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Chitosan/PVA/Moringa Leaf Extract Hybrid Hydrogel for Wound Healing Applications.

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ABSTRACT

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INTRODUCTION

Wound healing is a complex and highly regulated biological process involving overlapping phases of hemostasis, inflammation, proliferation, and tissue remodeling. Successful healing requires a coordinated interaction between inflammatory cells, fibroblasts, keratinocytes, endothelial cells, extracellular matrix components, and growth factors. However, chronic wounds, infections, excessive inflammation, and oxidative stress can interrupt this process, resulting in delayed healing and increased risk of complications. Therefore, the development of advanced wound dressings capable of maintaining a moist environment, preventing microbial contamination, and promoting tissue regeneration has become an important area of biomedical research. Hydrogels have emerged as one of the most promising biomaterials for wound management because of their high water content, excellent biocompatibility, flexibility, and ability to mimic the extracellular matrix. They provide an ideal moist environment that facilitates cell migration, angiogenesis, and tissue regeneration while reducing pain and minimizing wound dehydration (1,2).

Among the various polymers used in hydrogel fabrication, polyvinyl alcohol (PVA) is widely recognized for its excellent hydrophilicity, mechanical strength, chemical stability, and non-toxic nature. PVA-based hydrogels exhibit high swelling capacity and can absorb substantial amounts of wound exudate while maintaining structural integrity. Additionally, PVA forms stable polymeric networks that allow controlled and sustained drug release, making it an attractive component for wound dressing applications. Nevertheless, PVA alone possesses limited biological activity, necessitating its combination with naturally derived polymers and bioactive compounds to enhance its therapeutic effectiveness (2).

Chitosan, a naturally occurring polysaccharide obtained by the deacetylation of chitin, has gained significant attention in tissue engineering and wound care due to its remarkable biological properties. It demonstrates excellent biocompatibility, biodegradability, antimicrobial activity, and hemostatic potential. Furthermore, chitosan promotes fibroblast proliferation, collagen deposition, and cell adhesion, thereby accelerating tissue repair. The positively charged amino groups of chitosan also interact with negatively charged bacterial cell membranes, inhibiting microbial growth and reducing the risk of wound infection. These unique characteristics make chitosan an ideal natural polymer for incorporation into hydrogel systems intended for wound healing (3).

Moringa oleifera, commonly referred to as the “miracle tree,” is a medicinal plant extensively used in traditional medicine due to its broad spectrum of pharmacological activities. The leaves of Moringa oleifera are rich in biologically active phytochemicals, including flavonoids, polyphenols, phenolic acids, tannins, alkaloids, saponins, vitamins A, C, and E, and essential minerals. These compounds exhibit potent antioxidant, antimicrobial, anti-inflammatory, and wound healing properties. The antioxidant constituents effectively neutralize reactive oxygen species generated at the wound site, thereby reducing oxidative damage to surrounding tissues. Simultaneously, its anti-inflammatory activity suppresses the production of pro-inflammatory cytokines such as tumor necrosis factor-alpha (TNF-α), interleukin-1β (IL-1β), and interleukin-6 (IL-6), preventing prolonged inflammation that can delay tissue repair. Moreover, Moringa leaf extract has been reported to

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stimulate angiogenesis, enhance collagen synthesis, promote epithelialization, and improve fibroblast proliferation, collectively accelerating wound closure and improving the quality of regenerated tissue (4).

The integration of PVA, chitosan, and Moringa oleifera leaf extract into a hybrid hydrogel combines the mechanical stability of synthetic polymers with the biological functionality of natural materials. Such hybrid hydrogels are expected to exhibit superior swelling behavior, enhanced biocompatibility, sustained release of bioactive compounds, and improved antimicrobial and anti-inflammatory activities. These characteristics make them promising candidates for advanced wound dressings capable of accelerating tissue regeneration while minimizing infection and inflammation. Therefore, the present study aims to develop and evaluate a chitosan/PVA/Moringa oleifera leaf extract hybrid hydrogel for wound healing applications

MATERIALS AND METHODS

A hybrid hydrogel was developed by combining **0.1 g of Moringa oleifera leaf powder** dissolved in **10 mL of distilled water**, **10% polyvinyl alcohol (PVA)** solution, and **2% chitosan** solution. The mixture was stirred thoroughly to obtain a homogeneous blend, after which **2.5% glutaraldehyde (GLUT)** was added as a cross-linking agent to enhance the stability and mechanical strength of the hydrogel. The prepared hydrogel was then stored and **lyophilized (freeze-dried)** for further characterization.

The fabricated hydrogel was evaluated for its **swelling and absorption properties** by immersing it in **distilled water and phosphate-buffered saline (PBS)**. In addition, a **drug release study** was performed at different time intervals to determine its sustained release capability. These evaluations were carried out to assess the hydrogel's suitability as a wound dressing material with high absorption capacity and controlled release of bioactive compounds.

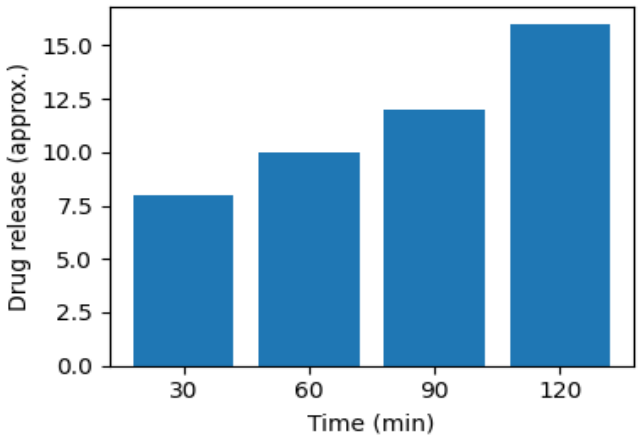
Results

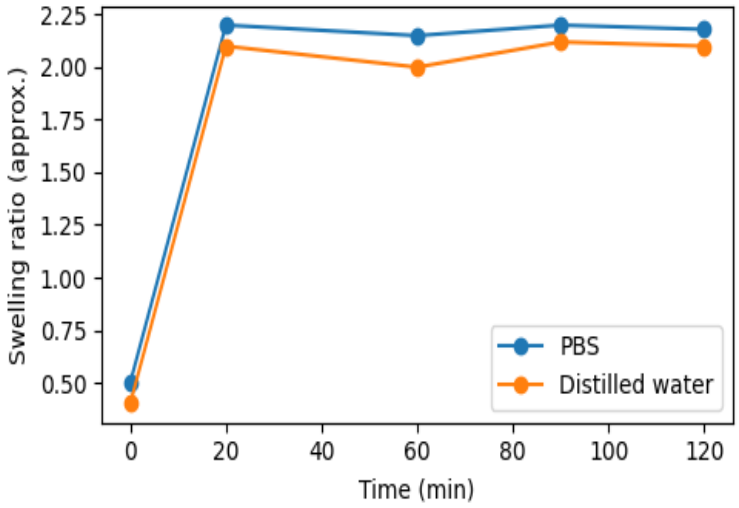
The developed **Chitosan/PVA/Moringa oleifera** hybrid hydrogel demonstrated favorable swelling and drug release characteristics, indicating its potential application as a wound dressing material.

The **swelling and absorption study** showed that the hydrogel exhibited good solvent uptake in both **distilled water** and **phosphate-buffered saline (PBS)**. The swelling capacity increased rapidly during the initial time period and gradually reached a plateau, suggesting that the hydrogel attained equilibrium after prolonged immersion. The hydrogel showed **greater absorption in PBS than in distilled water**, indicating improved swelling under physiological conditions. This enhanced swelling behavior is beneficial for wound healing, as it enables the hydrogel to absorb wound exudate while maintaining a moist environment that supports tissue regeneration.

The **drug release study** demonstrated a gradual increase in the release of the incorporated bioactive compounds over time. The release profile indicated a **controlled and sustained drug release pattern**, rather than an immediate burst release. Such sustained release can help maintain therapeutic concentrations of the bioactive compounds at the wound site for a longer duration, thereby enhancing antimicrobial, antioxidant, and anti-inflammatory effects while reducing the need for frequent dressing changes.

Overall, the results suggest that the fabricated hydrogel possesses **high swelling capacity, excellent fluid absorption, and sustained drug release properties**, making it a promising biomaterial for wound healing applications.





DISSCUSION

Hydrogels have emerged as one of the most promising biomaterials for wound management owing to their high water content, excellent biocompatibility, flexibility, and ability to provide a moist environment that closely resembles the natural extracellular matrix. An ideal wound dressing should protect the wound from microbial contamination, absorb excess exudate, maintain adequate moisture, and facilitate tissue regeneration. The Chitosan/PVA/*Moringa oleifera* hybrid hydrogel developed in the present study demonstrated favorable swelling and sustained drug release characteristics, suggesting its suitability as an advanced wound dressing. The high swelling capacity observed in phosphate-buffered saline (PBS) indicates that the hydrogel can efficiently absorb wound exudate while maintaining a hydrated environment, which is essential for promoting fibroblast proliferation, epithelialization, and collagen synthesis. Furthermore, the controlled drug release profile indicates that the hydrogel can continuously deliver bioactive compounds to the wound site, thereby prolonging their therapeutic effect and reducing the frequency of dressing replacement (1,2).

The incorporation of **polyvinyl alcohol (PVA)** provides the hydrogel with excellent mechanical strength, flexibility, and hydrophilicity, while **chitosan** enhances its biological performance through its biodegradability, hemostatic activity, and antimicrobial properties. Chitosan possesses positively charged amino groups that interact with negatively charged bacterial cell membranes, resulting in disruption of bacterial growth and reduced wound infection. In addition, chitosan promotes fibroblast migration, collagen deposition, and cell adhesion, all of which are essential processes during tissue repair. The synergistic interaction between PVA and chitosan creates a stable polymeric network capable of maintaining structural integrity while allowing efficient swelling and sustained release of therapeutic agents. Similar findings have been reported by Ahmed and co-workers, who demonstrated that chitosan-based hydrogels exhibit superior biocompatibility, enhanced water absorption, and improved wound healing efficiency due to their unique physicochemical properties (3).

Moringa oleifera leaf extract serves as the bioactive component of the developed hydrogel and significantly contributes to its therapeutic potential. The leaves contain abundant phytochemicals including flavonoids, polyphenols, tannins, alkaloids, vitamins, and phenolic acids that possess potent antioxidant and anti-inflammatory activities. During wound healing, excessive production of reactive oxygen species can damage newly formed tissues and delay regeneration. The antioxidant compounds present in *Moringa oleifera* neutralize these free radicals, thereby minimizing oxidative stress and protecting regenerating tissues. In addition, flavonoids and polyphenols suppress the release of inflammatory mediators such as tumor necrosis factor-alpha (TNF-α), interleukin-1β, and interleukin-6, preventing prolonged inflammation that can impair normal wound healing. These mechanisms collectively accelerate tissue regeneration and improve wound closure (4).

Another important property of *Moringa oleifera* is its ability to stimulate **angiogenesis**, the formation of new blood vessels within the wound bed. Angiogenesis plays a critical role during the proliferative phase of wound healing by increasing oxygen and nutrient supply to regenerating tissues. Improved vascularization enhances fibroblast proliferation, collagen maturation, extracellular matrix deposition, and epithelial cell migration, thereby accelerating wound closure. The sustained release of *Moringa* phytochemicals from the hydrogel matrix may provide continuous stimulation of these regenerative processes, contributing to improved tissue repair and functional recovery (5).

The antimicrobial activity of *Moringa oleifera* further enhances the clinical potential of the developed hydrogel. Wound infections remain one of the major causes of delayed healing and chronic wound formation. Bioactive constituents such as

flavonoids, isothiocyanates, phenolic compounds, and tannins exhibit broad-spectrum antibacterial activity against both Gram-positive and Gram-negative microorganisms. In a study conducted by **Liliya et al.**, the authors reported that the phytochemicals present in *Moringa oleifera* leaves demonstrated significant antimicrobial activity against a wide range of pathogenic bacteria, supporting their application in wound management. Incorporating these bioactive compounds into a hydrogel system enables localized and sustained antimicrobial action, thereby reducing microbial colonization while minimizing the adverse effects associated with systemic antibiotic therapy (6).

The results obtained in the present study correlate well with previous investigations evaluating natural polymer-based hydrogels for wound healing. The higher swelling capacity observed in PBS indicates that the hydrogel can function effectively under physiological conditions by absorbing wound exudate without losing its structural stability. Similarly, the sustained drug release profile suggests prolonged availability of bioactive compounds at the wound site, which may reduce repeated drug administration and improve patient compliance. The combination of synthetic polymers with natural biomaterials and medicinal plant extracts has been increasingly recognized as an effective strategy for developing multifunctional wound dressings. Therefore, the Chitosan/PVA/*Moringa oleifera* hybrid hydrogel developed in this study demonstrates considerable promise as a biodegradable wound dressing with enhanced absorption, controlled drug release, antioxidant, anti-inflammatory, and antimicrobial properties that collectively support accelerated wound healing.

CONCLUSION

The developed **Chitosan/PVA/Moringa oleifera** hybrid hydrogel demonstrated excellent swelling capacity, good solvent absorption, and sustained drug release properties. The incorporation of *Moringa oleifera* leaf extract, together with PVA and chitosan, enhanced the hydrogel's potential as a biocompatible wound dressing. Overall, the formulated hydrogel shows promising effectiveness for wound healing applications by providing a moist environment, controlled release of bioactive compounds, and supporting tissue regeneration.

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