dressings have the capacity to hold a significant amount of exudate and prevent leakage or seepage from the wound site. Additionally, dressings with semi-permeable or moisture-retentive properties, such as hydrocolloid or hydrogel dressings, are commonly utilized to create an optimal moist wound environment by retaining the absorbed fluid and preventing excessive drying or desiccation.

3.6 Durability

Durability is a fundamental characteristic of wound dressings, as they must maintain their integrity throughout normal wear, resist environmental stresses, and provide effective protection during movement or minor trauma. The durability of dressings is essential for several reasons. Firstly, dressings need to withstand the mechanical forces exerted on them during daily activities and movements. Wound dressings are subject to various stresses, such as friction, shear, and tension, which can lead to dressing displacement, detachment, or premature failure. By maintaining their integrity, dressings remain securely in place, ensuring continuous coverage of the wound and preventing exposure to external contaminants. This is particularly important for wounds located in areas prone to friction or movement, such as joints or pressure points, where dressings are subjected to increased stress and have a higher risk of displacement. Secondly, dressings should be able to resist environmental stresses, such as moisture, temperature changes, and exposure to chemicals or microorganisms. Wounds can be exposed to different environments, including wet or humid conditions, dry climates, or contaminated settings. Dressings that can withstand these environmental stresses help provide a protective barrier for the wound, preventing excessive moisture loss or absorption, temperature fluctuations, or potential contamination [25-32]. By maintaining their integrity under varying environmental conditions, dressings support the creation and maintenance of an optimal wound healing environment.

3.7 Antimicrobial Activity

Antimicrobial activity is a critical feature in wound dressings, as the incorporation of antimicrobial agents plays a vital role in preventing infection by inhibiting microbial colonization and biofilm formation. The ability of dressings to effectively combat microbial growth and prevent infection is of utmost importance in wound care for several reasons. Firstly, wounds are vulnerable to microbial colonization, which can delay the healing process and lead to complications. Microorganisms, such as bacteria, fungi, and viruses, can easily enter wounds through various sources, including the environment, healthcare settings, or the patient's own skin. Once established, these microorganisms can multiply rapidly, forming biofilms that provide protection and promote their survival. Biofilms are complex structures composed of microorganisms embedded within a self-produced matrix, making them highly resistant to the immune system and conventional antimicrobial treatments. By incorporating antimicrobial agents, dressings can effectively inhibit microbial colonization and disrupt biofilm formation, thus preventing the establishment of infections. Secondly, the prevention of infection is crucial for promoting optimal wound healing. Infections in wounds can lead to prolonged inflammation, impaired cellular functions, and delayed tissue repair. They can also cause systemic complications, such as sepsis, which can be life-threatening. By incorporating antimicrobial agents, dressings provide an additional layer of protection against infection, reducing the risk of complications and facilitating the healing process.

Table 1: Comparison of four types of wound dressings based on their mechanical properties, biological aspects, and drug release capabilities

Dressing Type	Mechanical Properties	Biological Aspects	Drug Release
Alginate Dressings	Alginate dressings exhibit good absorbency, allowing them to effectively manage exudate. They have moderate tensile strength and conformability, enabling them to adapt to irregular wound shapes. However, they can be fragile when wet and may require secondary dressings for added support.	Alginate dressings have biocompatible and biodegradable properties, making them suitable for various wound types. They create a moist environment that promotes autolytic debridement and facilitates granulation tissue formation. Alginate dressings also demonstrate hemostatic properties and can help control bleeding in heavily exuding wounds.	Alginate dressings have a limited capacity for drug release. They can serve as a carrier for antimicrobial agents or other therapeutic substances, allowing localized delivery to the wound site. However, the release rate is relatively slow and may require frequent dressing changes for sustained drug release.
Foam Dressings	Foam dressings have excellent absorbency and fluid handling capabilities, making them suitable for heavily exuding wounds. They provide cushioning and protection against mechanical forces while maintaining their integrity. Foam dressings are flexible, conformable, and highly comfortable for patients, promoting mobility and adherence during wear.	Foam dressings create a moist wound environment that supports granulation tissue formation and re-epithelialization. They also provide thermal insulation and reduce pain by minimizing nerve exposure. The foam structure allows for gas exchange and oxygen permeability, promoting wound healing.	Foam dressings can provide sustained and controlled drug release. They can be impregnated with various therapeutic agents, such as antimicrobials or growth factors, enabling localized delivery. The foam matrix helps retain the drug, allowing for gradual release over time.
Hydrogel Dressings	Hydrogel dressings have high moisture content, maintaining a moist wound environment and promoting autolytic debridement. They have low adhesion to the wound bed, minimizing pain and trauma during dressing changes. However, hydrogel dressings can be less absorbent and may require additional absorbent layers for heavily exuding wounds.	Hydrogel dressings provide a cooling and soothing effect, reducing pain and inflammation. They can be used on dry or minimally exuding wounds and are suitable for necrotic or sloughy wounds. Hydrogel dressings also have a non-toxic and non-allergenic nature, ensuring biocompatibility.	Hydrogel dressings have limited drug release capabilities. They can serve as a carrier for topical agents or medications, providing localized delivery. However, the release rate is generally faster, requiring more frequent dressing changes for sustained drug release.

Table 1 shows four types of wound dressings, focusing on their mechanical properties, biological aspects, and drug release capabilities. Alginate dressings exhibit good absorbency and moderate tensile strength, while foam dressings excel in absorbency and fluid handling. Hydrogel dressings maintain a moist wound environment and have a cooling effect, while hydrocolloid dressings provide a gel-like barrier and excellent adhesion. Biologically, alginate dressings promote autolytic debridement, foam dressings support granulation tissue formation, hydrogel dressings soothe and reduce inflammation, and hydrocolloid dressings offer a semi-occlusive barrier.

4. Moisture Management

Maintaining moist conditions at the wound-dressing interface through adequate fluid absorption, retention and regulation is critical for wound healing progression [27,28]. Table 1 summarizes literature comparing exudate uptake capacities of common dressings and HA, Al_2O_3 or ZnO reinforced polymer composites. Gauze typically absorbs 15 times (1500%) its own weight but dries out rapidly [32,33]. Hydrocolloids absorb 3-5 times while hydrogels and alginates absorb over 20 times their weight in fluid, with slower drying profiles better maintaining a moist environment for up to 5 days. Composite dressings show markedly enhanced absorption capacities ranging 30-200 times their weight, attributed to increased hydrophilicity and void spaces within ceramic particles [34-36]. For instance, chitosan–ZnO films absorbed 180-200 times weight in simulated wound fluid (SWF) through chemical modification enabling efficient hydrogen bonding with exudate [35]. Similarly, alginate–HA sponges achieved 160% swelling due to the hydrophilic HA phase interacting strongly with fluid through surface hydroxyl groups [34]. Results emphasize the excellent moisture handling abilities of ceramic reinforced matrices far exceeding traditional dressings. Ceramic particles introduce reinforcing effects while facilitating rapid transport and retention of wound exudate. Mechanical properties of wound dressings, such as tensile strength, elasticity and flexibility, play an important role in maintaining the integrity of the dressing during use and movement. Insufficient mechanical properties can lead to premature tearing or detachment from the wound site. This disrupts the moist healing environment and requires frequent dressing changes, prolonging the healing process. Ceramic reinforcements have been shown to significantly enhance the mechanical properties of wound dressing materials.

Table 2: Comparison of four types of nanoparticles commonly used in wound dressings based on their properties and applications:

Nanoparticle Type	Properties	Applications
Silver Nanoparticles	Silver nanoparticles exhibit excellent antimicrobial activity against a broad spectrum of microorganisms, including bacteria, fungi, and viruses. They have a high surface area-to-volume ratio, enhancing their effectiveness. Silver nanoparticles can be incorporated into dressings to prevent infection and promote wound healing. They are particularly useful for chronic wounds, burn injuries, and wounds at risk of infection. Silver nanoparticles can also help reduce biofilm formation and promote the migration of skin cells, aiding in tissue regeneration.	Antimicrobial dressings, wound debridement, chronic wound management, burn dressings, biofilm control, tissue regeneration.
Zinc Oxide Nanoparticles	Zinc oxide nanoparticles possess antimicrobial and anti-inflammatory properties. They can inhibit the growth of various bacteria and fungi, including antibiotic-resistant strains. Zinc oxide nanoparticles also promote wound healing by enhancing cell proliferation, collagen synthesis, and angiogenesis. They have been used in dressings for infected wounds, diabetic ulcers, and venous leg ulcers. Zinc oxide nanoparticles can help reduce inflammation, control infection, and accelerate tissue repair.	Antimicrobial dressings, infected wound management, diabetic ulcers, venous leg ulcers, inflammation control, tissue repair.
Nanofibrous Scaffolds	Nanofibrous scaffolds are three-dimensional structures composed of nanoscale fibers. They can be made from various materials, such as synthetic polymers or natural proteins. Nanofibrous scaffolds mimic the extracellular matrix and provide a favorable environment for cell adhesion, proliferation, and differentiation. They have large surface areas, high porosity, and interconnected pore structures, facilitating nutrient and oxygen diffusion. Nanofibrous scaffolds have been used in tissue engineering and regenerative medicine for wound healing applications. They can support cell growth, guide tissue regeneration, and provide a physical barrier to protect the wound.	Tissue engineering, regenerative medicine, wound healing, cell adhesion, proliferation, differentiation, tissue regeneration, physical barrier.

Table 2 shows four types of nanoparticles commonly used in wound dressings, highlighting their properties and applications. Silver nanoparticles exhibit potent antimicrobial activity, making them effective in preventing infection and promoting wound healing. Zinc oxide nanoparticles possess antimicrobial and anti-inflammatory properties, aiding in infection control and tissue repair. Chitosan nanoparticles are biocompatible and biodegradable, offering antimicrobial benefits and sustained drug release capabilities. Nanofibrous scaffolds, composed of nanoscale fibers, provide a favourable environment for cell adhesion, proliferation, and tissue regeneration. These nanoparticles find applications in a range of wound care scenarios, including chronic wound management, diabetic ulcers, tissue engineering, inflammation control, and antimicrobial dressings. The information presented in this table serves as a valuable resource for researchers and clinicians seeking to harness the potential of nanoparticles in wound dressings for improved therapeutic outcomes.

5. Mechanical properties of wound dress

The mechanical properties of wound dressings are important considerations when choosing the right dressing for a particular type of wound. Figure 3 shows some mechanical properties. Tensile strength refers to the maximum stress a material can withstand before failure due to stretching or pulling. Polymeric wound dressings typically exhibit low tensile strengths ranging from 5-30 MPa [37-39]. Incorporation of rigid HA, Al_2O_3 and ZnO nanoparticles has been demonstrated to improve tensile strength through stress transfer mechanisms. HA particulate reinforced polycaprolactone films showed a tensile strength of 27.5 MPa compared to 16.7 MPa for unfilled PCL, a 65% improvement [37]. Al_2O_3 inclusion into polyvinyl alcohol increased tensile strength from 59 MPa to 85 MPa, offering 45% reinforcement.[38] Composites containing 5-15% ZnO nano/microparticles in carboxymethyl cellulose exhibited tensile strengths of 30-50 MPa, doubling the matrix strength [39]. Improved tensile strength enhances the dressing's ability to withstand stresses during application and removal without tearing. Elasticity, described as percentage elongation at break, is another key mechanical parameter influencing dressing flexibility and conformability. Traditional materials like gelatin and carboxymethyl cellulose possess high elasticity over 600-800% but lack strength [27,40]. Ceramic reinforced composites demonstrate a balanced profile of strength and extensibility through stress transfer. For example, chitosan-nano ZnO films stretched 200-300% at break, maintaining shape memory without compromising integrity [35]. Similarly, PVA-Al_2O_3 composites extended 150-200% prior to failure [38. Enhanced elasticity permits conformal adherence to irregular wound contours during dressing changes, reducing trauma. Stiffness, quantified as Young's modulus, impacts a dressing's flexibility. Typically, synthetic foams and hydrocolloids are quite stiff with moduli between 1-10 MPa [40].

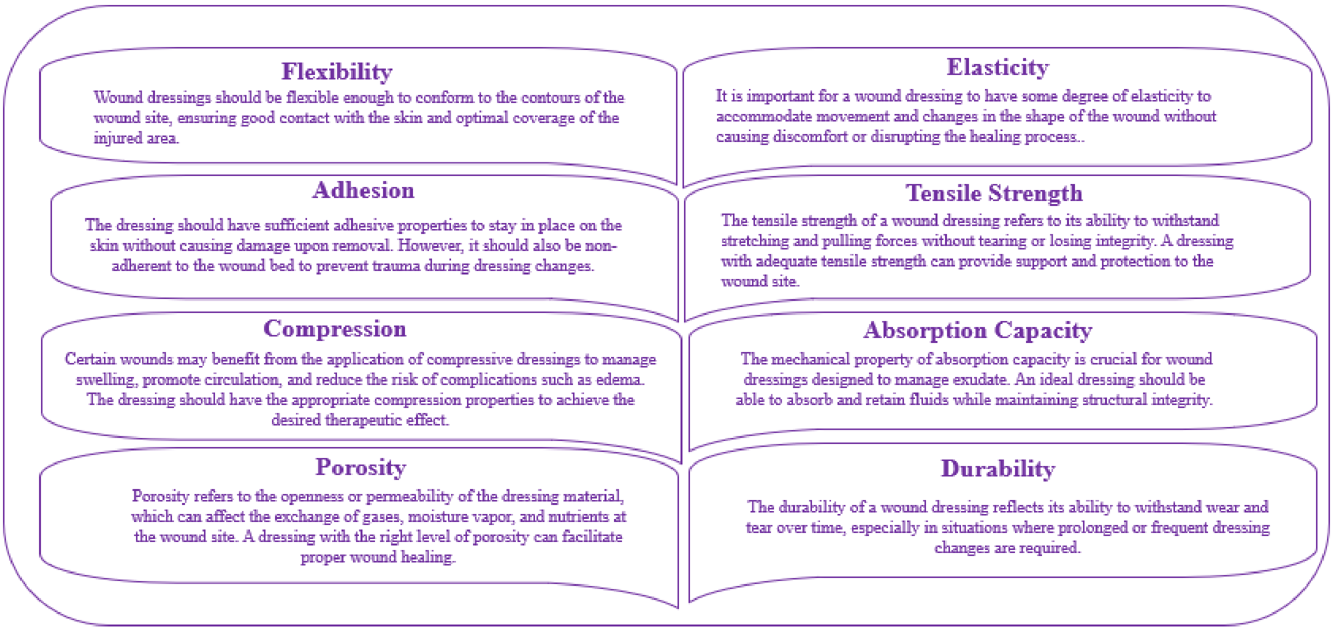

Fig.3. Mechanical properties of wound dressing

Ceramic fillers significantly reduce matrix stiffness by transferring stress. Polycaprolactone became more flexible, decreasing modulus from 0.5 GPa to 0.08 GPa upon HA reinforcement [40]. Improved elastic compliance permits dressings to conform closely without irritation during body movements.

6. Conclusion

Wound dressings are an essential component of wound care, helping to maintain a moist healing environment and protect wounds from infection. Traditional dressings often face limitations such as inadequate moisture retention, lack of antimicrobial properties, and low mechanical strength. Ceramic reinforced polymer composite dressings have emerged as a promising alternative to overcome these limitations. Ceramics like HA, Al_2O_3 and ZnO impart multifaceted benefits when incorporated into polymer matrices. This review analyzed the effects of ceramic reinforcement on key wound dressing properties. Research shows ceramic particles significantly enhance moisture absorption capacities, with composites achieving over 100 times their weight in fluid uptake. This endows dressings with superior moisture retention ability for prolonged wound hydration. Ceramic fillers also boost tensile strengths and elastic moduli, allowing dressings to withstand stresses during application and movement without tearing prematurely. Ceramic dressings exhibit potent antimicrobial activity from ion release, reducing the risk of wound infection. Studies demonstrate HA, Al_2O_3 and ZnO reinforced composites achieve over 90% bacterial inhibition. The combined effect of these enhanced properties supports optimal wound healing conditions. While offering distinct advantages, ceramic reinforced dressings also face challenges related to fabrication complexity and high material costs. Producing uniform distributions with minimal agglomeration demands optimization of synthesis techniques.

Availability of data and materials

The datasets supporting the conclusions of this study are included within the article.

Competing Interests Statement

The authors have declared that no competing interests exist.

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