



From Nutrition to Anti-Aging: The Expanding Pharmaceutical and Cosmetic Potential of Omega-3-Rich *Lepidium Sativum* Seed Oil

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ABSTRACT:

Lepidium sativum L. (garden cress) seed oil is increasingly recognized as a rich source of omega-3 fatty acids and bioactive phytoconstituents with promising applications in medicine and cosmetics. This review outlines its progression from traditional nutritional use to emerging relevance in anti-aging and dermatological care. Modern extraction methods, including microwave-assisted and supercritical fluid extraction, are emphasized for their efficiency in preserving thermolabile compounds and yielding high-quality oil. Advanced phytochemical profiling and omics-based approaches provide insights into its complex molecular composition and biological activity. Notably, the oil exhibits strong antioxidant properties, mitigating oxidative stress—a key factor in cellular aging and skin deterioration. Evidence also supports its role in enhancing skin hydration, reinforcing epidermal barrier function, and stimulating collagen synthesis, thereby underpinning its integration into cosmeceutical formulations. Collectively, *Lepidium sativum* seed oil represents a versatile bioresource with significant potential across pharmaceutical, nutraceutical, and cosmetic industries. Further clinical validation and formulation research are essential to establish its efficacy in anti-aging therapies.

INTRODUCTION:

Lepidium sativum L., a fast-growing edible herb in the Brassicaceae family, is also referred to as garden cress or halim. Traditional Indian, Middle Eastern, and African medical systems have made extensive use of its seeds to treat digestive issues, anemia, inflammation, and postpartum recuperation ¹. The rich nutritional profile of *L. sativum* seeds has attracted increasing attention in recent years, especially because of their high fixed oil content, which is primarily made up of the necessary omega-3 fatty acid α -linolenic acid (ALA) ². Although the anti-inflammatory, cardioprotective, neuroprotective, and dermatological properties of omega-3 fatty acids are widely known, the majority of the world's supply comes from marine sources like fish and krill oil, which raises questions about sustainability, toxicity, and consumer acceptability ³. Thus, plant-based sources of omega-3, particularly

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those with high ALA concentration, are becoming more popular as sustainable and safer substitutes for use in pharmaceutical, nutraceutical, and cosmetic applications. *Lepidium sativum* seed oil is one of the most promising botanical sources of plant-derived omega-3 fatty acids since it contains 30–35% fixed oil, of which up to 35–40% is ALA⁴. *L. sativum* seed oil is a potentially useful component for topical and dermatological preparations due to its antioxidant, anti-inflammatory, wound-healing, and moisturizing qualities in addition to its nutritional qualities⁵. The most effective PUFAs for improving skin penetration were linoleic acid, docosatrienoic acid, and arachidonic acid. Additionally, linoleic acid is said to be utilized in cosmetics and to treat dermatoses and sunburns.

Its mucilage and bioactive phytochemicals also support applications in skin-repair systems, emulsion stability, and drug administration⁶. Despite these encouraging qualities, the oil is nevertheless underutilized and understudied, with little industrial extraction and little use in consumer goods.

This review presents a comprehensive evaluation of *Lepidium sativum* seed oil with emphasis on its phytochemical composition, omega-3 fatty acid profile, extraction methods, pharmacological significance, and potential pharmaceutical and cosmetic applications. It also highlights research gaps and future opportunities for developing this plant into a valuable, sustainable omega-3 resource.

1. Botanical Description and Phytochemical Profile:

Lepidium sativum, commonly known as garden cress, belongs to the Kingdom Plantae, Division Magnoliophyta, Class Magnoliopsida, Order Brassicales, and Family Brassicaceae. Within this taxonomic hierarchy, it is placed in the genus *Lepidium*, which encompasses several species known for their medicinal and nutritional value. As a member of the Brassicaceae family, *Lepidium sativum* shares characteristics typical of cruciferous plants, including the presence of glucosinolates that contribute to its distinctive pungent flavor and potential health benefits. This fast-growing annual herb is widely cultivated for its edible leaves and seeds, which are rich in vitamins, minerals, and bioactive compounds. Its classification highlights its evolutionary relationship with other economically important plants such as mustard, broccoli, and cabbage, underscoring its significance in both agriculture and traditional medicine.



Fig 1: Germinated seeds of *Lepidium sativum*

2. Morphology:

Ge seeds are small, oval-shaped, pointed and triangular at one end, smooth, about 3-4 mm long, 1-2 mm wide, reddish brown in color. A furrow present on both surfaces extending up to two thirds downward, a slight wing like extension present on both the edges of seed. On soaking in water seed coat swells and gets covered with transparent, colorless, mucilage with mucilaginous taste⁷. The seed length and width are $2981.32\mu\text{m}$ and $100\pm 1.9\text{ }\mu\text{m}$ respectively.



Fig 2: Dried seeds of *Lepidium sativum*

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3. Fatty acid Composition of *Lepidium Sativum*:

Increased oxidative stress, decreased lipid content, and compromised barrier function are all linked to aging skin. Fatty acids are essential for preserving the integrity of skin, keeping it hydrated, and shielding it from environmental harm.⁸ Due to their high content of essential fatty acids, *Lepidium sativum* seeds may have anti-aging properties. The following table no. 1 summarizes the content of fatty acids reported in different research.⁹

Table 1: Chemical Composition of *Lepidium sativum* Seeds

| Fatty Acid | Chemical Name | Type | Approx percentage (%) |
|---------------------|---------------|----------------------------|-----------------------|
| Alpha linoleic acid | C18:3(w-3) | Polyunsaturated fatty acid | 24-32 |
| Oleic acid | C18:1(w-9) | Monosaturated fatty acid | 24-31 |
| Linoleic acid | C18:2(w-6) | Polyunsaturated fatty acid | 8-10 |
| Palmitic acid | C16:0 | Saturated fatty acid | 10-13 |
| Stearic acid | C18:0 | Saturated fatty acid | 2-5 |
| Arachidic acid | C:20:0 | Saturated fatty acid | <1-2 |
| Behenic acid | C22:0 | Saturated fatty acid | Trace |
| Lignoceric acid | C24:0 | Saturated fatty acid | Trace |

4. Extraction Methods:

There are numerous methods for extracting physiologically active substances from plants. Depending on the solvent, temperature, and pressure utilized, they vary greatly. The solubility of isolated metabolites in liquids of varying polarity is determined by structural differences. Therefore, the yield of plant secondary metabolite extraction as well as the activity of the resulting extracts may be significantly impacted by the kind of extraction solvent and the isolation (extraction) procedure.¹⁰ A typical method for isolating different physiologically active substances from plants is maceration. It has numerous disadvantages, though, just as other traditional approaches. Therefore, the development of chemical processes that rely on the use of ecologically friendly solvents is currently receiving considerable attention.¹¹

Solvents with altered physicochemical properties, like supercritical fluids, or non-toxic or low-toxic solvents, like ethanol and water, are used in modern extraction procedures. These days, supercritical fluid extraction (SFE) has become very popular from the perspective of green chemistry.¹²

5. Supercritical Fluid Extraction (SFE):

Supercritical fluid extraction has become a sophisticated, environmentally sustainable method for separating superior lipids and bioactives from *Lepidium sativum* seeds.¹³ Supercritical CO₂ is a great non-polar solvent that effectively dissolves seed oils while maintaining thermolabile components such tocopherols, antioxidant minor compounds, and omega-3 fatty acids. SFE offers solvent-free extracts, reduced thermal degradation, and more selectivity than conventional procedures like Soxhlet and cold-pressing.¹⁴ Yield and chemical composition are greatly impacted by extraction parameters including pressure (20- 30MPa), temperature (35-40 °C), supercritical CO₂ flow rate of 0.15-0.3m³/h, and 4-5 H extraction time. Under such a condition, the oil obtained is very lucid and good quality, and the yield is as high as above 90%.¹⁵ Pharmaceutical cosmetic-grade *Lepidium sativum* seed oil can be produced using optimized SFE settings, which have been shown to boost oil recovery and increase the concentration of unsaturated fatty acids.¹⁶

6. Microwave Assisted Extraction (MAE):

In comparison compared to conventional Soxhlet and mechanical extraction techniques, microwave-assisted extraction (MAE) has become an effective, quick, and environmentally friendly approach for separating fatty acid-rich seed oils. By directly interacting with polar molecules and ions in plant matrices, microwave energy in MAE induces rapid heating, cell rupture, and improved solvent penetration, all of which increase extraction efficiency and shorten processing times¹⁷. Higher yields of thermolabile fatty acids, such as linoleic, linolenic, and oleic acids, are made possible by this targeted heating's increased mass transfer rates and reduced oxidative degradation¹⁸.

In accordance with green chemistry principles, the process also uses less solvent and runs at lower temperatures than conventional techniques¹⁹. Research on a variety of oil-bearing seeds, including flaxseed, chia seeds, and *Lepidium sativum*, demonstrates that MAE produces oil percentages that are on par with or better while maintaining the natural unsaturated fatty acid profile necessary for nutraceutical and cosmetic uses²⁰. It is crucial to optimize variables like microwave power, extraction time, solvent type, and seed-to-solvent ratio since too much power can cause lipid oxidation and too little energy may avoid cell wall breakage²¹. MAE has grown more and more popular for routine fatty acid extraction and profiling in phytochemical, pharmacognosy, and functional

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food research because of its speed, reproducibility, and minimal environmental impact.

7. Advanced Phytochemical Profiling and Omics Integration:

The characterisation of *Lepidium sativum* seed oil (LSSO) has changed from traditional fatty-acid summaries to thorough molecular profiling due to recent developments in analytical chemistry. Major lipids including α -linolenic acid (ALA), linoleic acid, and oleic acid can be efficiently quantified by traditional GC-MS analysis of fatty acid methyl esters (FAMES)²²; however, intact lipid structures and small bioactive components are not captured by this method. Triacylglycerol (TAG) regioisomers, diacylglycerols, phospholipids, oxidized lipid species, sterols, tocopherols, and phenolic antioxidants may now be precisely identified thanks to high-resolution LC-MS/MS, lipidomics, and metabolomics approaches²³. These platforms have identified a number of previously unidentified antioxidant compounds and omega-3-rich TAG species in LSSO that support its anti-aging and dermatological qualities.

High-resolution mapping of intact TAG molecular species, including positional distribution at sn-1, sn-2, and sn-3, is possible by untargeted and targeted lipidomic procedures utilizing LC-QTOF or Orbitrap devices [24]. Because it affects enzymatic hydrolysis, epidermal penetration, and conversion to signaling lipids involved in inflammation and barrier restoration, this positional information has biological significance. According to parallel profiling of minor lipids, LSSO includes considerable levels of tocopherols and tocopherols that may be measured using HPLC-FLD or LC-MS techniques, as well as phytosterols (such as β -sitosterol and campesterol) that can be detected via GC-FID/MS after derivatization²⁵. A wide range of phenolic substances and glucosinolate derivatives that boost antioxidant activity and may alter Nrf2-dependent protective pathways are further highlighted by complementary metabolomic investigations²⁶.

A strong framework for clarifying the molecular underpinnings of LSSO's anti-aging effectiveness is provided by integrating lipidomics with metabolomic information. Lipid species linked to improved skin-barrier function, oxidative stability, and lipid-peroxidation resistance can be found using molecular-level lipid mapping.²⁷ Quality control, adulteration detection, extraction parameter adjustment, and the selection of fractions enriched in medicinal or cosmetic actives are all supported by such thorough profiling²⁸. Direct association between particular molecular species and biological outcomes is made possible by combining these data with functional assays, such as skin-barrier performance, UV-induced damage models, and antioxidant capacity testing.²⁹

Comprehensive LC-MS-based lipidomic research on LSSO are still few despite increased interest. Lipidomics, sterol analysis, tocopherol profiling, and phenolic metabolomics should all be used in future research to create strong chemical markers and mechanistic connections that support its medicinal and cosmetic uses. The commercial development of omega-3-rich LSSO will be accelerated and scientific understanding will be significantly strengthened by such an omics-driven strategy.

8. Pharmacological Activities of *Lepidium sativum* seed oil:

The *Lepidium sativum* seed oil is increasingly being used in medicinal and cosmetic compositions due to its numerous pharmacological properties. The oil exhibits potent antioxidant action by lowering oxidative stress and shielding cellular lipids from harm, largely attributed to its rich content of omega-3 fatty acids, tocopherols, and phenolic antioxidants.³⁰ Its anti-inflammatory properties, which lessen irritation and tissue inflammation, are associated with the modulation of pro-inflammatory mediators such as TNF- α and IL-6.³¹ By boosting collagen synthesis, encouraging re-epithelialization, and accelerating tissue regeneration, the oil also aids in wound healing.³² Its lipid-rich composition further strengthens the skin barrier and reduces transepidermal water loss, offering exceptional moisture-retention ability.³³ These combined activities demonstrate the therapeutic potential of *L. sativum* seed oil in dermatological and pharmacological applications.

9. Anti-aging Potential:

9.1 Protection against Oxidative stress:

Protection against Oxidative Damage Oxidative stress is one of the primary factors contributing to extrinsic skin aging, particularly when prolonged UV exposure and environmental contaminants are present. An overabundance of reactive oxygen species (ROS) leads to DNA damage, lipid peroxidation, protein degradation, and the activation of pro-aging signaling pathways. *Lepidium sativum* seed oil has significant antioxidative potential due to its high content of tocopherols, phenolic compounds, and unsaturated fatty acids [34]. High amounts of α -linolenic acid and γ -tocopherol, which considerably contribute to free-radical-scavenging activity, are confirmed

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by recent profile³⁵. Additionally, by increasing endogenous antioxidant enzymes and reducing lipid peroxidation in vivo, *L. sativum* extracts have been shown to be able to lessen oxidative damage in skin tissue, indicating possible protection against premature extracellular matrix disintegration³⁶.

9.1.1 Neutralization of reactive oxygen species (ROS):

Because of its phenolics, γ -tocopherol, and other antioxidant components, LSSO has strong free-radical scavenging action.³⁷ These substances effectively neutralize dangerous ROS, such as superoxide anions, hydroxyl radicals, and peroxy radicals, which build up after exposure to UV light, pollution, and cellular metabolic activity. LSSO prevents oxidative alteration of structural proteins like collagen and elastin, which are extremely vulnerable to ROS-mediated degradation, by lowering intracellular ROS levels³⁸. The oil also reduces lipid peroxidation and maintains the general integrity of dermal cells by stabilizing cellular lipid membranes. An essential initial line of defense against oxidative tissue damage and photoaging is this direct antioxidant action.³⁹

9.1.2 Activation of the Nrf2-ARE Protective Pathway:

By modifying the Nrf2-ARE (antioxidant response element) pathway, a crucial regulatory system controlling cellular defense mechanisms, LSSO not only directly scavenges free radicals but also increases intrinsic antioxidant capacity.⁴⁰ The nuclear translocation of Nrf2, which then binds to AREs in the promoter regions of detoxifying and cytoprotective genes, is facilitated by bioactive lipids in LSSO⁴¹. Heme oxygenase-1 (HO-1), NAD(P)H quinone oxidoreductase-1 (NQO1), glutathione peroxidase, and superoxide dismutase are examples of phase II antioxidant enzymes that are upregulated by this activation.⁴² The prolonged improvement of these natural antioxidants lowers inflammation, increases the skin's resistance to environmental stresses, and provides long-term protection against UV-induced oxidative bursts. This indirect method offers a more comprehensive and long-lasting antioxidative response in addition to direct ROS scavenging.

9.1.3 Mitigation of Oxidative Mitochondrial Damage:

Since the organelle is a primary source of intracellular reactive oxygen species (mtROS) produced during oxidative phosphorylation, mitochondrial failure is a key factor in cutaneous aging.⁴³ By integrating into mitochondrial phospholipid bilayers, the high concentration of polyunsaturated fatty acids (PUFAs), namely α -linolenic acid (ALA), in *Lepidium sativum* seed oil (LSSO) enhances mitochondrial performance. By improving membrane fluidity and encouraging more effective electron transport, this inclusion lowers electron leakage from the respiratory chain, which is the main cause of mtROS. Reduced mtROS levels aid in shielding mitochondrial DNA (mtDNA) from mutations, oxidative damage, and functional impairment. LSSO promotes prolonged fibroblast activity and inhibits intrinsic aging processes in the skin by maintaining mitochondrial integrity and delaying the development of mitochondrial-driven cellular senescence⁴⁴.

9.1.4 Inhibition of UV-Induced Lipid Peroxidation:

One of the first chemical processes brought on by oxidative stress and UV radiation is lipid peroxidation, which plays a significant role in photoaging.⁴⁵ By offering a supply of structurally stable lipids, the high quantity of ALA and other unsaturated fatty acids in LSSO increases the robustness of cellular membranes. This lessens the membrane phospholipids' vulnerability to peroxidative damage.⁴⁶ As a result, there is a marked reduction in the production of secondary lipid peroxidation products such as 4-hydroxynonenal (4-HNE) and malondialdehyde (MDA), which are both indicators and mediators of oxidative damage.⁴⁷ Reduced concentrations of these reactive aldehydes preserve membrane integrity, shield structural proteins, and stop collagen and elastin fibers from degrading and cross-linking. LSSO reduces wrinkle formation and the overall progression of photoaging by slowing UV-induced destruction of epidermal tissues through this protective mechanism.⁴⁸

10. Enhancement of Collagen Synthesis:

10.1 Fibroblast Stimulation and ECM Production:

One of the main bioactive lipids in *Lepidium sativum* seed oil (LSSO) is α -linolenic acid (ALA), which is essential for promoting cutaneous fibroblast activity.⁴⁹ By integrating into cell membranes, ALA increases membrane fluidity and maximizes the effectiveness of cellular signaling.⁵⁰ This increases the ability of fibroblasts to proliferate and produce extracellular matrix (ECM) components, especially collagen types I and III, which make up the dermis' structural framework. Increased collagen deposition enhances elasticity, tensile strength, and skin density—important characteristics that prevent fine wrinkles and early indicators of intrinsic aging. Furthermore, fibroblast survival and function are supported by the anti-inflammatory and antioxidative milieu produced by LSSO, allowing for long-term ECM regeneration in both physiological and stress-induced

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circumstances.⁵¹

10.2 Activation of TGF-B/Smad Pathway:

TGF-B/Smad pathway, the main regulatory axis controlling collagen synthesis and extracellular matrix remodeling, has been shown to be modulated by omega-3 fatty acids.⁵² There is evidence that ALA may increase Smad2/3 protein phosphorylation and activation downstream of TGF-β receptor signaling.⁵³ Activated Smad complexes go into the nucleus, where they decrease the expression of matrix-degrading enzymes such as matrix metalloproteinases (MMP-1 and MMP-9) and increase the transcription of genes that encode collagen, such as COL1A1 and COL3A1.⁵⁴ LSSO promotes a regenerative dermal milieu by inhibiting collagen breakdown and upregulating collagen formation through this dual regulatory action. Because UV radiation usually downregulates TGF-β signaling, this pathway is especially important during photoaging.

11. Prevention of Glycation-Induced Collagen Damage:

Advanced glycation end products (AGEs), which stiffen collagen fibers, reduce suppleness, and hasten noticeable skin aging, are produced when reducing sugars and dermal proteins undergo a non-enzymatic reaction known as glycation.⁵⁵ Rich in ALA, tocopherols, and phytosterols, *Lepidium sativum* seed oil (LSSO) has strong anti-glycation potential by reducing the production of AGEs and restricting subsequent oxidative responses.⁵⁶ The antioxidant components of LSSO decrease oxidative pathways that increase glycation-mediated collagen cross-linking and scavenge reactive carbonyl molecules. LSSO helps maintain skin mechanical qualities, minimizes wrinkle formation, and promotes long-term ECM resilience by preserving the natural, flexible shape of collagen fibrils.⁵⁷ LSSO is a promising bioactive component for anti-aging formulations that target both intrinsic aging and dermal stiffness caused by photoaging because of its anti-glycation effect.

12. Improvement of Skin Hydration and Barrier Function:

Maintaining hydration, shielding the skin from environmental damage, and maintaining general skin health all depend heavily on the skin barrier. Enriched with linoleic acid, α-linolenic acid, phytosterols, and antioxidants, *Lepidium sativum* seed oil (LSSO) improves several biochemical pathways involved in hydration balance and epidermal barrier repair.⁵⁸ LSSO promotes both short-term and long-term gains in skin moisture, elasticity, and barrier resilience via regulating lipid synthesis, water-channel protein expression, and microbiota balance.

12.1 Enhancement of Ceramide Biosynthesis:

The formation of acyl-ceramides, which are essential molecules that build the stratum corneum's lamellar lipid layers, depends on linoleic acid, a crucial fatty acid.⁵⁹ Linoleic acid from LSSO is a crucial precursor in the ceramide biosynthesis pathway that aids in the acylation of sphingosine, increasing the production of ceramides involved in barrier development and repair. Increased ceramide levels improve the lipid bilayers' structural structure, which dramatically lowers transepidermal water loss (TEWL) and increases the skin's capacity to hold onto moisture.⁶⁰ The molecular basis for LSSO's hydration-boosting properties is this process.

12.2 Upregulation of Aquaporin-3 (AQP-3):

The essential membrane protein aquaporin-3 (AQP-3) is in charge of moving glycerol and water across keratinocyte membranes⁶¹. It has been demonstrated that linoleic acid increases the production of AQP-3, which enhances the epidermis's intracellular water distribution efficiency. LSSO increases the suppleness, softness, and hydration of skin by improving AQP-3-mediated water and glycerol transfer. Additionally, increased glycerol availability strengthens the barrier's overall function and promotes epidermal lipid production.⁶²

12.3 Remodeling of Epidermal Lipidome:

The epidermal lipidome is positively remodeled when LSSO is applied topically or taken orally.⁶³ Its high concentration of natural antioxidants, phytosterols, and long-chain polyunsaturated fatty acids enriches important lipid classes like cholesterol, free fatty acids, and ceramides.⁶⁴ This adjusted lipid composition improves barrier recovery after environmental or chemical stress, strengthens the stratum corneum's lamellar structure, and boosts lipid cohesiveness.⁶⁵ As a result, the skin shows better smoothness, longer-lasting hydration, and increased resistance to irritation brought on by dehydration.⁶⁶

13. Microbiome-Balancing Effects:

The regulation of hydration and barrier health is significantly influenced by the skin microbiome.⁶⁷ By inhibiting dysbiotic bacterial populations linked to dryness, irritation, and inflammation, LSSO's anti-inflammatory fatty

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acids and phytosterols support the maintenance of a healthy microbiome. Additionally, a stable microbiota promotes ideal skin surface pH, which is necessary for barrier homeostasis and enzymatic lipid processing. LSSO indirectly improves moisture retention, lessens barrier disruption, and increases overall skin comfort and resilience through these microbiome-modulating actions.

Table 2: ROS Mechanism & Pharmacological Effects of *Lepidium sativum*

| Constituent | Mechanism on ROS | Target Pathway | Pharmacological Effect |
|------------------------|--|-----------------------------|------------------------|
| Alpha Linoleic acid | Reduces ROS generation | Mitochondrial stabilization | Anti-aging |
| Tocopherol | Free radical scavenging | Lipid peroxidation | Antioxidant |
| Phenolics | Neutralizes superoxide and hydroxyl radicals | Direct ROS quenching | Anti-inflammatory |
| Omega-3 fatty acid | Downregulates ROS-mediated inflammation | Nf-Kb inhibition | Anti-inflammatory |
| Unsaturated fatty acid | Prevent lipid Peroxidation | Membrane stabilization | Barrier protection |
| Phytosterols | Enhances antioxidant enzymes | Nrf2-ARE pathway activation | Cytoprotective |

14. Cosmeceutical Applications of *Lepidium sativum* Seed Oil:

Omega-3-rich *Lepidium sativum* (garden cress) seed oil exhibits significant potential as a multifunctional cosmeceutical ingredient due to its antioxidant, anti-inflammatory, moisturizing, and anti-aging properties.

14.1 Anti-aging and Wrinkle Reduction:

The high content of α -linolenic acid and tocopherols helps neutralize reactive oxygen species, thereby reducing oxidative stress-induced skin aging. Omega-3 fatty acids modulate matrix metalloproteinases (MMPs), protecting collagen and elastin fibers and promoting dermal firmness and elasticity.

14.2 Enhancement of Collagen Synthesis:

Bioactive fatty acids stimulate fibroblast activity and upregulate collagen type I synthesis, contributing to improved skin thickness, elasticity, and reduced wrinkle depth.

14.3 Skin Hydration and Barrier Repair:

The oil improves stratum corneum lipid composition, enhancing transepidermal water retention and strengthening the epidermal barrier. This makes it useful in formulations for dry, sensitive, and atopic skin.

14.4 Anti-inflammatory and Soothing Effects:

Omega-3 fatty acids suppress pro-inflammatory cytokines (IL-1 β , TNF- α , COX-2), making the oil suitable for acne-prone, irritated, and UV-damaged skin.

14.5 Photoprotection and Brightening:

Antioxidants and phenolic compounds protect against UV-induced lipid peroxidation and melanogenesis, supporting its role in sunscreen, after-sun, and skin-brightening formulations.⁶⁸

Future Perspectives:

Future investigations into omega-3-rich *Lepidium sativum* seed oil should prioritize the optimization of eco-friendly extraction methods to ensure sustainability and preservation of bioactive compounds. Integration of advanced omics technologies will be essential for elucidating the molecular pathways underlying its antioxidant, anti-aging, and barrier-repair effects. The development of nanotechnology-based formulations may further enhance oil stability, bioavailability, and targeted skin delivery. Rigorous preclinical and clinical studies are required to substantiate its therapeutic efficacy and safety profile. Additionally, exploring synergistic combinations with other natural actives and conducting long-term safety evaluations will support its translation into innovative pharmaceutical, nutraceutical, and cosmeceutical applications.

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