

A REVIEW OF SMART HERBAL WOUND DRESSINGS: ADVANCES IN pH RESPONSIVE COLORIMETRIC MONITORING AND PLANT BASED THERAPEUTICS

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ABSTRACT

Conventional wound dressings mainly protect the wound and manage exudate, whereas smart dressings aim to provide additional information about the wound microenvironment. Among measurable wound parameters, pH is attractive for visual monitoring because the wound microenvironment changes during healing and persistent alkaline conditions have been associated with chronic and infected wounds. This review examines the concept of a smart herbal wound dressing that combines pH-responsive colorimetric monitoring with plant-based therapeutics, focusing on Aloe vera, Azadirachta indica (neem), and Curcuma longa-derived curcumin. Published evidence on wound pH, optical sensing, smart dressings and the wound-healing properties of the selected botanicals was reviewed. pH-responsive dressings can incorporate colorimetric indicators that translate local chemical changes into a visible signal, while herbal actives can provide complementary moisturizing, antioxidant, anti-inflammatory and antimicrobial functions. Anthocyanin-containing systems demonstrate the feasibility of visible pH-dependent colour changes in wound-dressing materials, while recent smart-dressing research increasingly integrates sensing with therapy. The proposed concept therefore uses a layered architecture in which wound exudate reaches an indicator region and the visual response is interpreted alongside clinical assessment. However, colour response alone cannot establish infection, and factors such as exudate composition, lighting, indicator stability, calibration, cytocompatibility, sterilization, reproducibility and regulatory validation must be addressed. Future development should emphasize quantitative colour standards, smartphone-assisted interpretation, validated pH thresholds, standardized botanical extracts and controlled preclinical and clinical studies.

Keywords: pH-responsive wound dressing; Smart wound dressing; Colorimetric monitoring; Herbal therapeutics; Aloe vera; Neem; Curcumin; Anthocyanin

1. INTRODUCTION

Wound healing is a coordinated biological process involving haemostasis, inflammation, proliferation and tissue remodelling. Failure to progress through these stages can result in persistent inflammation, microbial colonization, biofilm formation and delayed closure. Conventional dressings provide protection, fluid management and a favourable local environment, but many do not directly communicate the changing biochemical status of the wound to the patient or caregiver.

The wound microenvironment is dynamic. pH is one of the parameters that can change during healing and can influence enzymatic activity, cellular behaviour, microbial growth and antimicrobial performance. Reviews of wound pH describe a tendency toward a more acidic environment during uncomplicated healing, whereas chronic wounds can remain at elevated or alkaline pH. The relationship is not absolute and varies with wound type, stage, exudate and treatment; therefore pH should be regarded as a useful biomarker rather than a standalone diagnostic test.[1–4]

Smart wound dressings attempt to convert information from the wound microenvironment into a usable signal or response. Colorimetric systems are particularly attractive because the output can be read visually without specialized equipment. Recent reviews have described pH-sensitive dyes and plant-derived pigments incorporated into hydrogels, films, nanofibres and other dressing platforms.[5,6]

At the same time, medicinal plants and natural bioactives are being investigated for wound management. Aloe vera has been

studied for skin and burn wounds; neem has reported antimicrobial and wound-healing properties; and curcumin has attracted interest because of antioxidant, anti-inflammatory and antimicrobial activities. Evidence varies by formulation and study design, so botanical claims should be interpreted according to the strength of available evidence.[7–12]

This review focuses on the integration of pH-responsive colorimetric monitoring with selected plant-based therapeutics. The objective is not to claim that a proposed formulation is clinically proven, but to organize the scientific rationale, design principles, evidence, limitations and future validation requirements for a smart color-changing herbal wound dressing.

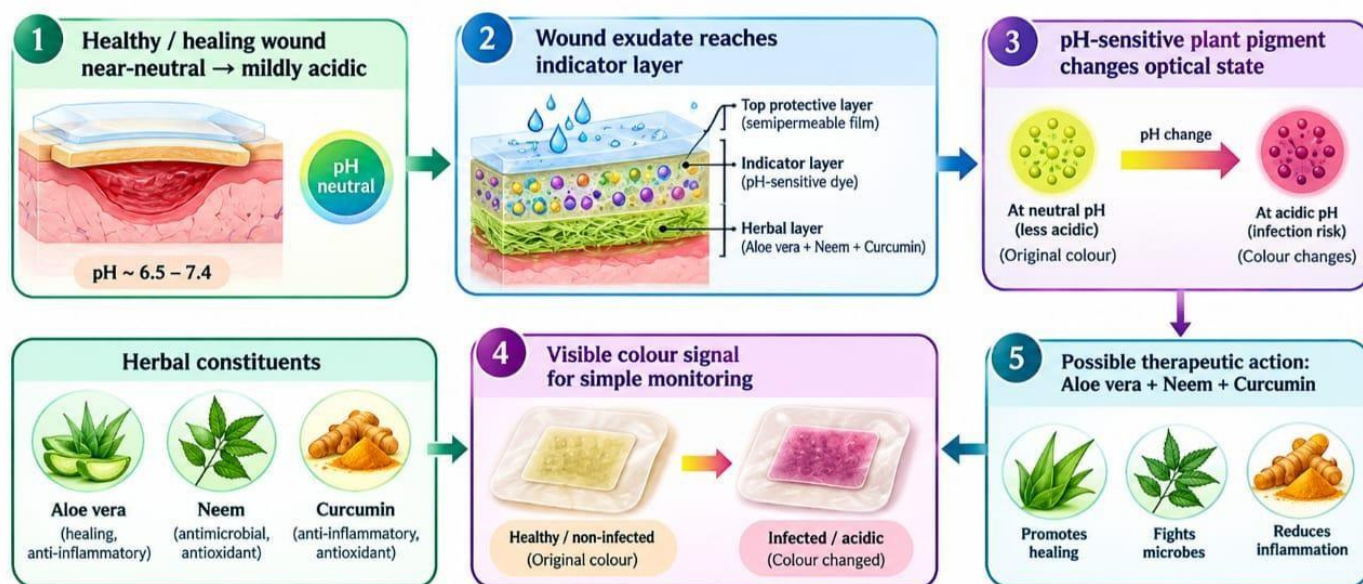


Fig. 1.1: Conceptual mechanism of a smart color- Changing herbal wound dressing

2. WOUND HEALING AND THE WOUND MICROENVIRONMENT

2.1 Phases of wound healing

Haemostasis limits blood loss and forms the initial clot. The inflammatory phase removes debris and helps control microbial contamination. During proliferation, fibroblasts, keratinocytes and endothelial cells contribute to granulation tissue formation, re-epithelialization and angiogenesis. Remodelling then reorganizes extracellular matrix components and progressively increases tissue strength. Persistent infection, excessive inflammation, ischemia, metabolic disorders and other factors can disturb this sequence.

2.2 Importance of wound pH

Wound pH is influenced by tissue metabolism, exudate, microbial activity and treatment. Research has shown that pH can affect protease activity, extracellular matrix degradation, fibroblast and keratinocyte behaviour, microbial proliferation and the activity of some antimicrobial agents.[3,4,13] Chronic wounds have been reported to display neutral-to-alkaline or elevated pH conditions, although individual measurements vary substantially.[1,2]

Because pH is dynamic, a single threshold should not be treated as a universal definition of infection. Instead, a colorimetric dressing could be designed to indicate a change outside a validated reference range and prompt closer examination. Clinical signs, wound appearance, exudate, odour, pain, temperature and microbiological assessment remain important where infection is suspected.

Table 2.1: Wound-microenvironment parameters relevant to smart dressings.

Wound-related parameter	Potential significance	Relevance to smart dressing
pH	Changes with healing, inflammation, exudate and microbial environment	Can be translated into a visible colour response
Exudate	Carries proteins, metabolites and inflammatory mediators	Provides fluid for sensing and can be managed by absorbent layers
Temperature	May increase with inflammation/infection	Potential secondary sensing parameter
Moisture	Important for cell migration and tissue repair	Can be controlled through dressing architecture
Microbial burden	Associated with infection and delayed healing	Can be indirectly suggested by biomarker changes; confirmation requires clinical/microbiological assessment

3. SMART WOUND DRESSINGS AND COLORIMETRIC MONITORING

Smart dressings can be broadly categorized according to the parameter detected or the stimulus used for response. Examples include pH, temperature, oxygen, enzymes, reactive oxygen species and bacterial metabolites. Colorimetric, fluorescence and electrochemical strategies have all been investigated. Colorimetric systems have the practical advantage of producing an intuitive visible output, although their analytical precision may be lower than instrument-based measurements.[5,6,14]

3.1 pH-responsive colour change

A pH-sensitive indicator changes its protonation state as hydrogen-ion concentration changes. This molecular change can alter electronic structure and therefore light absorption, producing a visible shift in colour. In a dressing, the indicator may be immobilized within a hydrogel, polymer film, fibre, paper-like substrate or other matrix. The material should permit sufficient contact with wound fluid while limiting leaching into the wound.

3.2 Plant-based indicators

Anthocyanins are prominent plant pigments with pH-dependent optical behaviour and have been incorporated into wound-dressing materials. A published carboxymethyl cellulose/polyvinyl alcohol dressing containing red-cabbage anthocyanin demonstrated colorimetric monitoring of wound-mimicking fluid and reported visible colour changes associated with pH variation.[17] More recent work has continued to develop anthocyanin-based hydrogels that combine pH sensing with antibacterial or therapeutic functions.[18]

For the proposed herbal dressing, the indicator should be selected and standardized specifically for the desired pH transition. The plant therapeutic ingredients and the indicator are conceptually separate functions: Aloe vera, neem and curcumin provide therapeutic potential, whereas a validated pH-sensitive pigment provides the colorimetric signal. This distinction is important when explaining the mechanism of the dressing.

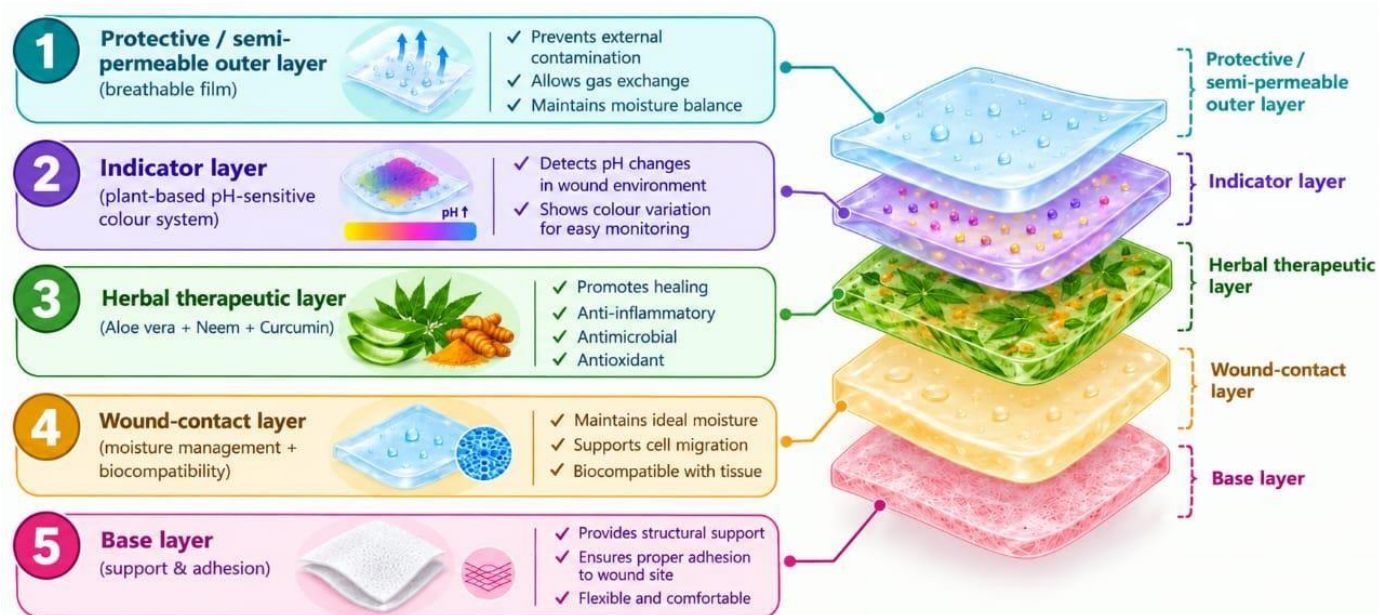


Fig. 3.1: Proposed multilayer architecture of the smart herbal dressing

4. PLANT-BASED THERAPEUTICS FOR WOUND MANAGEMENT

4.1 Aloe vera

Aloe vera gel contains polysaccharides and other constituents that have been investigated for skin repair, hydration and wound-healing effects. Clinical evidence is mixed across wound types. Systematic reviews have evaluated Aloe vera in burns and other skin wounds, while more recent mechanistic work describes potential effects on growth factors, extracellular matrix components and cellular proliferation.[7,10]

In a smart dressing, Aloe vera may be considered primarily as a moisturizing and wound-supportive component. Its inclusion requires attention to gel standardization, microbial quality, stability, water activity, compatibility with the dressing matrix and sterilization.

4.2 Neem (*Azadirachta Indica*)

Neem has a long history of traditional medicinal use and contains diverse limonoids and other phytoconstituents. Reviews describe antimicrobial, anti-inflammatory, antioxidant and dermatological applications, while experimental wound-dressing studies have explored neem-containing biomaterials.[11,12] A neem-silk fibroin hydrogel has been investigated as a wound-healing material, illustrating how neem can be integrated into an advanced dressing platform.[11]

For the proposed system, neem may contribute antimicrobial and supportive wound-healing functions. However, botanical variability is a major consideration. Extract type, plant part, solvent, marker compounds and extraction conditions can substantially influence activity and safety.

4.3 Curcumin (*Curcuma Longa*)

Curcumin is a major bioactive constituent associated with *Curcuma longa*. It has been investigated for antioxidant, anti-inflammatory and antimicrobial actions relevant to wound healing. Reviews of curcumin-based wound delivery systems describe hydrogels, nanofibres, micelles and films designed to improve topical delivery.[13,16]

Curcumin also has formulation challenges, including low aqueous solubility and chemical instability under some conditions. A smart dressing therefore requires an appropriate delivery strategy, protection from degradation and a controlled release profile. Importantly, the yellow-orange colour of curcumin should not automatically be considered the infection indicator; the sensing function should be assigned to a validated pH-responsive indicator.

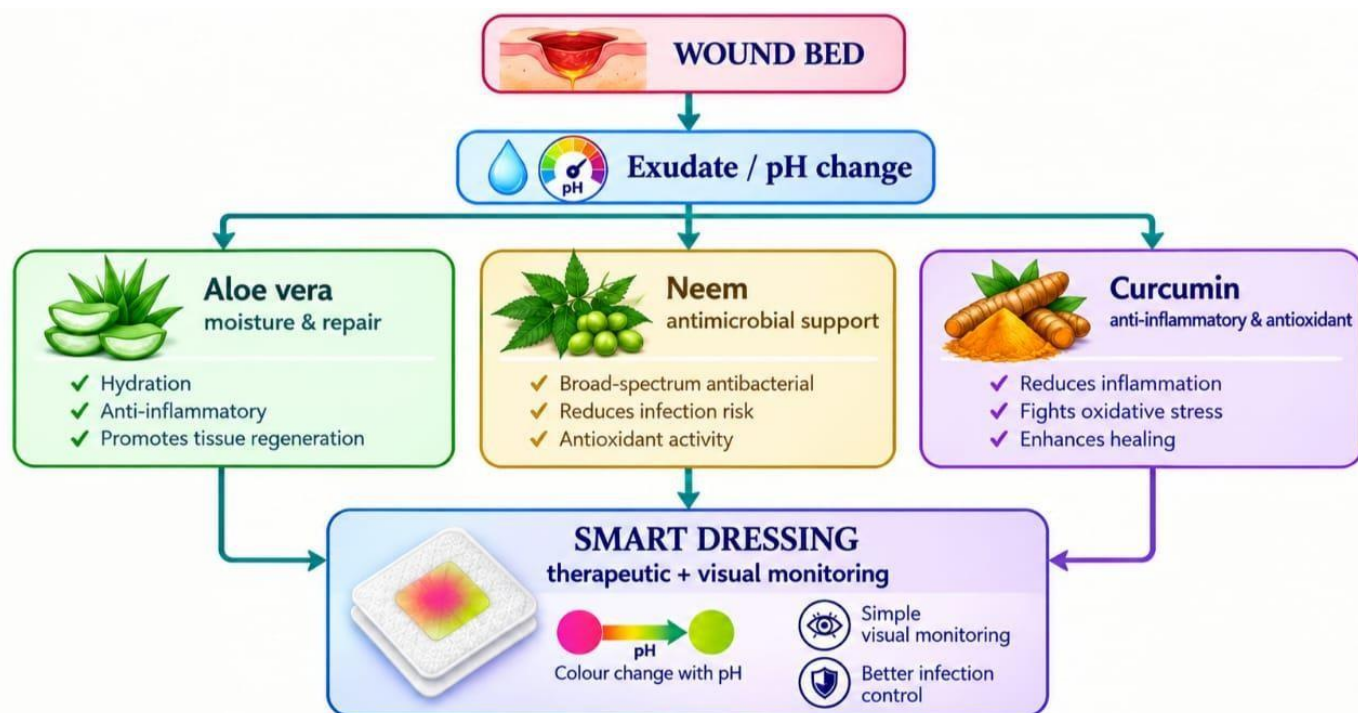


Fig. 4.1: Proposed integration of plant-based therapeutics with pH- responsive monitoring

5. PROPOSED CONCEPT OF A SMART COLOR-CHANGING HERBAL WOUND DRESSING

The proposed concept combines two functions within one dressing: (i) therapeutic support from standardized herbal components and (ii) visual monitoring of the wound environment through a pH-responsive colorimetric indicator. The concept is intended as a development framework rather than a clinically validated product.

5.1 Functional Layers

A possible architecture consists of an outer protective layer, an indicator layer, a therapeutic layer and a wound-contact layer. The indicator layer should be positioned so that wound exudate can reach it without unnecessarily exposing the indicator to mechanical

abrasion. The therapeutic layer can contain standardized Aloe vera, neem and curcumin in a compatible matrix. The wound-contact layer should be non-irritant, sufficiently permeable to relevant fluids and capable of maintaining an appropriate moisture balance.

5.2 Operating Principle

After application, wound exudate reaches the sensing region. A change in local pH modifies the optical state of the indicator and produces a visible colour change. The colour can be compared with a calibrated reference chart or, in an advanced version, captured using a smartphone for semi-quantitative interpretation. The visual signal should be treated as an early warning or monitoring aid rather than a definitive diagnosis of infection.

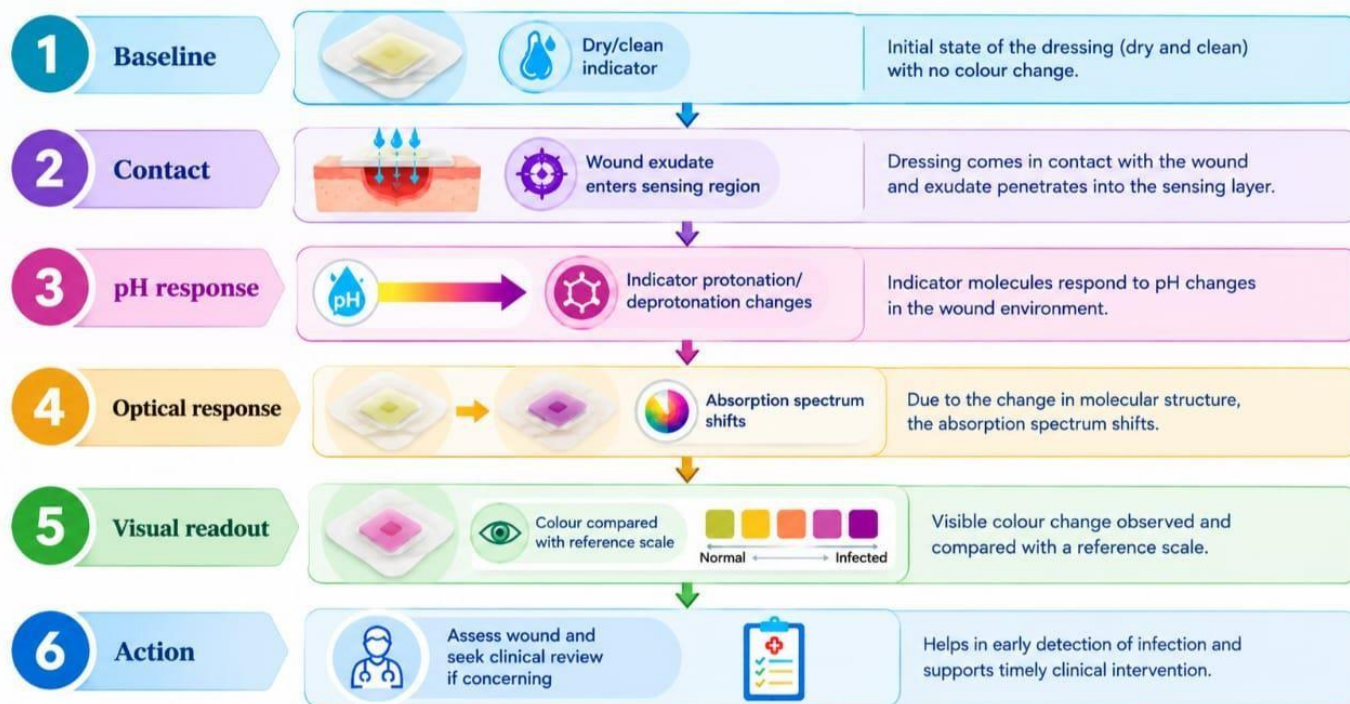


Fig. 5.1: Stepwise operating principle of colorimetric smart dressing

6. OLE OF THE SELECTED CONSTITUENTS

Table 6.1: Rationale for selected constituents in the proposed smart herbal dressing.

Constituent	Principal rationale	Proposed role in dressing	Key development concern
Aloe vera	Moisturizing and wound-supportive properties	Moisture management and tissue-supportive therapy	Stability, microbial quality, extract/gel standardization
Neem	Antimicrobial, anti-inflammatory and antioxidant potential	Supportive antimicrobial function	Botanical variability, extract standardization, irritation testing
Curcumin	Antioxidant, anti-inflammatory and antimicrobial potential	Therapeutic bioactive for wound environment	Solubility, stability, controlled release
pH-responsive plant pigment	pH-dependent optical response	Colorimetric sensing / visual indicator	Calibration, leaching, light stability, reproducibility

7. LITERATURE COMPARISON

Recent literature demonstrates that the individual components of the proposed concept are scientifically active areas, while integrated systems remain dependent on material design and validation. pH-responsive wound-dressing reviews have described multiple platforms for monitoring and therapy, and newer studies have combined colorimetric sensing with antibacterial functions.[5,6,17,18]

Table 7.1: Selected literature relevant to smart color-changing herbal wound dressings.

Study / year	Platform or focus	Main reported contribution	Relevance to proposed concept
Han et al., 2023	pH-responsive wound dressings	Reviewed pH-responsive materials, indicators and monitoring functions	Supports pH as a design parameter and organizes sensing approaches
Alsahag et al., 2023	CMC/PVA + anthocyanin dressing	Visible pH-dependent colour response with wound-dressing functions	Demonstrates feasibility of plant-pigment colorimetry
Miao et al., 2026	Anthocyanin hydrogel	pH-responsive visual indication plus antibacterial function	Supports integration of sensing and therapy
Optical pH-sensing review, 2025	Optical wound monitoring	Compared colorimetric and fluorescent sensing agents	Supports plant-based optical sensing as an accessible approach
Nasrine et al., 2023	Neem–silk fibroin hydrogel	Explored neem-containing wound-healing biomaterial	Supports neem as a candidate therapeutic component
Curcumin delivery review, 2025	Curcumin delivery systems	Reviewed advanced systems for acute/chronic wound management	Supports need for suitable curcumin delivery strategy
Aloe vera review, 2024	Aloe vera mechanisms	Reviewed active principles and wound-healing mechanisms	Supports Aloe vera as a complementary therapeutic component

8. BENEFITS AND POTENTIAL APPLICATIONS

- Simple visual indication: a visible colour response may be easier to interpret than an invisible biochemical change, particularly where laboratory equipment is unavailable.
- Potential early warning: a validated change outside a predefined pH range could prompt closer wound assessment and earlier professional review.
- Theranostic concept: combining monitoring and therapy may reduce the need to remove the dressing solely to inspect the wound, depending on the final design.
- Plant-based therapeutic platform: standardized botanical actives can provide complementary biological functions within the same dressing.
- Digital extension: smartphone image analysis could support semi-quantitative colour interpretation and longitudinal documentation.

9. LIMITATIONS AND CHALLENGES

The principal limitation is that pH is not specific for infection. Wound type, exudate, medications, dressings, tissue status and other variables can influence pH. Therefore, a colour change must not be presented as a definitive diagnosis.

Colour interpretation is also affected by ambient lighting, camera characteristics, background colour, pigment concentration, moisture, temperature and ageing of the indicator. A practical product requires calibration against known pH standards, stability testing, reproducible manufacturing and a defined visual or digital interpretation method.

Botanical materials introduce additional variability. Authentication, extraction, marker-based standardization, microbial limits, pesticide/heavy-metal controls where applicable, compatibility, stability and batch-to-batch consistency are necessary. The final dressing also requires evaluation of mechanical properties, swelling/exudate handling, adhesion, oxygen/water-vapour transmission, cytocompatibility and skin tolerance.

Clinical translation requires evidence beyond in vitro colour change. Preclinical studies should evaluate wound closure, histology, inflammatory markers, microbial burden and local/systemic safety, followed by appropriately designed human studies. Sterilization must not destroy the indicator or degrade the herbal constituents.

10. FUTURE PERSPECTIVES

Future smart herbal dressings may progress from qualitative colour change toward calibrated semi-quantitative or quantitative monitoring. Smartphone-based image analysis is particularly promising because it can reduce subjective colour interpretation and permit longitudinal recording. Recent literature has highlighted smartphone-assisted supervision as an extension of optical wound sensing.[6]

Another direction is multimodal sensing. Combining pH with temperature, oxygen, bacterial enzymes or other biomarkers may improve specificity compared with a single parameter. The therapeutic layer could also be designed for stimulus-responsive release,

creating a closed-loop system in which sensing and treatment are linked.

For herbal products, future research should use chemically characterized extracts rather than poorly defined crude materials. Standardized marker compounds, validated extraction methods, stability-indicating assays and reproducible manufacturing processes will be important for translation. Regulatory and quality requirements should be considered from the earliest formulation stage.

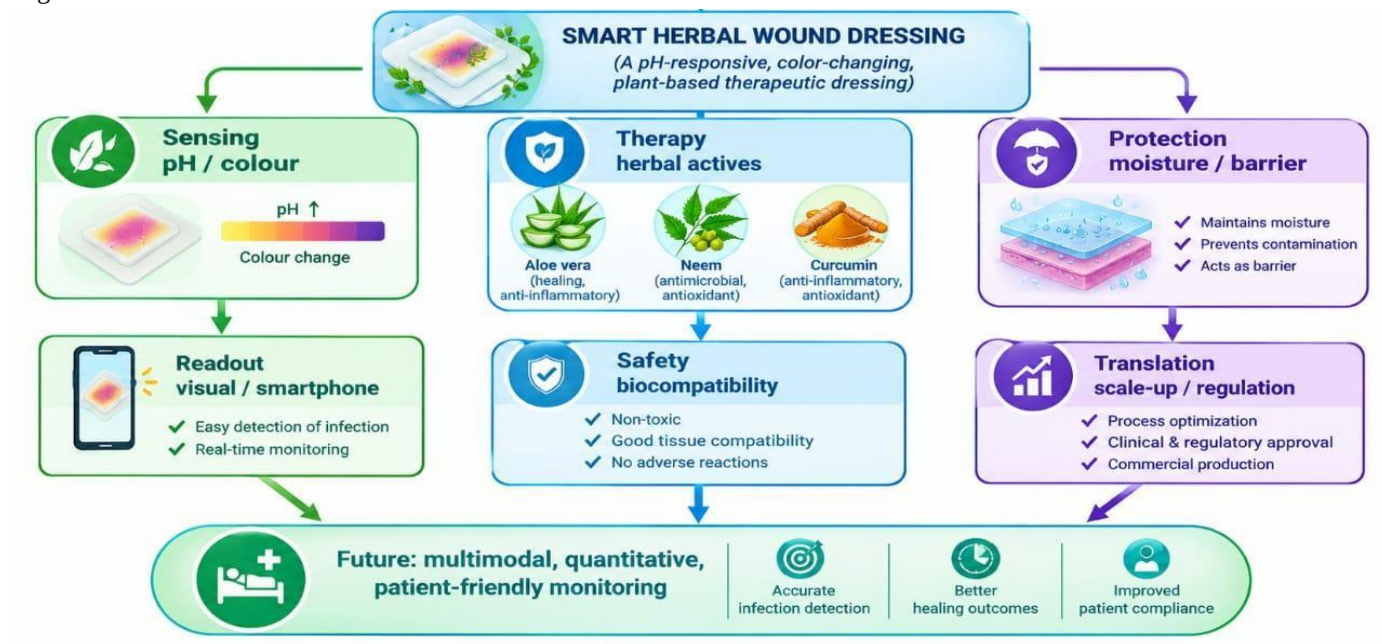


Fig. 10.1: Development pathway and translational priorities

11. PROPOSED EVALUATION WORKFLOW

Table 11.1: Suggested development and evaluation workflow.

Stage	Key tests / activities	Purpose
1. Botanical authentication	Macroscopy, microscopy, physicochemical and marker-based evaluation	Confirm identity and quality
2. Extract standardization	Marker assay, chromatographic fingerprint, microbial quality	Improve batch consistency
3. Indicator screening	pH buffer series, UV–Vis, colour coordinates, response time	Select and calibrate sensing system
4. Dressing fabrication	Layer formation, loading and compatibility studies	Develop reproducible dosage form
5. Physicochemical tests	Thickness, swelling, moisture handling, tensile properties, WVTR where applicable	Characterize dressing performance
6. Safety testing	Cytocompatibility, irritation/sensitization as appropriate	Establish preliminary safety
7. Antimicrobial evaluation	Relevant standardized organisms and validated assays	Assess therapeutic antimicrobial potential
8. Wound-model studies	Healing rate, histology, inflammatory markers, microbial burden	Generate preclinical efficacy/safety evidence
9. Digital readout	Controlled-light imaging and calibration algorithm	Reduce subjective colour interpretation
10. Translation	Stability, sterilization, scale-up, regulatory and clinical evaluation	Prepare for real-world application

12. CONCLUSION

Smart color-changing herbal wound dressings represent a convergence of wound monitoring, biomaterials and plant-based therapeutics. The scientific rationale for the concept is supported by evidence that wound pH changes during healing and that pH-responsive optical systems can provide visible signals. Aloe vera, neem and curcumin each have literature supporting selected wound-related biological activities, although the strength of evidence differs by preparation and indication. A future dressing combining these components should therefore be positioned as a research and development concept rather than an established

clinical product.

The most important development requirement is functional separation and validation: a standardized pH-responsive indicator should provide the monitoring signal, while standardized herbal constituents provide therapeutic support. Successful translation will depend on reproducible colour response, biocompatibility, stability, extract standardization, reliable interpretation and clinical validation. With these requirements addressed, smart herbal dressings could offer a practical platform for patient-friendly wound monitoring and supportive therapy.

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