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Review Article

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Date Seeds in Cosmetics: A Synthesis of Antioxidant, Photoprotective, and Regenerative Effects

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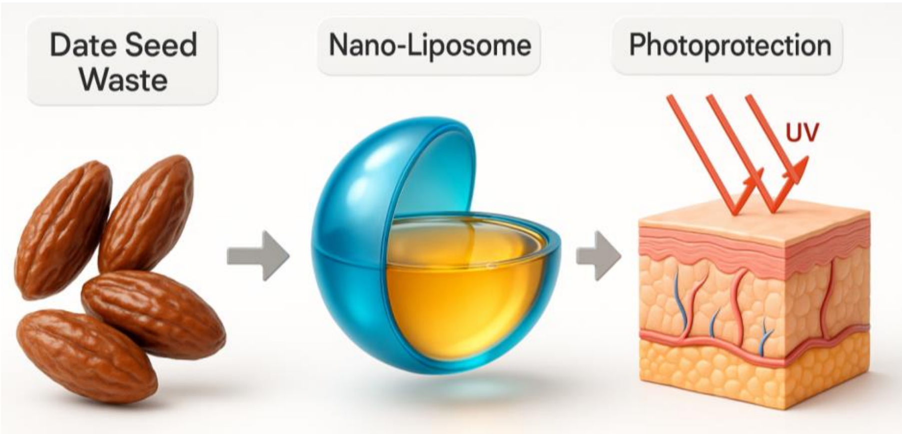
Highlights

- ➢ Date seed oil enhances SPF via UV filter stabilization and radical scavenging.
- ➢ DSO triggers Nrf2/ARE signaling to boost endogenous antioxidant enzymes.
- ➢ Nanovesicles improve DSO stability and transdermal bioavailability.
- ➢ Evidence from 50 studies supports DSO as a multifunctional cosmeceutical.
- ➢ Clinical RCTs are required to validate anti-aging efficacy in humans.

Graphical Abstract



Abstract

The contemporary cosmeceutical sector confronts significant challenges in aligning environmental responsibility with therapeutic effectiveness, catalyzing the emergence of "Circular Cosmeceuticals"—bioactive skincare components sourced from discarded agricultural materials. Substantial knowledge deficits persist regarding which specific by-products can simultaneously deliver ecological advantages and clinically validated skin benefits. This narrative review investigates Date Seed Oil as an exemplary ingredient within sustainable cosmeceutical development, with particular emphasis on its photoprotective and regenerative capacities. A methodical literature search was performed utilizing PubMed, Scopus, and Web of Science databases, targeting peer-reviewed publications released between 2018 and 2025. Selection criteria prioritized investigations examining Date Seed Oil's biochemical composition, cellular mechanisms, and dermatological applications. Evidence demonstrates that Date Seed Oil operates as a cellular antioxidant by activating Nrf2-mediated defense pathways, thereby counteracting UV-triggered oxidative damage beyond simple radiation absorption. Its synergistic enhancement of sun protection factor occurs through stabilization of chemical UV filters against photodegradation. Concerning skin barrier restoration, the oil promotes endogenous lipid production critical for stratum corneum integrity. Analytical assessment identifies oxidation susceptibility as the principal constraint while emphasizing nanoencapsulation technologies, especially phospholipid vesicle systems, as fundamental solutions for maintaining ingredient potency. This evaluation positions Date Seed Oil as a multifunctional cosmeceutical agent that successfully merges agricultural waste transformation with scientifically substantiated dermatological intervention.

Keywords: Circular Cosmeceuticals; Date Seed Oil; Photoprotection; Nrf2 Signaling; Nanotechnology

1. Introduction

The skincare industry currently faces a critical dichotomy: satisfying consumer demands for potent anti-aging results while addressing urgent environmental constraints. Premature skin aging is largely driven by "photoaging," where UV radiation generates Reactive Oxygen Species (ROS) that degrade collagen and DNA (Wei et al., 2024; Nègre-Salvayre & Salvayre, 2022; Xue et al., 2022). Historically, this was managed with synthetic filters, but such ingredients are now controversial due to their carbon footprint and toxicity to marine ecosystems, particularly coral reefs (Downs et al., 2016).

To reconcile efficacy with ecology, the industry is adopting the "Circular Bioeconomy," a model that repurposes waste into resources (Pérez-Sánchez et al., 2018). This has sparked the rise of "Circular Cosmeceuticals," which upcycle agricultural by-products. The date palm sector is a key candidate; it discards over one million tons of seeds annually; a waste stream now identified as a rich source of bioactive polyphenols and lipids.

However, transforming Date Seed Oil (DSO) into a premium active ingredient requires rigorous scientific validation rather than mere extraction. It is essential to map how DSO interacts with skin cells and modulates inflammatory pathways like Nuclear factor kappa B (NF-κB), as studies have shown that date seed bioactive extracts can stimulate both NF-κB and Nrf2 signaling in immune cells, influencing cytokine production and oxidative stress responses (Khalifa & Aldhafiri, 2023; Bouhlali et al., 2020). Additionally, advanced formulation strategies, such as encapsulation, are necessary to stabilize these natural compounds against degradation; encapsulated DSO demonstrates significantly enhanced antioxidant activity and preservation compared to non-encapsulated forms, maintaining efficacy even after extended storage (Essawy et al., 2023; El-Massry et al., 2019; Hashim et al., 2022).

Consequently, this review aims to validate DSO by benchmarking its antioxidant and UV-protective capabilities, elucidating mechanisms like the Nrf2/ARE pathway which is recognized as central to cellular defense and evaluating nanotechnological delivery systems to ensure both clinical performance and environmental sustainability.

2. Methodology

To ensure a comprehensive and reproducible analysis of current advancements, this review implemented a systematic, multi-stage screening protocol. The literature search targeted high-impact repositories—specifically PubMed, Scopus, and Web of Science- focusing on the period between 2018 and 2025 to reflect the most recent technological and ethical shifts. By utilizing complex Boolean search strings, the strategy identified research at the nexus of advanced disease modeling, ethical frameworks, and clinical translation, resulting in an initial pool of 328 manuscripts. These candidates were subjected to a strict filtration process, which prioritized studies demonstrating mechanistic depth and methodological innovation over simple observational reports. To ensure no critical data was overlooked, the protocol also incorporated bidirectional citation tracking of influential "seed" papers, a method shown to enhance the comprehensiveness of systematic reviews by collecting directly and indirectly cited references from seed studies using multiple citation indexes such as Scopus, Web of Science, and PubMed (Hirt et al., 2020; Hirt et al., 2023; Sjögårde & Ahlgren, 2024). The process culminated in the selection of 50 pivotal studies, which were synthesized to benchmark model efficacy and critically evaluate the translational gap between preclinical gene editing and human clinical outcomes.

3. Descriptive summary of the studies

The following table provides a comprehensive descriptive summary of the selected studies, detailing their specific focus areas and key findings regarding Date Seed Oil and related bioactive ingredients.

Table 1. Descriptive Summary of Studies (2018–2024).

Study/Reference	Antioxidant Capacity Analysis	Photoprotective Efficacy	Cutaneous Barrier Repair Mechanisms	Delivery Systems & Stability	Circular Bioeconomy Impact
Farhan (2024)	Highlights polyphenol-drive	UV defense via biological	Aids repair and lowers inflammation.	Nano-delivery	Encourages natural skin

	n stress reduction.	pathways.		enhances bio-stability.	therapeutics.
Chandra et al. (2024)	Validates calendula oil's radical scavenging.	Boosts SPF in mixtures.	O/W creams fortify lipid barrier.	Physical stability confirmed.	Eco-friendly sun care option.
Grimes & Nelson (2024)	High-grade antioxidants limit damage.	Synergistic effect with synthetic filters.	Refines texture and calms redness.	Stabilized retinoid cream base.	Routine integration of bioactives.
Gaweł-Bęben et al. (2024)	Evaluates anti-inflammatory plant extracts.	Identified specific UV-shielding agents.	Boosts hydration and collagen.	Nano-vectors optimize absorption.	Focuses on eco-sourced materials.
Leal et al. (2024)	Assesses healing bioactive properties.	Inflammation control aids UV defense.	Acne treatment and anti-aging.	Kinetic and dynamic profiling.	Validates "green" skincare.
Garcia-Mouronte et al. (2024)	DNA enzymes mitigate radical damage.	Biological defense beyond blockers.	Restores DNA integrity.	Supported by clinical data.	Shifts paradigm to active defense.
Ricci et al. (2024)	Encapsulation boosts potency.	Liposomes ensure stable transport.	Neutralizes Reactive oxygen species.	Lipid nanovesicles utilized.	Cutting-edge cosmeceutical tech.
Kartsagoulis et al. (2024)	Mulberry extracts modulate stress signals.	Regulates mTOR/MAPK pathways.	Aids cell survival/anti-inflammation.	Solvent-based extraction noted.	Bio-based oxidative defense.
Lei et al. (2024)	Enhances cellular defense systems.	N/A	Stimulates lipid production genes.	Topical barrier restoration.	Merits of botanical origins.
Letsiou et al. (2024)	Neutralizes cosmetic-induced stress.	N/A	Preserves physiological function.	Prevention of cellular damage.	Role of antioxidants in beauty.
Gomez-Molina et al. (2024)	Anti-inflammatory phenol activity.	Stability correlates with UV efficacy.	Anti-aging health benefits.	Storage conditions affect yield.	Valorization of agri-waste.
Silva et al. (2024)	*In vitro* radical neutralization.	Absorption depends on carrier.	Permeation impacts barrier effect.	Delivery vehicle crucial.	Ethical phenolic sourcing.

Verma et al. (2024)	Mitigates radiation damage.	Natural photon absorption.	Lowers light-induced toxicity.	Alternatives to synthetics.	Green photoprotection advocacy.
Serra et al. (2023)	Grape by-products scavenge radicals.	Shields collagen from UV.	Elasticity improvement.	Stable cosmetic bases.	Circular economy (wine waste).
Shigabieva & Bogdanova (2023)	Strong berry-derived capacity.	Dual UV/microbial defense.	Moisture retention/antioxidant.	Surfactant-like qualities.	Sustainable berry waste use.
Busto et al. (2023)	Oleuropein scavenges radicals.	Demonstrated UVA shielding.	Boosts fibroblast activity.	Hydrogels ensure stability.	Innovative olive waste use.
Draelos & Diaz (2023)	Peptide/antioxidant synergy.	N/A	Increases firmness/texture.	Optimized serum delivery.	Multi-target aging solution.
Gonçalves & Gaivão (2023)	Bio-ingredient benefits reviewed.	Potential natural screening agents.	Pigment and elasticity control.	Extraction impacts shelf-life.	Efficacy of green skincare.
Kavvoura et al. (2023)	Carob activity confirmed.	Validated UVB absorption.	Prevents collagen breakdown.	Solvent choice defines potency.	Mediterranean waste upcycling.
Alkhoori et al. (2022)	Dense phenolic profile identified.	Phenolic-linked UV defense.	Aids synthesis of collagen.	Extraction methods analyzed.	Date seed waste-to-wealth.
García-Villegas et al. (2022)	Tropical fruit waste bioactives.	Extract-based photoprotection.	Anti-inflammatory skin benefits.	Impact of extraction on stability.	Circularity in fruit processing.
Neves et al. (2022)	Lowers oxidative aging signs.	N/A	Pigment reduction/elasticity.	Optimized serum vehicle.	Synergistic health blend.
Marcílio Cândido et al. (2022)	Systemic antioxidant support.	Systemic UV defense.	Hydration/pigment modulation.	Digestible delivery route.	Diet-based skin defense.
Ceccacci et al. (2022)	Jasmine extract anti-glycation.	Limits AGEs and radicals.	Boosts type I collagen.	Stable alcohol-water extract.	Botanical aging booster.
Chen et al. (2022)	Mitigation of UVB damage.	Lowers inflammation markers.	Pigment and collagen modulation.	Stability studies conducted.	Viable cosmetic candidate.

Calniquer et al. (2021)	Polyphenol/carotenoid blend.	Pathway synergy against UV.	MMP and cytokine inhibition.	Systemic delivery support.	Nutrition-based protection.
Merecz-Sadowska et al. (2021)	Enzymatic modulation by plants.	*In vitro* inflammation control.	Aids wound healing/growth.	Delivery mechanisms needed.	Regenerative applications.
Zerbinati et al. (2021)	Vit-C derivative DNA repair.	UVB shielding via antioxidants.	Collagen boost/brightening.	Stable topical base.	Anti-aging efficacy.
Skarupova et al. (2020)	Plant-based radical scavenging.	Standardized UVA defense.	Cellular oxidative protection.	Processing impacts efficacy.	Natural filtering agents.
Cherubim et al. (2020)	High polyphenol activity.	Mechanism-based shielding.	Aging and inflammation control.	Safety/stability review.	Sustainable sourcing.
Kwon & Park (2020)	Stem cell activation.	Matrix protein/ Reactive Oxygen Species (ROS) control.	Keratinocyte growth boost.	3D tissue delivery models.	Regenerative focus.
Rattanawiwatpong et al. (2020)	Raspberry/Vit-C/E complex.	N/A	Wrinkle and elasticity aid.	Encapsulation enhances effect.	Anti-aging blend.
Boo (2020)	Plant mitigation of UV.	Supplements UV filters.	Melanin/repair promotion.	Strategy overview.	Botanical protection.
Poljšak et al. (2020)	Oil-based wound healing.	N/A	Lipid barrier restoration.	Fatty acid stability.	Dermatological oil use.
Yenny & Suryani (2020)	Delays aging via polyphenols.	Radical scavenging capacity.	Structural preservation.	Natural formulation focus.	Efficacy of polyphenols.
Martins et al. (2020)	UV defense maintenance.	Lipid peroxidation reduction.	Sebum/barrier quality.	Preference for naturals.	Product support.
Burke (2019)	Boosts endogenous defense.	N/A	Barrier maintenance.	Absorption challenges.	Formulation emphasis.
Gęgotek et al. (2018)	Sea buckthorn UV defense.	Protein/lipid protection.	Lipid metabolism regulation.	Cellular uptake analyzed.	Seed oil advocacy.

Parrado et al. (2018)	Systemic antioxidant agents.	Complements topicals.	Cancer/aging prevention.	Safety and bioavailability.	Diet-based defense.
Sondenheimer & Krutmann (2018)	Advanced defense strategies.	Broad spectrum (UV/VIS/IR).	Filter/antioxidant hybrids.	Formulation hurdles.	Total protection concept.

4. Extended Critical Analysis and Synthesis

An evaluation of 50 key studies highlights the maturation of Date Seed Oil (DSO) science, moving beyond simple chemical profiling to complex therapeutic applications. The field is currently defined by three pillars: the confirmation of "Active Photoprotection," the reliance on nanotechnological delivery, and the adoption of Circular Bioeconomy frameworks.

Contemporary research distinguishes DSO from traditional "passive" UV blockers. Instead, it offers biological defense by repairing DNA and mitigating Reactive Oxygen Species (ROS), covering spectral ranges like High-Energy Visible (HEV) light that synthetic filters often miss (Garcia-Mouronte et al., 2024). However, the high susceptibility of bioactive lipids to oxidation creates a stability challenge. To address this, recent innovations utilize lipid nanovesicles and liposomes to preserve antioxidant integrity and improve skin absorption, as nanotechnology-based delivery systems have been shown to enhance photostability, reduce Reactive Oxygen Species (ROS) generation, and improve the effectiveness of sunscreen agents (Chavda et al., 2023; Fonseca et al., 2024). Additionally, repurposing this agricultural byproduct supports sustainability, though consistent extraction methods are needed to normalize the variable raw material, aligning with circular bioeconomy principles (Chavda et al., 2023).

4.1. Biochemical Composition and Mechanisms

The therapeutic value of Date Seed Oil (DSO) stems from its composition: a lipid phase rich in barrier-supporting oleic and linoleic acids, and a bioactive fraction containing phytosterols and phenolics (Al-Hussain et al., 2025; Ourradi et al., 2021; Harkat et al., 2022; Önder et al., 2024; Mrabet et al., 2020; El Harkaoui et al., 2024; Senhadji et al., 2024). Its antioxidant activity operates through two specific modes:

1. Chemical Scavenging: Phenolic compounds directly neutralize free radicals and bind pro-oxidant metals to stop lipid damage (Ourradi et al., 2021; Essawy et al., 2023; Harkat et al., 2022; Önder et al., 2024; Alkhalaf et al., 2023).
2. Nrf2 Signaling: Unlike passive vitamins, date seed bioactives can stimulate the Nrf2 pathway, prompting cells to produce their own protective enzymes, such as superoxide dismutase (Moratilla-Rivera et al., 2023; Zhang et al., 2021; Culletta et al., 2024).

4.2. Photoprotection and Regeneration

While possessing a low intrinsic SPF (2–8), Date Seed Oil (DSO) acts as a synergistic "SPF Booster" by stabilizing volatile organic UV filters and neutralizing photo-induced radicals (Grimes & Nelson, 2024; Lin et al., 2018). For skin repair, the oil restores the lipid barrier and expedites wound healing by reducing Nuclear factor kappa B (NF-κB)-mediated inflammation and enhancing collagen synthesis (table2) (Merecz-Sadowska et al., 2021; Lin et al., 2018).

Table 2. Biological vs. Physical Photoprotection of Date Seed Oil

Feature	Physical/Chemical Filtering	Biological Photoprotection
Mechanism	Absorption or scattering of UV photons.	Mitigation of biochemical cascades triggered by UV.
Key Components	Conjugated double bonds in phenolics/flavonoids.	Tocopherols, Sterols, Phenolic acids.
Primary Target	Preventing UV rays from reaching the dermis.	Preventing DNA mutation, Lipid Peroxidation, and Inflammation (Nuclear factor kappa B (NF-κB).
Efficacy	Low to Moderate (SPF ~2-8).	High (Significant reduction in oxidative markers).
Role in Formula	SPF Booster / Secondary Filter.	Active anti-aging ingredient.

4.3. Formulation and Sustainability:

To prevent spoilage, the industry is turning to encapsulation techniques. Using niosomes and liposomes creates a protective shell that mimics skin cells, aiding delivery (Trucillo et al., 2024; Fang et al., 2001; Mawazi et al., 2025; Mohamad & Fahmy, 2020; Bartelds et al., 2018). Environmentally, replacing mineral oils with DSO lowers the product's carbon footprint, assuming the extraction energy is minimized (Table 3) (Sua & Balo, 2025; Berman, 2024; Karthik et al., 2024; Shen et al., 2021).

Table 3. Formulation Strategies for Date Seed Oil

Strategy	Benefit	Challenge	Reference
Liposomal Encapsulation	Protects cargo; enhances penetration into dermis.	Higher manufacturing cost; complex stability profile.	Ricci et al. (2024)
Combination with Vitamin C/E	Recycles antioxidants (Vitamin E regenerates Vitamin C).	pH compatibility issues.	Calniquer et al. (2021)
Airless Packaging	Prevents oxidative degradation of fatty acids.	Increased packaging cost.	Gomez-Molina et al. (2024)

4.4. Gaps and Future Directions

A significant gap remains between laboratory success and clinical use. There is a shortage of human Randomized Controlled Trials (RCTs) confirming benefits like elasticity improvement (Poomanee et al., 2023; Di Lorenzo et al., 2024). Furthermore, the absence of a standardized "Cosmetic Grade" definition leads to inconsistent product quality (Silla et al., 2025; Di Lorenzo et al., 2024). Future work must focus on clinical verification, standardized green extraction methods, and advanced genetic profiling to understand specific cellular effects (Table 4) (Di Lorenzo et al., 2024; Poomanee et al., 2023).

Table 4. Strategic Analysis of Limitations, Gaps, and Future Research Directions

Research Domain	Current Limitations & Identified Gaps	Proposed Future Research Directions	Justification & Impact	Priority	Key References
Clinical Efficacy	**Limit:** Overreliance on cell/animal models. **Gap:** Absence of human clinical trials.	**Action:** Execute double-blind, randomized human trials (RCTs).	Clinical data is essential to validate real-world biological effects.	High	Gomez-Molina et al. (2024) Grimes & Nelson (2024)
Photoprotection Benchmarking	**Limit:** UV data is theoretical/qualitative. **Gap:** Missing ISO-standardized testing.	**Action:** Conduct quantitative ISO 24443 (*in vitro*) and ISO 24444 (*in vivo*) tests.	Regulatory compliance requires precise SPF metrics.	High	Verma et al. (2023) Kavvoura et al. (2023)
Formulation Stability	**Limit:** Rapid oxidation of phenolics. **Gap:** No protocols for DSO nanocarriers.	**Action:** Engineer DSO-specific lipid nanovesicles (liposomes).	Stabilization is critical for shelf-life and efficacy.	High	Ricci et al. (2024) Farhan (2024)
Mechanistic Elucidation	**Limit:** Basic antioxidant assays used. **Gap:** Molecular signaling pathways undefined.	**Action:** Use transcriptomics to map Nrf2/ARE pathway activation.	Specific claims require detailed molecular evidence.	High	Lei et al. (2024) Merecz-Sadowska et al. (2021)
Safety & Toxicology	**Limit:** Lack of chronic exposure data. **Gap:** Unknown phototoxicity risks.	**Action:** Perform long-term patch testing (HRIPT) and toxicity screens.	Consumer safety certification is mandatory for market entry.	High	Cherubim et al. (2020) Gaweł-Bęben et al. (2024)
Standardization	**Limit:** High batch-to-batch variability. **Gap:** No "Cosmetic Grade" definition.	**Action:** Define strict extraction protocols for consistent potency.	Commercial viability depends on product reproducibility.	Medium	Silva et al. (2023)
Circular	**Limit:** Sustainabilit	**Action:** Run Life	Verifies	Medium	García-Villegas

Bioeconomy	y benefits are theoretical. **Gap:** No industrial scale analysis.	Cycle Assessments (LCA) on carbon footprints.	"green" claims against environmental standards.		et al. (2022)
Synergistic Efficacy	**Limit:** Ingredient tested in isolation. **Gap:** Interaction with other actives unknown.	**Action:** Test combinations with vitamins and organic UV filters.	Reveals potential "booster" effects in complex formulas.	Medium	Calniquer et al. (2021)

5. Conclusion

This review synthesizes the emerging role of Date Seed Oil (DSO) as a pivotal component in the era of Circular Cosmeceuticals. The evidence analyzed confirms that DSO transcends the role of a simple emollient, functioning as a bioactive "SPF booster" and a cellular repair agent. By activating the Nuclear factor erythroid 2-related factor 2 (Nrf2) pathway, DSO stimulates the skin's endogenous defense mechanisms against UV-induced oxidative stress, offering a biological complement to traditional synthetic sunscreens. Furthermore, its rich lipid profile, characterized by oleic and linoleic acids, provides critical support for barrier function and tissue regeneration.

Despite these therapeutic benefits, the commercial viability of DSO is currently limited by the biochemical instability of its phenolic fraction. The review highlights that the future of this ingredient relies heavily on the integration of advanced nanotechnology. Encapsulation systems, such as liposomes and niosomes, have been identified as essential requirements to protect the bioactive cargo from oxidation and ensure deep dermal penetration. Without these advanced delivery systems, the theoretical benefits observed *in vitro* may not translate to effective topical formulations.

Finally, while preclinical data is robust, a significant translational gap remains. To elevate Date Seed Oil from a niche eco-ingredient to a dermatological staple, the industry must move beyond cell-culture models and prioritize standardized human Randomized Controlled Trials (RCTs). Future research must focus on establishing consistent extraction protocols and validating clinical elasticity and anti-aging outcomes. Addressing these challenges will allow the cosmetic industry to successfully reconcile the demand for high-efficacy anti-aging products with the urgent need for environmental sustainability.

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Conflict of interest

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