Comparative Evaluation of Bioepoxy Resin Films Derived from Epoxidized Castor Oil and Karanja Oil as Novel Wound Dressing Materials

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ABSTRACT
Background: Bio-based polymers derived from renewable vegetable oils have gained considerable attention for biomedical applications because of their biodegradability, biocompatibility, and sustainability. Epoxidized vegetable oils can be converted into bioepoxy resins with desirable physicochemical and mechanical properties suitable for wound dressing applications.
Objective: The present study aimed to synthesize, characterize, and comparatively evaluate bioepoxy resin films prepared from epoxidized castor oil (ECO) and epoxidized karanja oil (EKO) for their wound healing potential.
Methods: Castor oil and karanja oil were epoxidized using hydrogen peroxide and acetic acid. Bioepoxy resin films were prepared using citric acid as a bio-based curing agent. The developed films were evaluated for thickness, folding endurance, surface pH, swelling index, moisture absorption, water vapor transmission rate (WVTR), tensile strength, and elongation percentage. Wound healing activity was assessed using the excision wound model in Wistar rats. Histopathological studies were performed to evaluate tissue regeneration and collagen deposition.
Results: Both bioepoxy films exhibited acceptable physicochemical characteristics suitable for wound dressing applications. ECO films demonstrated significantly higher tensile strength (22.6 ± 0.9 MPa) compared with EKO films (19.8 ± 0.8 MPa). EKO films showed comparatively higher moisture absorption and swelling behavior. In vivo studies revealed significantly enhanced wound contraction in both treatment groups compared with control ($p<0.05$). ECO films demonstrated superior wound contraction (93.4%) and shorter epithelization time (11.2 ± 0.6 days) than EKO films (88.6%; 13.1 ± 0.5 days). Histopathological findings confirmed enhanced collagen deposition, angiogenesis, and fibroblast proliferation in treated groups.
Conclusion: Bioepoxy resin films prepared from epoxidized castor oil and karanja oil exhibited promising wound dressing properties. However, castor oil-derived bioepoxy films demonstrated superior mechanical strength and wound healing efficacy, indicating their potential as sustainable biomaterials for wound management.
Keywords: Bioepoxy resin; Castor oil; Karanja oil; Wound healing; Biomaterials; Epoxidation; Bio-based polymers.
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1. INTRODUCTION

Wound healing is a dynamic biological process involving hemostasis, inflammation, proliferation, and remodeling phases that collectively restore tissue integrity following injury (1). Chronic and acute wounds remain major healthcare challenges worldwide, necessitating the development of advanced wound dressing systems capable of providing an optimal healing environment (2).

Modern wound dressings are expected to maintain moisture balance, facilitate gas exchange, prevent microbial invasion, and promote tissue regeneration (3). Conventional dressings often suffer from limitations including poor biocompatibility, inadequate mechanical properties, and environmental concerns associated with synthetic polymers (4). Consequently, there has been increasing interest in bio-based polymers derived from renewable natural resources.

Vegetable oils represent an attractive source of sustainable raw materials for the synthesis of biodegradable polymers due to their abundance, low toxicity, and structural versatility (5). Epoxidized vegetable oils are among the most widely investigated renewable precursors for the preparation of bioepoxy resins (6). Epoxidation converts carbon-carbon double bonds into reactive epoxy groups, facilitating subsequent polymerization and cross-linking reactions (7).

Castor oil obtained from Ricinus communis contains approximately 85–90% ricinoleic acid, making it highly suitable for chemical modification and biomedical applications (8). Previous studies have demonstrated anti-inflammatory, antimicrobial, and wound healing properties associated with castor oil derivatives (9).

Karanja oil extracted from Pongamia pinnata possesses significant medicinal value and contains flavonoids, karanjin, pongamol, and other bioactive compounds that contribute to antimicrobial and wound healing activities (10). Several reports have demonstrated the wound healing potential of karanja extracts and formulations in experimental animal models (11,12).

Bioepoxy resins synthesized from epoxidized vegetable oils have shown favorable mechanical properties, biodegradability, and moisture-retention characteristics suitable for wound dressing applications (13). However, comparative investigations evaluating the wound healing efficacy of castor oil-derived and karanja oil-derived bioepoxy resin films remain limited.

Therefore, the present study was designed to synthesize bioepoxy resin films from epoxidized castor oil (ECO) and epoxidized karanja oil (EKO) and comparatively evaluate their physicochemical characteristics and wound healing potential in Wistar rats.

2. MATERIALS AND METHODS

2.1 Materials

Castor oil and karanja oil were procured from certified local suppliers. Hydrogen peroxide (30%), glacial acetic acid, citric acid, tetrahydrofuran (THF), sodium sulfate, and analytical-grade reagents were purchased from standard commercial suppliers.

2.2 Epoxidation of Vegetable Oils

Epoxidation was carried out according to the reported method with minor modifications (14). Briefly, vegetable oil (24 g), toluene (7.68 mL), amberlite catalyst (3.84 g), and glacial acetic acid (2.26 g) were mixed in a round-bottom flask. Hydrogen peroxide (12.68 g, 30%) was added gradually under continuous stirring at 80°C. After completion of the reaction, the mixture was purified by washing and solvent evaporation to obtain epoxidized castor oil (ECO) and epoxidized karanja oil (EKO).

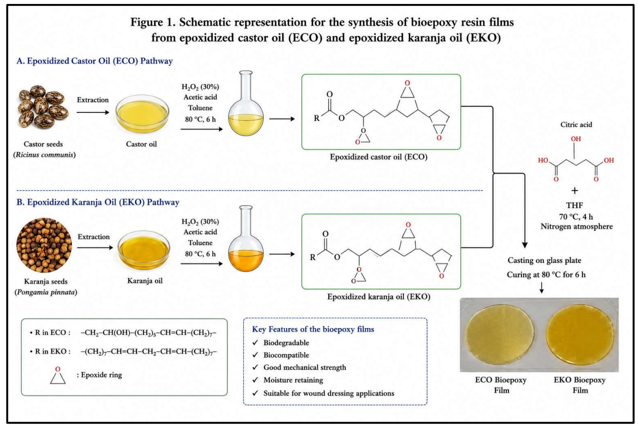

Figure 1. The synthesis pathway of ECO and EKO bioepoxy resins

2.3 Preparation of Bioepoxy Resin Films

Bioepoxy resin films were synthesized by solution polymerization using citric acid as a curing agent. Epoxidized oil (10 g) and citric acid (1.2 g) were dissolved in THF and reacted at 70°C under nitrogen atmosphere. The resulting viscous mixture was cast onto glass plates and cured at 80°C for 6 h to obtain flexible bioepoxy films. Table 1 presents the composition of developed formulations.

Table 1. Composition of Bioepoxy Resin Films

Formulation	Composition
F1	Epoxidized Castor Oil + Citric Acid
F2	Epoxidized Karanja Oil + Citric Acid

2.4 Evaluation of Bioepoxy Films

The prepared bioepoxy resin films were characterized for thickness, folding endurance, surface pH, swelling index, moisture absorption, water vapor transmission rate (WVTR), tensile strength, and percentage elongation to assess their suitability as wound dressing materials. All measurements were performed in triplicate.

2.5 In Vivo Wound Healing Study

Healthy Wistar rats (150–200 g) were randomly divided into three groups (n=6): Group I (Control), Group II (ECO Bioepoxy Film) and Group III (EKO Bioepoxy Film). Excision wounds of approximately 500 mm² were created under anesthesia. Films were applied topically once daily until complete wound closure.

Percentage wound contraction was calculated according to Equation 1.

$$\% \text{ Wound Contraction} = (\text{Initial wound area} - \text{Final wound area})/\text{Initial wound area} \times 100$$

2.6 Histopathological Evaluation

On day 21, wound tissues were excised, fixed in buffered formalin, processed, stained with hematoxylin and eosin, and examined microscopically for epithelialization, fibroblast proliferation, collagen deposition, and angiogenesis.

2.7 Statistical Analysis

Results were expressed as Mean ± SEM. Statistical significance was analyzed using one-way ANOVA followed by Tukey's multiple comparison test. Differences were considered significant at $p<0.05$.

3. RESULTS

3.1 Physical Characteristics

Both formulations produced flexible yellowish films with smooth appearance and uniform thickness.

Table 2. Physical Characteristics of Bioepoxy Films

Parameter	F1 (ECO)	F2 (EKO)
Thickness (mm)	0.11 ± 0.01	0.12 ± 0.01
Folding Endurance	512 ± 8	498 ± 6
Surface pH	5.8 ± 0.1	5.9 ± 0.1
Weight (g)	0.61 ± 0.02	0.60 ± 0.01

3.2 Mechanical Properties

The mechanical properties are summarized in Table 3.

Table 3. Mechanical Properties of Bioepoxy Films

Parameter	F1 (ECO)	F2 (EKO)
Tensile Strength (MPa)	22.6 ± 0.9	19.8 ± 0.8
Tensile Strain	0.028 ± 0.002	0.024 ± 0.002
% Elongation	2.8 ± 0.2	2.4 ± 0.2

As shown in Table 3, ECO films demonstrated superior tensile strength and elasticity compared with EKO films.

3.3 Swelling and Moisture Absorption

Table 4. Swelling Index and Moisture Absorption

Parameter	F1 (ECO)	F2 (EKO)
Swelling Index (%)	1.12 ± 0.08	1.47 ± 0.06
Moisture Absorption (%)	5.21 ± 0.28	8.74 ± 0.35

The EKO films exhibited significantly higher moisture absorption and swelling behavior than ECO films (Table 4).

3.4 Water Vapor Transmission Rate

Table 5. WVTR of Bioepoxy Films

Time (h)	ECO ($g/m^2/day$)	EKO ($g/m^2/day$)
24	0.014	0.018
48	0.010	0.014
72	0.008	0.011
96	0.006	0.008
120	0.005	0.006

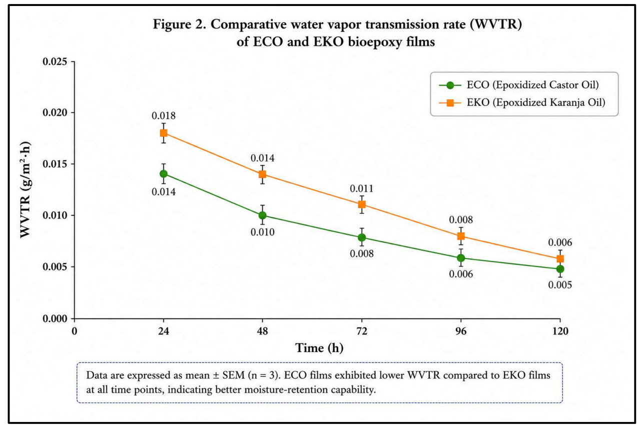

Figure 2. The comparative WVTR profiles of ECO and EKO films

3.5 In Vivo Wound Healing Activity

The wound healing potential of ECO and EKO bioepoxy films was evaluated using the excision wound model in Wistar rats. Progressive reduction in wound area was observed in all treatment groups; however, the rate of wound contraction was significantly higher in animals treated with bioepoxy films compared with the control group ($p<0.05$).

Table 6. Effect of ECO and EKO Bioepoxy Films on Percentage Wound Contraction

Group	Treatment	Day 0	Day 7	Day 14	Day 21
I	Control	0	22.4 ± 1.2	48.6 ± 1.8	76.8 ± 2.1
II	ECO Film	0	41.8 ± 1.5*	72.6 ± 2.2*	93.4 ± 1.3*
III	EKO Film	0	36.5 ± 1.7*	68.1 ± 2.0*	88.6 ± 1.5*

*p < 0.05 versus control.

Both treatment groups demonstrated significantly enhanced wound contraction from day 7 onward. ECO-treated animals exhibited the highest percentage wound contraction throughout the study period (Table 6).

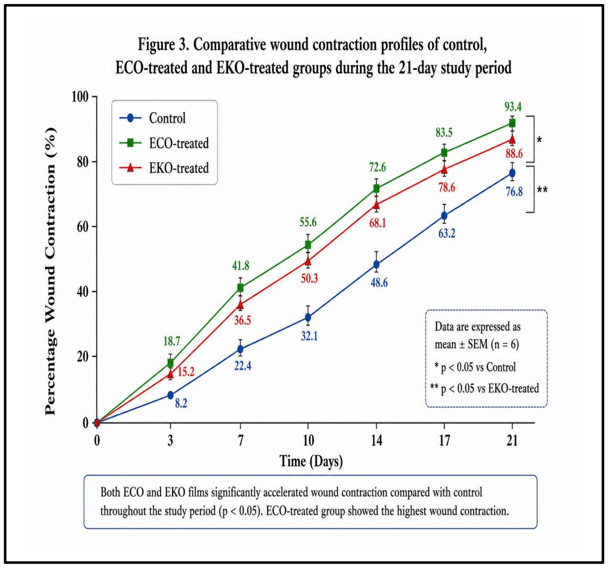

Figure 3. The comparative wound contraction profiles of control, ECO, and EKO groups

3.6 Epithelization Period

The time required for complete epithelization was significantly reduced in treatment groups compared with control.

Table 7. Effect of Bioepoxy Films on Epithelization Time

Group	Treatment	Epithelization Time (Days)
I	Control	17.4 ± 0.8
II	ECO Film	11.2 ± 0.6*
III	EKO Film	13.1 ± 0.5*

*p < 0.05 versus control.

The ECO film demonstrated the shortest epithelization period, indicating faster wound closure and tissue regeneration.

3.7 Histopathological Evaluation

Histological examination of wound tissues on day 21 revealed marked differences among treatment groups (Figure 4). Control animals exhibited incomplete epithelialization, inflammatory cell infiltration, sparse collagen deposition, and poor granulation tissue formation.

In contrast, wounds treated with the ECO bioepoxy film exhibited complete epithelialization, abundant collagen deposition, organized fibroblast proliferation, extensive neovascularization, and minimal inflammatory cell infiltration, indicating advanced tissue regeneration and wound remodeling.

EKO-treated animals also demonstrated improved tissue regeneration compared with controls but showed comparatively lower collagen organization than ECO-treated wounds.

Table 8. Histopathological Scoring of Wound Healing

Parameter	Control	ECO Film	EKO Film
Epithelialization	+	++++	+++
Collagen Deposition	+	++++	+++
Angiogenesis	+	++++	+++
Fibroblast Proliferation	++	++++	+++
Inflammation	++++	+	++

(+ minimal, ++ mild, +++ moderate, ++++ extensive)

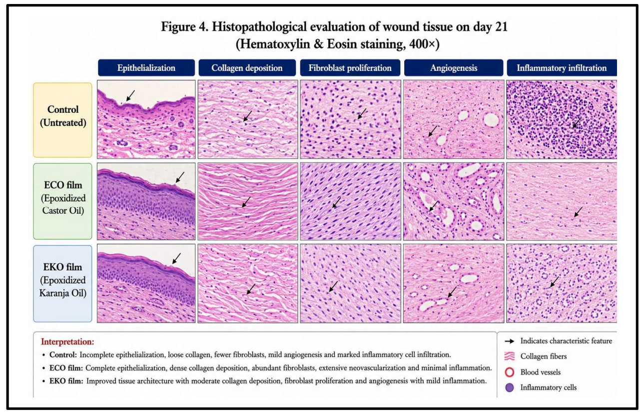

Figure 4. Histopathological sections of wound tissues showing epithelialization, collagen deposition, fibroblast proliferation, and angiogenesis

The histopathological observations corroborated the wound contraction results, indicating superior wound healing efficacy of ECO bioepoxy films.

4. DISCUSSION

The present investigation comparatively evaluated bioepoxy resin films derived from epoxidized castor oil and epoxidized karanja oil as potential wound dressing materials. Both oils were successfully converted into bioepoxy resins and fabricated into flexible wound dressing films possessing suitable physicochemical and biological characteristics.

Vegetable oil-based bioepoxy resins have emerged as attractive alternatives to petroleum-derived polymers because of their renewable nature, biodegradability, and reduced environmental impact (5,13). Epoxidation introduces reactive oxirane groups into unsaturated fatty acids, thereby facilitating crosslinking and enhancing polymer performance (6,14).

The developed films exhibited uniform thickness and good flexibility. Film thickness is an important parameter affecting oxygen permeability, moisture transport, and handling properties of wound dressings (15). The thickness values obtained in the present study were within the acceptable range reported for polymeric wound dressing systems.

Surface pH plays a crucial role in maintaining an environment favorable for wound healing. Healthy skin generally exhibits a mildly acidic pH ranging from 4.5 to 6.5 (16). The surface pH values observed for both films ranged from 5.8 to 5.9, suggesting compatibility with skin physiology and minimizing the risk of irritation.

Mechanical properties significantly influence the clinical performance of wound dressings. An ideal wound dressing should possess sufficient strength to withstand handling while remaining flexible enough to adapt to body movements (17). ECO films demonstrated superior tensile strength compared with EKO films. This finding may be attributed to the higher hydroxyl functionality of ricinoleic acid present in castor oil, which contributes to enhanced crosslinking density and improved mechanical integrity (18).

Moisture absorption and swelling characteristics are important indicators of wound exudate management capacity. Excessive wound exudate may delay healing and increase infection risk, whereas insufficient moisture may cause wound dehydration (19). The EKO films exhibited higher moisture absorption and swelling indices, suggesting improved fluid uptake capacity. These properties may be beneficial for moderately exuding wounds.

Water vapor transmission rate (WVTR) represents another critical parameter governing wound healing performance. An ideal dressing should maintain a moist environment while preventing excessive fluid accumulation (20). Both ECO and EKO films exhibited WVTR values compatible with reported requirements for wound healing applications. The slightly lower WVTR of ECO films may contribute to enhanced moisture retention at the wound site.

The wound healing study demonstrated significantly accelerated wound contraction in animals treated with bioepoxy films. Wound contraction reflects the ability of fibroblasts and myofibroblasts to reduce wound size and facilitate tissue repair (21). ECO films produced the highest wound contraction percentage and shortest epithelization period, indicating superior healing activity.

The enhanced wound healing observed with ECO films may be attributed to several mechanisms. Castor oil contains ricinoleic acid, which possesses documented anti-inflammatory and antimicrobial activities (22). These properties may reduce inflammation and promote tissue regeneration. Furthermore, the superior mechanical characteristics of ECO films likely provide a more stable microenvironment for cellular proliferation and migration.

Although EKO films demonstrated slightly lower wound healing efficacy than ECO films, they still produced significant improvements compared with untreated controls. Pongamia pinnata oil contains karanjin, pongamol, flavonoids, and other phytoconstituents known to possess antioxidant and antimicrobial properties (23,24). These compounds may contribute to the observed wound healing activity.

Histopathological findings supported the macroscopic observations. Enhanced collagen deposition, fibroblast proliferation, and angiogenesis were evident in treatment groups. Collagen synthesis is a key event during the proliferative phase of wound healing and contributes to wound strength and tissue remodeling (25). The dense collagen fibers observed in ECO-treated wounds indicate advanced tissue maturation.

Angiogenesis is essential for supplying nutrients and oxygen to regenerating tissues (26). Increased neovascularization observed in both treatment groups suggests improved tissue repair processes. Reduced inflammatory cell infiltration further indicates progression toward the remodeling phase of healing.

The findings of the present study are consistent with previous investigations reporting wound healing activity of castor oil and karanja-derived products (9–12). However, the current work provides a direct comparative evaluation of bioepoxy resin films prepared from both oils under identical experimental conditions.

Overall, the results indicate that both bioepoxy films possess favorable wound dressing characteristics. Nevertheless, castor oil-derived bioepoxy films demonstrated superior mechanical strength, faster wound contraction, and improved tissue regeneration compared with karanja oil-derived films.

5. CONCLUSION

The present study successfully synthesized and evaluated bioepoxy resin films derived from epoxidized castor oil and epoxidized karanja oil. Both films exhibited acceptable physicochemical characteristics, moisture management properties, and wound healing activity suitable for wound dressing applications.

Comparative evaluation revealed that epoxidized castor oil bioepoxy films exhibited superior tensile strength, faster wound contraction, shorter epithelization period, enhanced collagen deposition, and improved angiogenesis compared with epoxidized karanja oil films. The superior performance of castor oil-based films may be attributed to their favorable polymeric structure and inherent biological activity.

These findings suggest that castor oil-derived bioepoxy resin films represent a promising sustainable biomaterial for wound management and may serve as an alternative to conventional synthetic wound dressings. Future investigations involving antimicrobial evaluation, biodegradation studies, and clinical assessment are warranted to establish their translational potential.

Declarations

Ethical Approval

All animal experiments were conducted in accordance with CPCSEA guidelines and approved by the Institutional Animal Ethics Committee.

Funding

The authors received no specific funding for this work.

Conflict of Interest

The authors declare no conflict of interest.

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