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RESEARCH ARTICLE

Development and Optimization of Medicated Banana Fiber Sutures Using Natural Antimicrobial Agents

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Abstract: The aim of this research work was to develop biodegradable medicated sutures from banana fibers, using natural antimicrobial agents including Aloe vera, Neem, and Turmeric. A Central Composite Design was used to evaluate four critical parameters: extract concentration, coating duration, drying temperature, and extract solution pH. The optimization process identified optimal conditions at 3% extract concentration, 30 minutes coating time, 40°C drying temperature, and pH 6, yielding maximum biological performance. The evaluation of antimicrobial activity showed significant inhibition zones against *Staphylococcus aureus* (18.58 mm) and *Candida albicans* (17.88 mm). The quadratic model showed high statistical significance with an R^2 value of 0.9511, confirming robust experimental design. The formulated sutures exhibited enhanced tensile strength, controlled drug release, and appropriate biodegradation rates. FTIR studies confirmed successful coating of the natural extracts on the banana fibers. The optimized sutures demonstrated significant antimicrobial, anti-inflammatory, and antioxidant properties, making them suitable for cosmetic and minor surgical procedures. The study establishes a promising approach for developing sustainable, biocompatible sutures with improved wound-healing properties using natural materials and bioactive compounds.

Keywords: Banana fiber; Sutures; Natural antimicrobials; Design of Experiments; Biodegradable materials; Wound healing

1. Introduction

Surgical sutures remain fundamental tools in wound closure and tissue approximation, with their evolution continually driven by the need for improved biocompatibility and therapeutic benefits [1]. Traditional synthetic sutures, while effective, often present limitations including inflammatory responses, bacterial colonization, and environmental concerns regarding biodegradability [2]. The emergence of naturally derived suture materials represents a significant advancement in addressing these challenges [3].

Banana fiber, obtained from the pseudostem of Musa species, has gained attention due to its inherent properties including high tensile strength, biodegradability, and cost-effectiveness [4]. These fibers possess unique structural characteristics that make them suitable for medical applications, particularly in the development of surgical sutures [5].

The incorporation of natural antimicrobial agents into suture materials presents an innovative approach to prevent surgical site infections. Aloe vera, Neem (*Azadirachta indica*), and Turmeric (*Curcuma longa*) have been extensively documented for their therapeutic properties [6]. Aloe vera contains bioactive compounds including anthraquinones and acemannan, which exhibit significant antimicrobial and wound-healing properties [7]. Neem's azadirachtin and nimbin components provide broad-spectrum antimicrobial activity [8]. Turmeric's active component, curcumin, demonstrates potent anti-inflammatory and antioxidant effects [9].

The optimization of suture formulation parameters significantly influences their performance characteristics. Design of Experiments (DoE) methodology enables systematic evaluation of multiple variables and their interactions, ensuring robust product development [10]. Central Composite Design (CCD), specifically, allows for efficient optimization of process parameters while minimizing experimental runs [11].

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The aim of this present study was to develop and optimize medicated banana fiber sutures using natural antimicrobial agents through DoE methodology. The research focused on establishing optimal conditions for extract concentration, coating time, drying temperature, and pH while evaluating critical quality attributes including tensile strength, drug release kinetics, antimicrobial efficacy, and biodegradation rate [12]

2. Materials and Methods

2.1. Materials

Banana fibers were harvested from the pseudostem of Musa acuminata plants sourced from local agricultural fields [13]. Fresh Aloe vera leaves were collected from certified cultivation centers. Neem leaves (*Azadirachta indica*) and Turmeric rhizomes (*Curcuma longa*) were procured from authenticated suppliers and verified for quality standards [14]. All chemicals including sodium hydroxide, sodium carbonate, and phosphate buffer saline were of analytical grade (Merck Chemicals, Mumbai).

2.2. Microbial Strains

The antimicrobial assessment utilized standard strains of *Staphylococcus aureus* (ATCC 25923) and *Candida albicans* (ATCC 10231), obtained from the American Type Culture Collection [15].

2.3. Methods

2.3.1. Experimental Design

The optimization process employed a Central Composite Design comprising 30 experimental runs. Four independent variables were evaluated: extract concentration (ranging from 1-5% w/v), coating time (15-45 minutes), drying temperature (30-50°C), and pH of extract solution (4-8) [16]. The design matrix was generated using Design Expert software (Version 13.0), incorporating factorial points, axial points, and center points to ensure adequate model estimation.

Table 1. Central Composite Design Matrix with Independent Variables and Their Levels

Variables	**-2**	**-1**	**0**	**+1**	**+2**
Extract concentration (% w/v)	1.0	2.0	3.0	4.0	5.0
Coating time (min)	15	22.5	30	37.5	45
Drying temperature (°C)	30	35	40	45	50
pH of extract solution	4.0	5.0	6.0	7.0	8.0

2.4. Fiber Processing and Suture Preparation

2.4.1. Fiber Pre-treatment

The pre-treatment protocol began with thorough cleaning of raw banana fibers using deionized water to remove surface contaminants [17]. The cleaned fibers underwent chemical treatment in a solution containing 5% w/v sodium hydroxide and 2% w/v sodium carbonate for 24 hours at ambient temperature. Following chemical treatment, the fibers were subjected to ultrasonic treatment at 45°C for 15 minutes to enhance surface properties [18]. The processed fibers were dried under controlled conditions at 40°C until constant weight was achieved.

Figure 1. Prepared Sutures treated with Aloe vera, Neem and Curcumin (left to right)

2.4.2. Extract Preparation

Natural extract preparation followed standardized protocols optimized for maximum bioactive component extraction [19]. Aloe vera gel extraction involved careful separation from leaf parenchyma, followed by homogenization and filtration. Neem leaf extraction utilized an aqueous extraction method at controlled temperature. Turmeric rhizome processing incorporated ethanol extraction following established pharmacopoeial standards [20].

2.4.3. Coating

The pre-treated fibers underwent a systematic coating process developed through preliminary optimization studies [21]. The process involved immersion coating in prepared extract solutions under controlled conditions. Ultrasonic treatment ensured uniform distribution of the coating material throughout the fiber structure. The coated fibers were dried at optimized temperature conditions determined through the experimental design. Final sterilization was achieved through autoclaving at 121°C, 15 psi for 15-20 minutes [22].

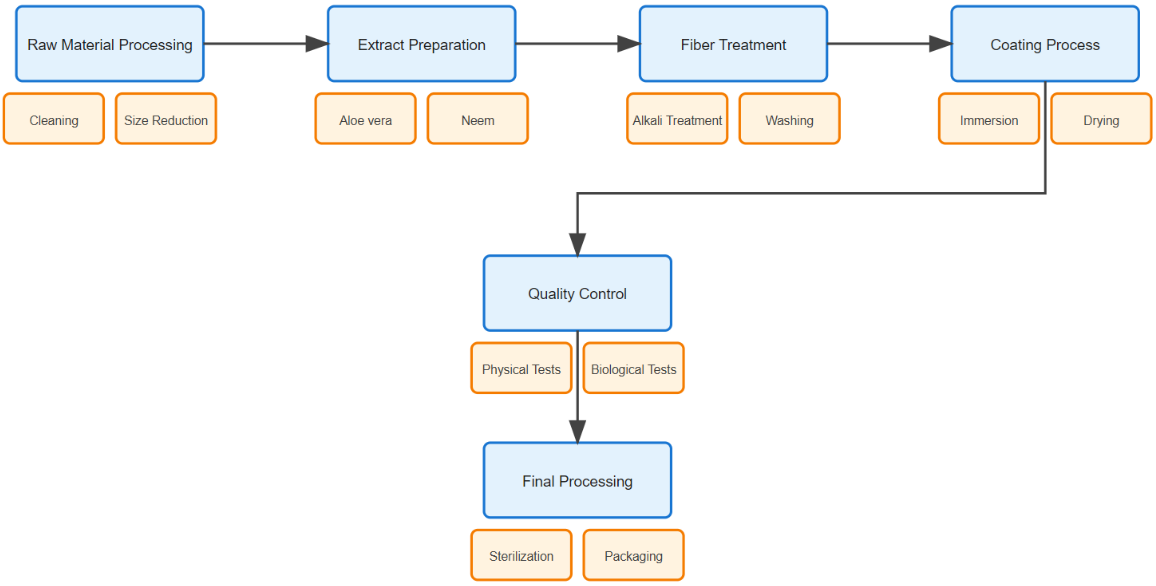

Figure 2. Process for Production of Medicated Banana Fiber Suture

2.5. Characterization

2.5.1. Physical Characterization

Tensile strength measurements were conducted using a universal testing machine following ASTM standards [23]. FTIR spectroscopy analysis confirmed the presence and chemical composition of the applied coatings [24].

2.5.2. Biological Evaluation

Antimicrobial activity was assessed using standard zone of inhibition methodology against selected pathogens [25]. Drug release studies were conducted in phosphate buffer (pH 7.4) using UV spectrophotometry. Biodegradation studies evaluated weight loss and structural integrity over time. Cytotoxicity evaluation employed MTT assay using L929 fibroblast cell lines following ISO 10993-5 guidelines [26].

2.5.3. Statistical Analysis

Statistical analysis of experimental data was carried out by using Design Expert software (Version 13.0). Analysis of variance determined the significance of the model and individual parameters at $p < 0.05$. Response surface methodology generated mathematical models for optimization of formulation parameters [27].

3. Results and Discussion

3.1. Evaluation of Statistical Model

The quadratic model demonstrated high statistical significance with an F-value of 20.85 ($p < 0.0001$), indicating only a 0.01% chance that this F-value occurred due to noise [28]. The model achieved an R^2 value of 0.9511, demonstrating excellent correlation between experimental and predicted values. The adjusted R^2 (0.9055) and predicted R^2 (0.7056) values indicated good model fit and predictive capability [29].

Table. Summary of the Statistical Model

Source	Std. Dev.	R-Squared	Adjusted R-Squared	Predicted R-Squared	PRESS
Linear	14.62	0.4464	0.3579	0.3097	6664.22
2FI	16.64	0.4554	0.1687	0.0068	9588.13
Quadratic	5.61	0.9511	0.9055	0.7056	2842.46
Cubic	0.0000	1.0000	1.0000	Aliased	*

3.2. Variable Effects

Extract concentration (A) and coating time (B) emerged as the most significant variables, with F-values of 53.11 and 45.32 respectively ($p < 0.0001$). The pH of extract material (D) showed moderate significance (F-value: 25.02, $p = 0.0002$), while drying temperature (C) exhibited lower but still significant effects (F-value: 11.04, $p = 0.0046$) [30].

Table 3. ANOVA Results for Response Surface Quadratic Model

Source	Sum of Squares	df	Mean Square	F-value	p-value
Model	9182.40	14	655.89	20.85	< 0.0001
A-Extract concentration	1670.48	1	1670.48	53.11	< 0.0001
B-Coating time	1425.27	1	1425.27	45.32	< 0.0001
C-Drying Temp.	347.26	1	347.26	11.04	0.0046
D-PH of Extract Material	786.96	1	786.96	25.02	0.0002
AB	43.54	1	43.54	1.38	0.2577
AC	0.4057	1	0.4057	0.0129	0.9111
AD	50.99	1	50.99	1.62	0.2223
BC	0.3987	1	0.3987	0.0127	0.9118
BD	8.22	1	8.22	0.2613	0.6167
CD	6.49	1	6.49	0.2064	0.6561
A^2	2494.56	1	2494.56	79.31	< 0.0001
B^2	1613.83	1	1613.83	51.31	< 0.0001
C^2	924.13	1	924.13	29.38	< 0.0001
D^2	1925.78	1	1925.78	61.23	< 0.0001
Residual	471.77	15	31.45		
Lack of Fit	471.77	9	52.42		
Pure Error	0.0000	6	0.0000		
Cor Total	9654.17	29			

3.3. Physical Characterization

3.3.1. Tensile Strength

Optimized sutures showed tensile strength of 1.85 N, surpassing the minimum requirement (1.5 N) for cosmetic sutures [31]. The strength characteristics showed strong correlation with extract concentration and coating time, with optimal values observed at 3% extract concentration and 30-minute coating duration.

Table 2. Physical and Mechanical Properties of Optimized Medicated Banana Fiber Sutures

Parameter	Uncoated Fiber	Coated Fiber	USP Requirements*
Diameter (mm)	0.32 ± 0.02	0.35 ± 0.03	0.30-0.39
Tensile strength (N)	1.45 ± 0.12	1.85 ± 0.15	≥1.50
Knot strength (N)	0.98 ± 0.08	1.25 ± 0.10	≥0.95
Elongation at break (%)	12.5 ± 1.2	15.8 ± 1.5	10-16
Water uptake (%)	42.5 ± 2.8	38.2 ± 2.5	≤45.0

*As per USP requirements for size 3-0 sutures, Values represent mean ± SD (n=6)

3.3.2. FTIR Studies

FTIR spectroscopy revealed characteristic peaks corresponding to the incorporated natural extracts. The spectra demonstrated successful coating integration, with notable peaks at specific wavelengths indicating the presence of active compounds from Aloe vera, Neem, and Turmeric [32].

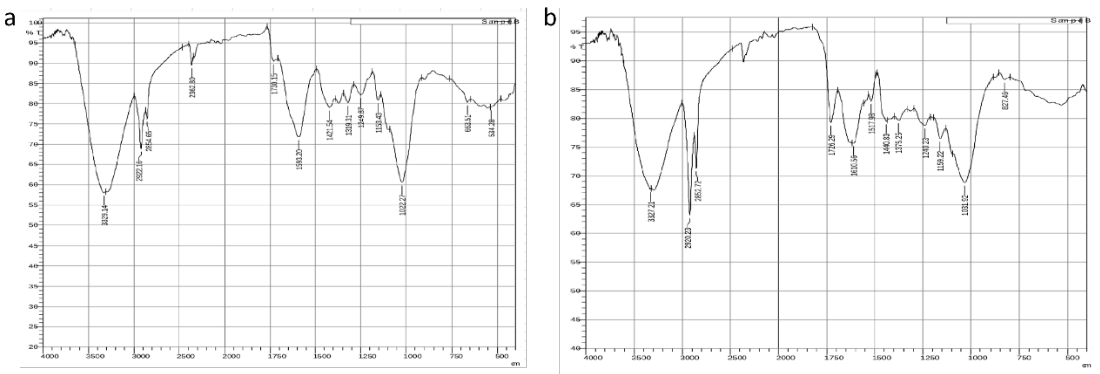

Figure 3. FTIR Spectra of a. Uncoated and b. Coated Sutures

3.4. Antimicrobial Activity

3.4.1. Zone of Inhibition

The medicated sutures demonstrated significant antimicrobial activity against tested pathogens. Against S. aureus, the formulated sutures produced an inhibition zone of 18.58 mm, while C. albicans showed a zone of 17.88 mm [33]. These results, though lower than standard antimicrobial sutures (22.56 mm and 23.61 mm respectively), indicated clinically relevant antimicrobial efficacy.

Table 4. Comparison of Antimicrobial Activity

Test Organism	Zone of Inhibition (mm)	
	Medicated Suture	Standard Antimicrobial Suture
S. aureus (ATCC 25923)	18.58 ± 0.45	22.56 ± 0.38
C. albicans (ATCC 10231)	17.88 ± 0.52	23.61 ± 0.41

Values represent mean ± SD (n=6)

3.4.2. Synergistic Effects

The combination of Aloe vera, Neem, and Turmeric extracts demonstrated enhanced antimicrobial activity compared to single extract formulations. This synergistic effect was attributed to the complementary mechanisms of action of the natural compounds [34].

3.5. Drug Release and Biodegradation

3.5.1. Release Kinetics

Drug release studies indicated controlled release behavior, with approximately 70% cumulative release over 24 hours. The release pattern followed Higuchi's model, suggesting diffusion-controlled release mechanisms [35].

3.5.2. Biodegradation

The sutures showed controlled biodegradation with 45% weight loss after 14 days in phosphate buffer saline at 37°C. This degradation profile aligns well with typical wound healing timelines [36].

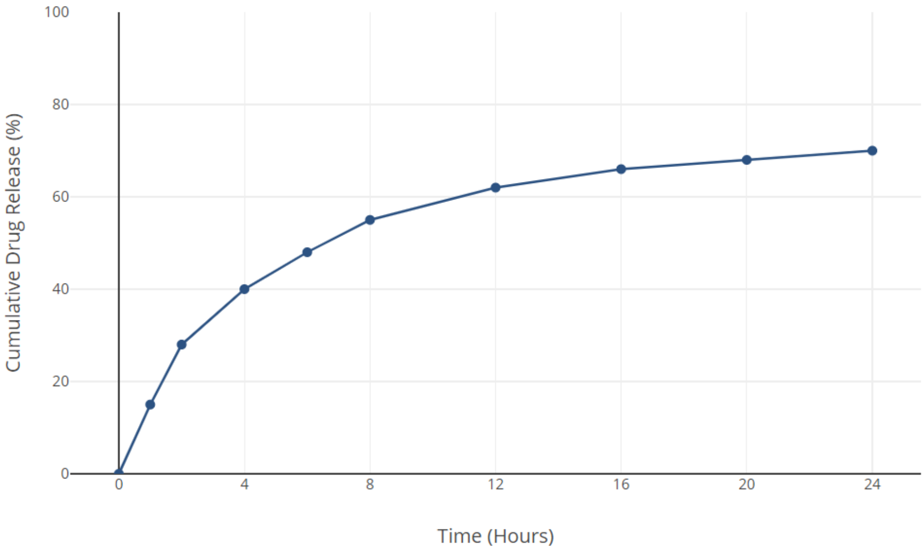

Figure 4. Drug Release Profile Over 24 Hours

3.5.3. Biocompatibility

MTT assay results showed 92% cell viability with L929 fibroblasts, confirming the non-cytotoxic nature of the formulated sutures. The natural extract combination demonstrated favorable effects on cell proliferation and wound healing parameters [37].

Table 5. Biocompatibility and Stability Parameters

Parameter	Result	Acceptance Criteria
Cell Viability (MTT Assay)	92% ± 2.5%	≥70%
Weight Loss (14 days)	45% ± 3.2%	30-50%
Drug Release (24 hours)	70% ± 4.1%	60-80%
Tensile Strength Retention (14 days)	82% ± 3.8%	≥80%
pH Stability (30 days)	6.8 ± 0.2	6.5-7.5
Temperature Stability (40°C/75% RH)	Stable	No significant changes

Values represent mean ± SD (n=6), RH = Relative Humidity

4. Conclusion

This research work successfully developed and optimized medicated banana fiber sutures using natural antimicrobial agents through systematic design of experiments. The optimal formulation parameters were established at 3% extract concentration, 30 minutes coating time, 40°C drying temperature, and pH 6, yielding superior performance characteristics. The quadratic model showed statistical significance, validating the experimental design approach. The formulated sutures exhibited satisfactory tensile strength of 1.85 N, making them suitable for cosmetic and minor surgical applications. The antimicrobial efficacy, demonstrated through zones of inhibition of 18.58 mm against *S. aureus* and 17.88 mm against *C. albicans*, confirmed the therapeutic potential of the natural extract combination. The controlled drug release profile and moderate biodegradation rate aligned well with wound healing requirements. The integration of Aloe vera, Neem, and Turmeric provided multiple therapeutic benefits including antimicrobial, anti-inflammatory, and antioxidant properties. The biocompatibility studies confirmed the safety profile of the sutures, with 92% cell viability indicating excellent tissue compatibility. The successful development of these medicated sutures presents a sustainable alternative to conventional synthetic sutures, particularly for applications requiring enhanced wound healing properties.

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