

Advanced Biodegradable Nano-formulated Sanitary Napkin Using Banana Fiber Infused with Herbal Extracts

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Abstract

The present study focuses on the design and development of a multifunctional, biodegradable sanitary napkin utilizing banana fiber as a core absorbent matrix integrated with herbal nanoformulations. Neem extract is formulated into a nanoemulsion to impart potent antimicrobial activity, while mint extract is nanoencapsulated for sustained odor control. Fenugreek powder is incorporated within an inner permeable layer to provide localized anti-inflammatory and antispasmodic effects for menstrual cramp relief. The application of nanotechnology enhances stability, bioavailability, and controlled release of active compounds. This formulation offers a sustainable alternative to conventional sanitary products with improved therapeutic benefits and environmental compatibility.

Rationale and Novelty

The development of an advanced biodegradable sanitary napkin incorporating banana fiber and herbal nanoformulations is driven by the urgent need to address both menstrual health challenges and environmental sustainability concerns associated with conventional sanitary products. Existing commercial sanitary napkins are largely composed of synthetic polymers and superabsorbent materials that are non-biodegradable, potentially causing skin irritation, microbial growth, and long-term ecological pollution. This highlights the need for safer, eco-friendly, and more effective alternatives.

A key novelty of the present formulation lies in the design of a **triple-functional sanitary napkin**, integrating antimicrobial, analgesic, and deodorizing properties within a single platform. The use of neem extract provides broad-spectrum antimicrobial activity, helping to prevent infections and maintain hygienic conditions during prolonged usage. Fenugreek is uniquely incorporated as a therapeutic agent to alleviate menstrual discomfort, representing an innovative shift from passive absorption systems to **active therapeutic hygiene products**. Additionally, mint extract offers natural deodorizing and cooling effects, improving overall user comfort and confidence.

Another significant innovation is the **utilization of banana fiber as a primary absorbent material**, which not only exhibits excellent fluid absorption and retention capacity but also promotes the valorization of agricultural waste. This contributes to a circular economy model, reducing dependency on wood pulp and synthetic fibers while lowering production costs and environmental burden.

The use of nanotechnology improves the stability, absorption, and controlled release of herbal ingredients, ensuring long-lasting effectiveness and better performance. This multifunctional biodegradable sanitary napkin not only provides absorbency but also supports infection protection, pain relief, and odor control. By combining banana fiber, herbal extracts, and nanotechnology, the formulation offers a sustainable, affordable, and innovative solution for menstrual hygiene, especially beneficial in low-resource settings.

Detailed Formulation Design

Layer-wise Structural Architecture

The proposed biodegradable sanitary napkin is designed as a **multi-layered functional system**, where each layer is engineered to perform a specific role, ensuring optimal absorbency, comfort, therapeutic action, and environmental compatibility.

Top Layer (Contact / Acquisition Layer)

The top layer is the **skin-contact interface**, responsible for rapid fluid acquisition, dryness, and comfort.

Material Composition:

- Biodegradable nonwoven fabric (e.g., cotton-based, bamboo fiber, or polylactic acid (PLA) fibers)
- Surface treated for softness and hypoallergenic properties

Functional Modification:

- Coated or spray-loaded with **mint nanoextract (Mentha piperita)**
- Nanoencapsulation ensures:
 - Controlled release of menthol
 - Prolonged cooling sensation
 - Continuous odor suppression

Key Properties:

- High permeability for rapid fluid transfer
- Low rewet characteristics (keeps surface dry)
- Antimicrobial support (secondary effect from mint)

Distribution / Acquisition Layer

To improve performance, an intermediate acquisition-distribution layer can be introduced between the top layer and absorbent core.

Material:

- Lightweight cellulose or air-laid pulp

Function:

- Rapidly distributes menstrual fluid across the pad
- Prevents localized saturation (clumping)
- Enhances overall absorbency efficiency

Absorbent Core Layer

This is the **primary fluid retention zone** of the napkin.

Material Composition:

- Mechanically processed **banana fiber matrix**
- Optionally blended with:
 - Natural superabsorbents (e.g., starch-grafted polymers)

Functional Loading:

- Infused with **neem nanoemulsion (Azadirachta indica)**
 - Applied via spraying, dipping, or padding method

Nanoformulation Role:

- Uniform distribution within fiber matrix
- Sustained antimicrobial release during usage

Key Functionalities:

- High absorbency and retention capacity
- Antimicrobial protection against pathogens
- Reduction in odor-causing bacterial growth
- Prevention of skin irritation and infections

Structural Advantage:

- Banana fiber provides:
 - High porosity
 - Good capillary action
 - Biodegradability

Therapeutic Layer (Middle Pouch System)

A unique feature of this formulation is the **incorporation of a therapeutic compartment**.

Composition:

- Finely powdered **fenugreek (Trigonella foenum-graecum)**
- Enclosed in a **biodegradable, breathable sachet (gauze or nonwoven pouch)**

Placement:

- Centrally located within or just beneath the absorbent core

Mechanism of Action:

- Releases bioactive compounds (e.g., diosgenin)
- Provides:

- Anti-inflammatory effect
- Reduction in uterine muscle contraction
- Mild localized soothing (heat-like effect)

Design Considerations:

- Controlled permeability to avoid direct leakage of powder
- Maintains user comfort without bulkiness

Barrier / Bottom Layer (Back Sheet)

The bottom layer acts as a **fluid-impermeable protective barrier**.

Material Composition:

- Biodegradable polymer films such as:
 - **Polylactic acid (PLA)**
 - Polyhydroxyalkanoates (PHA)

Key Properties:

- Leak-proof and fluid-resistant
- Breathable (microporous structure optional)
- Flexible and durable

Additional Features:

- Adhesive strip for secure placement
- Biodegradable release paper covering adhesive

Layer Integration and Assembly

- Layers are assembled using **thermal bonding or biodegradable adhesives**
- Compression techniques are applied to maintain:
 - Structural integrity
 - Uniform thickness
- Edges are sealed to prevent leakage and fiber displacement

Functional Synergy of Layers

The overall performance of the napkin is achieved through **synergistic interaction of all layers**:

- **Top layer** ensures dryness and comfort
- **Distribution layer** enhances fluid spread
- **Absorbent core** retains fluid and prevents microbial growth
- **Therapeutic layer** provides active health benefits
- **Bottom layer** ensures leakage protection

Design Advantages

- Multi-functional (absorbent + therapeutic + antimicrobial)

- Fully biodegradable system
- Improved hygiene and comfort

Advanced Nanoformulation Techniques

Neem Nanoemulsion

Method:

- High-energy ultrasonication / high-pressure homogenization
- Oil-in-water (O/W) nanoemulsion system

Formulation Components:

- Neem oil/extract (active phase)
- Surfactant: Tween 80 / Span 80
- Co-surfactant: Ethanol or propylene glycol
- Aqueous phase: Distilled water

Process Parameters:

- Sonication time: 10–20 min
- Amplitude: 40–60%
- Temperature control to prevent degradation

Particle Characteristics:

- Size range: 50–200 nm
- Polydispersity index (PDI): < 0.3 (uniform distribution)
- Zeta potential: ± 20 –30 mV (stable system)

Advantages:

- Increased surface area → enhanced microbial interaction
- Improved penetration into porous banana fiber matrix
- Enhanced antimicrobial efficacy at lower concentrations

Mint Nanoencapsulation

Method:

- Ionic gelation / nanoprecipitation technique

Polymeric System:

- Chitosan (cationic, biodegradable, antimicrobial)
- Crosslinker: Sodium tripolyphosphate (TPP)

Encapsulation Process:

- Mint extract added to chitosan solution
- Dropwise addition of TPP under stirring
- Formation of nanoparticles via electrostatic interaction

Particle Characteristics:

- Size: 100–300 nm
- Encapsulation efficiency: 70–90%

Benefits:

- Sustained release up to 6–8 hours
- Protection of volatile menthol from evaporation
- Enhanced stability under storage conditions

Fenugreek Functional Layer

Active Phytoconstituents:

- Diosgenin
- Flavonoids
- Saponins

Formulation Enhancement

- Microencapsulation of fenugreek powder using starch or alginate
- Improves:
 - Controlled release
 - Stability
 - Reduced irritation

Mechanism:

- Anti-inflammatory via COX pathway inhibition
- Smooth muscle relaxation (antispasmodic effect)
- Possible transdermal diffusion of bioactives

Mechanism of Action

Antimicrobial Action (Neem)

Mode of Action:

- Disruption of microbial cell membrane integrity
- Inhibition of enzyme systems and protein synthesis
- Interference with bacterial adhesion

Target Microorganisms:

- *Staphylococcus aureus*
- *Escherichia coli*

- *Candida albicans* (optional fungal testing)

Outcome:

- Reduced microbial load
- Prevention of dermatitis, itching, and infections

Anti-cramp Mechanism (Fenugreek)

Biochemical Action:

- Inhibits prostaglandin synthesis (reduces uterine contractions)
- Anti-inflammatory effect via cytokine suppression

Physiological Effect:

- Reduced intensity and frequency of cramps
- Muscle relaxation
- Improved comfort during menstruation

Odor Control Mechanism (Mint)

Key Component: Menthol

Mechanism:

- Antimicrobial action against odor-causing bacteria
- Volatile aromatic compounds neutralize unpleasant odor
- Cooling sensation via TRPM8 receptor activation

Role of Nanotechnology

- Controlled and sustained release of herbal actives
- Improved permeability and bioavailability
- Protection of sensitive phytochemicals from degradation

Characterization Studies

Nanoformulation Characterization

- **Particle Size Analysis:** Dynamic Light Scattering (DLS)
- **Zeta Potential:** Stability prediction
- **Morphology:** SEM / TEM imaging
- **Encapsulation Efficiency (%)**
- **Drug Release Studies:** In-vitro diffusion models

Banana Fiber Characterization

- Water absorbency capacity (g/g)
- Swelling index

- Capillary rise (wicking ability)
- Porosity analysis
- FTIR for functional group identification

Finished Product Evaluation

- Absorption capacity (ml/g)
- Rewet test (surface dryness)
- Strike-through time (fluid penetration rate)
- Leakage and retention test
- Mechanical strength (tensile test)
- Thickness and flexibility

Biological Evaluation

Antimicrobial Study

- Method: Agar well diffusion / disc diffusion
- Parameters:
 - Zone of inhibition (mm)
- Comparative study with commercial pads

Skin Irritation Test

- OECD guideline-based testing
- Human patch test (preferred for publication)
- Evaluation:
 - Redness
 - Edema
- Expected: Non-irritant, hypoallergenic

Anti-inflammatory Study

- In-vitro: COX inhibition assay
- In-vivo: Carrageenan-induced paw edema model
- Outcome:
 - Reduction in inflammation markers

Biodegradability Study

- Method: Soil burial test (ASTM standards)
- Conditions:
 - Controlled moisture and temperature

Evaluation Parameters:

- Weight loss (%) over time
- Structural degradation (visual + SEM)

Expected Outcome:

- Complete degradation within 60–90 days
- Compared to synthetic napkins (~500 years)

Challenges and Limitations

- Stability of nanoformulations under varying humidity
- Risk of phytochemical degradation over time
- Batch-to-batch variability in plant extracts

Future Scope

- Integration of **biosensors** for:
 - pH monitoring
 - Infection detection
- Exploration of:
 - Essential oil nano-blends
 - Herbal synergistic combinations
- Use of **green nanotechnology approaches**
- Development of **personalized menstrual care products**

Conclusion

This study presents a biodegradable sanitary napkin made from banana fiber combined with herbal nanoformulations for improved menstrual hygiene. Neem nanoemulsion offers long-lasting antimicrobial protection, while fenugreek helps relieve menstrual cramps and mint provides odor control and freshness. The use of nanotechnology enhances the stability and controlled release of herbal ingredients, improving overall effectiveness. Additionally, banana fiber makes the product eco-friendly, sustainable, and cost-effective by utilizing agricultural waste. Although further testing and large-scale production studies are needed, this innovative formulation shows strong potential as a safe, sustainable, and therapeutically enhanced menstrual hygiene product that supports both women's health and environmental protection.

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