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Review

Candlenut Oil (*Aleurites moluccana* Seed Oil): An Indonesian Bioresource for Scalp Care—Scientific Evidence, Cosmetic Formulation, and Comparative Analysis with Brazilian Biodiversity

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Abstract

Candlenut or kukui oil, extracted from the seeds of *Aleurites moluccanus* (L.) Willd. (INCI name: *Aleurites moluccana*), is a lipid-rich Southeast Asian bioresource with a long history of use in hair and scalp care. This narrative review examines its botanical origin, lipid chemistry, safety profile, biological evidence, and formulation potential, with particular emphasis on follicular vigor and scalp homeostasis. The oil contains a high proportion of linoleic and α-linolenic acids, which provide emollient properties but also enhance susceptibility to oxidative instability. Previous animal studies have indicated hair-growth-promoting activity. More recent evidence has strengthened these findings by demonstrating increased hair shaft length in ex vivo human scalp follicles. To contextualize this Indonesian bioresource within broader tropical cosmetic innovation, the review draws a comparative analysis with three Brazilian oils: andiroba (*Carapa guianensis* seed oil), pracaxi (*Pentaclethra macroloba* seed oil), and buriti (*Mauritia flexuosa* fruit oil) oils, revealing complementary rather than equivalent profiles across anti-inflammatory, hair-conditioning, and photoprotective properties. Formulation considerations, existing evidence gaps, and the importance of traceability, community engagement, and access-and-benefit-sharing mechanisms in biodiversity-derived ingredient supply chains are also discussed.

Keywords: *Aleurites moluccana* seed oil; Brazilian biodiversity; candlenut oil; hair follicle; kukui oil; scalp care

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1. Introduction

1.1. Hair and Scalp Health as an Integrated Dermatological and Cosmetic Concern

Hair is simultaneously a functional appendage of the skin and a significant component of visible identity. Beyond its roles in physical protection, thermoregulation, and sensory interaction, changes in hair density, caliber, and distribution can result in psychosocial effects that exceed their direct medical implications [1]. Androgenetic alopecia (AGA), the most prevalent patterned form of hair loss, is a progressive disorder with increasing frequency with age. Other forms, such as alopecia areata, telogen effluvium, scarring alopecias, and hair damage induced by mechanically or chemically means, represent distinct biological causes of reduced hair density or quality [2–4]. This distinction is critical in cosmetic science,

as products intended to maintain scalp and hair condition should not be conflated with medical treatment of alopecia. Nevertheless, the biological environment in which hair fibers are produced remains highly relevant to both cosmetic performance and perceived hair health.

Contemporary hair biology challenges the assumption that visible hair shedding is a unique indicator of hair health. The hair follicle functions as a small organ that undergoes cyclical regeneration, progressing through the anagen, catagen, and telogen phases, with the hair shaft ultimately expelled during exogen. These changes are driven by coordinated interactions among epithelial matrix cells, hair-follicle stem cells, dermal papilla cells, perifollicular fibroblasts, vascular elements, and various molecular signaling systems [3]. Consequently, reductions in hair density may result not only from follicle loss, but also from a shortened anagen period, progressive miniaturization, altered matrix-cell proliferation, impaired dermal papilla signaling, or modifications in the scalp environment. A thorough understanding of the biological background is essential before evaluating any plant-derived oil proposed to support hair follicles or the scalp.

1.2. The Hair Follicle as a Regenerative and Immunologically Regulated Mini-Organ

The key aspect of follicular regeneration is the interaction between the stem-cell populations within the hair follicle and the dermal papilla. The dermal papilla acts as a signaling center, influencing the timing of the hair cycle, the diameter of the hair shaft, and follicle type. In contrast, stem-cell populations located in the bulge and secondary hair germ are responsible for the regenerative ability required for repeated growth cycles [3]. Recent studies have expanded upon the traditional model by demonstrating that the follicular niche is affected by both systemic and local signals, as well as by adjacent immune cells, rather than operating as an isolated epithelial structure. Macrophages, regulatory T cells, mast cells and other immune cells participate in the maintenance or transition of follicular states. Simultaneously, the anagen bulb and specific stem-cell compartments maintain a state of relative immune privilege, which protects regenerative structures from inappropriate inflammatory responses [5].

This concept is relevant since the follicular microenvironment is altered through distinct mechanisms in various hair-loss disorders. In alopecia areata, the primary pathological mechanisms involve the loss of immune privilege and increased cytotoxic immune activity. In contrast, adult male AGA is predominantly associated with genetic predisposition, androgen signaling, and dihydrotestosterone-dependent follicular miniaturization, together with additional factors, such as perifollicular microinflammation, oxidative stress, fibrosis, and changes in the scalp microbiome [6]. The current follicular model is therefore not dependent on a single molecular target; rather, it represents a network in which endocrine signaling, tissue redox homeostasis, immune regulation, extracellular-matrix remodeling, and the local scalp environment collectively determine the follicle's capability to sustain productive anagen growth.

1.3. Botanical Oils as Functional Lipid Matrices in Modern Cosmetic Science

Oxidative stress represents a critical factor potentially decreasing follicular vigor. Reactive oxygen species (ROS), which are typical by-products of cellular metabolism, take part in signaling pathways when maintained at controlled levels. Pathological effects occur when ROS production exceeds antioxidant capacity, thereby disrupting redox homeostasis. Studies using hair-follicle models have linked excessive oxidative stress to damage of proteins, lipids, DNA, and mitochondria, as well as to alterations in pathways involved in follicular proliferation and cycling, such as Nrf2/ARE, Wnt/β-catenin, NF-κB, MAPK, PI3K/Akt, and TGF-β/Smad signaling [7]. Clinical and translational studies in patients

with alopecia areata showed alterations in oxidative and antioxidant markers, suggesting an association between redox imbalance and inflammatory damage to hair follicles. However, the extent and causal significance of individual biomarkers vary across studies [8,9].

The skin surrounding the follicle provides an additional layer of biological regulation. This lipid-rich surface is continuously exposed to ultraviolet radiation (UV), pollutants, cleansing agents, styling products, friction, and a diverse array of microorganisms. Recent reviews state that the scalp microbiome contributes to local homeostasis and inflammation, with disease-related alterations observed in conditions such as dandruff/seborrhoeic dermatitis, alopecia areata, psoriasis, folliculitis decalvans, and, more recently, AGA [10]. At the same time, the current literature on scalp care underscores the significance of the stratum corneum barrier, as disruption of barrier lipids can result in increased transepidermal water loss and greater vulnerability to environmental and inflammatory stress [11]. However, these findings do not demonstrate that repairing the barrier or modifying the microbiome alone is sufficient to reverse alopecia. On the contrary, they suggest a more attainable cosmetic objective: maintaining a scalp environment that minimizes excessive dryness, irritation, oxidative stress, and inflammatory imbalance while preserving the structural integrity of newly growing hair fibers.

Rigorous evaluation is crucial when assessing botanical ingredients. Although a compound may enhance emollience, decrease transepidermal water loss, limit lipid oxidation, or affect a redox-sensitive pathway, the effects do not necessarily lead to clinically significant hair regrowth.

Within this mechanistic framework, fixed plant oils have regained scientific interest since they comprise complex, multiple-component lipid matrices, rather than single-molecule compositions. The specific triglyceride profile of these oils influences their spreading properties, occlusivity, sensory characteristics, susceptibility to oxidation, and interactions with the stratum corneum. Additionally, minor constituents such as tocopherols, phytosterols, carotenoids, and phenolic compounds may confer further antioxidant or biological activities [12]. However, natural origin alone does not ensure consistent performance or a universal barrier effect, as individual oils interact differently with cutaneous lipids and, under certain conditions, some oils may disrupt barrier organization. Consequently, botanical oils should be selected according to their composition and supporting evidence, rather than being regarded as interchangeable groups [12].

Linoleic acid is particularly pertinent to this discussion. As an essential ω-6 fatty acid (C18:2 ω-6), it contributes to the epidermal lipid metabolism and the formation of complex barrier lipids, such as acylceramide-related compounds. A recent review of linoleic acid in skin and hair biology reported that oils rich in linoleic acid show barrier-supporting, anti-inflammatory, photoprotective, wound-healing, and hair-related effects in various experimental studies. However, the review also emphasized the need for more rigorous clinical validation and a clearer understanding of the underlying mechanisms [13]. This observation serves as an important warning for research on hair oils: while a high linoleic acid content suggests biological plausibility, composition alone does not provide evidence for follicle growth stimulation. The most compelling support for a botanical oil arises when chemical composition, mechanistic data, organ-level responses, formulation feasibility, and human evidence are all consistent.

1.4. Why Candlenut Oil Has Become Scientifically Timely

Candlenut, known as kukui oil and derived from the seeds of *Aleurites moluccanus* (L.) Willd., exemplifies the transition from traditional ethnobotanical applications to mechanistic investigations of its potential as a cosmetic bioresource. Recent physicochemical studies have identified candlenut oil as a highly unsaturated lipid, with linoleic and α-linolenic acids

as its primary constituents. The yield and quality of oil depend on the specific extraction conditions employed [14,15]. Although this composition benefits its use as an emollient and in replenishing skin lipids, the high degree of unsaturation increases the oil's vulnerability to oxidation. Consequently, the same chemical properties that confer biological and sensory benefits also necessitate careful attention to stabilization, antioxidant protection, packaging selection, and processing conditions during product development.

Current evidence supporting the use of candlenut oil for hair growth is primarily derived from traditional practices and preclinical research. Nanoemulsion and nanostructured lipid-carrier formulations containing candlenut oil showed hair-growth-promoting effects in rodent models, while combinations of candlenut oil with celery extract have also exhibited hair-growth activity [16–18]. Although these studies were helpful in forming hypotheses, they did not establish whether candlenut oil alone directly affects human hair follicles or identify a specific molecular pathway. This gap was addressed in a subsequent study, which reported significant elongation of the hair shaft in ex vivo human scalp follicles treated with *Aleurites moluccana* seed oil. The observed effect was attributed to activation of the Nrf2/ARE-AKR1C family-PGF2α axis. Additionally, the study identified increased expression of cell proliferation markers and demonstrated that reduced Nrf2 expression led to decreased downstream antioxidant gene expression and PGF2α production, thus providing a mechanism linking redox regulation to follicular activity [19]. This study has several limitations. Although *Aleurites moluccana* seed oil appears to induce hair growth through a PGF2α-mediated pathway, it is not yet clear whether PGF2α-independent mechanisms also contribute to this process. Additionally, the use of a single-dose trial design in humans limits the ability to characterize dose–response relationships; future studies should assess multiple dosing regimens. Finally, to enhance broader applicability, the antioxidant effects on overall health should be evaluated in addition to effects on hair and eyelash growth.

The same study also carried out a randomized, double-blind, left–right comparison in humans and found that a serum containing candlenut oil increased eyelash length after four weeks compared with placebo [19]. This result strengthens the evidence base behind animal studies and compositional assumptions. Nevertheless, several limitations remain: the human study focused on eyelashes rather than scalp hair, included a small sample size, utilized a specific formulation, and did not demonstrate efficacy for androgenetic alopecia or other forms of scalp alopecia. Current evidence suggests that candlenut oil has emerging support from human and human-follicle studies for its potential as a cosmetic ingredient that may promote follicular vigor. Further research is required, including scalp-specific trials, dose–response studies, identification of active components, and long-term assessments of safety and efficacy.

1.5. From an Indonesian Bioresource to Cross-Biodiversity Cosmetic Innovation

Candlenut oil provides an opportunity to examine how tropical biodiversity can be turned into modern cosmetic innovations while preserving the unique characteristics of regional bioresources, rather than reducing them to generic 'natural oils'. Although both Indonesia and Brazil both have extensive ethnobotanical knowledge and a variety of lipid-rich plants, the chemical compositions of their cosmetic oils vary considerably. Recent reviews of Amazonian oils identify bioresources that are rich in oleic acid, long-chain saturated fatty acids, limonoids, carotenoids, tocopherols, and other minor components with potential dermatological or formulation relevance [20,21]. Innovation driven by biodiversity increasingly relies not only on biological efficacy but also on traceability, certification, community partnerships, equitable value sharing, and technological adaptation to local raw materials [22]. Since *Aleurites moluccanus*, even if not native, was recently introduced and cultivated in Brazil, a comparison between different Brazilian oils, such as andiroba, pracaxi and buriti,

has been conducted. Based on their similar chemical composition, it can be argued that these oils can be proposed as complementary ingredients in hair care formulation [23]. Andiroba oil is known for its anti-inflammatory bioactivity, which has been attributed to its limonoid content. Pracaxi oil is notable for its unique long-chain fatty acid composition relevant to hair fiber conditioning. Buriti oil is distinguished by its high carotenoid content, providing antioxidant and photoprotective properties. Including candlenut oil alongside these Brazilian oils enables a more nuanced inquiry than a simple geographical comparison. This approach facilitates examination of which biochemical functions are common among tropical oils and which are species-specific, and how these differences can inform rational formulation strategies rather than encouraging direct substituting of ingredients.

This review examines the seed oil of *Aleurites moluccanus* (L.) Willd. across five interrelated dimensions: botanical origin and processing methods, lipid and minor component chemistry, safety and biological evidence, formulation and delivery challenges, and comparative potential with selected Brazilian bioresources. Special attention is placed on mechanistic inferences supported by established evidence. The review evaluates scenarios in which Indonesian and Brazilian lipid resources may be combined to achieve complementary cosmetic effects. By contextualizing candlenut oil within follicular biology, scalp homeostasis, formulation science, and biodiversity-driven innovation, and subsequently addressing cultivation and processing, this review aims to provide a narrative discussion on candlenut oil linoleic as a contemporary ingredient in hair and scalp care.

2. Methodology

Search Strategy

This review was conducted following SANRA principles [24] for narrative reviews. To ensure a comprehensive evaluation of the literature, a non-systematic literature search was conducted across the PubMed, Scopus and Web of Science databases updated to 15 October 2026. The search strategy employed combinations of the following keywords and Boolean operators: ("Aleurites moluccana" OR "Candlenut" OR "kukui oil") AND ("scalp care" OR "scalp health" OR "hair follicle") AND ("Brazilian biodiversity" OR "Brazilian bioresources" OR "Andiroba" OR "Pracaxi" OR "Buriti"). These terms were used individually and in various Boolean combinations to maximize retrieval of relevant studies. The selection was restricted to peer-reviewed articles, ethnopharmacological studies, and cosmetic science literature published in English language.

Furthermore, because a substantial part of the primary literature on candlenut oil originates from Indonesian institutions and appears in regional journals and conference proceedings (e.g., KnE Life Sciences, KnE Medicine, IOP Conference Series, Journal of Vocational Studies on Applied Research, and Tropical Journal of Natural Product Research) that are incompletely indexed in PubMed, Scopus, and Web of Science, the database search was complemented by three additional routes. First, Google Scholar was searched with the same keyword combinations, because it retrieves regionally published and grey literature that bibliographic databases often miss [25]. Second, the reference lists of all retrieved articles were screened, and articles citing key studies were tracked (backward and forward citation searching), a strategy that identifies a large proportion of relevant sources in reviews of heterogeneous evidence [26]. Third, regulatory and policy documents were retrieved directly from official sources (EUR-Lex for Regulation (EC) No 1223/2009, the Brazilian government portals for Law No. 13,123/2015 and the SisGen system, and the Indonesian legal databases for Law No. 11/2013). Non-database sources were included only when they reported original data (composition, stability, formulation, or biological activity) or primary regulatory text; supplier technical documents were used solely to describe commercial practice and not as evidence of efficacy.

3. From Cultivation to the Cosmetic Laboratory

3.1. Botany

Aleurites moluccanus (L.) Willd. is a tropical evergreen tree in the family Euphorbiaceae, native to Indo-Malaysian region, spread across the Pacific in ancient times, and now cultivated throughout the tropics [27,28]. This species typically reaches 10 to 15 m in height and is characterized by palmate, silver-green leaves and round fruits measuring about 5 to 6 cm in diameter [27]. The fruits contain one or two hard, whitish seeds, commonly known as "candlenuts" because of their high lipid content, which historically rendered them valuable as a fuel source [27,28]. The species thrives in warm, humid climates with temperatures ranging from 18 and 28 °C. It is mostly cultivated in Indonesia, the Philippines, Malaysia, southern India, and the Pacific Islands, with harvesting generally occurring 3 to 4 years after planting [27].

The toxicological effects of raw *Aleurites moluccanus* seeds differ significantly from those of cosmetic-grade seed oil. Experimental studies indicate that the toxicity of seed preparations depends on both dosage and preparation method [29,30]. In contrast, the Cosmetic Ingredient Review's safety assessment of plant-derived fatty acid oils, including *Aleurites moluccana* seed oil, determined that these oils are generally considered safe ingredients in the present practices of use and concentration in cosmetics [31]. For formulation and safety evaluation, factors such as extraction process, degree of refining, oxidation level, and product exposure are more critical than the general claim that roasting alone removes all potentially harmful components.

3.2. Chemistry

Candlenut oil can be produced through mechanical pressing or solvent extraction. The fatty acid composition and physicochemical properties are influenced by both geographical origin and processing conditions [14,32]. For cosmetic applications, mechanical extraction at lower temperatures is preferred to preserve unsaturated lipids and minor components. Nevertheless, the final oil composition must be verified using analytical methods rather than inferred solely from the extraction technique.

Key physicochemical parameters for formulation include saponification value, density, iodine value, peroxide value, and organoleptic properties. Studies report that candlenut oil typically exhibits saponification values consistent with vegetable oil rich in triglycerides, with variations attributed to extraction method and sample origin [14]. For industrial applications, batch-specific specifications provide more relevant information than single literature values, as the oil's high unsaturation increases its susceptibility to oxidation during processing and storage.

3.2.1. Essential Fatty Acids

Candlenut oil contains high levels of polyunsaturated fatty acids (PUFAs), with linoleic acid (C18:2 ω-6) and α-linolenic acid (C18:3 ω-3) as the primary components, whereas oleic acid (C18:1 ω-9) is present at lower concentrations [15,32]. Comparative GC-MS analysis of 39 vegetable oils demonstrated that candlenut oil contains a notably high proportion of PUFAs [15]. The reported percentages should be interpreted as ranges rather than fixed values, since both the source and processing methods can affect the oil's composition. From a formulation standpoint, the high PUFA content aligns with the emollient properties of kukui oil and supports the use of plant-derived fatty acid oils to organize lipids in the stratum corneum and condition the skin [31,33]. However, the fatty acid composition alone does not provide sufficient evidence to conclude that dermal papilla cells are directly stimulated or that anagen is induced.

3.2.2. Flavonoids and Polyphenols

Phytochemical analyses of *Aleurites moluccanus* (L.) Willd. have identified phenolic and flavonoid compounds in leaf and other non-oil extracts [23,28]. However, the presence and concentration of these compounds in cosmetic-grade candlenut seed oil are not characterized as consistently as the fatty acid fraction. Consequently, antioxidant claims attributed to minor phenolics in the oil should be substantiated by batch-specific chemical profiling or functional antioxidant assays, rather than extrapolated from non-oil plant extracts.

3.2.3. Minor Unsaponifiable Components and Phytochemical Uncertainty

The minor unsaponifiable fraction of candlenut oil is less thoroughly characterized compared to its triglyceride fraction. Current studies on seed and extract lack sufficient evidence to determine the precise concentration of residual alkaloids or to identify a specific cytokine-inhibitory mechanism in cosmetic oil. This represents a significant evidence gap. Future studies should characterize sterols, tocopherols, phenolics, and other minor components in the same oil batches used for biological assays, enabling mechanistic activity to be linked to verified chemical composition.

3.2.4. Vitamin E (Tocopherols)

Tocopherols and other lipophilic antioxidants can contribute to the biological antioxidant potential of vegetable oils and protect the oil phase from oxidation. In candlenut oil, the concentration of these compounds depends on cultivar, origin, extraction method, and storage conditions. Therefore, tocopherol-related claims are most robust when supported by direct quantitative analysis of the cosmetic raw material rather than by comparison with unrelated oils [12].

3.3. Formulation

Candlenut oil is employed in the formulation of hair and scalp care cosmetics. Among the characteristics that make oil interesting in the trichological field are:

- It has high affinity with cutaneous and capillary lipids, due to its richness in PUFAs (linoleic acid approximately 34–42% and α-linolenic acid 27–32% in oils of Indonesian origin) [32].
- The biological evidence has moved from using animal hair-growth models [16,17] to relying on direct evidence from human follicles and human eyelashes [19], thus supporting a more robust yet still appropriately limited claim regarding follicular vigor.
- The cosmetic safety assessment is favorable since the Expert Panel of the Cosmetic Ingredient Review concluded that the plant-derived fatty acid oils under assessment, such as *Aleurites moluccana* seed oil, are safe when used in cosmetics [31].

Candlenut oil is liquid at room temperature and can easily be added to anhydrous systems or to the oil portion of emulsions. Technical data from one of the candlenut oil distributors (DKSH Holding AG) supports its application in hair care formulations, at usage levels aligned with those in the published literature for comparable oils [34–37]. Hence, candlenut oil is suggested in oil-in-water emulsions as an emollient in shampoos and rinse-off conditioners, or in masks and creams for intensive and trichological treatments. Moreover, it can be used as a functional ingredient in aqueous or biphasic serums and leave-on products.

The candlenut oil formulation steps must take into account the challenges associated with the physicochemical characteristics of the oil itself. Because of its high degree of unsaturation, candlenut oil is susceptible to oxidation and requires protective measures for long-term use. Moreover, variability in raw materials—due to their geographic origin, the

method of extraction, their storage history, and the refining process—can cause changes in composition; it is therefore essential to have robust supplier specifications and to carry out incoming quality control [14,32].

Strategies for Enhancing Candlenut Oil Stability

Due to the high PUFA content, the chemical stability of candlenut oil requires targeted formulation and packaging strategies. Formulation development should emphasize oxidative stability rather than relying solely on general shelf-life estimates. Recommended approaches include incorporating antioxidants; monitoring peroxide value and odor during stability testing; minimizing exposure to oxygen, heat, and light; utilizing protective packaging when appropriate; and assessing antioxidant performance in the final formulation [32,38,39].

In recent years, nano- and microtechnological delivery systems have opened new prospects for oil's use, improving oxidative stability [38,39]. A study demonstrated that polyvinyl alcohol (PVA)-based nanoencapsulation represents a viable alternative for protecting the oil from degradation [39]. The results showed that after a 35-day storage period, the nanoencapsulated oil exhibited a significantly lower mean peroxide value (0.41 meq/100 g) compared to 3.8 meq/100 g for pure candlenut oil.

Microencapsulation of candlenut oil was performed using two polymeric film formers, hydroxypropyl methylcellulose (HPMC) and maltodextrin [38]. Based on the peroxide values, encapsulation efficiency, wettability, and moisture content of the microcapsules obtained via a spray drying process, the authors demonstrated that the wall polymeric materials might protect its polyunsaturated fatty acids from thermal oxidation. Body lotion samples formulated with encapsulated concentrations of 2%, 6% and 10% candlenut oil exhibited significant antioxidant activity, with IC50 values ranging from about 50 to 60 ppm [38].

In vivo experiments involving rats demonstrated that the incorporation of candlenut oil into nanostructured lipid carriers (NLCs) influenced both carrier properties and hair-growth-stimulating activity [17]. Similarly, a study utilizing mice investigated candlenut-oil nanoemulsions formulated as a hair tonic [16]. These NLC/nanoemulsion systems intended for trichological use contained 5–7% of candlenut oil as the liquid lipid phase [16,17]. Although these studies show the feasibility of nanocarrier formulations, results from animal models should be distinguished from the direct evidence now available concerning human hair follicles [19].

3.4. Mechanistic and Translational Evidence for Follicular Vigor

A recent development in the literature stated that ex vivo treatment of human scalp hair follicles with oil from the seeds of *Aleurites moluccanus* (L.) Willd. led to a significant increase in hair shaft elongation compared with controls [19]. This effect correlated with elevated levels of PGF2α, upregulation of the AKR1C enzyme family responsible for PGF2α synthesis, and increased expression of cell proliferation markers such as Ki67 and cyclins. Mechanistic studies using transcriptional analysis and gene knockdown showed that activation of the Nrf2/antioxidant-response-element pathway preceded the regulation of AKR1C [19].

The mechanistic nature of these findings is particularly relevant, as it extends beyond compositional analysis of the oil. Current evidence shows a direct association between a defined oil preparation and measurable responses in intact human hair follicles, specifically involving a redox/prostaglandin signaling pathway. Furthermore, a randomized, double-blind, left–right trial demonstrated that the oil promoted eyelash growth [19]. When considered alongside previous animal studies [16,17], these results create a translational

framework from formulation feasibility and in vivo animal responses to human follicle biology and potential cosmetic application.

Accurate representation of the evidence remains essential. The available data do not establish candlenut oil as an effective treatment for androgenetic alopecia, alopecia areata, or other scalp disorders, and likewise the eyelash study cannot substitute for a controlled scalp trial. Currently, candlenut oil demonstrates emerging mechanistic and human evidence supporting a positive influence on follicular vigor and hair growth biology; however, its efficacy for specific conditions and its long-term effects on the scalp have yet to be determined.

4. Indonesian and Brazilian Bioresources in Trichological Cosmetics: Comparative Analysis and Complementary Potential

4.1. Scientific Rationale for Comparing Indonesian and Brazilian Bioresources

Indonesia and Brazil are both highly biodiverse tropical countries where plant oils are incorporated into local practices and are increasingly being used in cosmetic and pharmaceutical value chains. Although *Aleurites moluccanus* (L.) Willd. is not native to Brazil, Brazilian phytopharmacological research has still investigated material from *Aleurites moluccanus* (L.) Willd. cultivated in southern Brazil [23]. This species provides a valuable basis for comparison, highlighting the distinction between a bioresource originating in Indonesia and oils native to the Amazon. The present review does not propose botanical equivalence between these regions but rather assesses whether different tropical oils can fulfill similar cosmetic functions through distinct chemical mechanisms. Recent reviews of Amazonian oils have shown considerable variation in triglyceride composition, unsaponifiable constituents, antioxidant activity, anti-inflammatory activity, emollient properties, and their suitability for structured or nanostructured delivery systems [20,21]. Candlenut oil is notably rich in PUFAs, while many well-known Brazilian oils are primarily composed of oleic acid, long-chain saturated fatty acids, carotenoids, or limonoids. This diversity offers the potential for combining these oils to achieve complementary effects, rather than substituting one for another. The following comparison focuses on three Brazilian bioresources identified in the literature as having distinct cosmetic benefits: andiroba oil, valued for its anti-inflammatory properties and limonoid content; pracaxi oil, which conditions hair fibers and contains a unique fraction of behenic acid; and buriti, which is rich in carotenoids and has photoprotective and antioxidant properties [20,21,40].

The three Brazilian oils were selected using four criteria. First, each is a seed or fruit with documented traditional or commercial use in hair scalp or scalp care [21,40,41]. Second, each has at least one peer-reviewed experimental study on a cosmetically relevant endpoint conducted with the oil itself or a defined fraction, in vitro, in vivo, or in topical formulations [40–42]. Third, the dominant chemistry of each contrasts with, rather than duplicates, the PUFA-rich profile of candlenut oil so that complementarily can be examined: andiroba oil is dominated by oleic acid and palmitic acids and contains limonoids, pracaxi oil combines oleic acid with 16–23% behenic acid, and buriti oil combines oleic acid with exceptionally high carotenoid and tocopherol contents [21,40,43]. Fourth, all three are supplied through value chains regulated by a formal access-and-benefit-sharing framework [44,45], which allows the bio-innovation and inclusion aspects discussed to be grounded in concrete example. Brazil was chosen as the comparator country because *Aleurites* is also cultivated and investigated there [23,30], providing a shared production and research context.

Other Indonesian, Southeast Asian, and tropical oils were considered but not retained as primary comparators. Coconut oil (*Cocos nucifera*), the most extensively studied tropical hair oil, has robust experimental evidence for reducing protein loss from hair [46]; however,

its lauric-acid-dominated chemistry and large existing literature would not add a new functional dimension to the comparison. Tamanu oil (*Calophyllum inophyllum*), which also occurs in Indonesia and the Pacific, has shown wound-healing-related activity in human skin cells [47], but lacks hair- or scalp-specific experimental data. Several other Amazonian oils, such as babassu and patawa, are supported for hair applications mainly by traditional or industry sources [48]. These oils remain candidates for future comparative studies.

4.2. Andiroba Oil (Carapa guianensis Seed Oil): The Brazilian Anti-Inflammatory Parallel

Andiroba oil, extracted from the seeds of *Carapa guianensis* Aubl., is one of the most widely known Amazonian medicinal oils. Its cosmetic value is attributed to both its lipid content and the presence of limonoids and related tetranortriterpenoids [41,49]. Bioactive limonoids have been identified in both the seed oil and its by-products [50]. Experimental studies demonstrated anti-inflammatory and anti-allergic effects, including reductions in pro-inflammatory mediators [41,51]. However, these data derive from non-cutaneous inflammation models, and andiroba oil has not yet been tested on scalp or hair-follicle endpoints. Compared to candlenut oil, andiroba oil contains higher concentrations of oleic acid (42–55%) and palmitic acid (27–38%), and linoleic acid (4–9%) [21,52]. This compositional difference is relevant for formulation, as an oil phase rich in oleic acid may yield a unique sensory profile and enhanced oxidative stability relative to one dominated by PUFAs. Nevertheless, final stability must be established through experimental validation. Consequently, candlenut and andiroba oils should be considered complementary lipid sources rather than interchangeable alternatives.

The primary rationale for combining the two oils is that their respective bodies of evidence are complementary rather than redundant. Candlenut oil has direct evidence from human follicles studies related to Nrf2/ARE-AKR1C-PGF2α signaling [19], whereas andiroba oil is supported by a broader literature on the anti-inflammatory effects of limonoids [41,50,51]. A mixture of these oils may offer both follicular vigor and anti-inflammatory benefits for the scalp. However, none of the reviewed studies provided direct evidence of a synergistic effect on hair growth from the combination of candlenut and andiroba oils. Therefore, any assertion of synergy remains hypothetical rather than an established advantage.

For formulation purposes, andiroba oil is best utilized as an anti-inflammatory agent and as a contributor to sensory properties and stability. Potential applications include scalp serums, pre-shampoo oils, and leave-on emulsions. In these formulations, both oils should be chemically standardized, and the mixture should be tested for oxidative stability, irritation potential, and effects on inflammatory biomarkers before making any efficacy claims.

4.3. Pracaxi Oil (Pentaclethra macroloba Seed Oil): A Complementary Hair-Fiber Active

Pracaxi oil, extracted from the seeds of *Pentaclethra macroloba* (Willd.) Kuntze, exemplifies a Brazilian ingredient with both traditional and commercial relevance in hair care. It is commonly used for hair styling, enhancing shine, and improving overall appearance. The oil's fatty acid profile is mainly oleic acid, with a relatively high behenic acid content ranging from 16% to 23% according to various analyses [40].

Pracaxi oil is chemically complementary to candlenut oil. While candlenut oil primarily consists of shorter-chain unsaturated C18 fatty acids and is increasingly supported by follicle-related biological evidence [19], pracaxi oil contains a significant proportion of very-long-chain fatty acids relevant to lubrication, film formation, manageability, and conditioning of the hair fiber [40]. Current evidence supports a division of functional roles: candlenut oil provides follicle and scalp support, whereas pracaxi oil primarily contributes to surface

conditioning. This finding challenges the assumption that both oils promote hair growth through identical mechanisms.

Pracaxi further shows the value of Brazil's biodiversity in advancing formulation technology and ingredient chemistry. The oil has been studied as the lipid component of nanostructured delivery systems and Pickering-type emulsions [40]. This research parallels studies involving candlenut oil in NLCs and nanoemulsions [16,17], presenting opportunities for comparative analysis. Identical carrier systems could be formulated with candlenut oil, pracaxi oil, or defined blends, and subsequently evaluated for droplet or particle size, oxidative stability, rheological properties, deposition on hair fibers, combing force, and scalp tolerability.

4.4. Buriti Oil (Mauritia flexuosa Fruit Oil): Photoprotective Properties and Effects on the Scalp Microenvironment

Oil extracted from the pulp of *Mauritia flexuosa* L.f. represents a chemically distinct category among Brazilian oils. It is characterized by a high content of oleic acid (approximately 62–79%), carotenoids (mainly β-carotene, reported at about 780 mg/kg in one characterization), and tocopherols (about 2360 mg/kg), which accounts for the interest in its use in topical and photoprotective formulations [20,21,43]. In contrast to candlenut oil, the principal value of buriti oil in hair and skin applications lies in its ability to protect the skin from oxidative and UV-induced stress, rather than promoting follicle growth. This distinction is supported by experimental studies showing that emulsions containing buriti oil exhibited photoprotective effects in keratinocyte and fibroblast cell models exposed to UVA/UVB [42]. Further research incorporated buriti oil into nanoemulsion-based photoprotective formulations, evaluating their stability and cytotoxicity in keratinocytes. These findings indicated that buriti oil is compatible with current topical delivery systems [53]. Buriti oil also shown to reduce wet combing force, increase gloss, and reduce split-end formation in human hair, although the results were reported for the oils as a group [34].

In cosmetic formulations targeting the scalp, buriti oil therefore serves as a complementary ingredient to candlenut oil, particularly when addressing concerns related to UV exposure, oxidative stress, and sensory emollience. However, buriti oil should not be considered a substitute for approved UV filters, and current photoprotection data do not indicate any effect on hair growth. The combination of candlenut and buriti oils represents a multifunctional approach to scalp-protection. If photoprotective claims are to be made, it is necessary to conduct SPF/UVA testing of the final product, assess its photostability, and evaluate its tolerance on the scalp.

4.5. Comparative Summary and Formulation Opportunities

The comparative analysis reveals a consistent and significant pattern (Table 1). Although these oils share emollient, antioxidant, and topical application properties, the strongest supporting evidence for each oil relates to distinct functional areas. Of the four ingredients examined, candlenut oil demonstrates the most direct evidence for promoting follicle growth [19]. Andiroba oil provides a well-defined anti-inflammatory effect linked to its limonoid content [41,51]. Pracaxi oil is characterized by a distinct long-chain fatty acid profile from which hair-fiber conditioning is inferred, supported by traditional and commercial use rather than by instrumental testing [40]. Buriti oil provides antioxidant activity due to its carotenoid content and demonstrates photoprotective properties [42,43,53].

Table 1. Evidence-based comparison between candlenut oil and selected Brazilian bioresources for hair and scalp cosmetics.

Buriti Oil (***Mauritia flexuosa*** **Fruit Oil**) **Brazil**	**Pracaxi Oil** (***Pentaclethra macroloba*** **Seed Oil**) **Brazil**	**Andiroba Oil** (***Carapa guianensis*** **Seed Oil**) **Brazil**	**Candlenut Oil** (***Aleurites moluccana*** **Seed Oil**) **Indonesia**	**Characteristic**
Oleic-rich; carotenoid-containing fruit oil [21,43]	Oleic-rich with distinctive behenic acid (~16–23%) [40]	Oleic-rich seed oil plus limonoid fraction [21,50]	PUFAs-rich; linoleic + α-linolenic acids [15,32]	Dominant lipid feature
Antioxidant/photoprotective effects in skin cell and topical formulation studies [42]	Hair-fiber conditioning, emollience, lubrication; traditional hair use [40]	Limonoid-associated anti-inflammatory/anti-allergic activity [41,51]	Human follicle elongation; Nrf2/ARE-AKR1C-PGF2α; human eyelash growth [19]	Best-supported bioactive axis
Protective emulsions/nanoemulsions and multifunctional scalp products [53]	Conditioners, masks, leave-ons, Pickering/nanostructured systems [40]	Blends and scalp emulsions; chemically standardized limonoid-rich fractions [21]	NLCs, nanoemulsions, serums, oils	Hair care products

This evidence-based hierarchy supports the development of complementary products and challenges the prevailing practice of attributing uniform claims to all tropical oils.

- Candlenut and andiroba oils: This hypothesis focuses on scalp health by integrating evidence from candlenut oil's support for follicular vigor with the anti-inflammatory properties of andiroba oil, attributed to its high limonoid content. Validation should prioritize oxidative stability, scalp tolerability, and inflammatory biomarkers before asserting any synergistic effects.
- The combination of candlenut and pracaxi oils involves a complete approach for hair and scalp care. Candlenut oil targets follicular and scalp biology, while pracaxi oil is evaluated for its effects on fiber lubrication, manageability, shine, and protection against damage. Recommended validation includes the evaluations combining force, tensile properties, fiber deposition, and sensory performance.
- Candlenut and buriti oils together form a scalp care concept that supports follicular vigor and offers antioxidant and photoprotective benefits, attributed to the high carotenoid content of buriti oil. Recommended validations encompass assessment of product performance under UVA and UVB exposure, photostability, irritation potential, and chemical stability. Buriti oil should not be used as a sole sunscreen filter.

From a regulatory perspective, the natural origin of ingredients does not exempt manufacturers from requirement such as ingredient characterization, contaminant control, stability testing, and finished-product safety assessment. In the European Union, the use of plant oils in cosmetics is subject to the general requirements outlined in Regulation (EC) No. 1223/2009 [54]. For ingredients derived from biodiversity, comprehensive documentation of botanical identity, geographic origin, extraction method, oxidation status, and traceability is essential, as these factors can significantly influence both composition and reproducibility.

The Brazilian case highlights an aspect of inclusion that extends beyond ingredient chemistry. Household-level research in the Brazilian Amazon has shown that the extraction of non-timber forest products and participation in cooperatives linked to cosmetic industry partnerships are correlated with increased household incomes [55]. While not all biodiversity supply chains are inherently equitable, these findings indicate that community involvement, local processing, transparent purchasing practices, and value retention should be regarded as integral components of cosmetic bioinnovation, rather than being considered merely as separate sustainability claims.

4.6. Bio-Innovation, Inclusion, and Responsible Access to Biodiversity

Brazil offers a leading example of integrating biodiversity innovation with traditional knowledge and benefit sharing. The Brazilian Ministry of the Environment identifies the cosmetics industry as a key user of the country's genetic resources and associated traditional knowledge and emphasizes that access to specific traditional knowledge requires prior informed consent. The national SisGen platform enables the registration of access, benefit payments, product notifications, and related procedures within this regulatory framework [45,56]. These mechanisms are significant for the international cosmetics market since they formalize inclusion by embedding traceability and benefit sharing into research and commercialization processes.

In the context of Indonesian candlenut oil, the key lesson is not to directly import Brazilian legal framework to a different jurisdiction, but rather to apply similar scientific and ethical principles. Indonesia already has a legal basis for doing so, having ratified the Nagoya Protocol on access and benefit-sharing [44]. These includes accurately identifying the biological resource, documenting sourcing and processing, recognizing the origin of traditional knowledge when it informs product development, and designing value chains in which local producers are recognized participants rather than anonymous raw-material suppliers. This approach strengthens both the reproducibility and the social legitimacy of biodiversity-derived cosmetic innovation.

4.7. Research Agenda for Indonesian-Brazilian Bioresource Combinations

Comparative analysis leads to several experimentally testable questions. First, factorial blend studies are needed to determine whether Brazilian oils high in oleic acid can enhance the oxidative stability and sensory qualities of candlenut oil, which is rich in PUFAs, without reducing its follicular activity. Second, combinations of candlenut and andiroba oils should be evaluated in keratinocyte, dermal papilla, or ex vivo scalp models, incorporating both hair-growth indicators and inflammatory biomarkers. Third, candlenut–pracaxi oil systems should be investigated from the perspective of follicular biology and the instrumental performance of the hair fiber. Fourth, candlenut–buriti oil formulations should be tested for antioxidant and photoprotective properties in the final product, rather than inferring sunscreen performance simply from the composition of the raw oil. For all combinations, chemical fingerprinting of the oils used in biological studies is essential to ensure reproducibility. Finally, the same framework could be extended to other tropical oils, such as coconut and tamanu oils, to test whether the complementarity observed here holds beyond the oils selected.

These studies would shift the current cross-biodiversity comparison from a conceptual formulation framework to an evidence-based platform for the development of new cosmetic products. Until such studies are performed, it is most scientifically accurate to state that Indonesian and Brazilian bioresources present complementary opportunities rather than established synergistic effects.

5. Conclusions

Candlenut oil is a promising Indonesian bioresource for hair and scalp cosmetics, since its traditional use is increasingly supported by scientific evidence. Its composition, particularly the high content of polyunsaturated fatty acids, offers a robust basis for formulation. Recent studies involving follicles and eyelashes in different experimental models demonstrate that candlenut oil produces measurable effects on hair growth [16–19]. On the other hand, the high degree of unsaturation poses a significant challenge for formulation. Therefore, oxidation control, batch characterization, and chemical standardization should be

prioritized as essential issues of product development rather than considered as secondary quality attributes.

Comparisons between Brazilian and Indonesian biodiversity actually strengthen the emphasis on Indonesian resources. Andiroba, pracaxi, and buriti oils do not merely replicate the functions of candlenut oil; instead, they offer distinct chemical and functional properties that can inform the development of novel research hypotheses. For instance, andiroba oil may provide anti-inflammatory effects, pracaxi oil may enhance hair fiber conditioning, and buriti oil may deliver antioxidant and photoprotective benefits for the scalp. Presenting these potential applications in accordance with the current evidence base prevents overstated claims and delineates which outcomes require direct experimental validation.

Assessment of bioinnovation in natural cosmetics requires consideration of the novelty of both the ingredient and the delivery system, particularly in relation to the transformation of biodiversity into economic and social value. Brazil's experience with community-linked value chains for non-timber forest products, alongside the implementation of formal access-and-benefit-sharing mechanisms, serves as a model for establishing traceable, inclusive and scientifically reproducible supply chains [45,55,56]. For candlenut oil, Indonesia's ethnobotanical heritage exemplifies a broader approach to tropical cosmetic innovation, where scientific validation, formulation technology, biodiversity conservation, and social inclusion develop in an integrated manner.

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