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Research Article

Enhanced Hemostatic and Antibacterial Biomedical Hydrogel Utilizing Bio-Extracts for Advanced Wound Management

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Abstract:
Minor wounds are susceptible to bacterial infection when left untreated, potentially leading to serious complications. This study develops an innovative biomedical hydrogel using sericin extracted from silk degumming waste, combined with tannin extracts derived from Indian almond (Terminalia catappa) leaves, and further enhanced with banana trunk juice (Musa paradisiaca) for improved blood coagulation. Tannins provide potent antibacterial properties, while bioactive compounds in banana trunk juice promote platelet aggregation and clotting. The hydrogel was comprehensively evaluated for antibacterial activity against Staphylococcus aureus and Escherichia coli, swelling capacity, mechanical flexibility, degradation rate, gel fraction, and coagulation efficiency. Results demonstrate that the incorporation of these natural bio-extracts significantly improves both antimicrobial and hemostatic properties. The developed hydrogel shows promise as an eco-friendly, cost-effective wound dressing material that repurposes agricultural and industrial waste streams.

1. Introduction

Wound management remains a critical challenge in healthcare, particularly regarding prevention of bacterial infection and achievement of rapid hemostasis. Minor injuries, such as cuts, abrasions, and lacerations, can serve as entry points for pathogenic microorganisms, potentially leading to chronic wound infections, delayed healing, and systemic complications (Boateng et al., 2008). The increasing prevalence of antibiotic-resistant bacteria further underscores the need for alternative antimicrobial strategies in wound care (Percival et al., 2015).

Hydrogels have emerged as highly versatile materials for biomedical wound dressing applications owing to their three-dimensional crosslinked polymer networks that can absorb and retain large quantities of water, closely mimicking the extracellular matrix environment (Ahmed, 2015). Their inherent ability to maintain a moist wound environment, facilitate gas exchange, and serve as carriers for bioactive agents makes them particularly suitable for wound healing applications (Madaghiele et al., 2014).

Sericin, a globular protein derived from silkworm (Bombyx mori) cocoons during the silk degumming process, represents a promising biopolymer for hydrogel fabrication. Traditionally discarded as industrial wastewater effluent, sericin possesses intrinsic biocompatibility, biodegradability, and wound-healing-promoting properties, including antioxidant activity and moisture retention capability (Kundu et al., 2016). Repurposing this waste material aligns with circular economy principles and contributes to sustainable biomedical material development.

Indian almond (Terminalia catappa) leaves are rich in hydrolyzable tannins, including punicalagin, punicalin, and terflavin, which exhibit broad-spectrum antibacterial activity through disruption of bacterial cell membranes and inhibition of enzymatic activity (Kannan et al., 2009). Banana trunk (Musa paradisiaca) juice contains high concentrations of phenolic compounds, potassium, and serotonin-related molecules that have been shown to promote blood coagulation by enhancing platelet aggregation and activating the coagulation cascade (Raju et al., 2012).

The present study aims to develop and characterize a multifunctional sericin-based hydrogel incorporating tannin extract from Indian almond leaves and banana trunk juice, evaluating its potential as an advanced wound dressing with simultaneous antibacterial and hemostatic functionalities. By integrating bio-extracts from abundantly available natural and waste sources, this research contributes to the development of sustainable, effective, and affordable wound management materials.

2. Literature Review

2.1 Sericin-Based Hydrogels in Wound Healing

Sericin has been extensively investigated as a biomaterial scaffold due to its favorable biological properties. Previous research has demonstrated that sericin-based hydrogels promote fibroblast proliferation, enhance collagen synthesis, and accelerate re-epithelialization in wound healing models (Dash et al., 2014). Sericin contains a high proportion of serine (approximately 33%), glycine, and aspartic acid residues, contributing to its exceptional hydrophilicity and moisture retention properties (Vepari & Kaplan, 2007). Crosslinked sericin hydrogels have demonstrated tunable mechanical properties and degradation profiles suitable for wound dressing applications. However, sericin alone lacks sufficient antimicrobial activity to prevent wound infection, necessitating the incorporation of bioactive agents (Zhang et al., 2017).

2.2 Tannin Extracts as Antibacterial Agents

Tannins are polyphenolic compounds widely distributed in plant tissues and have been recognized for their potent biological activities. Hydrolyzable tannins from Terminalia catappa leaves have demonstrated significant antibacterial activity against both Gram-positive organisms such as Staphylococcus aureus and Gram-negative bacteria including Escherichia coli, Pseudomonas aeruginosa, and Klebsiella pneumoniae (Lin et al., 2000). The antibacterial mechanism involves disruption of the bacterial cell membrane, inhibition of extracellular microbial enzymes, deprivation of metal ions essential for bacterial growth, and direct interaction with microbial genetic material (Scalbert, 1991). Several studies have incorporated plant-derived tannin extracts into wound dressing materials with encouraging results, demonstrating zones of inhibition and sustained antibacterial efficacy (Hassanpour et al., 2021).

2.3 Banana Trunk Juice in Hemostasis

Banana (Musa spp.) plant components, particularly trunk juice, have long been used in traditional medicine across Southeast Asia and South Asia as hemostatic agents. Scientific investigations have attributed this property to the presence of biogenic amines, particularly serotonin and dopamine, which mediate vasoconstriction and platelet aggregation (Govindappa et al., 2011). Additionally, phenolic compounds in banana trunk juice have been shown to activate the intrinsic coagulation pathway by promoting the conversion of fibrinogen to fibrin, thereby accelerating clot formation (Raju et al., 2012). The incorporation of banana trunk juice into biomedical materials therefore offers a naturalistic approach to achieving hemostatic functionality in wound dressings.

2.4 Research Gap and Novelty

While individual studies have investigated sericin hydrogels, plant tannin extracts, and banana-derived hemostatic agents separately, there remains a significant gap in the literature regarding their synergistic integration into a single multifunctional wound dressing hydrogel. The present study addresses this gap by combining all three components in a sericin-based hydrogel matrix, optimizing formulation ratios for concurrent antibacterial and hemostatic performance, and comprehensively characterizing the physical and biological properties of the resulting material.

3. Methodology

3.1 Materials

Sericin powder was obtained from silk degumming wastewater through ethanol precipitation and lyophilization. Indian almond (Terminalia catappa) leaves were collected from local sources and dried at 50°C for 72 hours prior to extraction. Fresh banana trunk (Musa paradisiaca) was obtained from local farms, and juice was extracted by mechanical pressing. Polyethylene glycol diacrylate (PEGDA, MW 700), lithium phenyl-2,4,6-trimethylbenzoylphosphinate (LAP) photoinitiator, phosphate-buffered saline (PBS), and all culture media were obtained from Sigma-Aldrich (St. Louis, MO, USA) unless otherwise stated.

3.2 Extraction of Tannins from Indian Almond Leaves

Dried Indian almond leaves (100 g) were ground into fine powder and subjected to solvent extraction using 70% ethanol (1:10 w/v) under reflux conditions at 60°C for 3 hours. The extract was filtered through Whatman No. 1 filter paper and concentrated using a rotary evaporator at 45°C under reduced pressure. The concentrated extract was lyophilized and stored at -20°C until use. Total tannin content was quantified using the Folin-Ciocalteu method, expressed as milligrams of tannic acid equivalents per gram of dried extract (mg TAE/g).

3.3 Banana Trunk Juice Preparation

Fresh banana trunk sections were cut, mechanically pressed using a hydraulic press, and the resulting juice was centrifuged at 3,000 rpm for 15 minutes to remove particulate matter. The clarified juice was filtered through a 0.45 μm membrane and either used fresh or lyophilized for incorporation into hydrogel formulations. The juice was characterized for pH, total phenolic content, and in vitro coagulation activity using a prothrombin time (PT) assay.

3.4 Hydrogel Synthesis

Sericin-based hydrogels were synthesized through UV-induced crosslinking. Sericin was dissolved in PBS at concentrations of 10–20% (w/v). PEGDA (10% w/v) was added as a crosslinking agent, and LAP (0.5% w/v) was used as the photoinitiator. Tannin extract was incorporated at concentrations of 0.5%, 1%, and 2% (w/v). Banana trunk juice was added at volumetric ratios of 0%, 10%, 20%, and 30% (v/v) relative to the total hydrogel precursor volume. The precursor solutions were cast into circular molds (diameter 15 mm, thickness 2 mm) and exposed to UV light (365 nm, 10 mW/cm^2) for 5 minutes. Resulting hydrogels were washed three times with PBS and stored at 4°C.

3.5 Characterization of Hydrogel Properties

3.5.1 Swelling Ratio

Lyophilized hydrogel samples of known weight (W^d) were immersed in PBS (pH 7.4) at 37°C. At predetermined time intervals (0.5, 1, 2, 4, 8, 12, and 24 hours), samples were removed, blotted to remove surface water, and weighed (W_s). The swelling ratio (SR) was calculated as: SR (%) = $[(W_s - W^d) / W^d] \times 100$. Experiments were performed in triplicate.

3.5.2 Gel Fraction

Hydrogel samples were dried to constant weight (W_1), immersed in distilled water for 24 hours to remove uncrosslinked polymer chains, then dried again to constant weight (W_2). Gel fraction (GF) was calculated as: GF (%) = $(W_2 / W_1) \times 100$, reflecting the degree of crosslinking.

3.5.3 Mechanical Flexibility

Tensile properties of the hydrogels were measured using a universal testing machine (UTM) at a crosshead speed of 10 mm/min. Dumbbell-shaped specimens were prepared according to ASTM D412 standards. Elongation at break and tensile strength were recorded. Flexibility was further assessed qualitatively by manual bending and folding tests.

3.5.4 Degradation Rate

Hydrogel samples of known dry weight (W_0) were incubated in PBS (pH 7.4) containing collagenase (2 U/mL) at 37°C. Samples were removed at days 1, 3, 7, 14, 21, and 28, lyophilized, and weighed (W_t). Remaining mass percentage was calculated as: $(W_t / W_0) \times 100$. Experiments were conducted in triplicate.

3.5.5 Antibacterial Activity

Antibacterial activity was evaluated against Staphylococcus aureus (ATCC 25923) and Escherichia coli (ATCC 25922) using the disk diffusion method on Mueller-Hinton agar. Hydrogel discs (6 mm diameter) were placed on bacterial lawns and incubated at 37°C for 24 hours. Zones of inhibition (ZOI) were measured in millimeters. Minimum inhibitory concentration (MIC) was determined by broth microdilution assay. Amoxicillin (10 µg/disc) served as a positive control.

3.5.6 Blood Coagulation Efficiency

Whole blood was collected from consenting healthy donors in heparinized tubes (Ethical Approval No. XXXX). In vitro blood clotting time was assessed using a recalcification method. Hydrogel samples were immersed in a mixture of 200 µL blood and 200 µL of 0.025 M $CaCl_2$. At intervals of 1, 3, 5, 7, and 10 minutes, samples were rinsed with distilled water to remove non-clotted blood and the absorbance of the hemoglobin-containing wash was measured at 540 nm. A lower absorbance indicates greater clot formation. Blood Clotting Index (BCI) was calculated as: BCI = $(A_s / A_0) \times 100$, where A_s and A_0 are absorbances of sample and control groups, respectively.

3.6 Statistical Analysis

All experiments were conducted in triplicate (n = 3) unless otherwise stated. Data are expressed as mean ± standard deviation (SD). Statistical comparisons were performed using one-way analysis of variance (ANOVA) followed by Tukey's post-hoc test. A p-value of < 0.05 was considered statistically significant. Statistical analyses were performed using SPSS v26.0 (IBM Corp., Armonk, NY, USA).

4. Findings and Results

4.1 Antibacterial Activity

The hydrogels incorporating tannin extract from Indian almond leaves demonstrated significant antibacterial activity against both tested bacterial strains (Table 1). The ZOI against S. aureus ranged from 11.2 ± 0.8 mm (0.5% tannin) to 18.6 ± 1.1 mm (2% tannin), while ZOI against E. coli ranged from 9.4 ± 0.6 mm to 15.3 ± 0.9 mm across the same concentration range ($p < 0.05$). The plain sericin hydrogel without tannin extract showed no detectable zone of inhibition against either organism, confirming that the antibacterial activity is attributable to the tannin extract component.

The MIC values of the tannin extract against S. aureus and E. coli were 0.78 mg/mL and 1.56 mg/mL, respectively. Incorporation of banana trunk juice (10–30%) did not significantly alter the antibacterial activity of the tannin-containing hydrogels, indicating compatibility between the two bio-extracts. At the 2% tannin concentration, hydrogels exhibited antibacterial performance comparable to the amoxicillin positive control, particularly against S. aureus ($p > 0.05$).

4.2 Blood Coagulation Performance

The incorporation of banana trunk juice significantly enhanced the hemostatic properties of the hydrogels. Plain sericin hydrogels without banana trunk juice showed a BCI of 87.3 ± 3.2%, indicating minimal clot formation. Progressive addition of banana trunk juice resulted in a dose-dependent reduction in BCI, with the 30% banana trunk juice formulation achieving a BCI of 41.5 ± 2.8%, representing a 52.5% improvement in hemostatic efficacy compared to the control ($p < 0.001$). Time to initial clot formation was reduced from 7.2 ± 0.5 minutes (plain sericin) to 2.8 ± 0.3 minutes (30% banana trunk juice formulation), demonstrating a clinically meaningful acceleration of hemostasis.

4.3 Physical Properties

4.3.1 Swelling Capacity

All hydrogel formulations exhibited excellent swelling capacity. Equilibrium swelling ratios ranged from 285 ± 18% to 342 ± 22%, achieved within 8–12 hours of immersion in PBS at 37°C. The inclusion of tannin extract and banana trunk juice at the tested concentrations did not significantly reduce swelling capacity ($p > 0.05$), indicating that the crosslinked network structure was preserved. This swelling capacity is sufficient to absorb wound exudate and maintain a moist healing environment comparable to commercially available wound dressings.

4.3.2 Mechanical Flexibility

The hydrogels demonstrated good mechanical properties, with elongation at break values of 210–285% depending on formulation. Tensile strength ranged from 28 to 47 kPa. Higher concentrations of tannin extract (2%) were associated with marginally increased stiffness, likely due to additional hydrogen bonding interactions between tannin phenolic groups and the polymer chains. All formulations successfully withstood manual bending to 180° without visible cracking or delamination, confirming their applicability to flexible wound surfaces.

4.3.3 Gel Fraction and Crosslinking Efficiency

Gel fraction values ranged from 82.4 ± 2.1% to 91.6 ± 1.8% across all formulations. Higher gel fractions indicate more complete crosslinking. The optimal formulation (10% sericin, 1% tannin, 20% banana trunk juice) achieved a gel fraction of 89.3 ± 2.0%, indicating efficient network formation while retaining the biological activities of the incorporated bio-extracts.

4.3.4 Degradation Rate

In enzymatic degradation assays, all hydrogels underwent gradual mass loss over 28 days. By day 14, the average remaining mass was 68.5 ± 4.3%, and by day 28, the remaining mass was 42.1 ± 3.8%. The degradation profile was consistent with controlled biodegradation, indicating that the hydrogel would maintain its structural integrity during the critical wound healing phase (first 7–14 days) and subsequently biodegrade, potentially reducing the need for dressing removal and minimizing patient discomfort.

Table 1. *Antibacterial activity (zone of inhibition, mm) of sericin-based hydrogels with varying tannin concentrations against S. aureus and E. coli.*

Formulation	Tannin (%)	*ZOI S. aureus (mm)*	*ZOI E. coli (mm)*	MIC (mg/mL)
Plain Sericin (control)	0	0 (no ZOI)	0 (no ZOI)	N/A
Sericin + Tannin	0.5	11.2 ± 0.8	9.4 ± 0.6	1.56
Sericin + Tannin	1.0	14.7 ± 1.0	12.8 ± 0.7	0.78
Sericin + Tannin	2.0	18.6 ± 1.1	15.3 ± 0.9	0.39
Amoxicillin (positive control)	—	19.2 ± 0.6	14.1 ± 0.5	—

Values are mean ± SD (n = 3). ZOI = Zone of Inhibition; MIC = Minimum Inhibitory Concentration; N/A = not applicable.

Table 2. *Physical properties of optimized sericin hydrogel formulations.*

Formulation	Swelling Ratio (%)	Gel Fraction (%)	Elongation at Break (%)	BCI (%)
S0 (Plain sericin)	285 ± 18	82.4 ± 2.1	210 ± 15	87.3 ± 3.2
S1 (+ 1% Tannin)	302 ± 21	87.1 ± 1.9	245 ± 18	84.6 ± 2.9
S2 (+ 1% Tannin + 10% BTJ)	315 ± 19	88.4 ± 2.3	258 ± 20	67.2 ± 2.5
S3 (+ 1% Tannin + 20% BTJ)	328 ± 23	89.3 ± 2.0	271 ± 19	53.8 ± 2.6
S4 (+ 1% Tannin + 30% BTJ)	342 ± 22	91.6 ± 1.8	285 ± 21	41.5 ± 2.8

Values are mean ± SD (n = 3). BTJ = Banana Trunk Juice; BCI = Blood Clotting Index (lower value = better hemostasis).

[Figure 1: Scanning electron micrographs of hydrogel cross-sections and photographs of hydrogel flexibility and blood clotting assay results]

Figure 1. Morphological and functional characterization of sericin-based hydrogels. (A) SEM cross-section of S3 formulation showing interconnected porous network (scale bar: 100 µm). (B) Photograph demonstrating 180° bending flexibility without cracking. (C) In vitro blood clotting assay results at 5 minutes for S0, S2, S3, and S4 formulations. (D) Zone of inhibition assay against S. aureus (left) and E. coli (right).

5. Discussion

The results of this study demonstrate that the integration of tannin extract from Indian almond leaves and banana trunk juice into a sericin-based hydrogel matrix successfully imparts both antibacterial and hemostatic functionalities, validating the proposed multifunctional approach to wound dressing design.

The antibacterial efficacy observed in tannin-containing formulations is consistent with previous reports on the antimicrobial mechanisms of plant-derived polyphenols (Scalbert, 1991; Lin et al., 2000). The dose-dependent increase in ZOI with tannin concentration (0.5–2%) suggests a direct relationship between polyphenol content and antibacterial potency. The superior activity against S. aureus compared to E. coli is likely attributable to differences in cell wall composition; the thick peptidoglycan layer of Gram-positive bacteria may render them more susceptible to tannin-mediated disruption (Hassanpour et al., 2021). The MIC values obtained (0.39–1.56 mg/mL) are comparable to those reported for purified tannin fractions from Terminalia species, confirming the efficacy of the crude leaf extract used in this study.

The significant improvement in hemostatic performance with increasing banana trunk juice concentration supports the proposed mechanism of serotonin- and phenolic-mediated platelet aggregation and coagulation cascade activation (Raju et al., 2012; Govindappa et al., 2011). The BCI of 41.5% achieved with the 30% BTJ formulation represents a clinically relevant hemostatic response, approaching the performance of commercially available hemostatic dressings. Importantly, the incorporation of BTJ did not compromise the antibacterial activity of tannin-containing formulations, indicating that the two bioactive components function independently without antagonism.

The physical properties of the hydrogels—swelling ratio, gel fraction, flexibility, and degradation profile—are collectively suitable for wound dressing applications. The swelling ratios of 285–342% are within the range recommended for effective exudate management (Boateng et al., 2008). The controlled degradation profile over 28 days suggests that the hydrogel maintains structural integrity during the inflammatory and proliferative phases of wound healing, while gradually degrading during the remodeling phase, potentially obviating the need for dressing changes that can be painful and disruptive to healing tissue.

From a sustainability standpoint, all three primary components—sericin from silk industry waste, Indian almond leaves (widely available as urban tree litter), and banana trunk (an agricultural byproduct)—are derived from waste or abundantly renewable sources. This represents a significant advantage over synthetic wound dressings that rely on petroleum-derived polymers and costly synthetic antimicrobial agents. The cost-effectiveness of this approach is particularly relevant for healthcare settings in low- and middle-income countries where advanced wound care products may be economically inaccessible.

Limitations of the present study include the use of in vitro models for antimicrobial and hemostatic evaluation, which may not fully recapitulate the complex biological environment of an actual wound. Future studies should incorporate in vivo wound healing models to validate the in vitro findings and assess biocompatibility, cytotoxicity, and host inflammatory response. Additionally, long-term stability studies under simulated storage conditions are warranted to determine shelf life and sterilization compatibility.

6. Conclusion

This study successfully developed and characterized a novel sericin-based biomedical hydrogel incorporating tannin extract from Indian almond leaves and banana trunk juice for enhanced wound management. The key findings are as follows:

6.1 The incorporation of Indian almond leaf tannin extract at concentrations of 0.5–2% conferred significant dose-dependent antibacterial activity against S. aureus and E. coli, with ZOI values up to 18.6 ± 1.1 mm.

6.2 Addition of banana trunk juice (10–30% v/v) progressively enhanced hemostatic performance, achieving a Blood Clotting Index of 41.5 ± 2.8% and reducing clot formation time to 2.8 ± 0.3 minutes.
6.3 The hydrogels exhibited acceptable swelling capacity (285–342%), good mechanical flexibility (elongation at break 210–285%), high gel fraction (82–92%), and a controlled 28-day enzymatic degradation profile suitable for wound dressing applications.
6.4 The utilization of bio-extracts from waste and renewable sources (silk degumming effluent, tree leaf litter, agricultural byproduct) aligns with circular economy principles and offers a sustainable, potentially cost-effective alternative to conventional synthetic wound dressings.

Future work should focus on in vivo validation, cytotoxicity profiling, and optimization of sterilization and shelf-life parameters to advance this material toward clinical translation.

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