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REVIEW ARTICLE

A Review on Phytochemistry and Therapeutic Applications of *Ocimum gratissimum* L.

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Abstract: *Ocimum gratissimum* L. (Lamiaceae), widely recognized as African basil or clove basil, is an aromatic perennial subshrub extensively utilized in ethnomedicine across tropical and subtropical regions. The plant exhibits a diverse phytochemical matrix predominantly composed of volatile monoterpenes, sesquiterpenes, and complex polyphenolic derivatives. Major secondary metabolites include eugenol, linalool, 1,8-cineole, thymol, rosmarinic acid, and ursolic acid, the proportions of which vary across distinct environmental and geographic chemotypes. Past literature indicates broad-spectrum bioactivities, including antimicrobial actions against clinical and agricultural pathogens, selective antiparasitic effects against *Leishmania* species and veterinary nematodes, anti-inflammatory and antioxidant mitigation of oxidative cellular damage, and enzymatic inhibition of aldose reductase linked to diabetic pathologies. In oncological models, bioactive extracts modulate critical signaling cascades, downregulate repair proteins such as BRCA1, and enhance chemosensitivity. Protective interventions with botanical fractions attenuate chemically induced organ toxicity and restore biochemical and reproductive indices in animal models. The ethnobotanical applications and pharmacological evidence show that *O. gratisssimum* can be a viable source for standardized phytotherapeutic agents and lead bioactive molecules.

Keywords: Essential oil; *Ocimum gratissimum*; Pharmacological activity; Phytochemical profile; Terpenoids.

1. Introduction

The escalation of antimicrobial resistance among bacterial, fungal, and protozoan pathogens constitutes an urgent global health challenge, necessitating the exploration of alternative bioactive scaffolds [1]. Adverse drug reactions, chronic organ toxicities, and economic constraints associated with long-term synthetic pharmacotherapy highlight the ongoing utility of natural botanical products [2, 3]. According to the World Health Organization, a substantial portion of the global population continues to rely on traditional, plant-based remedies for primary healthcare, driven by cultural reliance, geographical accessibility, and economic necessity [2]. *Ocimum gratissimum* L., commonly known as African basil, clove basil, or wild basil, belongs to the family Lamiaceae. The species is widely distributed across tropical and subtropical regions of Africa, Asia, and Central and South America [4].

Figure 1. Leaves and Fruits of *O. gratissimum*

Historically incorporated into indigenous medical systems for the management of gastrointestinal disorders, respiratory infections, fevers, and cutaneous lesions, *O. gratissimum* serves as a rich biological source of structurally diverse secondary metabolites [4]. Phytochemical investigations have characterized high concentrations of phenylpropanoids, monoterpenes, sesquiterpenes,

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flavonoids, and phenolic acids within its foliar and stem tissues [5]. Systematic extraction and pharmacological evaluation of *O. gratissimum* essential oils and polar fractions show marked antimicrobial, antiparasitic, antioxidant, anti-inflammatory, and antineoplastic activities [5–8]. This review shows the evaluation of the botanical, anatomical, phytochemical, and pharmacological profiles of *O. gratissimum*, detailing its cellular and molecular mechanisms of action across experimental and therapeutic models.

2. Pharmacognostic Characteristics

2.1. Taxonomic Classification

Ocimum gratissimum L. is classified systematically within the kingdom Plantae, division Tracheophyta, class Magnoliopsida, order Lamiales, family Lamiaceae, genus *Ocimum*, and species *O. gratissimum* [9].

2.2. Macroscopical Characteristics

Ocimum gratissimum is an erect, multi-branched perennial subshrub typically attaining heights between 1.0 and 2.5 meters, often developing a distinctly woody base as it matures. The foliar organs are arranged in opposite, decussate patterns. The lamina is ovate to oblong-lanceolate, measuring 5 to 15 cm in length and 3 to 8 cm in width, supported by slender petioles up to 6 cm long. The leaf apex is acute to acuminate, while the base is cuneate or attenuate. The margins are coarsely crenate-serrate, and the surfaces display visible glandular punctations alongside varying densities of trichome pubescence. Table 1 summarizes the complete taxonomic classification and salient macromorphological characteristics of *Ocimum gratissimum* L

Table 1. Taxonomic Classification and Botanical Characteristics of *Ocimum gratissimum* L.

Parameter	Botanical Description / Classification Detail
Kingdom	Plantae
Division	Magnoliophyta (Tracheophyta)
Class	Magnoliopsida
Order	Lamiales
Family	Lamiaceae
Genus	*Ocimum*
Species	*Ocimum gratissimum* L.
Plant Habit	Perennial, erect, highly branched subshrub growing up to 2–2.5 m tall with a woody base
Foliar Morphology	Ovate to oblong-lanceolate, coarsely crenate-serrate margins, glandular punctate, pubescent surface
Inflorescence	Elongated terminal racemes in panicle arrangement; 6–10 flowered verticillasters
Floral Features	Campanulate calyx (5–7 mm), creamy-white to pale yellow corolla with four-lobed upper lip
Fruit / Nutlets	Subglobose dry capsules/nutlets (~1.5 mm diameter), non-mucilaginous when wetted

The inflorescence consists of elongated terminal racemes forming paniculate arrangements. Bracts are small, ovate-lanceolate, and caducous. The hermaphroditic, zygomorphic flowers are arranged in 6- to 10-flowered verticillasters supported by short pedicels (1–4 mm). The calyx is bilabiate, campanulate, 5 to 7 mm long, greenish-white to yellowish-green, and accrescent in fruit. The corolla is pale yellow, cream, or whitish, featuring a distinct four-lobed upper lip and an entire, flat lower lip. The fruit comprises four subglobose, dry nutlets, approximately 1.5 mm in diameter, enclosed within the persistent calyx. The pericarp is reticulate-foveolate and does not produce mucilage when hydrated [4, 10].

2.3. Microscopical Characteristics

Microscopic examination of the foliar lamina reveals a dorsiventral leaf structure bounded by a single-layered upper and lower epidermis with sinuous to wavy anticlinal cell walls. Stomata are predominantly diacytic (caryophyllaceous), occurring in higher frequency on the abaxial surface (hypostomatic or weakly amphistomatic distribution). Both glandular and non-glandular trichomes are distributed across the epidermal layers. Glandular trichomes comprise peltate types with broad secretory heads containing eight cellular sectors, as well as smaller capitate types with unicellular or bicellular stalks and unicellular heads. These structures function as the primary storage and secretion sites for volatile mono- and sesquiterpenes. Non-glandular trichomes are uniseriate, multicellular (ranging from 2 to 6 cells), conical, and exhibit prominent cuticular striations. Transverse sections across the midrib exhibit a pronounced abaxial protrusion with a pot-shaped or crescent-shaped central vascular bundle surrounded by parenchymatous ground tissue. Angular collenchyma bundles provide mechanical support beneath both epidermal layers. The mesophyll is differentiated into a single layer of elongated palisade parenchyma cells and loosely packed spongy mesophyll traversed by spiral xylem vessels, phloem elements, and scattered calcium oxalate crystals. The stem shows a quadrangular outline with prominent collenchymatous

tissue located at the four angular ridges. The vascular system is organized as a continuous ring of secondary xylem and phloem, enclosing a central parenchymatous pith [4, 11].

3. Phytochemical Composition

The therapeutic versatility of *O. gratissimum* is directly linked to its specialized secondary metabolite profile, categorized into volatile essential oils and non-volatile polyphenolic fractions.

3.1. Volatile Terpenoid and Phenylpropanoid Constituents

Hydrodistillation and gas chromatography-mass spectrometry (GC-MS) characterization of foliar essential oils show distinct chemotypes influenced by geographical origin, climate, and soil conditions. The eugenol chemotype contains eugenol as the predominant phenylpropanoid (35% to over 70% of total volatile content), commonly found alongside methyl eugenol, *cis*-ocimene, and β-caryophyllene [5, 8, 12]. The linalool chemotype features high concentrations of linalool (30% to 50%) paired with 1,8-cineole (eucalyptol), α-terpineol, and terpinen-4-ol [5, 13]. Other regional chemotypes exhibit high proportions of thymol, carvacrol, citral, and germacrene D [4, 14]. Table 2 shows the primary phytochemical classes, representative chemical constituents, and corresponding bio-functional mechanisms documented in *Ocimum gratissimum* extracts and essential oils

Table 2. Phytochemical Classes and Major Bioactive Compounds of *Ocimum gratissimum*

Phytochemical Class	Major Bioactive Compounds Identified	Functional / Structural Role
Monoterpenes & Oxygenated Monoterpenes	Linalool, 1,8-Cineole, Thymol, Carvacrol, Borneol, Limonene, α-Terpinene	Disruption of microbial membranes, broad-spectrum antifungal and respiratory pathogen suppression
Phenylpropanoids	Eugenol, Methyl eugenol, Sinapic acid, Caffeic acid derivatives	Leishmanicidal action, cellular lysis, anthelmintic and potent antioxidant properties
Sesquiterpenes	β-Caryophyllene, Humulene, β-Bisabolol, α-Bergamotene, β-Selinene, β-Copaene	Membrane permeability modulation, anti-inflammatory and aromatic synergy
Phenolic Acids	Rosmarinic acid, Chlorogenic acid, Gallic acid, Nepetoidin A	Direct free-radical scavenging, protection against oxidative cellular damage, BRCA1 down-regulation
Flavonoids & Flavone Glycosides	Quercetin, Rutin, Luteolin, Apigenin, Epicatechin, Nevadensin, Salvigenin, Xanthomicol, Morin	Enzyme modulation, systemic anti-inflammatory pathways, and aldose reductase inhibition
Pentacyclic Triterpenoids & Saponins	Ursolic acid, Oleanolic acid, Basilimoside	Polyol pathway regulation, attenuation of diabetic microvascular complications, and anti-hyperglycemia

3.2. Non-Volatile Phenolic Acids and Flavonoids

Polar and semi-polar extracts contain significant amounts of caffeic acid derivatives and flavonoid glycosides. Rosmarinic acid represents the principal hydroxycinnamic acid derivative, accompanied by chlorogenic, sinapic, and gallic acids [4]. Flavonoid fractions include flavones, flavonols, and flavanones such as apigenin, luteolin, quercetin, rutin, nevadensin, salvigenin, xanthomicol, and epicatechin [4].

3.3. Triterpenoids, Sterols, and Miscellaneous Bioactives

The lipophilic and semi-polar fractions contain bioactive pentacyclic triterpenes, primarily oleanolic acid and ursolic acid, which contribute to the plant's anti-inflammatory and metabolic activities [4, 10]. Additional isolates include phytosterols (β-sitosterol, stigmasterol), long-chain fatty acids (palmitic and linoleic acids), and glycosidic derivatives such as basilimoside [4].

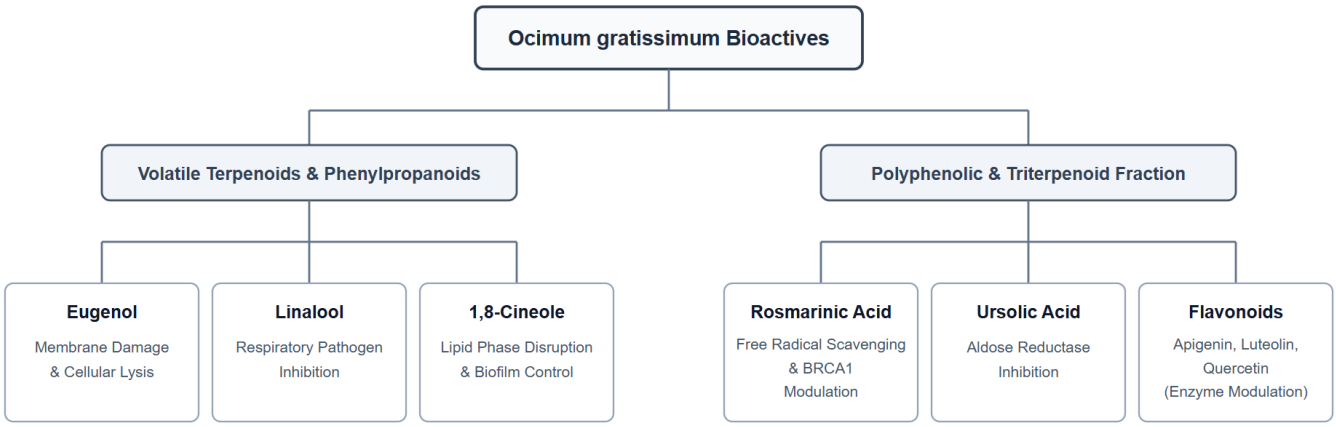

Figure 2. Phytoconstituents of *O. gratissimum*

4. Pharmacological Activities and Mechanisms

4.1. Antimicrobial and Antibiofilm Activity

Essential oils and organic extracts of *O. gratissimum* exhibit inhibitory activities against broad panels of Gram-positive and Gram-negative bacteria, including multidrug-resistant clinical isolates [4, 14]. The primary mechanism involves lipophilic monoterpenes and phenylpropanoids integrating into bacterial cell membranes. This process increases membrane fluidity, induces structural permeability, compromises intracellular adenosine triphosphate (ATP) pools, and triggers the leakage of vital cytoplasmic components [14]. Table 3 shows the comparative antimicrobial efficacy and inhibitory metrics of *Ocimum gratissimum* extracts across diverse clinical and food-associated bacterial and fungal strains.

Table 3. Antimicrobial Efficacy Against Clinical and Food-Spoilage Microorganisms

Microorganism	Strain / Target Category	Minimum Inhibitory Concentration (MIC) / Parameter	Proposed Mode of Antimicrobial Action
Staphylococcus aureus	Gram-positive pathogenic bacterium (MTCC)	8.0 mg/mL (Ethanol extract)	Bacterial cell wall lysis, cellular membrane disruption, and intracellular protein/nucleic acid leakage
Enterococcus spp.	Vancomycin-resistant enterococci (VRE)	14.0–20.0 mg/mL (Ethanol/Methanol extracts)	Irreversible cytoplasmic membrane permeabilization and severe envelope deformation
Cryptococcus neoformans	Opportunistic clinical yeast	0.078 mg/mL (Methanol extract)	Interference with fungal ergosterol pathway and rapid cell membrane lysis
Candida albicans	Pathogenic yeast	1.25 mg/mL (Methanol extract)	Hyphal formation suppression and cell envelope disintegration
Spoilage Molds (*Penicillium*, *Fusarium*, *Scopulariopsis*)	Artisanal dairy (*wagashi* cheese) isolates	Strong fungistatic activity / High spore reduction	Membrane integrity disruption and suppression of mycelial proliferation across storage systems

Gram-positive species, such as *Staphylococcus aureus*, *Bacillus subtilis*, and vancomycin-resistant *Enterococcus* (VRE), indicate notable sensitivity to eugenol-rich extracts [14]. In Gram-negative pathogens (*Escherichia coli*, *Pseudomonas aeruginosa*, *Klebsiella pneumoniae*), the essential oil disrupts outer membrane integrity and inhibits bacterial quorum sensing, reducing biofilm formation and adherence [4, 15].

4.2. Antifungal and Anti-Aflatoxigenic Properties

Ocimum gratissimum essential oil and solvent fractions show marked fungistatic and fungicidal actions against agricultural, food-spoilage, and clinical fungi [5, 8, 9]. Broth microdilution assays against phytopathogens including *Fusarium oxysporum*, *Rhizoctonia solani*, and *Macrophomina phaseolina* show minimum inhibitory concentrations (MICs) between 31.25 and 125 μg/mL, with high efficacy attributed to synergistic interactions between linalool and 1,8-cineole [5].

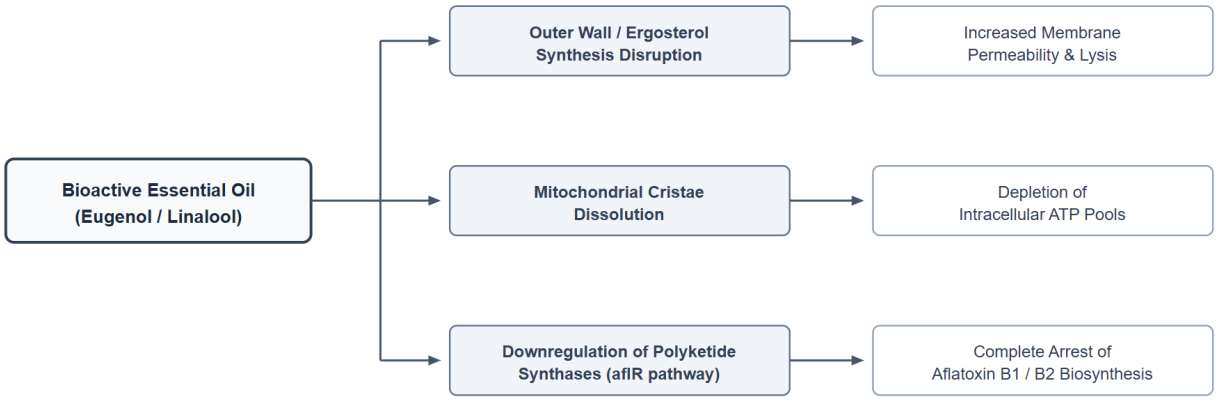

Figure 3. Mechanism of action of Bioactive Essential Oil of *O. gratissimum*

In post-harvest and food preservation models, *O. gratissimum* oil inhibits the growth of mycotoxigenic *Aspergillus flavus* strains and suppresses the biosynthesis of aflatoxins B_1 and B_2 [8]. This anti-aflatoxigenic effect occurs through downregulating regulatory genes (such as *aflR*) and disrupting early polyketide enzymatic steps in the aflatoxin pathway [8]. The extracts also show potent antifungal effects against *Candida albicans* (MIC ≈ 1.25 mg/mL) and *Cryptococcus neoformans* (MIC ≈ 0.078 mg/mL), driven by the disruption of fungal cell wall synthesis and membrane ergosterol binding [7].

4.3. Antiprotozoal and Antiparasitic Actions

Ocimum gratissimum extracts and its principal component, eugenol, display marked activity against *Leishmania* species [7, 13]. Evaluation of eugenol-rich essential oils against *Leishmania amazonensis* yielded half-maximal inhibitory concentrations (IC_{50}) of 135 μg/mL for promastigote forms and 100 μg/mL for intracellular amastigotes, with pure eugenol exhibiting an IC_{50} of 80 μg/mL [13].

Ultrastructural analyses by transmission electron microscopy reveal that exposure to the essential oil induces severe cellular damage, including mitochondrial swelling, disintegration of the inner mitochondrial membrane, abnormal multiplication of nuclei and flagella indicating cell cycle arrest, and total metabolic collapse [13]. The extract also inhibits *Leishmania chagasi* promastigotes ($IC_{50} = 71\ \mu$g/mL) [7].

In veterinary parasitology, the essential oil exhibit anthelmintic and ovicidal properties against gastrointestinal nematodes such as *Haemonchus contortus* [12]. In egg hatch assays, essential oil and pure eugenol formulations at 0.5% concentration completely inhibit larval hatching, showing potential for integrated parasite management in ruminants [12].

4.4. Antioxidant Mechanisms and Cytoprotective Pathways

The high concentration of phenolic hydroxyl groups in rosmarinic acid, quercetin, and luteolin gives *O. gratissimum* high radical scavenging capacity against reactive oxygen species (ROS), including hydroxyl (· OH), superoxide ($O_2^{\cdot-}$), and peroxyl radicals [4, 14]. These bioactives upregulate endogenous antioxidant defense systems superoxide dismutase (SOD), catalase (CAT), and glutathione peroxidase (GPx) while decreasing lipid peroxidation markers such as malondialdehyde (MDA) [4, 6]. In nutritional and aquaculture models, dietary administration of *O. gratissimum* leaf extract to African catfish (*Clarias gariepinus*) improved intestinal mucosal integrity, increased villus height, enhanced serum total protein, and reduced overall mortality following challenge with virulent *Listeria monocytogenes* [6].

4.5. Antidiabetic Activity and Metabolic Regulation

Ocimum gratissimum plays a functional role in glycemic control and the mitigation of long-term secondary diabetic complications. Polyphenolic and triterpenoid extracts inhibit α-amylase and α-glucosidase, moderating postprandial glucose absorption [4].

Additionally, standardized extracts and isolated ursolic acid inhibit rat lens aldose reductase (RLAR), human recombinant aldose reductase (HRAR), and the formation of advanced glycation end-products (AGEs) [10]. Aldose reductase converts excess intracellular glucose to sorbitol via the polyol pathway, causing hyperosmotic stress and cataracts. Extracts of *O. gratissimum* reduce

lens galactitol accumulation in galactose-fed animal models, identifying the plant as an effective botanical lead against diabetic cataractogenesis and associated microvascular damage [10].

4.6. Antineoplastic and Chemosensitizing Mechanisms

Extracts of *O. gratissimum* exhibit selective cytotoxicity against various cancer cell lines by inducing intrinsic apoptosis, elevating intracellular ROS levels, activating caspase-3 and caspase-9, and downregulating anti-apoptotic Bcl-2 proteins [4, 11].

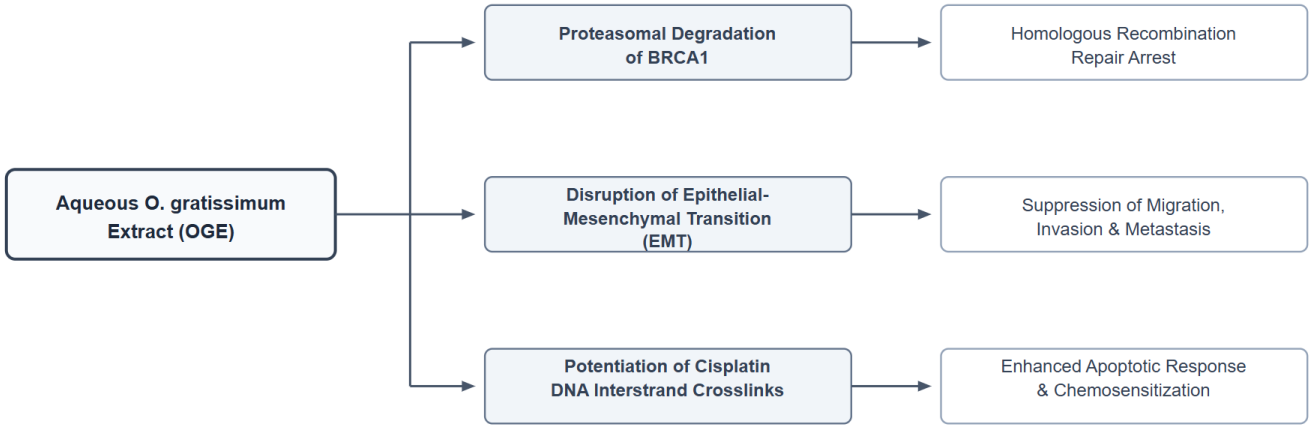

Figure 4. Mechanisms of antineoplastic and chemosensitizing effects for aqueous *O. gratissimum* extract

In hepatocellular carcinoma (HCC) models, aqueous extracts of *O. gratissimum* improve the therapeutic efficacy of platinum-based chemotherapeutic agents [11]. The extract sensitizes HCC cells to cisplatin by promoting the instability and proteasomal degradation of breast cancer type 1 susceptibility protein (BRCA1). The resulting loss of BRCA1 impairs DNA homologous recombination repair, magnifying cisplatin-induced DNA double-strand breaks and accelerating cell death [11]. The extract suppresses epithelial-to-mesenchymal transition (EMT) markers, reduces cancer stemness, inhibits cellular migration, and improves overall hepatic functional markers in orthotopic tumor-bearing murine systems [11].

4.7. Organoprotective and Antidotal Properties

The antioxidant and membrane-stabilizing actions of *O. gratissimum* protect against chemical and pharmacological toxicity in vital organs [4, 15]. In reproductive models of drug toxicity, prolonged administration of cimetidine induces testicular atrophy, suppresses gonadotropin levels, impairs spermatogenesis, alters testicular marker enzymes (alkaline phosphatase, acid phosphatase, and lactate dehydrogenase), and lowers circulating testosterone [15]. Co-treatment with aqueous *O. gratissimum* extract mitigates these gonadal disruptions, normalizes testicular enzyme activities, enhances gonadotropic hormone secretion, and protects sperm architecture through antiperoxidative mechanisms [15]. Table 4 shows the broad spectrum of pharmacological activities, experimental models, extract fractions, and cellular mechanisms associated with *Ocimum gratissimum*.

Table 4. Pharmacological Activities of *O. gratissimum*

Pharmacological Activity	Experimental Model / Test Organism	Extract Fraction	Observed Therapeutic Effect / Mechanism
Antifungal & Anti-aflatoxigenic	*Fusarium oxysporum*, *Rhizoctonia solani*, *Aspergillus flavus*	Leaf Essential Oil (Linalool, 1,8-Cineole, Eugenol)	Growth inhibition (MIC: 31.25–125 μg/mL); complete suppression of Aflatoxin B_1 and B_2 synthesis
Antiparasitic & Leishmanicidal	*Leishmania amazonensis*, *Leishmania chagasi*, *Haemonchus contortus*	Essential Oil & Isolated Eugenol	Promastigote (IC_{50} : 135 μ g/mL) and amastigote (IC_{50}: 100 μg/mL) inhibition; mitochondrial swelling; complete nematode egg hatch arrest
Antidiabetic & Aldose Reductase Inhibition	Rat lens/kidney aldose reductase, Human recombinant AR, Galactose-fed rats	Standardized extracts & Isolated Ursolic acid	Potent in vitro and in vivo inhibition of aldose reductase, prevention of advanced glycation end-products (AGEs), reduction of galactitol accumulation

Pharmacological Activity	Experimental Model / Test Organism	Extract Fraction	Observed Therapeutic Effect / Mechanism
Antineoplastic & Chemosensitization	Hepatocellular carcinoma (HCC) cell lines; murine orthotopic tumor models	Aqueous Leaf Extract (OGE)	Promotes BRCA1 proteasomal degradation, impairs homologous recombination DNA repair, reverses EMT, sensitizes tumor cells to cisplatin
Immunomodulatory & Cytoprotective	*Clarias gariepinus* (African catfish) challenged with *Listeria monocytogenes*	Dietary Leaf Extract (CBLE)	Enhances intestinal mucosal villi, elevates innate immunity and antioxidant enzymes, reduces post-challenge mortality from 85% to 13.5%
Gonadoprotective & Antiperoxidative	Male Wistar rats subjected to cimetidine-induced gonadotoxicity	Aqueous Leaf Extract	Restores serum testosterone, LH, and FSH levels; normalizes testicular marker enzymes (ALP, ACP, LDH); protects spermatogenesis

4.8. Toxicity and Safety

Although *O. gratissimum* is widely used as a culinary herb and traditional medicine, toxicological studies indicate that biological responses are dose-dependent. Acute oral administration of crude aqueous and hydroethanolic foliar extracts in murine models reveals low toxicity, with median lethal doses (LD_{50}) generally exceeding 5000 mg/kg body weight [4]. However, subchronic administration of high essential oil doses or concentrated extracts can alter hepatic transaminases, elevate renal biomarkers (urea and creatinine), and induce localized gastrointestinal irritation [6]. Pure essential oils rich in eugenol or thymol may produce mucosal irritation and contact dermatitis if applied topically without appropriate carriers. Consequently, clinical applications require standardized therapeutic windows, defined chemical concentrations, and rigorous human pharmacodynamic validation [4, 6].

5. Industrial and Food Applications

Apart from direct clinical applications, *Ocimum gratissimum* essential oils and secondary metabolite extracts fulfill major roles across the agro-industrial, food technology, and storage sectors. The continuous market and regulatory push away from synthetic additives driven by consumer aversion to chemical residues, environmental persistence, and toxicological risks has prioritized volatile botanical oils as effective biopreservatives and bio-fumigants.

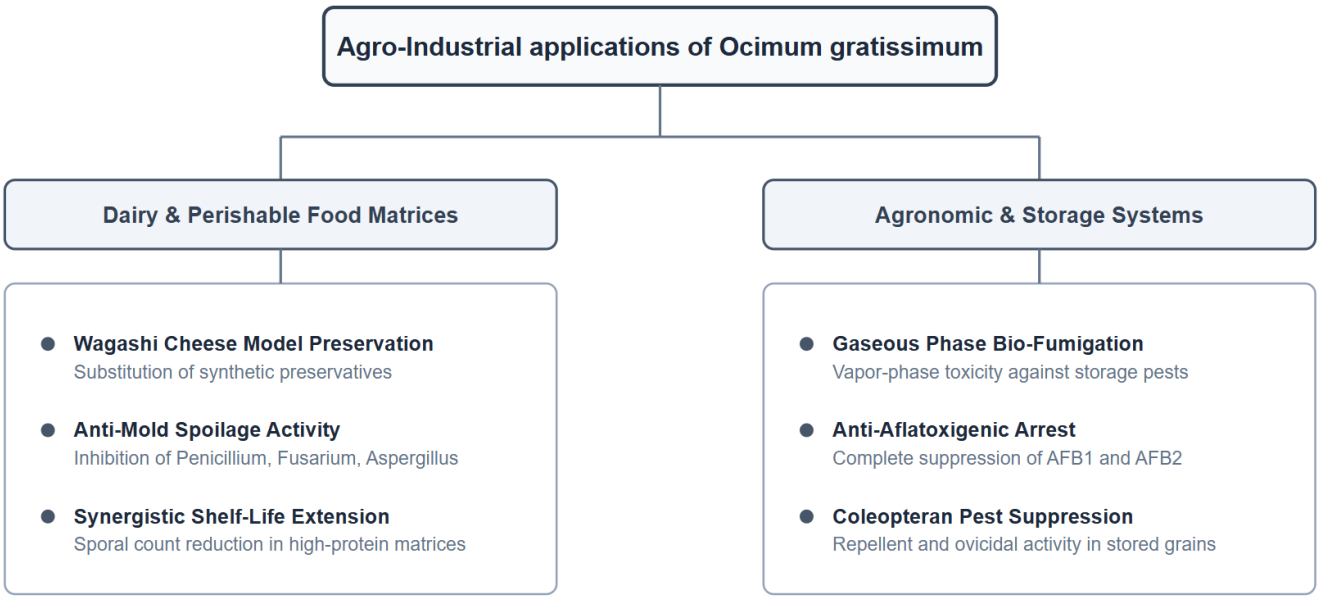

Figure 5. Agro-industrial applications of *O. gratissimum*

5.1 Preservation of Perishable Dairy and Food Matrices

In perishable dairy food systems, foliar essential oils of *O. gratissimum* serve as natural preservative agents. Artisanal dairy products, exemplified by traditional West African *wagashi* cheese, are highly susceptible to rapid post-production microbial deterioration caused by environmental molds.

When deployed within both culture media and active food matrices, the volatile fractions exert potent fungistatic and fungicidal actions against common spoilage isolates belonging to the genera *Aspergillus*, *Penicillium*, *Fusarium*, and *Scopulariopsis*. The bioactives destabilize fungal cell wall architectures, disrupt trans-membrane proton gradients, and cause severe sporal count reductions. This level of preservation matches the inhibitory metrics of conventional synthetic chemical preservatives while preventing toxic residues and improving the storage stability of high-moisture protein products.

5.2 Agronomic Protection, Bio-Fumigation, and Anti-Aflatoxigenic Action

In post-harvest agriculture and grain storage operations, the plant provides reliable protection against contamination and infestation. The volatile essential oil acts as a vapor-phase bio-fumigant against economically damaging grain storage pests, specifically targeting coleopteran beetles through fumigant toxicity, oviposition deterrence, and feeding suppression.

The oil effectively prevents post-harvest fungal spoilage in stored legumes, cereals, and oilseeds. Against toxicological hazards such as *Aspergillus flavus*, the essential oil not only arrests radial mycelial growth but also targets the enzymatic and transcriptional networks responsible for aflatoxin synthesis. The volatile constituents downregulate the polyketide pathways that govern mycotoxin formation, resulting in the complete arrest of aflatoxin B_1 (AFB_1) and aflatoxin B_2 (AFB_2) production. This dual capacity combining broad insecticidal repellency with enzymatic mycotoxin suppression positions *O. gratissimum* volatile fractions as an effective botanical alternative to synthetic organophosphate pesticides and chemical fungistats in post-harvest supply chains.

6. Conclusion

Ocimum gratissimum remains an invaluable ethnobotanical species with well-characterized phytochemistry and a broad spectrum of verified biological activities. Its volatile mono- and sesquiterpenes, together with polyphenols, provide antibacterial, antifungal, antiprotozoal, antioxidant, antidiabetic, and chemosensitizing therapeutic actions. These pharmacological profiles validate traditional applications and offer viable botanical solutions for overcoming antimicrobial resistance, managing chronic metabolic complications, and reducing chemotherapy resistance. Translating these pre-clinical findings into clinical and industrial settings will require standardized agricultural chemotype stabilization, targeted bioassay-guided fractionation, advanced nano-encapsulation delivery systems to protect volatile fractions, and robust human clinical trials to establish safety and dosing standards.

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