

ONION (*ALLIUM CEPA* L.) SEED OIL, EXTRACTION TECHNOLOGIES, BIOACTIVE COMPOSITION, PHARMACOLOGICAL ACTIVITIES AND INDUSTRIAL POTENTIAL - A REVIEW

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ABSTRACT

Allium cepa L. (Amaryllidaceae) is among the most economically important bulb crops globally, yet its seed fraction remains a chronically underexplored repository of structurally diverse and pharmacologically potent phytochemicals. Seeds of *A. cepa* accumulate a compositionally distinct matrix of unsaturated fatty acids, furostanol saponins, organosulphur cysteine sulfoxide derivatives, tocopherols, phytosterols, quercetin glycosides and hydroxycinnamic acid conjugates, a profile that diverges substantially from that of the bulb and that confers a unique spectrum of biological activities. The present review systematically examines the botanical and taxonomic context of *A. cepa* with emphasis on the seed organ, consolidates quantitative compositional data across extraction methods and genotypes, critically evaluates Soxhlet, cold pressing, oil expeller and supercritical CO₂ technologies and synthesises evidence on physicochemical quality indices including tocopherol, sterol, fatty acid and organosulphur profiles. Pharmacological evidence covering antimicrobial, anti-inflammatory, antidiabetic, antihypertensive, anticancer and hepatoprotective activities is evaluated at the mechanistic level and current knowledge gaps in postharvest management of onion seed for oil quality preservation are identified. This review positions onion seed oil as a high-value functional ingredient for food, cosmetic and pharmaceutical applications and underscores the need for standardised extraction protocols, cultivar-specific metabolomic profiling and systematic postharvest research.

KEYWORDS: *Allium cepa* seeds, Onion seed oil, Bioactive compounds, Extraction technologies, Nutraceuticals, Pharmaceutical applications.

1. INTRODUCTION

The genus *Allium* (Amaryllidaceae, subfamily Alliioideae) encompasses more than 900 species distributed across temperate and subtropical zones, of which *Allium cepa* L., the common onion, holds the greatest agronomic and ethnopharmacological significance. Globally, onions rank among the top five vegetable crops by production volume, cultivated across ecological zones ranging from the semi-arid plains of India and Egypt to the precipitation-enriched fields of Europe and the temperate highlands of South America (1,2). The crop's economic importance rests primarily on its bulb, whose distinctive organoleptic properties and dense bioactive content, principally organosulphur thiosulfonates, quercetin glycosides and fructooligosaccharides, have been extensively characterised over several decades (3,4).

The seed of *A. cepa* has received disproportionately limited scientific attention despite occupying a structurally and biochemically distinct niche within the plant's architecture. Seeds serve as the primary means of genetic conservation and commercial hybrid production in modern onion cultivation; since hybrid seed must be generated each season anew through controlled cross-pollination, they underpin a highly specialised and economically significant seed industry (5,6). Beyond their agronomic role, onion seeds accumulate lipid-rich reserves optimised for embryonic development, with oil contents ranging from 10.7% to 25.86% of seed dry weight depending on genotype, environment and extraction methodology (7,8). The fatty acid profile is dominated by linoleic acid (C18,2n-6; 49 to 74% of total fatty acids) with substantial contributions from oleic acid (C18,1; 19 to 27%), a composition of nutritional relevance to cardiovascular risk reduction (9).

The presence of furostanol saponins, unique to the seed fraction and absent in the bulb, represents a class of steroidal glycosides with documented anti-inflammatory, immunomodulatory and anticancer pharmacological

potential (10). The seed oil fraction additionally contains novel cysteine sulfoxide derivatives, high-potency tocopherol profiles (total tocopherols up to 2608.8 mg/kg) and a phytosterol complement including β -sitosterol, campesterol and Δ^5 -avenasterol at levels supportive of cardiovascular nutraceutical applications (11,12). Despite this compositional richness, standardised postharvest protocols for seed moisture management, control of storage-induced lipid oxidation and preservation of oil quality remain largely undescribed in the scientific literature. This review addresses the existing knowledge gap through a systematic examination of the botanical and taxonomic foundations of *A. cepa* with specific emphasis on seed morphology and composition, a comparative evaluation of extraction technologies and their impact on oil quality, a detailed synthesis of physicochemical and chemical characterisation data and a mechanistic appraisal of the biological activities attributable to onion seed oil constituents. In addition, the review identifies critical research priorities in postharvest science, extraction engineering and metabolomic characterisation that must be addressed to fully realise the commercial and therapeutic potential of this underutilised oilseed.

2. Taxonomic Classification and Botanical Description of Onion

The taxonomic history of *Allium cepa* has been substantially revised with molecular systematics. Current classification places it in Amaryllidaceae, subfamily Allioideae, based on internal transcribed spacer (ITS) and plastid DNA analysis (3,13–16). This reclassification from Alliaceae or Liliaceae reflects the monophyletic delimitation of Allioideae, a lineage unified by allinase-mediated organosulphur metabolites, a biochemical synapomorphy of Allium species (3). Within Allium, *A. cepa* belongs to section Cepa, showing closest affinity to wild relatives *A. vavilovii* and *A. asarense*, sharing the diploid chromosome complement $2n = 16$ (15,17,18) (Figure 1.). Phylogenomic analyses support a Central and Southwest Asian origin (Iran, Pakistan, Afghanistan), where selection on bulb morphology, pungency reduction and storage quality generated today's diverse cultivars (17,19). Historical synonyms (*Allium esculentum*, *Cepa vulgaris*) have been systematically retired, while *A. cepa* var. *aggregatum* retains a distinct status due to clustered bulb architecture and vegetative propagation (15,18). The crop spread westward into Egypt and the Mediterranean with archaeological evidence in Egyptian burial sites and eastward through India and China, establishing cultivation zones that persist today (1,3). Gene bank collections preserving this diversity are agriculturally vital, underpinning breeding programs for tolerance to water deficit, heat stress and soilborne pathogens, priorities under climate change (6,20).

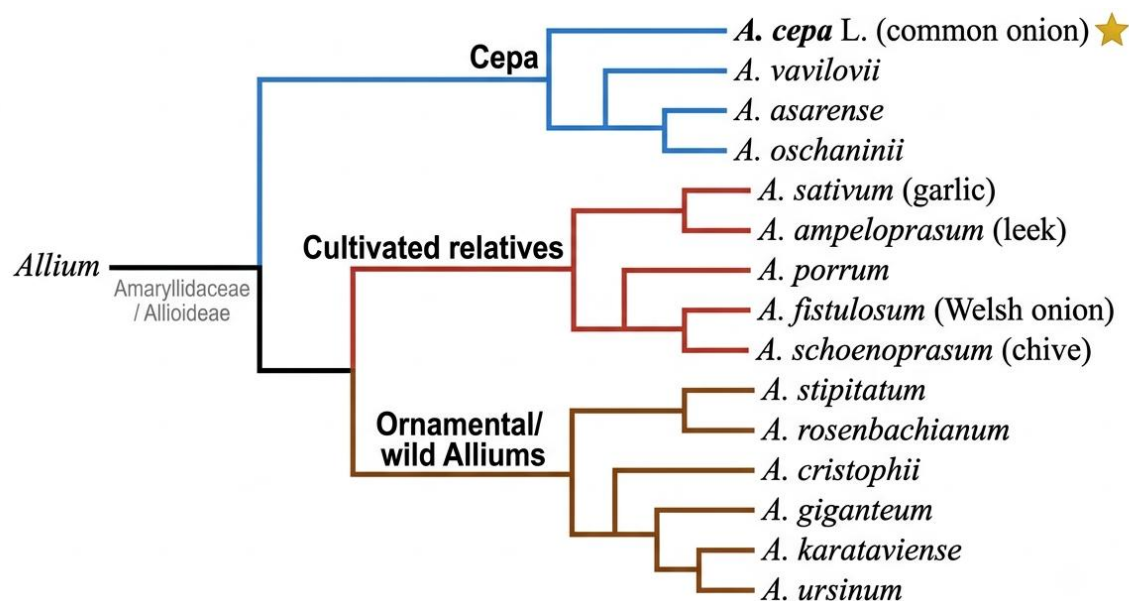


Figure 1. Phylogenetic relationships of *Allium cepa* within section Cepa and its placement among cultivated and wild *Allium* relatives, based on ITS and plastid DNA analyses

3. Seed Morphology

The seed of *Allium cepa* is small, black and angular, presenting a characteristically rough reticulated testa whose surface ornamentation has been exploited taxonomically to distinguish Allium species in seed morphology studies (21,22). Seeds range from 2.5 to 3.5 mm in length and 1.5 to 2.5 mm in width, with the testa composed predominantly of lignin and cellulose providing structural rigidity and desiccation resistance during storage (21,22). Internally, the cotyledon and endosperm tissues are rich in lipid bodies and protein storage vacuoles, which constitute the energy and nitrogen reserves mobilised during germination (10,23). Across onion varieties and production conditions, the thousand seed weight is consistently reported in the range of 2.2 to 4.2 g, equivalent to roughly 3.5 to 3.8 mg per seed, with values such as 3.75 g for the N-53 variety confirming this as a representative estimate (24–27).

4. Extraction Technologies for Onion Seed Oil

4.1. Soxhlet Extraction

Soxhlet extraction remains the reference method for total lipid determination in oilseed research, operating through continuous reflux of an organic solvent, conventionally n-hexane, over ground seed powder. Near-complete lipid recovery is achieved as the seed matrix is repeatedly contacted with fresh solvent, driving partition equilibrium toward extraction. Golubkina et al. (8) reported 13.5% oil yield from *Allium cepa* seeds using n-hexane Soxhlet extraction at 60°C for 6 hours, followed by solvent removal under reduced pressure (20 mbar, 30°C), obtaining oil rich in linoleic acid (61.5 to 73.7%) and oleic acid (19.0 to 27.2%), with 2,2-diphenyl-1-picrylhydrazyl (DPPH) radical scavenging activity of 13.58 to 38.26% and total phenolic content of 1.84 to 6.87 mg GAE/g (8,23). A critical limitation is thermal degradation of heat-labile bioactive, prolonged extraction at near-boiling temperatures degrades tocopherols, carotenoids and phenolics. Residual solvent contamination, even after reduced-pressure evaporation, raises food safety concerns, disqualifying hexane-Soxhlet extracts from direct food use without purification. The method also co-extracts non-glyceridic lipophilic compounds (waxes, pigments, oxidized polymers), reducing oil purity compared to cold-pressed preparations (23). Thus, Soxhlet extraction is best suited as a laboratory yield-reference method rather than a commercial production route, except where total lipid recovery outweighs quality considerations.

4.2. Cold Pressing

Cold pressing separates oil through mechanical compression, hydraulic piston presses or screw expellers, without external heat or solvents. Mechanical shear ruptures oil cells, releasing lipids, while solvent-free, low-temperature processing preserves phytochemical integrity. Topkafa (11) reported a 21.1% yield, the highest among five speciality seed oils, with polyunsaturated fatty acid (PUFA 58.7%), monounsaturated fatty acid (MUFA 30.3%) and total tocol content 2608.8 mg/kg, surpassing rosehip, okra, safflower and carrot seed oils. Parry (33) demonstrated antioxidant preservation, reporting α -tocopherol concentrations of 498 to 682 mg/kg in cold-pressed onion seed oil, exceeding those of extra-virgin olive (174 mg/L), peanut, corn and sunflower oils. Total phenolic content reached 3.35 mg GAE/g, the highest among speciality oils, with DPPH radical scavenging activity of 75.8 to 77.3%, confirming superior antioxidant retention compared to solvent extraction. Yalcin & Kavuncuoglu (7) confirmed cultivar effects, reporting 21.86 to 25.86% oil across 10 Turkish cultivars with linoleic acid at 49.42 to 60.66%, highlighting genotype-dependent yield and fatty acid composition. Commercially, cold pressing offers solvent-free processing, preservation of volatile flavours and bioactive, mechanical simplicity and low capital cost, making it the method of choice for speciality food and cosmetic-grade onion seed oil. The residual press cake, rich in protein (15.7 to 26.1%), fibre and minerals, provides an additional value stream that offsets costs and enhances biorefinery economics (7,23).

4.3. Supercritical CO₂ Extraction

Supercritical CO₂ (SC-CO₂) extraction exploits the adjustable solvating properties of CO₂ above its critical point (T_c = 31.1°C; P_c = 73.8 bar), where liquid-like density combines with gas-like diffusivity and low viscosity, enabling rapid, selective extraction of lipophilic compounds without thermal degradation or solvent residue (37). Pressure-temperature programming modulates selectivity, with higher pressure increasing density and polarity range, making SC-CO₂ well-suited for fractionated recovery of onion seed oil components. Hou et al. (38) reported 12.08% yield at 35 to 45°C and 15 to 25 MPa over 30 to 90 minutes, recovering oil with 41.7% linoleic acid, 37.3% oleic acid and an oleic/linoleic ratio of 0.89, selectively enriching oleic acid compared to Soxhlet extraction (23). Mestour et al. (39) showed that extraction conditions significantly modulate phenolic content, flavonoid yield and antibacterial activity, underscoring process -composition dependence requiring optimisation for target applications. Barriers to industrial adoption include high capital cost of supercritical equipment, energy demands for CO₂ compression/recycling and technical complexity of scale-up (37). For high-value pharmaceutical and cosmetic uses where purity and bioactive integrity are paramount, SC-CO₂ is the most defensible choice, for volume food ingredient production, cold pressing remains the most practical balance of cost, yield and quality.

5. Physicochemical of Onion Oil

5.1. Oil Content and Moisture Characteristics

The oil content of *Allium cepa* seeds ranks among the highest reported within the genus and exhibits notable variation attributable to genotype, environment and extraction methodology. Yalcin and Kavuncuoglu (7) documented oil levels of 21.86 to 25.86% across ten Turkish cultivars, with moisture contents of 6.49 to 9.79% and ash values of 3.58 to 4.80%, confirming the edible oil quality of well-managed Turkish germplasm. In contrast, Dini et al. (28) reported lower values for the Tropeana cultivar (20.4% oil; 10.5% moisture), consistent with cultivar-specific differences in lipid biosynthesis during seed filling. Golubkina et al. (8), analysing Russian and Italian accessions using Soxhlet extraction, observed a broader range of 10.7 to 26.6%, with Italian cultivars Ramata di Montoro and Rossa di Tropea yielding the highest values (16.5 to 16.6%), reflecting both genotypic superiority and warmer growing conditions that accelerate cotyledon lipid deposition. The divergence between Soxhlet and cold-pressed yields for identical seed material, 21.1% by cold pressing (11) and 13.5% by Soxhlet (8), is best explained by differences in solvent and mechanical efficiency, press calibration and seed

particle size distribution, rather than a true superiority of cold pressing for total lipid recovery. Moisture management during postharvest drying remains a critical determinant, seeds exceeding 6% moisture are prone to lipase activation, leading to elevated free fatty acids and accelerated hydrolytic rancidity, thereby compromising yield quality and shelf life (29 to 32). This postharvest dimension remains insufficiently addressed in the onion seed oil literature (23).

5.2. Colour, Refractive Index and Density

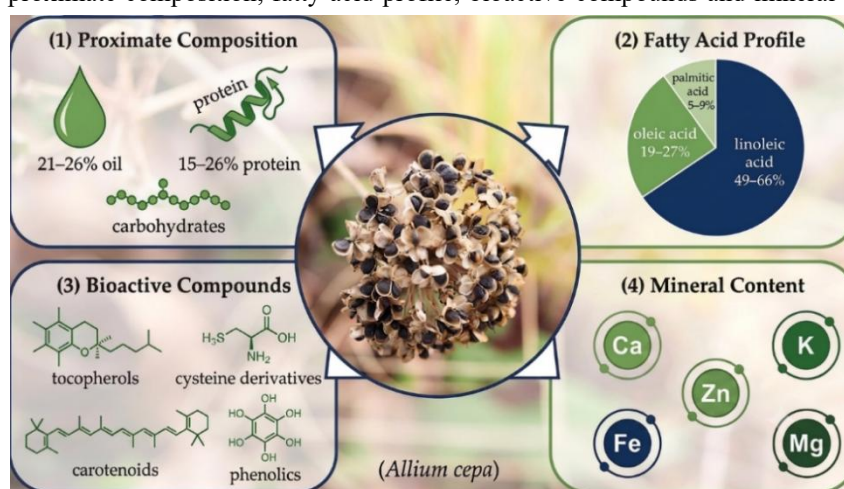
Cold-pressed onion seed oil exhibits a characteristic dark amber colour, quantified by Parry (33) as Hunter Lab values of $L = 3.50$, $a = -1.38$ and $b = 3.90$. This hue is darker than that of cold-pressed parsley, pumpkin and mullein seed oils under identical colorimetric conditions, reflecting the retention of carotenoids, chlorophyll derivatives and tocopherols in the unrefined matrix. The amber colour serves both as a visual quality marker and an indirect indicator of bioactive preservation. Progressive darkening during storage may signal Maillard browning from protein-lipid interactions under high-temperature pressing or oxidative polymerisation during shelf life (23,33). The refractive index of onion seed oil was reported at 1.4752 by Parry (33) for cold-pressed preparations, with Yalcin and Kavuncuoglu (7) confirming values of 1.4752 to 1.4771 in soxhlet-extracted oils across ten cultivars. This stability across extraction methods and genotypes supports its use as a reliable identity marker for adulteration detection. Aiboudi et al. (12) reported a density of approximately 0.930 g/mL for cold-pressed oil and a refractive index of 1.470 for hexane-extracted red onion Amposta seed oil, with minor variation attributable to differences in fatty acid profiles between Spanish and North American cultivars. These constants are of practical significance for establishing quality specifications in commercial supply chains (12,23).

5.3. Nutritional Characteristics of Onion Seed Oil

The proximate composition of *Allium cepa* seeds reflects their dual role as energy reserves and phytochemical repositories, with lipid and protein fractions comprising the majority of dry matter. Oil content is genotype-dependent and extraction-sensitive, ranging from 10.7% in Russian onion cultivars to 25.86% in Turkish onion seed cultivars using the Soxhlet and cold-pressing methods (7,8). This wide range, greater than in comparable oilseeds, highlights interactions among genotype, pedoclimatic conditions, seed maturity and drying temperature on cotyledon lipid deposition (30).

Moisture is a critical determinant for oil extraction, as high polyunsaturated fatty acids render lipids prone to oxidation if water activity is not controlled. Yalcin & Kavuncuoglu (7) reported 6.49 - 9.79% moisture and 3.58 to 4.80% ash across ten Turkish cultivars, while Dini et al. (35) documented 10.5% moisture and 20.4% oil in *A. cepa* var. Tropeana. Properly dried seeds meet stable oilseed storage thresholds (<8% moisture), though inadequate drying, which is common in smallholder contexts, can trigger free fatty acid accumulation through lipase activity within weeks (23).

Crude protein constitutes 15.7 to 26.1% of seed dry weight, comprising albumins, globulins and glutelins that enhance nutritional and technological value in defatted meal (7). Carbohydrate and dietary fibre fractions, though less quantified than in bulbs, support seed coat integrity and may provide mild prebiotic effects (2). The ash fraction supplies minerals essential for seedling vigour, including potassium, calcium, magnesium, phosphorus and trace metals zinc and iron, with concentrations influenced by soil geochemistry and fertilisation, underscoring the need for standardised agronomic protocols to ensure consistent seed quality (2,4,36). Figure 2. summarizes the proximate composition, fatty acid profile, bioactive compounds and mineral content of *Allium*



cepa seeds.

Figure 2. Overview of the proximate composition, fatty acid profile, bioactive compounds and mineral content of *Allium cepa* seeds

6. Bioactive Composition of Onion Seed Oil

6.1. Fatty Acid Profile

The fatty acid composition of *Allium cepa* seed oil is characterised by polyunsaturated fatty acid (PUFA) dominance, with linoleic acid (C18,2n-6, omega-6) consistently reported as the major component across genotypes and extraction methods. In ten Turkish cultivars, Yalcin and Kavuncuoglu (7) documented linoleic acid levels of 49.42-60.66% of total fatty acids, with oleic acid (C18,1n-9) and palmitic acid (C16,0) as the next most abundant constituents. Total unsaturated fatty acids accounted for at least 80% of the composition. Golubkina et al. (8) confirmed this pattern in Russian and Italian accessions, with Italian cultivars Ramata di Montoro and Rossa di Tropea showing the highest oil contents (16.5 to 16.6%) and oleic acid levels (25 to 27%), while linoleic acid remained dominant across all *Allium* species examined.

Amalfitano et al. (2019) demonstrated that delayed planting increases PUFA proportions while reducing monounsaturated fatty acids, with linoleic, oleic and palmitic acids remaining the principal representatives of their respective classes. Under SC-CO₂ extraction, Hou et al. (38) recovered oil containing 41.7% linoleic acid and 37.3% oleic acid, yielding an oleic/linoleic ratio of 0.89, notably higher than cold-pressed preparations suggesting selective enrichment of oleic-acid-rich triglycerides under supercritical conditions (23). Stearic acid (C18,0) and arachidic acid (C20,0) were consistently minor saturated components, contributing collectively no more than 5 to 8% across cultivars and extraction methods (33). The nutritional significance of high linoleic acid content has been substantiated epidemiologically. Marklund et al. (9) reported that elevated circulating linoleic acid biomarkers were associated with reduced risk of total cardiovascular disease, cardiovascular mortality and ischemic stroke. These findings provide mechanistic support for the cardiovascular benefits of incorporating linoleic-acid-rich onion seed oil into functional food matrices. The high PUFA to SFA ratio further lowers atherogenicity and thrombogenicity indices relative to saturated fat-rich oils, reinforcing its classification as a health-promoting edible oil in regulatory and clinical contexts (7,8).

6.2. Organosulphur Compounds

Organosulphur compounds represent the most compositionally distinctive bioactive constituents of onion seed oil, differentiating it from other plant-derived seed oils and providing a mechanistic basis for several pharmacological activities. More than 60 sulphur-containing compounds have been identified in onion bulb essential oil, including thio-sulfinates, sulphides, disulfides and S-alk(en)yl-L-cysteine sulfoxides (40). The latter serve as alliinase substrates, converted to volatile thio-sulfinates upon tissue disruption, releasing the lachrymatory factor and the characteristic *Allium* aroma (41). The seed fraction exhibits a distinct organosulphur profile beyond that of the bulb. Dini et al. (35) identified a novel cysteine sulfoxide (S(S)R(C))-S-(3-pentenyl) -L-cysteine sulfoxide, with methiin, etiin, alliin, isoalliin, propiin and butiin. This novel metabolite demonstrated antioxidant activity in FRAP and DPPH assays, confirming that sulphur compounds contribute to radical-scavenging capacity independently of tocopherols and phenolics. In *A. cepa*, dipropyl disulfide is recognised as the characteristic thiosulfinate degradation product, while the chemical instability of thiosulfinates, which rapidly decompose into odour active volatiles, has implications for the shelf life of onion-derived preparations (41). Antimicrobial activity has been demonstrated experimentally, propyl-propane thiosulfinate (PTS) and propyl-propane thiosulfonate (PTSO) inhibited *Verticillium dahliae* in both culture and plant bioassays, suggesting potential as natural antifungal agents in agriculture and food preservation (42). Additionally, S-methylcysteine sulfoxide, a non-volatile precursor present in bulb and seed tissues, reduces apolipoprotein B100 secretion and modulates hepatic lipid synthesis, providing a molecular mechanism for cholesterol-lowering effects beyond sterol-mediated pathways (40).

6.3. Tocopherol

The tocopherol composition of onion seed oil represents one of its most pharmacologically and commercially significant physicochemical attributes, with substantial variation across cultivars and extraction methods. Topkafa (11) reported the highest total tocopherol content among five cold-pressed speciality seed oils for onion seed, at 2608.8 mg/kg, exceeding rosehip, okra, safflower and carrot seed oils under identical conditions. Parry (33) identified α -tocopherol as the dominant isomer (498 to 682 mg/kg), followed by γ -tocopherol (156 to 219 mg/kg) and δ -tocopherol (23 to 29 mg/kg), yielding total tocopherol concentrations of 1.8 to 2.0 mmol/kg oil. In contrast, Aiboudi et al. (12) reported a divergent profile in hexane-extracted red onion Amposta seed oil, with total tocopherols reaching 1666 mg/kg but γ -tocopherol predominating, β - and δ -tocopherols present and α -tocopherol below detection. This inversion of the dominant homologue reflects both genotype-specific differences in tocopherol biosynthesis, particularly the activity of γ -tocopherol methyltransferase (γ -TMT), which converts γ - to α -tocopherol and selective partitioning of homologues between oil and seed residue under solvent versus mechanical extraction. Functionally, α -tocopherol carries the highest vitamin E biological activity (reference value 1.0 RRR- α -tocopherol equivalents), while γ -tocopherol demonstrates superior nitration-trapping activity relevant to suppression of reactive nitrogen species in inflammatory contexts. Cultivar selection and extraction method should therefore be jointly optimised according to application, cosmetic or nutraceutical formulations prioritising vitamin E activity benefit from cultivars with high γ -TMT expression, whereas anti-inflammatory formulations may favour γ -tocopherol-rich extracts (11,23,33).

6.4. Sterol Composition

Phytosterols constitute the major fraction of the unsaponifiable matter in onion seed oil and contribute directly to its cardiovascular and anti-inflammatory properties. Aiboudi et al. (12) quantified total sterols at 96.1 mg/100 g oil in red onion Amposta seed oil, with β -sitosterol as the dominant component (61.9%), followed by campesterol (17.9%), Δ^5 -avenasterol (10.8%), cholesterol (2.8%), Δ^7 -stigmasterol (1.09%), stigmasterol (0.45%) and Δ^7 -avenasterol (0.61%). β -sitosterol lowers cholesterol via competitive inhibition of intestinal absorption, displacing dietary cholesterol from mixed micelles. Clinical trials demonstrate that intakes of 0.8-3.0 g/day reduce LDL cholesterol by 8-15%, effects recognised in EU and US authorised health claims (12). Beyond lipid metabolism, β -sitosterol exhibits anti-inflammatory activity through inhibition of prostaglandin synthesis and Tumor Necrosis Factor (TNF)- α production, antipyretic effects, antineoplastic activity in prostate and colon cancer cell lines and immunomodulatory properties via stimulation of natural killer cell activity. These multi-target pharmacological actions reinforce the functional value of the sterol fraction in onion seed oil (12). Campesterol and Δ^5 -avenasterol contribute synergistically, with recognised antioxidant roles within the unsaponifiable fraction. Collectively, the phytosterol complement of onion seed oil, at levels exceeding those of most common vegetable oils, provides a robust basis for functional food and pharmaceutical applications aimed at cardiovascular risk reduction (12,23).

6.5. Phenolic Acids and Flavonoids

The phenolic and flavonoid profile of onion seed oil occupies an intermediate position between that of the bulb and other vegetable seed oils. Hydroxycinnamic acids such as ferulic, sinapic, p-coumaric and caffeic occur in both free and esterified forms, with HPLC (High-Performance Liquid Chromatography) surveys documenting cultivar-dependent variation in gallic acid, ferulic acid, protocatechuic acid and kaempferol concentrations (30,43). In *Allium cepa*, quercetin and its glycosides dominate the flavanol fraction, with red-skinned cultivars generally accumulating higher levels than yellow or white types due to elevated expression of flavonoid biosynthetic enzymes (44). The predominant bulb glycosides, quercetin-4'-glucoside and quercetin-3,4'-diglucoside, are also present in seed tissues, though their quantitative partitioning into the oil phase during cold pressing depends on seed polarity and water content (33,44). Cold-pressed onion seed oil exhibited a total phenolic content of 3.35 mg GAE/g, the highest among speciality seed oils compared by Parry (33), demonstrating that mechanical extraction without solvent washing effectively retains phenolics. This retention is mechanistically plausible, as phenolic compounds may associate with polar lipid membranes and oxidised lipid matrices rather than existing solely as aqueous solutes, making them accessible to the oil phase during pressing. Collectively, phenolic acids and flavonoids act synergistically with tocopherols to quench lipid peroxidation radicals and chelate transition metals that catalyse oxidative chain reactions, providing multi-mechanism antioxidant protection more robust than any single constituent in isolation (30,33). Figure 3. summarizes the principal bioactive compounds and lipid constituents of *Allium cepa* seed, emphasizing its richness in tocopherols, polyunsaturated fatty acids, sterols and phenolic compounds.

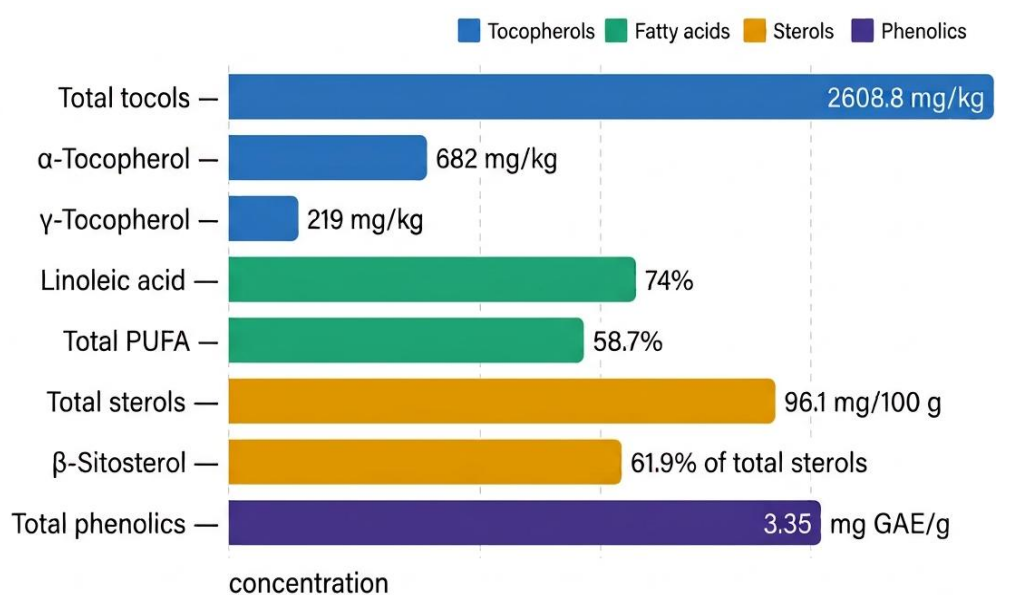


Figure 3. Major bioactive compounds and lipid constituents of *Allium cepa* seed

7. Biological Activities of Onion Seed Oil

7.1. Antimicrobial Activity

The antimicrobial activity of onion seed oil and its bioactive fractions have been documented against a spectrum of clinically relevant bacterial and fungal pathogens through multiple in vitro and in vivo model systems (45–47). The primary mediators of antimicrobial activity are the thiosulfinate and diallyl disulfide components of the

organosulphur fraction, whose mechanism involves disruption of bacterial cell membrane integrity, inhibition of cysteine-containing bacterial enzymes through thiol alkylation and induction of oxidative stress within the microbial cell (23). In a study utilising SC-CO₂-extracted onion seed oil, Mestour et al. (39) demonstrated antibacterial inhibition zones reaching 48.5 mm against *Pseudomonas aeruginosa*, a result that substantially exceeds the inhibition zones typically reported for garlic or onion bulb essential oils against the same organism, with activity also confirmed against Gram-positive pathogens, including *Staphylococcus aureus*. The superior inhibitory performance of the SC-CO₂ extract relative to cold-pressed preparations in this study may reflect selective concentration of sulphur volatiles and phenolic compounds under supercritical conditions, further supporting the process-dependent nature of bioactive recovery (23,35).

7.2. Anti-inflammatory Activity

Anti-inflammatory activity is one of the most mechanistically well-characterised pharmacological properties of onion-derived bioactive, with multiple constituents acting synergistically to suppress the inflammatory cascade (48,49). Complementary mechanisms are contributed by organosulphur compounds, particularly thiosulfinates, which inhibit prostaglandin E₂ synthesis through COX and LOX pathway suppression and by furostanol saponins, which modulate T-helper cell differentiation and cytokine secretion in an immunomodulatory manner (10,49). The convergent action of quercetin, thiosulfinates and saponins suggests that intact onion seed oil, retaining all fractions, may exert superior anti-inflammatory effects compared to purified constituents, a critical consideration for pharmaceutical product development.

7.3. Antihypertensive and Cardioprotective Activity

The antihypertensive and cardioprotective properties of onion seed oil bioactive operate through vascular, lipid-metabolic and anti-inflammatory mechanisms reinforced by fatty acid, sterol and flavonoid fractions. Khandre et al. (50) demonstrated that quercetin and its metabolite isorhamnetin lower blood pressure by inhibiting NADPH oxidase overexpression, a major source of reactive oxygen species in vascular smooth muscle and suppressing angiotensin II-induced endothelial dysfunction. Angiotensin II, the principal effector of the renin-angiotensin-aldosterone system, drives vascular hypertrophy and inflammation; quercetin's interference with this signalling decouples hypertensive stimulus from vascular consequences (50). β -sitosterol, the dominant phytosterol (61.9% of total sterols), reduces cardiovascular risk via competitive inhibition of intestinal cholesterol absorption, with clinically validated LDL-cholesterol-lowering effects at dietary intakes achievable through functional food consumption. The high PUFA content, particularly linoleic acid at 49 to 74% further supports substitution of saturated fats, independently reducing cardiovascular risk as shown in prospective cohort studies (9,12). The convergence of quercetin-mediated vascular protection, β -sitosterol-mediated cholesterol lowering and PUFA-mediated membrane fluidity positions onion seed oil as a mechanistically coherent cardioprotective functional oil (12,50).

7.4. Anticancer Activity

Evidence for anticancer potential derives primarily from in vitro and mechanistic studies of quercetin and related flavonoids. Quercetin-rich *Allium* extracts induce G2/M cell cycle arrest via inhibition of CDK1/cyclin B complexes, trigger intrinsic apoptosis through mitochondrial cytochrome c release and caspase-3/9 activation and inhibit topoisomerase II activity required for DNA replication (51). In adrenocortical carcinoma cell lines, quercetin-rich extracts produced significant antiproliferative effects correlated with quercetin concentration. Epidemiological meta-analyses further associate higher *Allium* consumption with reduced gastric cancer risk, supported mechanistically by quercetin and organosulphur inhibition of *Helicobacter pylori* colonisation and gastric inflammation (51). Furostanol saponins, concentrated in the seed fraction, contribute a distinct antiproliferative mechanism by disrupting cholesterol-rich lipid raft domains in cancer cell membranes (52–54). This impairs clustering of receptor tyrosine kinases and downstream PI3K/Akt and MAPK/ERK signalling. Such membrane-disruptive activity is increasingly recognised as a target-independent antiproliferative strategy, with potential selectivity for cancer cells that exhibit elevated cholesterol in lipid rafts, warranting systematic investigation in onion seed oil fractions (10,51).

7.5. Hepatoprotective Activity

Hepatoprotective activity is one of the most consistently demonstrated pharmacological properties of onion-derived bioactive in preclinical models. Dorrigiv et al. (55) reported significant dose-dependent reductions in serum alanine aminotransferase (ALT) and bilirubin in paracetamol-induced hepatotoxicity models treated with onion methanolic extract, confirming efficacy in drug-induced liver injury. Paracetamol hepatotoxicity involves CYP2E1-mediated metabolism to N-acetyl-p-benzoquinone imine (NAPQI), which depletes glutathione, binds hepatocellular proteins and triggers mitochondrial dysfunction, oxidative stress and necrosis. Quercetin and onion organosulphur compounds attenuate this cascade via CYP2E1 inhibition, glutathione replenishment through Nrf2/HO-1 activation and mitochondrial stabilisation (55). Tocopherols provide additional hepatoprotection by suppressing lipid peroxidation in hepatocellular membranes, reinforcing the multi-compound hepatoprotective profile of intact onion seed oil over purified constituents.

8. Industrial and Commercial Applications

8.1. Functional Foods and Nutraceuticals

Cold-pressed onion seed oil demonstrates strong potential as a premium functional edible oil ingredient, with compositional features supporting multiple health claim categories. Superior retention of flavour compounds, phenolics, tocopherols and phytosterols enables direct incorporation into functional food matrices without the bioactive losses typical of solvent-extracted oils. Encapsulation strategies extend this potential, Flammini et al. (56) showed that spray-dried microencapsulation of onion bioactive enhanced phenolic stability during storage, improved simulated gastrointestinal bioavailability and extended functional shelf life, facilitating incorporation into bakery, meat and beverage products without sensory compromise (23,56).

8.2. Cosmetic Applications

The combination of high α -tocopherol content (498 to 682 mg/kg), elevated linoleic acid proportion and documented anti-inflammatory activity supports applications in skin barrier restoration, anti-ageing and hair care. Linoleic acid serves as a substrate for ceramide synthesis in the stratum corneum and plays a structural role in maintaining the lipid barrier that regulates transepidermal water loss, topical application of linoleic-rich oils restores barrier function in ceramide-deficient conditions such as atopic dermatitis (11,23).

8.3. Pharmaceutical Applications

Pharmaceutical applications are reinforced by phytosterol-mediated cholesterol-lowering and anti-inflammatory properties, supporting cardiovascular nutraceutical development, while thiosulfinate antimicrobial potency offers opportunities in topical antiseptic and wound-healing formulations. The oil's oxidative stability index (OSI) of 31.4 hours further supports formulation stability in finished products (33,57).

9. Research Gaps and Future Perspectives

No systematic studies on seed moisture, drying temperature, storage and packaging atmosphere; critical for preventing free fatty acid development, lipid peroxidation and tocopherol degradation. High PUFA content susceptibility to rancidity; poor handling in producing regions. Metabolomic characterisation gap, Limited data (mainly Turkish, Italian and Spanish cultivars). Pharmacological potential of Indian, Egyptian, Chinese and Sub-Saharan African germplasm is uncharacterized. Likely cultivar-specific variation in furostanol saponins, tocopherol homologues, cysteine sulfoxides (6,20). Clinical evidence gap, No human trials, all data from in vitro/animal models. Need bioavailability studies on lipids, tocopherols, saponins and organosulphur derivatives in human GI systems before clinical interventions. Essential for batch-to-batch consistency and pharmaceutical-grade registration. Addressing these gaps will enable onion seed oil to become a commercially viable, scientifically credentialed functional ingredient across food, cosmetic and pharmaceutical markets.

CONCLUSION

Allium cepa L. seeds constitute a structurally specialised and phytochemically distinct fraction of the onion plant that has been chronically underutilised relative to its compositional potential. The seed's lipid-rich matrix dominated by linoleic acid, fortified by exceptional tocopherol levels (up to 2608.8 mg/kg total tocopherols), differentiated by furostanol saponins unique to this organ and complemented by organosulphur cysteine sulfoxides, phytosterols, quercetin glycosides and hydroxycinnamic acids, confers a multi-target pharmacological profile spanning antimicrobial, anti-inflammatory, antidiabetic, antihypertensive, anticancer and hepatoprotective activities. Cold pressing emerges from the comparative extraction analysis as the method of choice for functional food and cosmetic applications, preserving bioactive integrity while offering solvent-free, commercially scalable processing at competitive yields. Critical priorities for advancing the field include systematic postharvest research on seed moisture and storage management for oil quality preservation, comprehensive metabolomic characterisation of genotypically diverse germplasm, bioavailability and clinical intervention studies in human subjects and the development of standardised extraction protocols enabling pharmaceutical-grade quality specifications. The convergence of established nutritional value, documented pharmacological mechanisms and commercially attractive physicochemical properties positions *Allium cepa* seed oil as a high-value functional ingredient with substantial unrealised potential one that merits the sustained interdisciplinary research investment currently afforded to better characterised speciality seed oils.

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- Literature Search and Data Curation: B.A
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