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Original article

Comparative Evaluation of Individual and Combined Plant Extracts for Hair Conditioning: Effects of *Ziziphus lotus*, *Linum usitatissimum*, and *Opuntia ficus-indica* on Virgin and Bleached Hair

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Abstract
Chemical bleaching can substantially alter hair fibre structure, increasing porosity and surface damage. This study evaluated the effects of Ziziphus lotus, Linum usitatissimum, and Opuntia ficus-indica extracts on virgin and bleached hair and examined their potential use in a plant-based hair conditioner. We evaluated hair samples treated with the individual extracts and their combination using qualitative porosity testing, fluorescence microscopy, and scanning electron microscopy (SEM). Bleaching resulted in very high porosity and marked disruption of the cuticular surface, while the responses of bleached hair to the individual extracts varied. Treatment with the combined plant extracts reduced the qualitative porosity from very high to medium and resulted in a more continuous and organised surface morphology. The formulated conditioner showed satisfactory physical characteristics, including a smooth, homogeneous appearance, no visible phase separation, a pH of 5.41, a spreadability of 4.9 cm, and an adhesion value of 550 g. No visible irritation was observed during the preliminary testing. Overall, the results suggest that the plant extracts, particularly when used in combination, may have conditioning and surface-protective effects on bleached hair.
Keywords. Ziziphus Lotus; Linum Usitatissimum; Opuntia Ficus-Indica; Plant-Based Hair Conditioner; Hair Porosity.

Introduction

Human hair is continuously exposed to environmental, chemical, and mechanical stress throughout its lifetime. Solar ultraviolet (UV) radiation and atmospheric pollutants can induce oxidative and structural changes in the hair fibre [1]. Cosmetic procedures, including bleaching, dyeing, perming, and chemical straightening, can also cause substantial alterations to both the cuticle and cortex [2]. Routine grooming practices such as washing, combing, and drying may further contribute to surface damage through repeated friction and mechanical stress [3]. The cuticle forms the primary protective barrier of the hair fibre, and its progressive erosion, lifting, and disruption can increase surface roughness and porosity, leaving the underlying cortex more vulnerable to damage [4].

Prolonged exposure to these stressors may lead to protein and lipid loss, disruption of the cortical structure, reduced tensile strength and elasticity, and, ultimately, greater susceptibility to fibre breakage [5]. Since the mature hair shaft consists predominantly of dead, keratinised cells, it has no biological capacity to regenerate or repair structural damage once it has occurred. The treatment of damaged hair therefore relies mainly on external preparations that can modify the physicochemical properties of the fibre rather than on true biological regeneration [6, 7]. Plant-derived ingredients have received increasing attention in damaged-hair care as potential alternatives to conventional ingredients. Botanical extracts, oils, proteins, peptides, and other bioactive constituents may provide conditioning, antioxidant, film-forming, and surface-modifying effects. Through their interaction with or deposition onto damaged fibres, these substances may reduce surface roughness and friction, improve hair manageability, and partially restore properties affected by environmental, thermal, or chemical damage. Although plant-based preparations cannot regenerate damaged hair tissue, suitable botanical ingredients may therefore contribute to the cosmetic repair and protection of the hair fibre and help limit further deterioration [8-10]. The lack of biological regeneration in mature hair fibres has encouraged interest in plant-derived materials for the cosmetic protection and restoration of damaged hair.

Among Mediterranean and traditionally used plants, *Ziziphus lotus* (L.) Lam., *Linum usitatissimum* L., and *Opuntia ficus-indica* (L.) Mill. are potential candidates because of their diverse phytochemical profiles and functional properties. *Z. lotus* contains phenolic compounds, flavonoids, and other bioactive constituents associated with antioxidant activity, which may contribute to protection against oxidative damage. *L. usitatissimum* is of particular interest because its seed-derived polysaccharides have been incorporated experimentally into hair-care treatments and have been reported to improve the resistance and surface integrity of bleached and chemically treated hair fibres. *O. ficus-indica* is rich in polysaccharides, phenolic compounds, minerals, and other bioactive constituents and has also demonstrated moisturising and antioxidant potential relevant to cosmetic applications. Together, these properties suggest that preparations derived from *Z. lotus*, *L. usitatissimum*, and *O. ficus-indica* may be useful as plant-based ingredients for improving the surface properties and protection of virgin and chemically damaged hair. However, their comparative effects on bleached and virgin hair require systematic experimental evaluation [11-13]. Therefore, this study aimed to evaluate the effects of *Ziziphus lotus*, *Linum usitatissimum*, and *Opuntia ficus-indica* extracts on virgin and bleached hair fibres. The effects were assessed using hair porosity testing, fluorescence microscopy, and scanning electron microscopy. Based on the results, the most effective

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plant extract or combination of extracts was selected for the development of a plant-based hair conditioner, which was subsequently evaluated for its efficacy and stability.

Methods

Plant collection and identification

Ziziphus lotus and *Linum usitatissimum* were obtained from Alrabie Supplier, Tripoli, Janzour, Akwas Street, Libya. The plant materials were taxonomically identified and authenticated by Dr Mohammed Makhlouf, Head of the Herbarium, Faculty of Science, University of Tripoli, Libya. A voucher specimen of *Ziziphus lotus* was deposited in the herbarium under voucher number 1976-30-2-3.

Preparation of plant extracts

Dried leaves of *Ziziphus lotus* were ground into a coarse powder, and 135 g of the powdered material was subjected to maceration with methanol for 3 × 72 h. The methanol was replaced every three days to maintain extraction efficiency. After extraction, the combined methanolic extract was filtered and concentrated by evaporation of the solvent to obtain the crude extract (Figure 1).

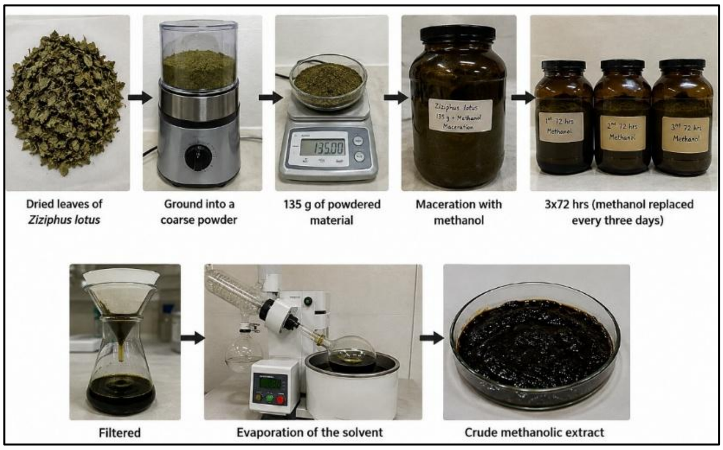

***Figure 1. Extraction method of* Ziziphus lotus leaves**.

For *Linum usitatissimum*, 380 g of crushed seeds were macerated with hexane for 3 × 72 h. The solvent was replaced every three days throughout the extraction period. The resulting extract was filtered, and the hexane was removed by evaporation to obtain the crude hexane extract (Figure 2).

Figure 2. Hexane extraction* of *Linum usitatissimum seeds.

The mucilage of *Linum usitatissimum* was prepared by infusion. Briefly, water was heated, after which the crushed seeds were added and allowed to stand for 10 min. The preparation was then filtered to obtain the aqueous mucilage extract (Figure 3).

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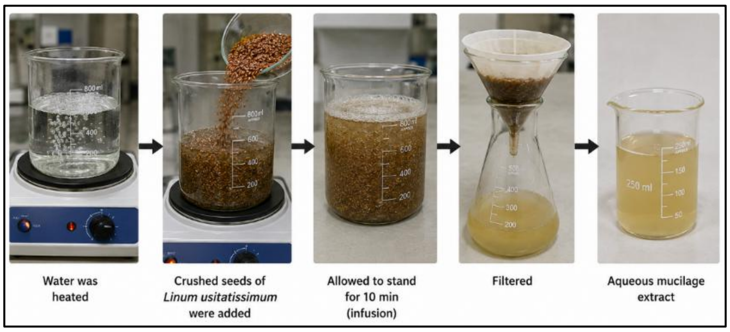

Figure 3. Mucilage extraction of Linum usitatissimum seeds

Fresh cladodes of *Opuntia ficus-indica* were collected on the day of the experiment. Approximately 65 g of fresh cladode material was processed to obtain the mucilaginous gel, which was used directly as the fresh plant preparation (Figure 4).

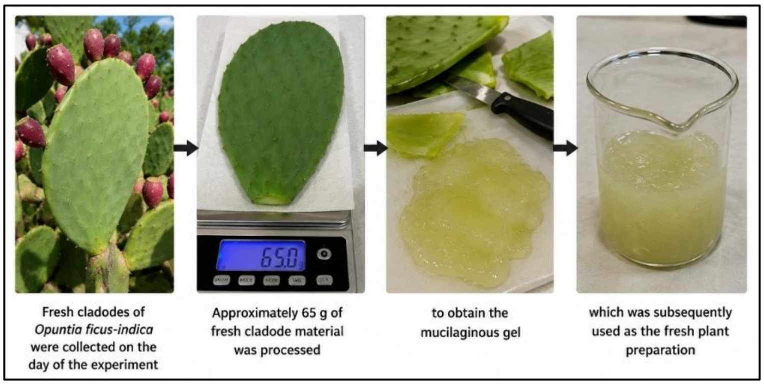

Figure 4. Gel preparation of fresh cladode of Opuntia ficus-indica.

Hair sample preparation and experimental grouping

Hair samples were obtained from a 9-year-old male volunteer with naturally dark-brown, straight hair. A total of 46 hair tresses were prepared and randomly divided into two experimental groups. The first group consisted of hair tresses that were chemically bleached before treatment with the selected plant extracts to evaluate the effects of the extracts on chemically damaged hair fibres. The second group consisted of untreated (virgin) hair tresses that were treated directly with the selected plant extracts without prior chemical treatment. For bleaching, a commercially available hair-bleaching product was used according to the manufacturer's instructions. The product was purchased from 212 Beauty Shop, Al-Hashan, Awlad Bin Al-Haj Street, Tripoli, Libya. The bleaching procedure was performed according to the product instructions (Figure 5).

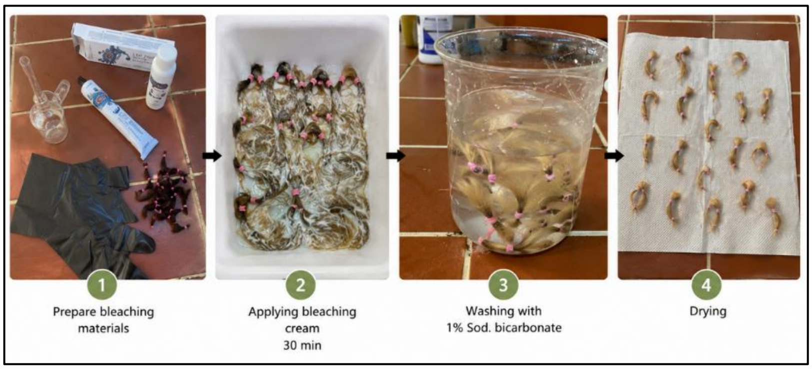

Figure 5. Hair bleaching procedure

Treatment of hair tresses with plant preparations

Both virgin and bleached hair tresses were treated separately with the individual plant preparations and their combination (Table 1). For each treatment, clean 10-mL glass beakers were labelled according to the corresponding hair sample and treatment group. Approximately 3 mL of fresh *Opuntia ficus-indica* gel was applied to the virgin and bleached hair tresses designated N1 and B1, respectively. The aqueous mucilage extract of *Linum usitatissimum* was applied to samples N2 and B2, whereas the hexane extract of *L. usitatissimum* was applied to samples N3 and B3. For *Ziziphus lotus*, a 20% (w/v) preparation was made using distilled water as the solvent, and approximately 3 mL was applied to the corresponding virgin and bleached hair tresses (N4 and B4, respectively). The same procedure was used for the treatment containing a mixture of the four plant preparations. After application, the treated hair tresses were left in contact with the respective preparations

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for 1 h. The samples were then rinsed with freshly prepared 1% (w/v) sodium bicarbonate solution (1g/100 mL), followed by washing with tap water to simulate routine hair-washing conditions. Sodium bicarbonate was used instead of sodium lauryl sulfate to minimise potential interference from a conventional surfactant and to provide a mild washing medium for removing residual aqueous and lipid-soluble materials from the hair surface (Figure 6).

Table 1. Different plant preparations used in the treatment of virgin and bleached hair.

Plant	Preparation
Opuntia ficus-indica	Fresh gel
Linum usitatissimum	Aqueous mucilage
Linum usitatissimum	Hexane extract
Ziziphus lotus	20% aqueous preparation

Figure 6. Hair treatment procedure with individual plant extracts and mixture.
B1-B4 = bleached hair samples; N1-N4 = non-bleached hair samples.

Hair evaluation
The effects of bleaching and subsequent treatment with the selected plant preparations were evaluated using complementary physicochemical and microscopic methods. Virgin hair tresses were used as the untreated control, while bleached and plant-treated tresses were compared with respect to changes in hair porosity and surface morphology.

Hair porosity
Hair porosity was qualitatively assessed using a water-immersion method. A clean beaker was filled with tap water, and three to five individual hair shafts from each experimental group were gently placed on the water surface. The position and movement of the hair shafts, particularly whether they remained on the surface or moved downward into the water, were observed and recorded. The procedure was performed for virgin, bleached, and plant-treated samples under comparable conditions. Hair porosity reflects the structural condition of the hair fibre and may be influenced by chemical treatments that alter the cuticle and underlying structures [14,15].

Fluorescence microscopy
Representative hair samples from the virgin, bleached, and plant-treated groups were examined by fluorescence microscopy in the Department of Pharmacognosy, Faculty of Pharmacy, University of Tripoli, Libya. The samples were mounted and examined under the same microscopic conditions, and representative images were captured for comparison. Fluorescence microscopy has been used to examine hair fibres because of their intrinsic fluorescence and can provide information on structural and morphological characteristics of the hair shaft [16].

Scanning electron microscopy (SEM)
Scanning electron microscopy (SEM) was used to assess the surface morphology and structural integrity of the hair fibres. Representative samples from the virgin control, bleached, and plant-treated groups were submitted to the Industrial Research Centre, Tajoura, Tripoli, Libya, for SEM analysis. The samples were examined at different magnifications to allow comparison of the cuticular surface and other morphological features. SEM is sensitive to structural changes in hair associated with cosmetic treatments, including bleaching, dyeing, and straightening [17]. Bleaching, in particular, has been reported to cause disruption, fragmentation, and separation of the cuticular scales, accompanied by increased surface roughness and, in more severe cases, exposure and alteration of the underlying cortical structure [15].

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Formulation of the Hair Conditioner

Based on the composition of the selected plant preparations, a plant-based hair conditioner was formulated as an oil-in-water (O/W) emulsion. The aqueous components, consisting of *Ziziphus lotus* preparation, linseed (*Linum usitatissimum*) mucilage, and prickly pear (*Opuntia ficus-indica*) gel, were combined with linseed oil and subjected to high-shear mixing to facilitate emulsification and produce a homogeneous preparation. The emulsion was then transferred to a hot plate and heated to 60 ± 2°C. Starch was gradually incorporated under continuous stirring until the desired consistency was obtained. Essential oil and vitamin E were subsequently added to the formulation in the specified amounts. The final preparation was allowed to cool to room temperature and stored in a suitable container until further evaluation. The composition of the formulated hair conditioner is presented in (Table 2).

Table 2. Hair conditioner formulation using Linum usitatissimum gel & oil, Ziziphus lotus preparation, Opuntia ficus-indica gel.

Ingredient	Amount
Linseed gel (*Linum usitatissimum)*	100 mL
Linseed oil (*Linum usitatissimum)*	25 mL
Ziziphus lotus preparation	25 mL
Prickly pear gel (*Opuntia ficus-indica*)	100 mL
Starch	6 g
Essential oil	1% w/w
Vitamin E	1% w/w

Evaluation of the formulated conditioner

The final hair conditioner formulation was evaluated for selected physicochemical and preliminary safety characteristics, including organoleptic properties, physical stability, pH, spreadability, adhesion, and skin compatibility. These parameters were selected to assess the physical quality, application characteristics, and short-term stability of the formulation. Such characteristics are relevant to the performance and stability of emulsion-based cosmetic preparations.

Organoleptic evaluation and short-term stability

The freshly prepared conditioner was visually examined for colour, odour, consistency, homogeneity, and evidence of phase separation. The formulation was then observed under the predetermined storage conditions at 0 h, 1 h, 1 day, 3 days, and 7 days. Any changes in colour, odour, consistency, homogeneity, or phase separation were recorded throughout the observation period. Organoleptic examination is commonly used as an initial assessment of the physical stability of emulsion-based cosmetic formulations, as changes in appearance or the occurrence of phase separation may indicate physical instability [18,19].

pH measurement

The pH of the formulated conditioner was determined using a calibrated digital pH meter. Briefly, 5 g of the formulation was dispersed in 50 mL of distilled water to obtain a 10% (w/v) dispersion. The dispersion was mixed until homogeneous, and the pH was measured at room temperature after stabilisation of the electrode reading. The pH of hair-care formulations is an important physicochemical parameter because alkaline conditions can increase the negative charge of the hair fibre and contribute to increased friction, whereas appropriately acidic formulations are generally more compatible with the physicochemical characteristics of the hair shaft [20].

Spreadability test

The spreadability of the conditioner was evaluated using a parallel-plate method. Briefly, 1 g of the formulation was placed at the centre of a calibrated glass plate. A second glass plate of known weight was carefully placed over the sample, followed by application of a 125-g load for 1 min. After removal of the load, the diameter of the spread formulation was measured in centimetres. The test was performed under controlled conditions, and the measured diameter was used as an indicator of the ease with which the formulation could be distributed over a surface. Spreadability is an important performance characteristic of semisolid formulations and is influenced by their composition and rheological properties [21].

Preliminary skin-compatibility assessment

A preliminary skin-compatibility assessment was performed by applying a small amount of the formulated conditioner to a limited area of skin and, separately, to the scalp for 5 min, after which the test areas were rinsed with water. The exposed areas were visually examined for apparent erythema, oedema, itching, burning, or other visible abnormal reactions. This procedure was considered a preliminary observation of acute local tolerance and was not intended as a definitive assessment of sensitisation or overall product safety [22].

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Adhesion test
The adhesive behaviour of the formulation was evaluated using a glass-slide method. Briefly, 0.5 g of the conditioner was placed on the surface of a clean glass slide, and a second glass slide was placed over the sample. A 1-kg load was applied for 5 min to ensure uniform contact between the two slides. The slides were then mounted on the test apparatus, and an 80-g load was applied to initiate separation. The time required for complete separation of the two slides was recorded as the adhesion time. The test was performed under identical conditions for each measurement. Glass-slide separation methods have been used to characterise the adhesive behaviour of semisolid formulations, with adhesion time serving as an indicator of the ability of a formulation to remain attached to the test surface [23].

Results and Discussion
Porosity test results
The porosity test showed that bleaching markedly affected the porosity of the hair samples (Table 3). Untreated non-bleached hair (N0) exhibited medium porosity, whereas untreated bleached hair (B0) sank directly to the bottom of the water, indicating very high porosity. All non-bleached hair samples treated with the individual extracts (N1-N4) showed medium porosity, indicating that the individual extracts did not produce a substantial qualitative change in the porosity of virgin hair. In the bleached samples, however, the response to the individual treatments varied, with porosity ranging from medium (B2 and B4) to medium-to-high (B3) and very high (B1). The non-bleached sample treated with the extract mixture (Nm) showed medium porosity. The bleached mixture-treated sample (Bm) also exhibited medium porosity, although it sank after shaking.

Table 3. Porosity test results for the bleached and virgin hair (treated and control)

Code	Sample name	Motional behavior	description
N0	Control (virgin)	Remained floating and in the middle.	Medium
B0	Control (bleached)	Directly sank to the bottom.	Very high
N1	Normal *Opuntia ficus-indica*	Partially floating with static parts in the middle of the water.	Medium
N2	Normal *Linum usitatissimum* seed gel	Partially floating with static parts in the middle of the water.	Medium
N3	Normal *Linum usitatissimum* seed oil	Partially floating with static parts in the middle of the water.	Medium
N4	Normal *Ziziphus lotus*	Partially floating with static parts in the middle of the water.	Medium
B1	Bleached *Opuntia ficus-indica*	Directly sinks to the bottom.	Very high
B2	Bleached *Linum usitatissimum* seed gel	Floating, sinks with slight shaking.	Medium
B3	Bleached *Linum usitatissimum* seed oil	Half-floating, half-sinking.	Medium to high
B4	Bleached *Ziziphus lotus*	Took time to sink.	Medium
Nm	Normal mix	Remained in the middle, with a part sank after several minutes of standing.	Medium (perfect behaviour)
Bm	Bleached mix	Remained in the middle, sank with shaking.	Medium

The marked difference between B0 and the treated bleached samples suggests that the extract treatments may have altered the wetting behaviour of the bleached hair. Because the float test is qualitative, however, these observations should not be considered direct evidence of structural repair. The very high porosity observed in B0 is consistent with previous studies showing that oxidative bleaching damages the hair cuticle and increases fibre permeability and water uptake [24]. The relatively low water uptake observed for sample Nm may indicate a more intact and less permeable cuticular surface. The role of surface lipids in regulating hair hydration and water diffusion has also been documented, although their contribution to water permeability appears to be complex and dependent on their distribution and physicochemical characteristics. Taken together, the present porosity results support the interpretation that Nm had comparatively better surface integrity [25,26].

Fluorescence Microscopy
Fluorescence microscopic examination revealed distinct morphological differences between normal untreated hair (N0) and bleached untreated hair (B0). The N0 hair shaft exhibited a relatively uniform and continuous appearance, with comparatively smooth and intact surface characteristics. In contrast, B0 showed greater surface irregularity, heterogeneity,

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and localised structural discontinuities, suggesting alteration of the cuticular region following bleaching. The B0 sample also exhibited greater variation in optical and fluorescence appearance along the hair shaft. These observations were consistent with the porosity results, in which N0 exhibited medium porosity, whereas B0 sank directly to the bottom of the water, indicating very high porosity. The greater surface disruption observed microscopically may facilitate increased water penetration into the bleached fibre. Such changes are consistent with previous reports that oxidative bleaching can disrupt the hair cuticle and alter the physical and chemical properties of the hair fibre, resulting in increased porosity and permeability [24,27].

Fluorescence microscopy also revealed differences in the morphology and optical appearance of bleached hair following treatment with the selected plant-derived preparations (Figure 7). *Opuntia ficus-indica*-treated hair (B1) exhibited a relatively continuous and homogeneous shaft with limited apparent surface irregularity. Hair treated with *Linum usitatissimum* gel (B2) showed greater optical heterogeneity, with localised irregular or discontinuous regions along the hair shaft. *Linum usitatissimum* oil-treated hair (B3) generally exhibited a continuous shaft, although localised surface roughness was evident in some fields. *Ziziphus lotus*-treated hair (B4) also showed a relatively continuous shaft with localised heterogeneous regions. Compared with the untreated bleached control (B0), the treated samples generally showed a more continuous surface appearance, suggesting that the treatments may have modified the exposed surface of the bleached fibres. This effect may be associated with the deposition of, or interaction between, extract constituents and the damaged cuticular surface. However, the observed microscopic changes should be interpreted as qualitative morphological differences rather than definitive evidence of structural repair, since fluorescence intensity and cuticle restoration were not quantitatively measured. These observations are consistent with previous reports that cuticular damage increases surface irregularity and permeability, while conditioning treatments containing lipidic materials may improve the surface properties of damaged hair fibres [26-28].

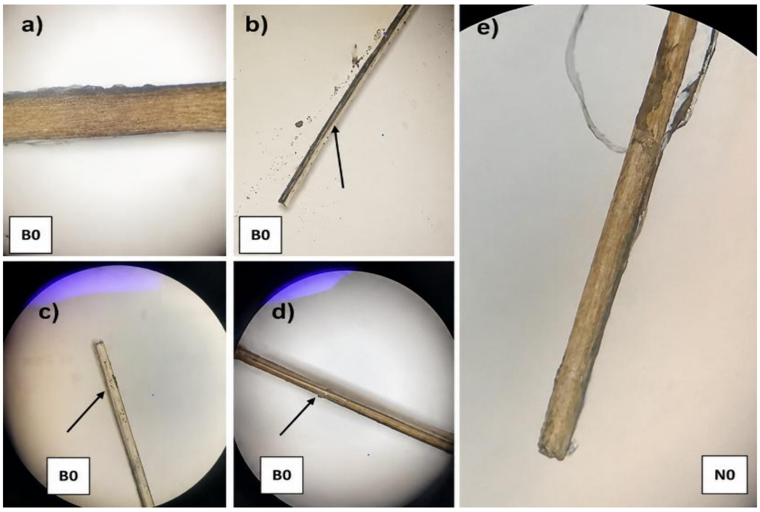

Figure 6. Fluorescence microscope results of normal N0 & bleached hair (no treatment) B0.

B0 images (a–d) show an irregular and heterogeneous hair surface. Less uniform shaft, surface roughness and localised irregularities. In several views, (b) discontinuities/raised or separated surface regions around the hair shaft. Disruption of the cuticle following bleaching.

Fluorescence microscopic examination of normal hair treated with the selected plant extracts (Figure 8) showed generally preserved hair-fibre morphology in all treatment groups. N1-N4 exhibited continuous and clearly defined hair shafts with relatively limited surface irregularities. N1 showed a relatively uniform shaft with no apparent major structural disruption, while N2 exhibited a particularly homogeneous appearance across the observed fields. N3 showed a continuous fibre with minor localised surface variations, and N4 demonstrated a generally preserved shaft with some localised optical heterogeneity. Overall, none of the treatments produced obvious severe morphological damage to normal hair. These observations were consistent with the porosity test, in which all treated normal-hair samples exhibited medium porosity, similar to the untreated normal control (N0). The results therefore suggest that treatment with the selected plant preparations maintained the general structural appearance and qualitative porosity characteristics of normal hair. The localised differences in optical appearance may reflect differences in surface deposition or interactions between constituents of the plant preparations and the hair fibre. However, fluorescence microscopy alone cannot establish cuticular repair or quantify changes in fluorescence intensity; such conclusions would require complementary quantitative or ultrastructural analyses.

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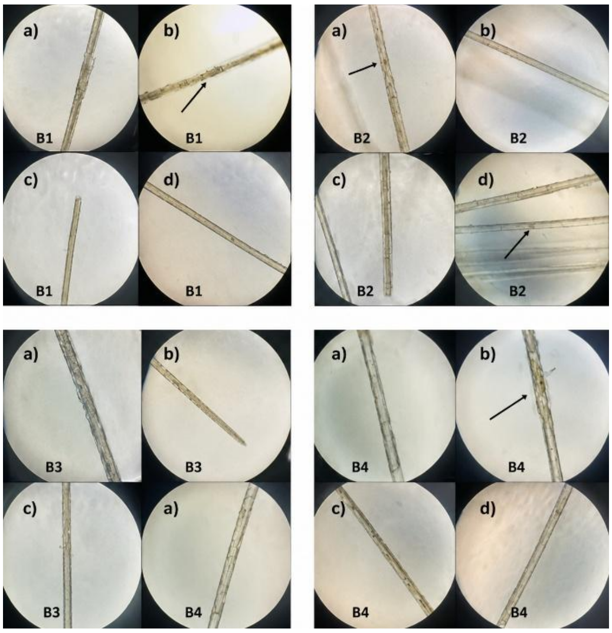

Figure 7. Fluorescence microscope results of bleached hair treated with plant extract.

B1: continuous and comparatively uniform hair shaft, limited visible surface disruption, localised irregularity in the higher-magnification views. B2: greater surface heterogeneity than B1. The hair shaft contains localised irregular or discontinuous regions, in panels (a) and (d), where the arrows indicate areas of apparent surface alteration. B3: distinct and continuous shaft; panel (a) shows noticeable surface irregularity/roughness along the fibre. The other views appear comparatively smooth, with relatively little obvious disruption. B4: relatively clear hair shaft with localised heterogeneous regions. Panel (b) shows a conspicuous irregular/darker area indicated by the arrow, while the other panels show comparatively continuous shaft morphology.

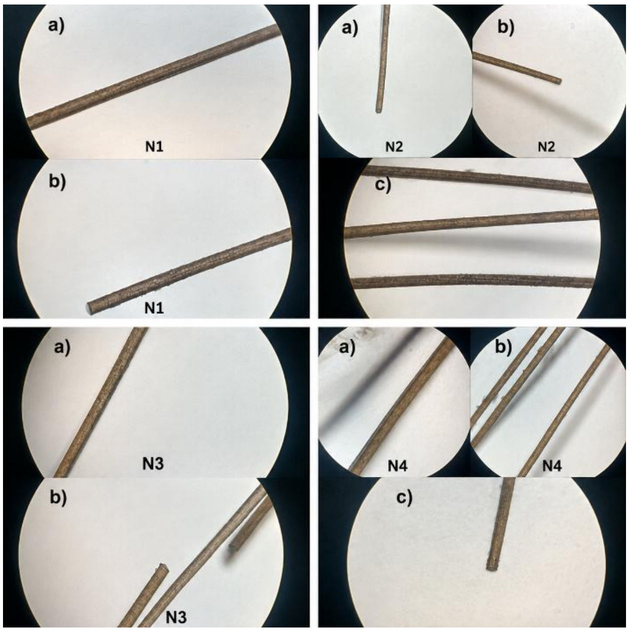

Figure 8. Fluorescence microscope result of normal hair treated with plant extract.

N1-N4: continuous, well-defined hair shaft, uniform appearance.

Fluorescence microscopy of hair treated with the formulated moisturiser (Figure 9) showed a relatively continuous and well-defined morphology in both normal and bleached hair. Normal hair treated with the formulation exhibited a relatively smooth and homogeneous shaft, indicating preservation of the normal hair structure. Bleached hair treated with the formulation (Bm) also showed generally continuous fibres with relatively smooth outlines, although some localised optical heterogeneity was observed. Compared with the untreated bleached control (B0), Bm exhibited a more continuous and less apparently disrupted surface morphology. Together with the porosity results, in which B0 showed very high porosity whereas Bm exhibited medium porosity, this observation suggests that the formulated moisturiser may have produced a conditioning or surface-coating effect that reduced the apparent accessibility of the bleached fibre to water. This effect may be related to the deposition of, or interaction between, moisturising and conditioning constituents and the damaged cuticular surface. In normal hair, the relatively preserved morphology suggests that the formulation primarily maintained

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the existing structural integrity rather than producing a marked morphological alteration. Nevertheless, fluorescence microscopy provides qualitative evidence, and further techniques such as SEM, FTIR, quantitative fluorescence analysis, or mechanical testing would be required to confirm actual cuticular repair or changes in the chemical structure of the hair fibre. Similar relationships between cuticular damage, increased hair porosity, and altered surface morphology have been reported previously [26,27]. The present observations therefore support a potential protective or conditioning effect of the formulation, although microscopy alone cannot confirm structural repair of the cuticle.

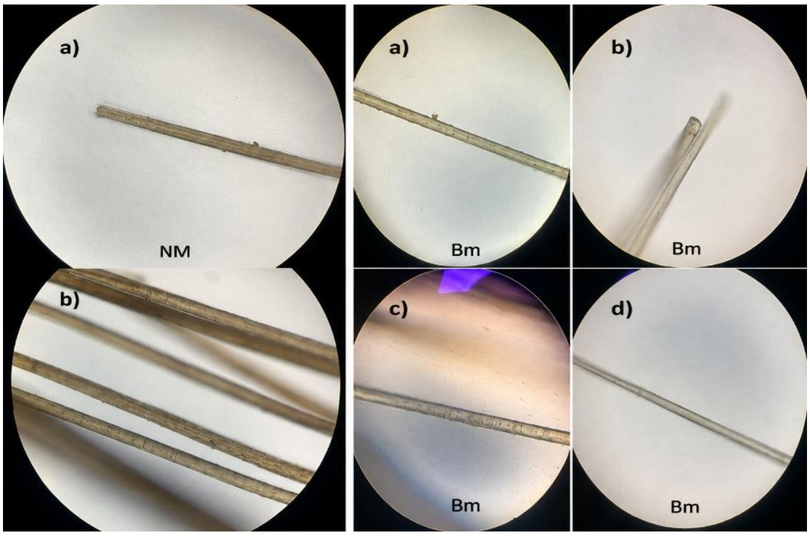

Figure 9. Fluorescence microscope results of Normal and bleached hair treated with formulated moisturiser.

The normal hair (Nm has continuous, smooth, well-defined hair shafts. The Bm has continuous hair fibres with generally preserved morphology. In panel (a), the fibre is delineated and appears uniform. Panel (b) shows a relatively smooth fibre with a well-defined outline, while panel (c) shows a more heterogeneous/rough optical appearance. Panel (d) shows a long, relatively uniform fibre with limited apparent surface irregularity.

Scanning electron microscopy (SEM) results

Scanning electron microscopy revealed distinct morphological differences between normal untreated hair (N0) and bleached untreated hair (B0) (Fig. 10). The N0 samples exhibited a relatively continuous and organised cuticular structure, with overlapping cuticle scales that appeared comparatively intact and closely associated with the hair shaft. Minor natural surface irregularities were observed, but no prominent large-scale cuticular disruption was evident. In contrast, B0 demonstrated pronounced surface alterations, including irregular and partially lifted cuticular scales, localised peeling, surface discontinuities, and fissure-like structures. The areas indicated by arrows in the SEM image show localised lifting and disruption of the cuticular layers. These morphological changes indicate that the bleaching process substantially altered the integrity and organisation of the hair cuticle. The SEM findings were consistent with the porosity results, in which N0 exhibited medium porosity whereas B0 showed very high porosity. Damage to and separation of the cuticular layers may increase the accessibility of water to the hair fibre and thereby contribute to the increased porosity observed in bleached hair. The findings are also consistent with previous descriptions of oxidative bleaching, which can alter the cuticle and increase hair-fibre permeability, surface roughness, and susceptibility to further damage [28,29]. SEM examination demonstrated differences in the surface morphology of bleached hair following treatment with the selected plant extracts (Fig. 11).

Compared with the untreated bleached control (B0), which exhibited pronounced cuticular irregularity, lifting, peeling, and fissure-like surface defects, the treated samples generally showed a more continuous and compact hair-fibre surface. Prickly bear-treated hair (B1) exhibited a relatively smooth and continuous surface with limited prominent cuticular disruption. Linseed gel-treated hair (B2) showed a generally continuous but heterogeneous surface, whereas linseed oil-treated hair (B3) exhibited a relatively compact fibre with localised surface irregularities. Jojoba-treated hair (B4) maintained overall fibre continuity but displayed some granular and heterogeneous surface features. These findings suggest that the plant treatments produced varying degrees of surface modification or conditioning of the bleached hair fibre. The apparent improvement in surface continuity may be associated with the deposition of, or interaction between, extract constituents and the damaged cuticular surface. The SEM findings were partly supported by the porosity results, particularly for B2 and B4, which exhibited medium porosity compared with the very high porosity of the untreated bleached control. However, B1 remained highly porous despite its relatively smooth SEM appearance, indicating that surface morphology does not necessarily directly reflect internal water permeability. The observed SEM changes are therefore best interpreted as evidence of surface conditioning or morphological modification rather than definitive structural repair.

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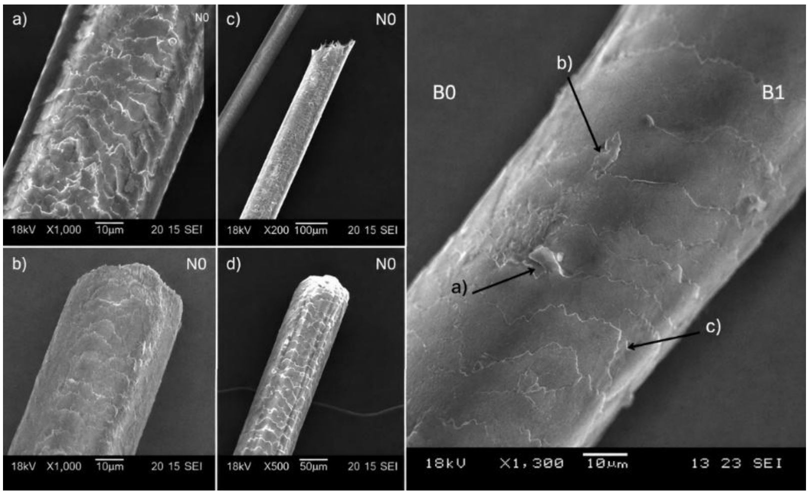

Figure 10. SEM results of Normal (N0) and bleached hair (B0).

Normal untreated hair (N0). N0 (panels a–d) has an organised and continuous cuticular structure along the hair shaft. The cuticle scales are clearly visible and appear to be arranged in an overlapping pattern along the longitudinal axis of the fibre. At higher magnification, the cuticular surface appears relatively compact and coherent, with the scales remaining attached to the underlying fibre. B0 image shows substantially greater surface irregularity and cuticular disruption. Partial lifting/separation of cuticular scales, indicated by the arrows in panels a and b. Irregular and disrupted scale edges, suggesting alteration of the normal overlapping cuticular arrangement. Surface cracks or fissures, particularly in the region indicated in panel c. Areas of peeling and loss of smooth continuity of the cuticular surface. The features indicated by arrows a, b, and c are consistent with localised cuticular damage. The apparent separation and lifting of the scales suggest that the bleaching process has weakened the cohesion between cuticular layers and/or altered the hair surface.

SEM examination of normal hair treated with the selected plant extracts (Figure 12) generally showed preservation of the integrity and organisation of the hair surface. N1 (prickly pear) exhibited a relatively continuous hair shaft with an organised cuticular surface and no prominent evidence of severe peeling or fragmentation. N2 (linseed gel) showed a relatively smooth and continuous surface, with discernible and comparatively organised cuticular scales. N3 (linseed oil) demonstrated a continuous fibre with generally preserved cuticular organisation and minor localised surface irregularities. N4 (jojoba) also maintained the overall integrity of the hair shaft, although some localised surface heterogeneity and more prominent longitudinal surface features were observed. Overall, none of the plant-extract treatments produced obvious severe structural damage to normal hair. Compared with the untreated normal control (N0), the treated samples maintained a generally intact cuticular morphology, suggesting compatibility of the treatments with the normal hair surface. The SEM findings were consistent with the porosity test, in which N1-N4, as well as N0, were classified as having medium porosity. Thus, treatment with the selected plant extracts did not produce an apparent qualitative change in the porosity category of normal hair. The localised surface variations observed in the treated groups may reflect deposition of, or interaction between, extract constituents and the hair surface rather than structural damage.

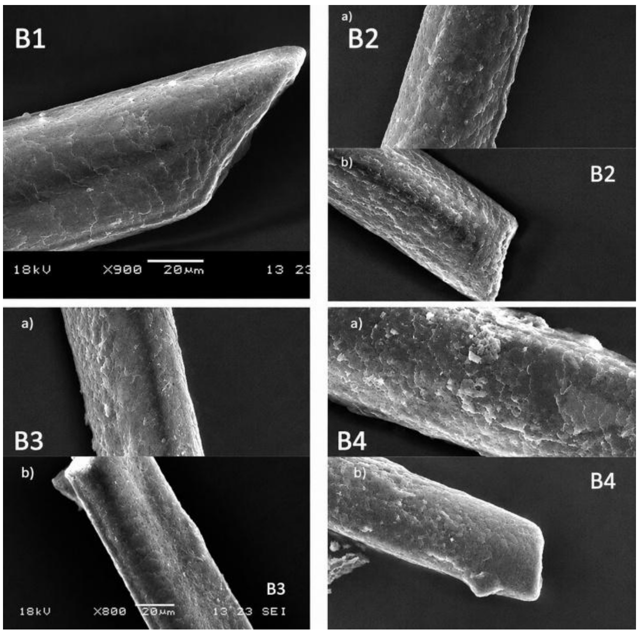

Figure 11. SEM results of bleached hair treated with plant extracts.

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In the treated groups B1–B4, the hair shafts generally appear more continuous and compact than the previous B0, with fewer prominent large-scale areas of cuticular separation. Plant extracts caused modification of the damaged hair surface and a conditioning/coating effect.

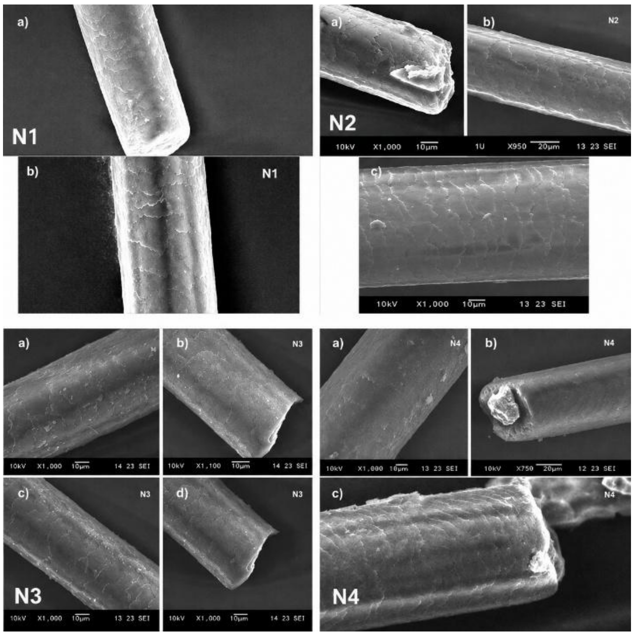

Figure 12. SEM result of Normal hair treated with plant extracts.

N1-N4 showed continuous hair shafts with preserved surface organisation, no obvious extensive peeling, cracking, or fragmentation.

SEM examination of hair treated with the plant-extract mixture (Figure 13) showed preservation of the overall structural integrity of normal hair and an apparent improvement in the surface morphology of bleached hair. Normal hair treated with the mixture (NM) exhibited a relatively continuous and compact surface, with no prominent cracking, peeling, or large-scale disruption of the cuticular structure. Minor surface irregularities and deposits were observed in some areas. Similarly, bleached hair treated with the mixture (BM) showed a generally continuous hair shaft with discernible cuticularorganisation andlocalised surface irregularities. Compared with the untreated bleached control (B0), which exhibited pronounced cuticular lifting, peeling, fissure-like structures, and surface disruption, BM appeared more continuous and compact. These observations suggest that the plant-extract mixture may have exerted a surface-conditioning or coating effect on the bleached hair fibre. The SEM observations were supported by the porosity results, in which normal hair remained in the medium-porosity category after mixture treatment, whereas the very high porosity observed in untreated bleached hair (B0) decreased to medium porosity following mixture treatment (Bm). This change may indicate that deposition of, or interaction between, constituents of the plant-extract mixture and the damaged cuticular surface reduced the apparent accessibility of the fibre to water.

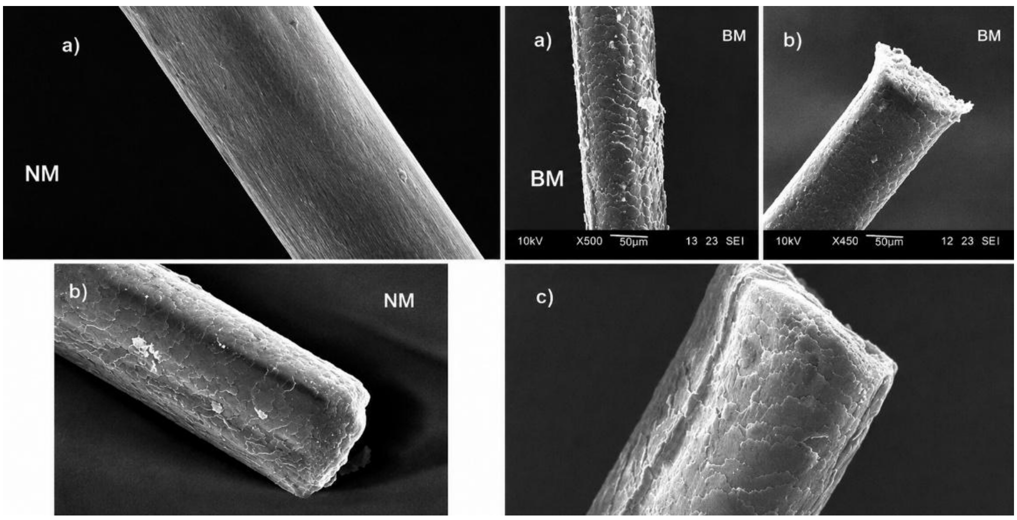

Figure 13. SEM results of Normal and bleached hair treated with a plant extract mixture.

NM Normal hair has a relatively intact cuticle, BM Bleached hair shows substantial cuticular damage, while the mixture-treated bleached hair appears more continuous and organised, with less obvious large-scale cuticular disruption.

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Evaluation of the Hair Conditioner Product

Organoleptic Evaluation Result

The final hair conditioner formulation was evaluated organoleptically to assess its macroscopic physical characteristics, including consistency, colour, odour, and phase separation. These parameters provide an initial indication of the formulation's physical acceptability, homogeneity, and apparent stability. The observations for the prepared conditioner are presented in (Table 4).

Table 4. Organoleptic evaluation of the formulated hair conditioner.

Property	Observation
Consistency	Smooth, clear, mucinous appearance, free from air bubbles and visible aggregates
Color	Pale green
Odor	Lavender with an orange fragrance
Phase separation	Not observed

The formulated hair conditioner showed satisfactory macroscopic characteristics (Table 4). It had a smooth, clear, mucinous consistency without visible air bubbles or aggregates, indicating good apparent homogeneity. The formulation was pale green in colour and had a characteristic lavender-orange fragrance. No visible phase separation was observed. A uniform consistency is desirable in a hair-conditioning preparation because adequate spreading and uniform contact with the hair fibre can facilitate the deposition of conditioning ingredients on the hair surface [29,30]. The pale-green colour may be attributed to naturally occurring constituents of the plant-derived ingredients incorporated into the formulation, whereas the lavender-orange odour reflects the fragrance components of the finished product. The absence of visible phase separation indicates satisfactory preliminary physical uniformity under the observation conditions. However, organoleptic assessment alone cannot establish long-term formulation stability. Further evaluation of physicochemical characteristics, microbiological quality, and stability under defined storage and accelerated conditions would therefore be required. Overall, the formulation showed favourable preliminary organoleptic characteristics and was considered physically acceptable for subsequent evaluation of its conditioning performance.

pH, Spreadability, Adhesion, and Sensitivity Evaluation

The formulated hair conditioner was evaluated for pH, spreadability, adhesion, and preliminary skin-sensitivity characteristics to assess its suitability for topical application to the hair and scalp. The results are presented in (Table 5).

Table 5. Physicochemical and preliminary safety evaluation of the formulated hair conditioner.

Physical parameter	Result
pH	5.41
Spreadability	4.9 cm
Adhesion	550 g
Sensitivity	Safe; non-sensitising under the test conditions

The formulation had a pH of 5.41, indicating a mildly acidic preparation compatible with the physiological acidic environment of the skin and with the conditions generally considered desirable for hair-care formulations. Maintaining an acidic pH is advantageous because highly alkaline conditions can promote hair-fibre swelling and adversely affect the cuticular structure, whereas mildly acidic formulations are generally more compatible with the physicochemical properties of the hair surface [28,31]. The formulation showed a spreadability of 4.9 cm, indicating satisfactory distribution and ease of application. This property is desirable in conditioners because uniform spreading facilitates contact between the formulation and the hair fibre and may support the deposition of conditioning constituents along its surface.

An adhesion value of 550 g was obtained, indicating measurable retention of the formulation under the experimental conditions. Adequate adhesion may provide sufficient residence time for the formulation on the hair surface; however, the significance of this value should be interpreted in relation to the specific test method and appropriate reference criteria. Overall, the spreadability and adhesion results indicate a favourable balance between ease of application and retention. The sensitivity assessment showed no observable redness, itching, or swelling during the 5-min test period, indicating good preliminary local tolerability under the conditions employed. This short-term observation should not, however, be considered definitive evidence of the absence of sensitisation. Longer-term and/or validated dermatological safety testing would be required to establish the safety profile of the formulation. Overall, the results indicate that the formulated conditioner possessed suitable preliminary physicochemical and sensory characteristics for further evaluation of its hair-conditioning performance.

Conclusion

The developed plant-based hair conditioner demonstrated satisfactory organoleptic and physicochemical characteristics, including a smooth and homogeneous appearance, absence of visible phase separation, a mildly acidic pH of 5.41,

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acceptable spreadability, and measurable adhesion. Bleaching substantially altered the hair fibre, as indicated by the very high porosity and pronounced cuticular disruption observed in the untreated bleached control. Treatment with the selected plant extracts produced variable changes in the surface characteristics of bleached hair, whereas treatment with the formulated plant-extract mixture was associated with a reduction in qualitative porosity from very high to medium and a more continuous surface morphology under SEM. Normal hair retained its generally intact morphology and medium porosity following treatment. Taken together, the results suggest that the formulated plant-based conditioner may have conditioning and surface-protective potential, particularly for bleached and damaged hair. Further quantitative and long-term studies are needed to confirm its efficacy, mechanism of action, stability, and safety.

Conflicts of Interest

The authors declare that they have no conflicts of interest related to this work. No financial, personal, or professional relationships influenced the design of the study, analysis and interpretation of the results, or preparation of the manuscript.

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