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Review

Squalene from *Silphium perfoliatum*: A Novel Source with Long-Term Stability and Applicability in Topical Formulations

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Abstract

Background: Squalene is a key sebum lipid that plays an important role in skin barrier function, suppleness, and antioxidant protection. Age-related or disease-associated reductions in squalene levels—for example, in atopic dermatitis—reduce skin resilience and increase susceptibility to environmental stressors. However, its oxidation products can have inflammatory, comedogenic, and pro-aging effects on the skin, which is why adequate stabilization is essential when used in topical formulations. **Objective**: Therefore, identifying sustainable sources of stable squalene with beneficial skin-care properties is of considerable interest. **Methods**: This review employed an application-focused literature search and comparative analysis of established and new squalene sources, evaluating chemical composition, manufacturing processes, stability, and biological effects following topical applications based on predefined analytical criteria across peer-reviewed studies. **Results**: Silphium oil appears to be a promising novel source of highly concentrated, sustainable, and stable squalene with potential skin-conditioning properties at concentrations typically used in cosmetic products (2.1–12.6%) while preliminary formulation tests indicate emulsifiability even at concentrations up to 15%. It contains over 3% squalene, a fatty acid profile with over 66% PUFA, and negligible levels of oxidation byproducts (hexanal < 3 ppm) even after years of storage in various types of packaging. Although independent validation and broader comparative studies are limited, these results reveal new possibilities for the use of previously underutilized plant sources in skin care applications.

Keywords: squalene; squalane; skin barrier; sebum lipids; antioxidant skin care; lipid oxidation; oxidative stress; skin aging

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1. Introduction

Squalene plays a central role in skin physiology: As a major component of human sebum (approximately 13%), it contributes substantially not only to skin lubrication and barrier function, but also to the antioxidant system. The isoprenoid structure with its numerous unsaturated carbon bonds protects cells from free radicals [1]. Even though its antioxidant effect is limited and depends on numerous other factors, squalene has been described as a primary oxidation scavenger in the skin and stabilizes oxidative stress for a limited period [2]. At the same time, it can itself undergo oxidation upon UV-light, having negative effects on the skin after prolonged exposure, if not compensated by antioxidants [3]. It is known that oxidized squalene—namely squalene hydroperoxides—induces inflammatory processes in the skin and has a pro-aging and comedogenic effect [4–8]. That is why oxidative stabilization is necessary to preserve positive properties.

Nevertheless, the skin has its own protective systems, including sufficient sebum production, which facilitates the removal of oxidized lipids [9]. Therefore, a healthy concentration of squalene in the skin is essential for its health and regenerative capacity [10]. Previous studies suggest that skin resilience peaks in early adulthood and then declines continuously thereafter. Not only age is relevant, but also skin condition: in atopic dermatitis, UV radiation has been shown to have a greater effect on skin health, which, among many other factors, could also be related to the reduced natural squalene content of the skin [2]. Therefore, topical supplementation may help restore insufficient squalene levels in the skin, thereby restoring the skin's antioxidant balance [10,11]. This may be achieved via topical application of cosmetic or medical emulsions.

As an ingredient for cosmetic, food, and pharmaceutical industries, for a considerable timeframe, the main source of squalene was shark liver oil. Due to restrictions on shark fishing and limitations of solvent-based extraction methods, renewable sources (e.g., oils from olive, cucurbit seeds, wine residue, tobacco, ginseng, nuts or microbial sources) and supercritical CO_2 extraction have emerged as safer, more sustainable, and cost-effective alternatives [12]. Topically applied squalene benefits the skin by acting as an emollient, antioxidant, and anti-inflammatory agent that reinforces the skin barrier, improves hydration, promotes wound healing, reduces erythema and protects against oxidative stress and premature aging [13]. For more information on the multifunctional benefits of squalene for skin health, please refer to this comprehensive review by Morgan et al. (2024) [14]. Cosmetic and medical products containing squalene thus offer the potential to protect the skin from oxidative stress and environmental irritants, strengthen its natural suppleness and regenerative capacity, and reduce inflammatory processes, therefore preventing dermatitis and skin aging [11]. However, to counteract the risk of oxidative instability and its undesirable effects [4–8], in recent years, the raw material squalane, the hydrogenated form of squalene, has come into focus in the cosmetics industry. Although the chemical saturation makes the ingredient squalane significantly more stable during storage, it limits its function to a neutral emollient. Unlike squalene, the saturated substitute ingredient squalane has a similar molecular structure; however, missing unsaturated bonds and consequently missing comparable reductive properties. Despite the similarity in name, it is therefore not an adequate replacement for squalene. However, both are described as safe for use in cosmetics [15–17].

Although there are numerous in vitro, ex vivo, and animal studies as well as safety assessments on squalene [17], to the best of the authors' knowledge, there are currently no studies that address the cosmetic/dermatological effects of squalene or squalene containing oils in topical emulsions (O/W or W/O) in -vivo studies or theoretical calculations. This raises the question of how feasible it is to use squalene or plant oils containing squalene in topical emulsions, and which raw materials would be suitable for this purpose. To address this, in this article various sources of squalene were compared regarding their composition and manufacturing process, and existing information from the literature on their effects and shelf life was discussed. This provides a basis for raw material suppliers and product manufacturers to evaluate the use of squalene and take appropriate measures to optimize its effectiveness.

2. Materials and Methods

This review presents a comparative analysis of different squalene sources, with a narrative focus on their chemical composition and production methods. Between October 2025 and January 2026, targeted literature searches were conducted in scientific databases, including PubMed, Scopus, Google Scholar and Web of Science, focusing on work addressing 'squalene', 'squalane', and 'skin'. The research screened existing literature using keywords

related to topical effects ('skin', 'dermal', 'topical', 'cosmetic', 'cosmeceutical ', 'medical use'), plant-derived oil sources ('seed oil', 'plant/vegetable/crop oil', 'cold-pressed', 'virgin oil', 'extraction', 'calibration', 'standardization', 'GC-analysis'), and oxidative stability ('squalene hydroperoxides', 'lipid oxidation', 'oxidative stress', 'stability', 'shelf life', 'storage conditions', 'oxidative degradation'). Relevant peer-reviewed publications on topical applications were included, with a focus on emulsions and oxidative stability, as well as oils derived from edible and non-edible crops—while excluding redundant, inaccessible, or methodologically insufficient studies. Title/abstract screening and full-text review followed to ensure transparency and reproducibility. Methods not using standard calibration but instead quantifying based on area ratios in the GC-chromatogram were marked. Although these approaches do not meet the requirements for reliable quantification, they still can serve as a semiquantitative guide given interest in the data. While English and German work was preferred, foreign-language literature was first translated by qualified translators or appropriate assistance systems to ensure accurate interpretation. No lower publication date limit was applied due to the historical relevance of early studies, to also incorporate foundational literature and original findings. Although broad search terms yielded many publications (e.g., 'squalene' and 'skin'), only a limited subset directly addressed the physiological, botanical, ecological and oxidative aspects relevant to the scope of this analysis.

To complement the literature overview, limited exploratory third-party analytical data from instrumental analyses are provided in Appendix A.

This approach allowed us to synthesize current knowledge on the practical application of squalene in topical emulsions and to provide a foundation for raw material and product developers to assess its potential applications and optimize efficacy.

3. Results and Discussion

This chapter presents the results together with the relevant contextual discussion. The following subsections describe selected edible and non-edible sources of squalene, its chemical stability, and cosmetic potential. Supplementary data from instrumental analyses are provided in Appendix A.

3.1. Squalene Sources

Mechanical oil pressing or pressure extraction (e.g., with a screw press) is a process in which seeds, nuts, or fruits are mechanically crushed under high pressure to extract the oil they contain. Ideally, temperatures are kept as low as possible (known as "cold pressing") to minimize thermal and chemical influences—this ensures that natural ingredients such as antioxidants, plant sterols, vitamins, and other secondary plant substances are better preserved [18]. For an overview of the squalene content of various plant, animal and microbial oils using other extraction methods, please refer to the review by Lozano-Grande et al. (2018) [19]. Although numerous squalene analyses of cold-pressed vegetable oils were found, the aim of this research was to compare established high-squalene sources narratively in order to achieve the best possible skin effectiveness at the lowest possible ingredient concentration in the cosmetic formulation and to find new sources that may meet these requirements. In this initial research, olive oils, amaranth oils, germ oils (e.g., rice, corn), and pumpkin seed oils exhibited the highest concentrations of squalene [20]. In Table 1, several analyses of currently known edible plant sources of squalene are compared.

Table 1. Established Sources of Squalene in Plant Oils and their Concentration (mg per 100 g).

Established Sources	Squalene Mean (Range) [mg/100 g]	Ref.
Extra Virgin Olive Oil (*Olea europaea*) [1,2]	372 (145–747)	[21]
Olive Oil (*Olea europaea*) [3]	438 (236–747) *	[22]
Pumpkin Seed Oil (*Cucurbita pepo*) [1]	605 (591–633)	[23]
Pumpkin Seed Oil (*Cucurbita pepo*) [1]	95 (95–96)	[24]
Amaranth oil [4]	73 (67–79)	[25]
Amaranth Oil (*Amaranthus hypochondriacus*, *Amaranthus cruentus*) [2,4]	5920 (5290–6790)	[26]
Amaranth Oil (*Amaranthus tricolor*) [1]	(6000–11,600)	[27]
Rice bran oil (*Oryza sativa*)	326 (300–400)	[22,28]
Peanut Oil (*Arachis hypogaea*) [1]	133 (132–134)	[29]
Sunflower Oil (*Helianthus annuus*)	8 (3–12) *	[22]

[1] different varieties; [2] different regions; [3] different qualities; [4] different species. * converted to mg/100 g with a density of 0.9 g/cm^3.

Depending on the species, variety, and region of cultivation, cold-pressed oils vary greatly in their squalene content, even if the plant genus is the same. Even though some oils are known for their squalene content, it was still relatively low. Only amaranth oil showed a relevant squalene amount that might have a considerable effect on the skin in cosmetic formulations at a realistic concentration in application. However, due to its high price, it is not commonly used in large quantities in the cosmetics industry.

Therefore, lesser-known sources of oil were also considered. Although food oil crops have been bred for taste, smell, and yield, they deplete the soil and require a certain crop rotation and cultivation breaks. Plants that regenerate the soil and can be used during cultivation breaks are therefore a more sustainable source of oil. While taste and smell are important criteria for edible oils, a bitter taste or stronger smell is not crucial for cosmetic oils that are used for skin care and not in the mouth area. In the following comparison, not only food and feed crops were analyzed, but also green fertilizers and intercrops. Their advantage is that they do not compete with human nutrition and do not divert resources from the food supply. In addition, plants with short intervals between sowing and harvesting were selected, as long growth periods until optimal fruit formation pose a risk of loss due to drought or disease, as olive oil shows [30]. Table 2 compares these oils with each other [31].

Table 2. New Sources of Squalene in Plant Oils and their Concentration (mg per 100 g).

New Sources	Oil Content [%]	Squalene Mean (Range) [mg/100 g]	Ref.
Arabidopsis thaliana	34.6–46.0	46–65 *	[32,33]
Silphium perfoliatum	15	3474 (3250–3560)	Appendix A.1
Silphium integrifolium	11.8–25.3	4890 **	[34,35]
Pongamia pinnata	26.7–33.1	1290–1860 **	[36–38]
Jatropha curcas	40	180 **	[36,39]
Nicotiana spp.	36.25–37.25	24 **	[40,41]
Rosaceae seed oils	3.49–46.15	88.4 (20–290) **	[42]

* Calculation based on seed oil content and squalene content per seed. Analysis of oil may result in different matrix effects. ** Semi-quantitative analysis based on GC peak area ratios. Quantification using standard calibration or standard addition might provide different results.

Since secondary crops usually are not cultivated and optimized for oil quality, analytical results were limited. However, the results clearly show that Silphium oil provides the highest squalene content (>3%), exceeding even that of most established food oil sources. This ingredient is already approved for cosmetic use under the INCI name SILPHIUM PERFOLIATUM SEED OIL and has a high ecological value [43]. It is recognized in the

EU CosIng/COSMILE database as a cosmetic ingredient with antioxidant, antimicrobial, astringent, and sebum-regulating functions, with no specific restrictions or concentration limits under the EU Cosmetic Regulation (EC) No. 1223/2009 [44,45]. To date, the ingredient is not included in any prohibition or restriction annexes in major cosmetic markets (EU, US, CN), indicating that it may be used in cosmetic formulations provided that general safety requirements are met and appropriate toxicological substantiation is available. Although smell and taste may not be of the greatest relevance for cosmetic products, Silphium oil has a pleasant nutty aroma and therefore appears to be particularly compatible with cosmetic applications.

However, the other green manure plant oils are not suitable for commercial use in cosmetics, either for their low squalene content, lack of approval or for potential topical toxicity. In addition, some of these are not yet approved or are very uncommon in practical use, due to, e.g., negative consumer associations.

The cultivation area and international dependencies should not be overlooked, giving greater importance to plants that can be widely cultivated. Additionally, cultivation in tropical regions combined with the extensive use of pesticides and fertilizers to increase yields, challenges the sustainability of many of the previously efficient oil sources [46]. However, *Silphium perfoliatum* shows a high oil yield of 15% (see Table 2), despite cultivation in colder regions on previously planted and exploited soil [43].

Overall, it can be shown that, measured in terms of squalene content and oil yield, Silphium oil might serve as a sustainable and efficient source of squalene for the future use in skin care among other well-established and emerging squalene sources. However, broader comparative studies are recommended, since semi-quantitative quantification methods used in many studies are not fully comparable and should still be interpreted with caution.

3.2. Oxidative Stability

To assess the stability of squalene, both its stability in oil as a raw material and in emulsion as a product were considered—specifically in terms of its reactivity with oxygen. Some publications investigated the stability of squalene in various vegetable oils: degradation under everyday conditions varies from insignificant losses to 47% [47], which illustrates that other components could control degradation. For example, a competitive reaction with other antioxidants has been described in olive oil, so that squalene remained stable and contributed little to oxidative spoilage [48]. In pumpkin seed oil, squalene showed a degradation of approximately 20% in the early stages of oxidation and remained stable as storage progressed, while tocopherol declined continuously [49]. This was also observed in olive oil [50]. However, according to initial analyses (Appendix A.1), squalene in Silphium oil did not degrade in significant quantities during storage of several years and was still quantified over 3%, independent of packaging material used. An oxidation-protective effect has also been described in rapeseed oil, where an addition of 0.5% squalene was even recommended to increase shelf life [51]. Hence, it becomes evident why Silphium oil with over 3% squalene (see Appendix A.1) and over 66% of poly-unsaturated fatty acids (PUFA), mainly linoleic acid (see Appendix A.3), appeared to be stable. This can also be proved by the low hexanal concentrations measured in *Silphium perfoliatum* oil of under 3 ppm (see Appendix A.2). Hexanal is known as a major volatile aldehyde breakdown product of omega-6 fatty acids such as linoleic acid [52]. Even though no regulatory limit exists at present, ingredient and product manufacturers define their own specifications, based on a rancidity perception threshold of 5–10 ppm in foodstuffs [53]. Despite years of storage and high PUFA-concentrations (see Appendix A.3), Silphium oil maintained low hexanal levels regardless of packaging and storage conditions (see Appendix A.2), indicating its resistance to rancidity and its consistently high quality without any sensory

limitations. This demonstrates not only its long shelf life but also its suitability for skin care, as unsaturated fatty acids in topical emulsions are known for their beneficial effects on inflammatory skin conditions [54].

As mentioned at the beginning, the formation of prooxidative squalene degradation products [4–8] should be avoided. Literature shows that their formation can be clearly prevented by primary antioxidants in water-free oil phases [55]. However, in heterogeneous phase systems, this is more complex. While water-in-oil emulsions (*W*/*O*) are characterized by a continuous oil phase that is in direct contact with air and their stability towards oxygen is similar to that of pure oil [56], oil-in-water emulsions are able to oxidize faster than unhomogenized oil itself due to the large surface area of the dispersed oil droplets [57]. To date, cosmetic squalene emulsions have been underrepresented in the literature, even though pharmaceutical emulsions allow for a certain degree of transferability and have already demonstrated high efficacy and stability [58–60]. However, the high unsaturated fatty acid (PUFA) content of *Silphium perfoliatum* oil of over 66% (see Appendix A.3) should be considered when estimating the shelf life of emulsions. Literature shows, that emulsified rapeseed and sunflower oils with similar PUFA-amounts have rapid oxidation rates, especially in bright and warm storage [61–63]. It is recommended to check the stability of Silphium oil and formulations thereof using similar approaches in future work.

It can therefore be concluded that squalene in oils and emulsions is stable and additionally has a stabilizing effect on the matrix composition.

3.3. Potential for Skin-Care Products

Even though other molecules have a considerably higher antioxidant capacity (ORAC, DPPH assay), squalene has significant regenerative, radical-scavenging, and oxidative stress-reducing effects on body cells, partly because, as a cell membrane component, it may repair oxidative damage directly at the source [47]. This is a major advantage, as it exhibits relatively high stability with biologically relevant efficacy.

Both squalane and squalene are described as promising for cosmetic, nutritional, and pharmaceutical industries, as they exhibit anticancer, antioxidant, drug carrier, detoxifier, skin hydrating, and emollient activities in both living and in vitro models [13]. However, the hydrogenated molecular variant squalane is not discussed in detail in this paper. Due to its moisturizing, radical-scavenging, and anti-cancerogenic properties, squalene is particularly recommended for topical formulations, including classic lipid emulsions (O/W and W/O) and nanostructured lipid carriers [11]. It is discussed as a treatment for anti-inflammatory skin diseases [64]. Additionally, its stabilizing and regenerating effect on vitamin E [65] and unsaturated fatty acids (PUFA) [66] provides stabilization of these anti-inflammatory and soothing ingredients in skin care products for dermatitis and psoriasis [67,68] to extend the shelf life and efficacy of these products. A high amount of unsaturated fatty acids was also identified in Silphium oil [69,70] (Appendix A.3), making it a promising source for skin caring and wound healing emulsions [54].

In addition to oxidative stability, physical emulsion stability is also relevant for cosmetic products—this has already been proven for squalene-containing O/W emulsions with 2% emulsifier and 2–10% squalene under various storage conditions [71]. Chitosan and whey protein [72] as well as phosphatidylcholine [73] also showed good stabilizing properties. A stable nano-emulsion for cosmetic applications has also been described in the literature [74]. Initial application tests (see Appendix A.4) showed good emulsifiability at 15% and a pleasant emulsion texture in a base formulation—however, further testing in more complex formulations, packaging materials and storage variations is recommended. This indicates that there are neither physical nor oxidative limitations to the development of a marketable skin care product containing squalene.

In addition to technological feasibility, there is also the question of effectiveness. Although squalene has been described as having many beneficial effects on the skin, a critical concentration for application has not yet been established. This proposed initial approach is based on knowledge of the natural squalene concentration of the skin, the amount of skin care products used, the concentration of squalene in oil, and oil in a topical skin care product. Even though the lipid content of human skin varies depending on the area of the body, between 57 and 288 µg/cm^2 of sebum was produced within 12 h by male subjects, of which 8.1–11.2% was squalene; after 3 h, the amount produced was 19–160 µg/cm^2 with 6.2–13.5% squalene [75]. Accordingly, each square centimeter of healthy male skin should contain 4.6–29.1 µg of squalene in 12 h. Another publication described an amount of 139 ± 28 µg squalene per biopsy area measuring 4 mm in diameter which corresponds to 1103.2 ± 222 µg/cm^2 [76]. Even though this value better describes the skin's content as it is extracted from a complete skin biopsy, the content of superficial sebum for further calculations was used, as this is most applicable to the use of topical cosmetics. However, due to the limited availability of usable data for other demographic and skin types, calculations will continue using this data based on male skin as a temporary and estimative measure. Nevertheless, a review of all genders and age groups is recommended, as hormone concentration can affect sebum production [77].

In accordance with the Commission's recommendation, the application amount for cosmetic products of 2 mg/cm^2 of skin was included in the calculation [78]. It is well known that with increasing UV radiation and the resulting oxidative stress, a linearly proportional amount of squalene is consumed to protect the skin—this process is significantly increased in atopic skin [2]. This is due to the reduced amount of sebum (approx. 30% less in non-lesional skin and 50% less in lesional skin of patients with atopic dermatitis) and its altered composition [79]. Since cosmetic products are intended to nourish and protect the skin, while healing is achieved with medical products, only the numbers for non-lesional skin were included for further calculation. Therefore, a topical skin care product would need to deliver 1.4–8.7 µg/cm^2 of squalene to restore healthy levels, assuming that cosmetic products are used twice a day (every 12 h, since both sebum and topical care products might be worn off). If this amount were contained in 2 mg of a skin care product, it would correspond to 70–430 mg/100 g product. The following scheme illustrates the individual steps of this calculation (Figure 1).

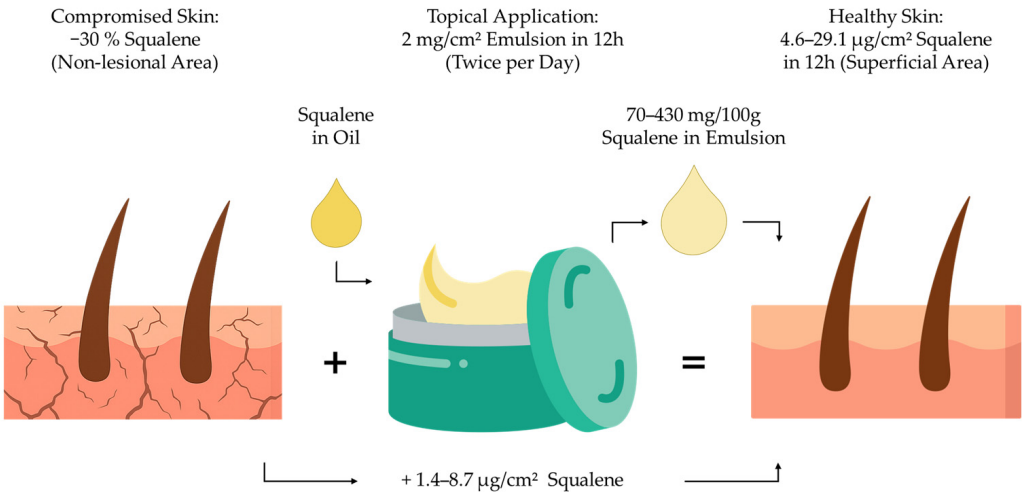


Figure 1. Scheme illustrating the calculation steps used to determine the required squalene concentration for compromised skin, which is supplemented through topical application of squalene-containing oil, based on the squalene content of healthy skin.

Assuming a squalene concentration of 3.4% as in silphium seed oil, this would correspond to an application concentration of 2.1–12.6% oil in an emulsion. These are standard concentrations used in *O*/*W* emulsions. The results indicate that with complete skin absorption, the healthy squalene concentration of sebum on the upper skin layer can be restored by a cosmetic product containing Silphium oil. The robustness of this calculation is demonstrated by the fact that even using twice the amount for skin care application would not exceed any regulatory safety margins of squalene. Considering that Silphium oil has no maximum regulatory threshold and many emulsions contain multi-fold higher oil-phase concentrations, consumers would also benefit from using even half than the amount typically specified in the safety assessment [22]. High-quality raw materials and stable formulations are essential requirements in each case.

Compared to other squalene sources, this calculation yields very different results: In some oils, including olive, Amaranthus and pumpkin seed oil [22,24,25], squalene concentration was too low for even 100% oil to meet the skin's needs at the recommended application amount. Calculations based on other data sources [23,26,34–38], however, yielded formulation-relevant concentrations for pumpkin seed oil (12.1–72.4%), amaranth oil (1.2–7.4%), *Silphium integrifolium* (1.5–9.0%), and *Pongamia pinnata* (3.9–34.0%). While most mentioned oils are approved by regulatory authorities, no entries for *Silphium integrifolium* were found in the INCI databases. This suggests that, in addition to *Silphium perfoliatum* oil, other oils may also be suitable for supplementing the skin's squalene content—subject to their topical applicability.

Although the results are promising, we recommend controlled, randomized, and double-blind studies to confirm these findings. It is particularly relevant that the data are based on male skin, whereas female skin in general, and in different phases of the menstrual cycle or at different ages, may differ, which should be investigated in more detail. Furthermore, the data here refers to the entire body. A distinction between different areas of the body should be taken into account in the study to avoid skin reactions caused by over-care.

4. Conclusions

Considering its biological activities, formulation compatibility, and sustainability profile, squalene represents a versatile and effective ingredient for future cosmetic applications, offering clear potential for innovation in modern skin care product development.

This review highlights the significant variability of squalene content across plant-derived oils and identifies *Silphium perfoliatum* as a possible sustainable and efficient new source with a high squalene yield per cultivated area, combined with favorable sensory properties. In addition, current evidence shows that squalene in plant oil exhibits notable oxidative stability. Its ability to protect and regenerate key bioactive compounds such as vitamin E and polyunsaturated fatty acids further underscores its value in skin-care formulations. Based on a calculation model, Silphium oil may compensate for the skin's own squalene deficiencies at realistic application concentrations of 2.1–12.6% emulsified oil. Meanwhile, on the one hand, other plant oils reached concentrations between 1.5 and 72.4%, or on the other hand, were not concentrated enough even with 100% concentration in formulation or were not approved yet for cosmetic application.

Specific and actionable future research directions include storage trials to additionally demonstrate stability in emulsions under various storage conditions, as well as placebo-controlled skin efficacy studies using cosmetic or medical topical emulsions on affected and sensitive skin to confirm the efficacy of the calculated concentration.

5. Patents

This article is a literature-based review. The preparation or analysis of additional samples to improve comparability falls within standard scientific practice and the current state of the art. No new patents have been filed or are planned based on the content of this review.

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Appendix A

Appendix A.1. Squalene Analysis in Silphium Seed Oil

The seeds were stored for varying periods of time after cultivation, pressed in different years, and the oil was then stored in different packaging materials and under different storage conditions. The squalene content of the tested Silphium oil samples was determined by the University of Udine, Department of Agri-Food, Environmental and Animal Sciences, Via Sondrio 2a, 33100 Udine, Italy using HPLC-DAD, following a slightly modified method based on Hayakawa et al., 2020 [22]. Sample preparation consisted of a 1:40 dilution in 2-propanol before HPLC injection (injection volume: 5 µL). Detection was performed using a DAD set at 215 nm. A short validation demonstrated the following method performance:

- linearity: R^2 = 0.9987 over the calibration range 0.046–18.6 mg/kg of squalene;
- repeatability (n = 7): RSD% = 0.2%;
- mean recovery: 102.0 ± 0.3% evaluated at two concentration levels (0.460 and 0.920 g/kg).

The resulting squalene concentrations are fully reported in Table A1.

Table A1. Squalene content of the analyzed Silphium oil samples (determined by HPLC-DAD).

Sample	Crop	Pressed	Packaging	Storage	Batch	Squalene [mg/100 g]
1	2024	April 2025	HDPE	Dark, 15 °C	PA25048	3250 ± 50
2	2018	April 2025	HDPE	Dark, 15 °C	PA25050	3560 ± 1
3	2020	April 2025	HDPE	Dark, 15 °C	PA25049	3350 ± 70
4	2022	2022	HDPE Can, later transferred to Green Glass	Dark, 15 °C	-	3560 ± 80
5	2022	2022	Glass	Dark, 15 °C	-	3560 ± 4
6	2022	2022	Glass	Office, Room Temperature	-	3490 ± 30
7	2022	2022	Glass	Dark, 15 °C	-	3550 ± 20

The result shows consistent squalene concentration that is independent of storage conditions and packaging material.

Appendix A.2. Hexanal Analysis in Silphium Seed Oil

The concentration of n-hexanal was examined by PiCA Prüfinstitut Chemische Analytik GmbH, Rudower Chaussee 29, 12489 Berlin, Germany using GC-MS after aqueous extraction and derivatization with a detection limit of 1 ppm with estimated measurement uncertainty of ±35%. The results are listed in Table A2.

Table A2. Hexanal content of the analyzed Silphium oil samples (determined by GC-MS).

Sample	Crop	Pressed	Packaging	Storage	Batch	Hexanal [ppm]
1	2024	April 2025	HDPE	Dark, 15 °C	PA25048	<1
2	2018	April 2025	HDPE	Dark, 15 °C	PA25050	2.3
3	2020	April 2025	HDPE	Dark, 15 °C	PA25049	1.1
4	2022	2022	HDPE Can, later transferred to Glass	Dark, 15 °C	-	1.2
5	2022	2022	Glass	Dark, 15 °C	-	1.4
6	2022	2022	Glass	Office, Room Temperature	-	<1
7	2022	2022	Glass	Dark, 15 °C	-	<1

This analysis shows an undetectable or very low hexanal concentration that is independent of storage conditions and packaging material, indicating high oxidation stability.

Appendix A.3. Fatty Acid Analysis in Silphium Seed Oil

The composition of fatty acids was examined by Untersuchungs- & Forschungslaboratorium (UBF) GmbH, An der Mühle 1d, 15345 Altlandsberg, Germany using a standardized gas chromatographic method. The results are listed in Table A3.

Table A3. Fatty acid composition analysis of selected Silphium oil samples (determined by GC).

Sample	Crop	Pressed	Batch	Palmitic Acid [%]	Stearic Acid [%]	Oleic Acid [%]	Linoleic Acid [%]
1	2024	April 2025	PA25048	7.0	2.3	17.4	69.2
2	2018	April 2025	PA25050	7.7	3.2	19.8	65.0
3	2020	April 2025	PA25049	7.2	2.5	18.6	66.4

The analysis reveals a high content of unsaturated fatty acids (PUFA) in all Silphium oil samples across different harvest times, highlighting the oil's consistent skin-nourishing properties.

Appendix A.4. Application Potential of Silphium Seed Oil

The unprocessed Silphium oil appeared golden in color and had a nutty aroma. An initial application analysis in emulsions (Ingredients: 15% Silphium perfoliatum seed oil, 7% Glyceryl Stearate SE, 0.5% Phenylethanol, 0.3% Xanthan Gum, 0.1% Citric Acid, q.s. 100% Aqua) showed good emulsifiability. Production instructions were conducted in accordance with [61–63]. The result was a nutty-smelling, light beige, smooth emulsion with a lightly absorbent texture. More detailed stability and packaging compatibility tests are recommended.

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