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Bioefficacy of Plant-Derived Essential oils against Fungal Pathogens Associated with Stored Agricultural Commodities

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***Abstract*-Storage fungi are major causes of post-harvest deterioration of agricultural commodities, resulting in substantial economic losses, reduced nutritional quality and contamination by harmful mycotoxins. Conventional synthetic fungicides are widely used to control fungal growth; however, their repeated application raises concerns regarding chemical residues, environmental pollution, resistance development, and food safety. In this context, essential oils extracted from higher plants have emerged as promising natural antifungal agents. These volatile, aromatic mixtures contain bioactive compounds such as thymol, carvacrol, eugenol, cinnamaldehyde, and terpinen-4-ol, which can inhibit fungal growth through several biochemical and physiological mechanisms. Essential oils obtained from cinnamon (*Cinnamomum* spp.), clove (*Syzygium aromaticum*), thyme (*Thymus vulgaris*), oregano (*Origanum vulgare*), lemongrass (*Cymbopogon citratus*), and peppermint (*Mentha piperita*) have demonstrated varying degrees of antifungal activity against storage-associated fungi, including species of *Aspergillus*, *Penicillium*, and *Fusarium*. Their activities may include disruption of fungal cell membranes, leakage of intracellular constituents, inhibition of spore germination, suppression of mycelial growth, and reduction of mycotoxin production. The effectiveness of these oils depends on their chemical composition, concentration, extraction method, fungal species, and storage conditions. This paper reviews the antifungal potential of essential oils from higher plants, their possible mechanisms of action, and their applications in post-harvest preservation. Essential oils represent promising candidates for developing sustainable fungal management strategies, although their commercial application requires further validation under realistic storage conditions.**

***Keywords*-Essential oils, higher plants, antifungal activity, storage fungi, *Aspergillus*, *Penicillium*, *Fusarium*, mycotoxins, post-harvest preservation and biological control.**

I. INTRODUCTION

Post-harvest storage is an essential component of agricultural production because it ensures the availability of food grains, seeds, fruits, vegetables, and other agricultural commodities throughout the year. However, stored products are vulnerable to microbial deterioration, particularly fungal contamination. Fungi can reduce the quality, nutritional value, germination capacity, and marketability of stored agricultural products.

Under favourable environmental conditions, certain fungal species also produce mycotoxins that threaten human and animal health. There are several storage-associated fungi. The most common among them are - *Aspergillus flavus, A. niger, A. clavatus, A. terreus, A. versicolor, A. candidus, Alternaria alternata, Curvularia lunata, Cladosporium cladosporoides, C. herbarum, Epicoccum nigrum, Emericella nidulans, Emericella rugulosa, Fusarium acuminatum, F. moniliforme, Mucor hiemalis, Penicillium citrinum, P. chrysogenum, P. expansum, P. funiculosum, P. italicum, Rhizopus arrhizus, Rhizopus nigricans, Syncephalastrum racemosum* etc. Several of these fungal pests such as species of *Aspergillus, Penicillium, Fusarium, Alternaria* and *Cladosporium* etc not only bring about deterioration in the quality and quantity of agricultural produce in storage and transit but also they create health hazards in animals and human beings, by producing toxic metabolites in the form of mycotoxins in the stored commodities. If the mould growth occurs, there is always the concomitant possibility of mycotoxin production [1].

Mycotoxins are dangerous chemical that cause several complications in the body. The contamination of food and feed by mycotoxin producing fungi during storage is alarming because the continued consumption of mycotoxin rich food damages the hereditary material and causes carcinogenicity [2]. The natural occurrence of mycotoxins in a variety of stored substrates viz. peanuts walnuts, almonds and other dried fruits has already been demonstrated [3,4]. Most of these mycotoxins find their way to human system through different routes [5]. Mycotoxin has eight categories actions on human and animals systems viz., immunosuppresion, myelosuppression, hepatotoxicity, nephrotoxicity, dermatotoxicity, estrogenicity, mutagenicity, terategenicity, and carcinogenicity [6]. Extreme toxicity of mycotoxins lies in the fact that they are extremely stable and dangerous in minute quantities. Further, once formed they cannot be removed from the commodity concerned by processing or removal of visible mould growth. They are heat stable, so they cannot be destroyed by cooking. Since mycotoxins are extremely toxic, regulatory and industry guidelines limit are set at very low levels.

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In developing countries often the good quality products are exported while substandard produce unacceptable to foreign buyers (because they exceed regulatory limits for mycotoxin content) is sold to the domestic market [7]. Therefore, the mycotoxin contamination of food and feeds is not a particular problem to the developed world, although heavy economic costs are incurred in ensuring low concentrations of mycotoxins [8]. In poorer developing countries such contamination has more serious consequences, affecting agricultural economies, reducing annual production and good quality exports and seriously affecting the health of the population.

Chemical fungicides and fumigants have traditionally been used to reduce fungal contamination. Although these treatments can be effective, concerns regarding residues, environmental effects, occupational exposure, and the development of resistant fungal populations have encouraged researchers to investigate alternative preservation methods. Essential oils extracted from higher plants offer a promising area of investigation. The ultimate aim of recent research in this area has been the development and evaluation of various alternative control strategies to reduce dependency on synthetic fungicides. Several non-chemical treatments have been proposed for fungal decay control. Although these approaches have been shown to reduce postharvest rots of fruit and vegetables, each has limitations that can affect their commercial applicability. When used as stand-alone treatments, none of the non-chemical control methods has been clearly shown to offer a consistently economic level of disease control that warrants acceptance as an alternative to synthetic fungicides.

Recently, the exploitation of natural products to control decay and prolong storage life of perishables has received more and more attention. Biologically active natural products have the potential to replace synthetic fungicides. Recent reviews have highlighted the potential of essential oils for controlling fungal spoilage and mycotoxin formation in stored cereal grains, while also identifying challenges associated with their practical application. The present paper reviews the antifungal properties of plant essential oils against storage fungi, their chemical constituents, potential applications, limitations and future research priorities. Some important plant's essential oils with their antifungal efficacy are listed below [9].

II. Higher Plants Having Antifungal Activity Against Storage Fungi

1. Aegle marmelos (Rutaceae)

It was found that the oil of *Aegle marmelos* (Rutaceae) was toxic to *Curvularia lunata, Fusarium moniliforme, Helminthosporium sacchari, Physalospora tucumanensis* and *Sclerotium rolfsii* [10]. The leaves yielded 0.4% oil, which killed 40 mycelial discs (5 mm. in diameter) of the test fungus *Rhizoctonia solani* within 2 hours (by contact) and completely inhibited the mycelial growth of *Helminthosporium corbonum* at 0.3% (3.0x 10^3 µl/l) dose [11]. The thermostable fungitoxic factor of the oil retained its toxicity upto 105 days in storage at room temperature and was non phytotoxic to seed germination of *Vigna mungo* [12].

2. Ageratum conyzoides (Asteraceae)

It was reported that the leaf oil of *Ageratum conyzoides* (Asteraceae) was toxic to *Colletotrichum capsici, Helminthosporium oryzae, H. turcicum, Penicillium chrysogenum, P. javanicum* and *Pyricularia setariae* [13]. It was also found to be toxic against *Alternaria helianthi, Fusarium moniliforme, F. solani, Pyricularia oryzae, Pythium vexans, Rhizoctonia bataticola* and *R. solani* [14]. Fungistatic nature of the oil at 0.2% (2.0 x 10^3 µl/l) concentration against *Absidia ramosa, Alternaria alternata, A. citri, A. raphani, Aspergillus flavipes, A. fumigatus, A. oryzae, A. quadrilineatus, A. ruber, A sydowi, A. tamarii, A. terreus, Botryodiplodia theobromae, B. palmicolum, Botrytis cinarea, Cladosporium cladosporioides, Colletotrichum falcatum, C. gloeosporioides, Cunninghamella elegans, Curvularia lunata, Fusarium oxysporum, Geotricum candidum, Gloeosporium fructigenum, Penicillium funiculosum, P. expansum, Rhizopus arrhizus* and *Tricothecium roseum* was recorded [15]. Further the oil controlled the blue mould rot during storage of oranges, caused by *Penicillium italicum* at 0.1 % (1.0 x 10^3 µl/l) concentration [16]. The vapours emitted by leaf extracts of 30 species of higher plants against *Penicillium italicum* causing blue mould rot of mandarins was evaluated. The vapours of *Ageratum conyzoides* exhibited the strongest toxicity inhibiting the mycelial growth of the test fungus completely.

Fungitoxicity in leaves stored at ambient room temperature persisted up to 8 days. The volatile fungitoxic constituent from leaves was isolated in the form of essential oil which was standardized by its various physico-chemical properties.

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The minimum inhibitory concentration (MIC) of the oil was found to be 0.2% at which the oil exhibited fungistatic nature and showed broad fungitoxic spectrum, inhibiting 32 storage fungi out of 35 tested. The efficacy of the oil on storage at ambient room temperature persisted for 330 days and remained unaltered even on heating up to 100 °C. The oil by dipping and fumigation successfully controlled blue mould rot of mandarins and imparted no adverse effect on the quality of treated fruits [17].

*3. Anethum graveolens (A*piaceae)

It was found that the oil of *Anethum graveolens* (Apiaceae) was reported to be toxic to species of *Aspergillus, Curvularia* and *Penicillium* [18]; and to *Alternaria* sp., *Aspergillus candidus, A. flavus, A. fumigatus, A. nidulans, A. niger, Cladosporium herbarium, Cunninghamella echinulata, Fusarium monilliforme, F. oxysporum, Helminthosporium sacchari, Mucor mucedo, Penicillium digitatum, Rhizopus* sp., and *Trichothecium roseum* [19] and *Alternaria tenuis, A. fumigatus, Diplodia natalensis, Penicillium digitatum* and *P. italicum.* [20,21,22]. The oil showed fungistatic nature at 1000 ppm (1.0 x 10^3 µl/l) dose, against *Alternaria alternata, Aspergillus flavus, A. awamori, A. niger, A. ochraceus, A. parasiticus, A. sydowi, A. terreus, Candida tropicalis, Cladosporium herbarum, Fusarium moniliforme, F. oxysporum, Nigrospora oryzae, Penicillium chrysogenum, P. citrinum* and *Rhizopus nigricans* [23]. The toxic principle of the oil i.e. Anethol, proved non phytotoxic to seed germination and seedling growth of *Pisum sativum* and was not affected by temperature as well as by long storage duration at room temperature [23].

4. Cinnamomum camphora (Lauraceae)

The oil *C. camphora* (Lauraceae) was toxic against *Aspergillus fumigatus* and *Penicillium notatum* [24]. It was also found that the oil at 1.0 x 10^3µl/l effectively reduced the decay due to *Aspergillus niger* of onion during storage [25]. When the oil was tested against *Macrophomina phaseolina* it was found to be toxic at 0.5x10^3 µl/l, 1.0 x 10^3 µl/l and 2.0 x 10^3 µl/l doses [26]. This fungus causes root rot disease of crops.

5. Cinnamomum tamala (Lauraceae)

The bark oil of C. *tamala* (Lauraceae) which contained α-phellendrene was toxic to *Alternaria helianthi, Fusarium moniliforme, F. solani, Helminthosporium oryzae, Pythium vexans, Rhizoctonia bataticoia* and *R. solani* [27].

6. Cinnamomum zeylanicum (Lauraceae)

It was reported that the bark oil of C. *zeylanicum* (Lauraceae) possess fungitoxicily [28]. Further its toxicity was reported against *Chrysosporium tropicum, Keratinophyton terreum, Malbranchea pulchella* and *Verticillium tenuipes* [29]. The bark oil at 1:64 dilutions inhibited the mycelial growth of *Aspergillus fumigatus, A. niger, Candida troipicalis, Fusarium* sp. and *Rhizopus oryzae* [30]. The essential oil isolated from leaves exhibited its toxicity against *Aspergillus flavus* at 2.0 x 10^3 µl/l dose [31]. The vapour emitted by bark completely inhibited the mycelial growth of *A. flavus* and *A. niger* [32]. The bark oil of *Cinnamomum zeylanicum also* have the insect repellent activity against the pulse bettle, *Callosobrachus chinensis* L. Besides, the insect repellent potency of the oil was found to be thermostable and posses long shelf life at its absolute repellency concentration (0.004%). Thus the oil of *Cinnamomum* demonstrated its activity as potent insecticides which may prove its usefulness as biodegradable, indigenous and herbal preservatives for safe storage of gram meant for human consumption [33].

A study was made to identify the most active fungitoxic component of cinnamon bark (*Cinnamomum zeylanicum*) oil that can be used as a marker for standardization of cinnamon extract or oil based natural preservative of stored seeds. *Aspergillus flavus* and *A. ruber* were used as test fungi. The hexane extracted crude oil and the hydro-distilled essential oil from cinnamon bark had complete growth inhibition concentration (CGIC) of 300 and 100 µl/l, respectively. Both oils produced three fractions on preparative thin layer silica-gel chromatography plates. The fraction-2 of either oil was the largest and most active, with CGIC of 200 µl/l, but the fungitoxicity was also retained in the other two fractions. The fraction-1 and 3 of the crude oil reduced growth of both the fungal species by 65% and those of distilled oil by 45% at 200 µl/l. The CGIC of these fractions from both the sources was above 500 µl/l. The gas chromatography and mass spectrometry (GC-MS) of the fraction-2 of the hexane extract revealed that it contained 61% cinnamaldehyde, 29% cinnamic acid, and two minor unidentified compounds in the proportion of 4% and 6%. The GC-MS of the fraction-2 of the distilled oil revealed that it contained 99.1% cinnamaldehyde and 0.9% of an unidentified compound. The CGIC of synthetic cinnamaldehyde was 300 µl/l and that of cinnamic acid above 500 µl/l. The 1:1 mixture of cinnamaldehyde and cinnamic acid had CGIC of 500 µl/l. The data revealed that cinnamaldehyde was the major fungitoxic component of hexane extract and the distilled essential oil of cinnamon bark, while other components have additive or synergistic effects on total fungitoxicity.

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It is suggested that the natural seed preservative based on cinnamon oil can be standardized against cinnamaldehyde [34].

7. Cymbopogon citratus (Poaceae)

During screening of essential oils isolated from different parts of 14 species of higher-order plants at 3,000 ppm, it was found only the essential oil of *Cymbopogon citratus* (Lemon grass oil) possessed absolute toxicity against *A. fiavus*. The percent inhibitions exhibited by the different plant species varied considerably, ranging from 40% (*Citrus reticulata*) to 100% (*C. citratus*). Therefore, cymbopogon oil was selected for further studies. Maximum recovery of cymbopogon oil was found in June (0.64%), and minimum recovery was recorded in January (0.29%). During the fungitoxic assay, the cymbopogon oil isolated in the months of May to November exhibited the maximum antifungal potency even at 1,000 ppm, while the oils isolated during December and January were 100% inhibitory only at 1,500 ppm. The oils isolated in February to April could not completely inhibit the growth of test fungus even at 1,500 ppm; thus, the fungitoxic potencies of the oil varied with different months of isolation during the year. The MIC of cymbopogon oil for complete inhibition of *A. flavus* was found to be 1,000 ppm. The oil at its lower concentration (500 ppm) showed a maximum of 52% inhibition. At the MIC (1,000 ppm), the oil exhibited its fungistatic nature but turned fungicidal at 2,000 ppm. The cymbopogon oil exhibited a broad spectrum of fungitoxicity by inhibiting completely growth of 35, 45, and 47 fungal species at 500, 1,000, and 1,500 ppm, respectively and its fungitoxic potency remained unaltered for 210 days of storage, after which it started to decline. Moreover, cymbopogon oil exhibited the thermostable nature of its fungitoxicity at concentrations of 1,000 and 1,500 ppm, since it exhibited absolute inhibition of fungal growth following all temperature treatments from 5 to 100°C. At a concentration of 1,000 ppm, the oil inhibited 64 fungal discs of *A. flavus* (approximate number of spores per dish 10); thus, the increased density of the inoculum of the test fungus could not alter the potency of cymbopogon oil. The oil was found to be more efficacious than the 10 synthetic fungicides tested. It was four times superior to Agrosan G.N. (organomercurial dust) and Thiride (tetramethylthiuram disulfide); five times superior to Ceresan (mercury) and Dithane M-45 (mancozeb); six times superior to Agrozim (carbendozim), Bavistin (carbendozim), Emison (mercury), and Thiovit; seven times superior to wettable sulfur (micronized sulfur); and eight times superior to copper oxychloride (Blitox-50).

Moreover, the oil was nonphytotoxic in nature, since it did not exhibit any adverse effects on germination and seedling growth of wheat and rice [35].

Experiments were carried out to determine the potential of using the powder and essential oil from dried ground leaves of *Cymbopogon citratus* (lemon grass) to control storage deterioration and aflatoxin contamination of melon seeds (*Colocynthis citrullus* L.). Four mould species: *Aspergillus flavus*, *A. niger*, *A. tamarii* and *Penicillium citrinum* were inoculated in the form of conidia suspension (approx. 106 conidia per ml) unto shelled melon seeds. The powdered dry leaves and essential oil from lemon grass were mixed with the inoculated seeds at levels ranging from 1-10% (w/w) and 0.1 to 1%v/vt respectively. The ground leaves significantly reduced the extent of deterioration in melon seeds inoculated with different fungi compared to the untreated inoculated seeds. The essential oil at 0.1 and 0.25% (v/w) and ground leaves at 10% (w/w) significantly reduced deterioration and aflatoxin production in shelled melon seeds inoculated with toxigenic *A. flavus*. At higher dosages (0.5 and 1.0% v/w), the essential oil completely prevented aflatoxin production. After 6 months in farmers' stores, unshelled melon seeds treated with 0.5% (v/w) of essential oil and 10% (w/w) of powdered leaves of *C. citratus* had significantly lower proportion of visibly diseased seeds and *Aspergillus* spp infestation levels and significantly higher seed germination compared to the untreated seeds. The oil content, free fatty acid and peroxide values in seeds protected with essential oil after 6 months did not significantly differ from the values in seed before storage. The efficacy of the essential oil in preserving the quality of melon seeds in stores was statistically at par with that of fungicide (iprodione) treatment [36].

8. Cymbopogon nardus (Poaceae)

A study was conducted to elucidate the chemical composition of essential oil from *Cymbopogon nardus* (Citronella oil) and its antifungal activity. Chemical composition of the citronella oil was determined by capillary gas chromatography and mass spectrometry (GC/MS). Major constituents of the oil were geraniol (35.7% of total volatiles), trans-citral (22.7%), cis-citral (14.2%), geranyl acetate (9.7%), citronellal (5.8%) and citronellol (4.6%). The antifungal assay using the vapor-agar contact method showed that the crude essential oil markedly suppressed the growth of several species of *Aspergillus, Penicillium* and *Eurotium* at a dose of 250 mg/L in air.

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The most active compounds among the 16 examined volatiles, consisting of 6 major constituents of the essential oil and 10 other related monoterpenes were citronellal and linalool. Citronellal and linalool completely inhibited the growth of all tested fungal strains at a dose of 112 mg/L. Their minimum inhibitory doses ranged from 14 to 56 mg/L. The α- and β- pinenes showed an inhibitory activity against some fungi, whereas the other 8 volatile compounds lacked this property [37].

9. Cymbopogon flexuosus (Poaceae)

The essential oil of lemongrass (*Cymbopogon flexuosus*) oil was analysed by gas chromatography-mass spectrometry (GC-MS). The antifungal activity of lemongrass essential oils (EOs) and the main compounds against *F. avenaceum* were evaluated *in vitro*, and the underlying mechanism was investigated. Geranial, geranyl acetate, β-citronellol, citronellal, limonene, and citral were demonstrated to be the major constituents of the EOs. Lemongrass EOs and the main compounds possessed the antifungal effect against *F. avenaceum*, and citral exerted the strongest antifungal effects against *F. avenaceum* compared with other compounds, with IC_{50} values of 0.087 µl/mL. Lemongrass EOs and their major constituents increased the permeability of the *F. avenaceum* plasma membrane, resulting in increased conductivity, protein and soluble sugar leakage. The activity of pectin methyl galacturonase (PMG) in *F. avenaceum* was suppressed after treatment with lemongrass EOs. The results indicated that lemongrass EOs inhibited *F. avenaceum* growth by targeting its plasma membrane and reduced its pathogenicity by inhibiting enzyme activity [38]. The toxicity of the oil of *C. flexuosus* (Poaceae) was reported againsnt *Aspergillus fumigatus, Candida albicans* and *Candida tropicalis* [22]. The oil from leaves was strongly toxic against following storage fungal pests viz. *Aspergillus flavus, Penicillium italicum* and *Alternaria alternata*. The oil showed broad spectrum, inhibited heavy doses of inocula, thermostable and toxicity persisted for at least 12 months [39]. The minimum bioactive concentration with fungicidal action of the oil was found to be 0.2 µl/ml for *Alternaria alternata,* 0.4 µl/ml for *A. flavus, A. fumigatus, A. parasiticus, Cladosporium cladosporioides, P. italicum, P. digitatum* and a number of other fungi, and 0.5 µl/ml for *Botrytis cyneria* and *Helminthosporium oryzae*. The bioactivity of oil was broad spectrum, thermostable and lasted upto 48 months. The oil was used for *in vivo* controlling post harvest spoilage of *Malus pumil* [40]. Further it was noted that oil from *Cymbopogon citratus* and the phytochemicals citral, eugenol and mircene showed significant antimould activity.

Among the products that evidenced the antimould activity citral and eugenol showed the lowest minimum inhibitory concentration, which was 1% and 4% respectively. The mould strains assayed are *Fusarium* sp. *Rhizopus* sp. *Aspergillus flavus, A. niger* and *Penicillium* sp. [41].

10. Cymbopogon martinii (Poaceae)

It was reported that the oil from shoots of *C. martinii* (Poaceae) completely prevented the growth and production of hepatocarcinogenic aflatoxin by *Aspergillus parasiticus* [42]. Evaluation of the essential oil against chili fruit rot caused by *Colletotrichum capsici* (syd) Butler and Bisby at different concentration viz. 0.1, 0.075, 0.05, 0.025, 0.01 and 0.005 percent *in vitro* following poisoned food technique and spore germination assay was done. It exerted cent percent inhibition on mycelial growth and spore germination even at 0.025 percent concentration. Because of its strong fungitoxic activity it may be exploited for the management of chili fruit rot disease [43]. The antifungal properties of the essential oil of *Cymbopogan martinii* was examined against *Alternaria solani,* the tomato leaf blight pathogen. This oil inhibited the mycelial growth and spore germination of *A. solani* at 0.3% concentration. [44].

11. Carum carvi (Apiaceae)

The essential oil from fruits of *Carum carvi* (Apiaceae) showed toxicity against *Aspergillus niger* [45]. The toxic nature of this oil was also recorded against *Aspergillus oryzae, Alternaria tenuis* and *Penicillium chrysogenum* [46]. The oil was later reported to possess toxicity against *Aspergillus flavus, A. fumigatus, A. versicolor, Fusarium* sp., *Trichoderma viride* and *Curvularia* sp. [47] *and Aspergillus candidus, A. nidulans, Cladosporium herbarum, Cunninghmella echinulata, Fusarium moniliforme, F. oxysporum, Helminthosporium sacchari, Mucor mucedo, Penicillium digitatum and Rhizopus* sp. [48] as well as *Candida tropicalis* and *Rhizopus oryzae* [30]

12. Cedrus deodara (Pinaceae)

The essential oil was isolated from the root wood of *Cedrus deodara* (Pinaceae). Yield of the oil was 2.72%. It was reported that the oil was toxic to *Helminthosporium oryzae* at 3000 ppm (3.0×10^3 µl/l) concentration [49]. Its oil was reported that the thermostable fungitoxic factor of the oil retained its toxicity during storage up to 600 days and sustained heavy inoculum density but got destroyed by autoclaving when kept at 20 lbs per square inch pressure for 20 minutes.

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The oil at 3000 ppm (3.0 x 10^3 µl/l) dose inhibited the growth of *Absidia romosa, Alternaria brasicae, A. raphani, A. solani, Aspergillus carneus, A. flavipes, A. fumigatus, A. niger, A. versicolor, Cephalosporium sacchari, Cladosporiun* sp., *Colletotrichum falcaturn, C. lindemuthianum, C. tinosporae, Cornespora casicola, Fusarium moniliforme, F. solani, Pacilomyces* sp., *Pyricularia oryzae, Talaromyces* sp. and *Trichoderma viride*. The oil killed the test fungus *H. oryzae* in 3 hr. by contact at 3.0 x 10^3 µl/l concentration and in 90 min at 5xl0^3 µl/l, while the contact of pure oil killed the fungus in seconds [50]. It was demonstrated that the oil successfully prevented the appearance of symptoms of leaf spot disease in paddy without any adverse effect on seed germination and general growth of the host plant [51]. It was reported that the oil at 5.0 x 10^3 µl/l dose controlled the fungal deterioration of fruits of *Foeniculum vulgare* and *Coriandrum sativum* during storage [52]. The essential oils extracted from different parts of some angiosperms collected either in the locality of Gorakhpur or from the local market were assayed for their fungitoxicity against the mycelial growth of *Aspergillus niger* and *Curvularia ovoidea*, two storage fungi found in blackgram, *Vigna mungo* L. The volatile oil from wood chips of *Cedrus deodara* (Roxb. ex Lamb) G. Don and that from seeds of *Trachyspermum ammi* (L.) Sprague exhibited absolute toxicity, inhibiting the mycelial growth of both the test fungi completely. The minimum inhibitory concentration (MIC) of the potent oils of *C. deodara* and *T. ammi* were found to be 1000 ppm and 500 ppm, respectively, at which level they were fungicidal. Both the oils showed a broad fungitoxic spectrum inhibiting the mycelial growth of 10 and 12 out of 15 fungi (all isolated from blackgram seeds) at their respective MICs. Moreover, the fungitoxicity of the oils was not destroyed by autoclaving (15 lb/in^2 for 20 min in closed vials) and storage (up to 90 days) [53]. The extracts of leaves and seeds of 15 angiospermic taxa *in vitro* was tested against the mycelial growth of *Macrophomina phaseolina* (Tassi) Goid. Amongst them the essential oil of seeds of *Trachyspermum ammi* L. (Sprauge) exhibited absolute toxicity against the test fungus. The minimum inhibitory concentration of *Trachyspermum ammi* seed oil was 200 ppm, which exhibited a fungistatic nature, but not phytotoxic properties, when tested at 100, 200 and 300 ppm on seed germination of the French bean (*Phaseolus vulgaris* L.). The oil exhibited a broad fungitoxic spectrum, inhibiting the mycelial growth of a number of fungi at 100, 200 and 300 ppm. The oil was thermostable and more efficacious than some synthetic fungicides, viz., Benlate, Ceresan, copper oxychloride, Dithan M-45 and Thiovit.

Thymol was also isolated as a fungitoxic factor and it exhibited toxicity against the test fungus at 300 ppm [54].

*13. Citrus sinensis (Rutacea*e)

The oil from epicarp of *Citrus sinensis* (Rutaceae) exhibited strong fungitoxicity at 0.5% concentration against *A. flavus, P. italicum* and *Alternaria alternata* as a contact toxicant. The oil at the same concentration inhibited heavy doses of inocula and exhibited quick killing action. The pesticidal action of the oil was thermostable upto 80°C and lasted even upto 24 months. The oil was broad spectrum [55].

14. Citrus lemon (Rutaceae)

The essential oil of *Citrus lemon* (Rutaceae) and the phytochemicals citral, eugenol and mircene showed significant antimould activity. Among the products that evidenced the antimould activity citral and eugenol showed the lowest minimum inhibitory concentration which was 1% and 4% respectively. The mould strains assayed are *Fusarium* sp. *Rhizopus* sp. *Aspergillus flavus, A. niger* and *Penicillium* sp. [41].

15. Citrus medico (Rutaceae)

The 0.5% oil from the leaves of *C. medico* (Rutaceae) was found to be a mixture of 3 major and 10 minor components. The oil was fungistatic at 2000 ppm (2.0 x 10^3 µl/l) concentration against the test fungi, *Aspergillus flavus* and *A. versicolor*. The fungitoxic factor of the oil was susceptible to temperature treatment beyond 80°C but retained its toxicity up to 380 days during storage at room temperature [56]. The oil at 2000 ppm (2.0 x 10^3 µl/l) dose, inhibited the mycelial growth of the *Acrophialospora fusispora, A. racemosa, Acremonium* sp., *Alternaria alternata, A. solani, Aspergillus nidulans, A. niger, A. flavipes, A. fumigatus, A. rubber, Chaetomium* sp., *Cladosporium cladosporioides, Colletotrichum capsici, Curvularia lunata, Paecilomyces varioti, Penicillium pinophilum, Rhizopus* sp. and *Trichoderma viride*. The vapour of the oil also controlled fungal deteriorations of the seeds of *Coriandrum sativum* and *Foeniculum vulgare* at 4000 ppm (4.0x 10^3 µl/l) concentration up to 120 days in storage, without showing any adverse effect on their germination and seedling growth [57]. The essential oil from the leaves showed its toxicity against *Aspergillus flavus* at 2000 ppm (2.0x 10^3 µl/l) dose [31].

*16. Citrus reticulata (Rutac*eae)

The leaf oil of *C. reticulata* (Rutaceae) was reported to show the germicidal property. It was reported that the oil was toxic to species of *Aspergillus* and *Torula* [58].

The oil also showed the fungitoxicity against *Candida albicans* and *Trichoderma lignorum* due to its adverse effect on respiration [59]. The fruits peels oil from this plant inhibited the spore germination of *P. digitatum* [60]. This oil inhibited the growth as well as aflatoxin production in *Aspergillus parasiticus* [61].

17. Coriandrum sativum (Apiaceae)

The oil of *Coriandrum sativum* (Apiaceae) was toxic to *Aspergillus niger* [62,45]. Inhibitory effect of the oil against *Alternaria tenuis, Aspergillus oryzae* and *Penicillium chrysogenum* was demonstrated [46]. The oil was toxic to *Alternaria* sp., *Aspergillus candidus, A. flavus, A. fumigatus, A. nidulans, Cladosporium herbarum, Cunninghamella echinulata, Fusarium moniliforme, F. oxysporum, Helminthosporium sachhari, Mucor mucedo, Penicillium digitatum, Rhizopus* sp., and *Trichothecium roseum* [19]. The oil was studied *in vitro* for its antifungal activity against 18 fungal organisms using "Filter Paper Disc Agar Diffusion Technique" [63]. The strong antifungal activity against *Alternaria alternata, Curvularia lunata, Pestalotia psidi, Phytopthora parasitica, Trichoderma viride* and *Collectotrichum capsici* can be exploited.

18. Cuminum cyminum (Apiaceae)

The oil of *Cuminum cyminum* (Apiaceae) produced inhibitory zone in culture seeded with *Aspergillus fumigatus, Fusarium tenuis,* and *Trichoderma viride* but was ineffective against *Aspergillus flavus, A. versicolor, A. oryzae, Curvularia* sp., *Penicillium javanicum* and *P. funiculosum* [47]. Using filter paper disc technique it was reported that *Alternaria* sp., *Aspergillus candidus, A. flavus, A. nidulans, A. niger, Cladosporium herbarum, Cunninghamella echinulata, Fusarium moniliforme, F. oxysporum, Helminthosporium sacchari, Mucor mucedo, Penicillium digitatum, Rhizopus* sp. and *Trichothecium roseum* were susceptible to the oil [19]. It was shown that the fungitoxic efficacy of the oil against *Aspergillus fumigatus*, *Candida albicans* and *C. tropicalis* was superior to griseofulvin [22]. It was also reported that the oil was strongly fungitoxicity against *Aspergillus flavus* and *A. niger* [64]. Oil from seeds of *Cuminum cyminum* contained more than 60 compound principal among them were cumin aldehyde (36 %), β-pinene (19.3%), p-cymine (18.4%) and γ- terpinene (15.3%). Antimicrobial testing showed high activity against *Aspergillus niger*, as well as the yeast *Saccharomyces cereviceae* and *Candida albicans* [65]

19. Curcuma amada (Zingiberaceae)

It was reported that rhizome oil of *Curcuma amada* (Zingiberaceae) was toxic to *Cephalosporium sacchari, Ceratocystis paradoxa, Curvularia lunata, Fusarium moniliforme, Helminthosporium sacchari, Physalospora tucumanensis* and *Sclerotium rolfsii* [10].The antifungal activity of the oil was also reported against *Aspergillus niger, A. flavus, Curvularia oryzae, Helminthosporium oryzae, Penicillium javanicum, P. liliacinum, Pestalotia lapagericola* and *Trichoderma viride* [66,67].

20. Curcuma longa (Zingiberaceae)

It was reported that the rhizome oil of *C. longa* (Zingiberaceae) to possess toxicity against *Aspergillus flauvs, A. niger, Curvularia oryzae, Helminthosporium oryzae, Penicillium javanicum, P. lilacinum, Pestalotia lapagericola* and *Trichoderma viride* [68]. The turmeric leaf and rhizome oils were fungicidal against *Candida albicans* MTCC-183 and *Cryptococcus neogormans* MTCC-1437 strains. Leaf oil showed better activities in comparison to rhizome oil [69]. Leaf oil killed the test pathogen with in 1-15 minute. The activities were well compared with standard antifungal drugs. The essential oil from the rhizomes of *Curcuma longa* has been studied for antifungal activity against five fungi viz. *Aspergillus niger, A. fumigatus, Curvularia lunata, Fusarium psidi* and *Rhizopus oryzae* [70]. The rhizome oil was toxic to several fungi and was more effective as compared to synthetic fungicides. The oil has no adverse effect on seed germination and seedling growth of some common agricultural crops. The fungitoxic spectrum shows that oil has strong fungitoxic activity (100% mycelial inhibition) against *Colletotrichum falcatum, Fusarium moniliforme, and Helminthosporium oryzae* at 1000 ppm concentration and against *Aspergillus niger, Curvularia pallescens, Fusarium oxysporum* and *Periconia atropurpurea* at 2000 ppm concentration. Mycelial growth of *A. flavus, Curvularia lunata* and *Rhizoctonia solani* was completely inhibited at 3000 ppm concentration [71].

21. Eucalyptus spp. (Myrtaceae)

The essential oil from leaves of *Eucalyptus globulus* by hydrodistillation, and its major compound 1,8-cineole, identified by gas chromatography coupled with a mass selective detector, and evaluated for their effectiveness against the storage fungi *Aspergillus flavus* and *Aspergillus parasiticus*. Complete fungal growth inhibition of both species was achieved with the essential oil by contact and volatile assays.

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Volatile exposure showed total inhibition at the lower level tested of 500 µL. The 1,8-cineole tested alone showed partial inhibition only at the highest level of 1.3492 µL. Aflatoxin B_1 production was reduced in headspace volatile assays and partial inhibition was observed at the 200 µL dose of the essential oil [72]. The effectiveness of *Eucalyptus* oil was observed to control the black mould of onion bulbs and it was found that the oil at 1.0 x 10^3 µl/l concentration effectively reduced the decay as well as the sprouting of stored onions [25]. Oil also showed inhibitory effect on the mycelial growth of three soil borne plant pathogen viz., *Sclerotium rolfsii, Rhizoctonia solani* and *Sclerotinia rolfsii* [73]. The *Eucalyptus camaldulensis* oil was found to be toxic to *Aspergillus fumigatus, Penicillium notation* and some human pathogens [74].

The *E. citriodora* oil was toxic to *Aspergillus niger* and some human pathogens [75,76]. The pure oil of *E. citriodora* controlled fruit rot of apple caused by *Clathridium corticola* and 1: 1000 dilution of the same oil completely checked the growth of *A. niger* and *Clathridium corticola* [24]. The toxicity of the *E. citriodora* oil against *Aspergillus flavus, A. fumigatus, Fusarium oxysporum* and *Penicillium digitatum* was also reported [77]. The fungitoxicity of the volatile constituent from *E. gennii* against *Aspergillus niger* was recorded [78]. The gallic acid and unidentified isomers of benzene from the volatile constituent of the same plant was isolated and reported that the compounds were inhibitory to conidial germination of *Cochliobolus miyabenaus* [79]. However, the toxicity of the oil against *Alternaria tenuis, Diplodia metalensis* and *Penicillium digitatum* was also recorded [21, 93]. The *E. globulus* oil was recorded to be toxic against *Aspergillus flavus, A. fumigatus, Fusarium oxysporum* and *Penicillium digitatum* [77]. The oil was reported to possessed broad antifungal spectrum [80] and the oil was inhibitory to sclerotial germination of *Macrophomina phaseoli* [81]. The toxicity of the *E. piperita* oil was recorded against *Aspergillus flavus, A. fumigatus, Fusarium oxysporum* and *Penicillium digitatum* [77]. The essential oils from *Eucalyptus citriodora, E. dalarympleana, E. laveopinea, E. pauciflora* at 1000 ppm showed complete inhibition of the storage spoilage test fungus *Penicillium italicum.* The oil of *E. dalarympleana* and *E. laveopinea* showed fungistatic toxicity against the test fungus at 3000 ppm but the oil of *E. laveopinea* showed partial inhibition at 3000 ppm. The oil of *E. citriodora* at 1000 ppm exhibited fungicidal nature and withstood heavy inoculums [82].

The essential oil extracted from leaves of *Eucalyptus pauciflora* showed toxicity against fungal pests viz., sp. of *Alternaria, Aspergillus, Penicillium,* and *Rhizopus.* The effective pesticidal concentration (EPC) of the oil was found to be 0.3 x10^3, 0.4 x10^3, 0.5x10^3 and 0.6x10^3µl/l respectively inhibiting the mycelial growth of the tested pests completely [83]. A study to explore the effect of volatile oils from *Eucalyptus citriodora* and its major constituent citronellal against two well-known rice pathogens, *Rhizoctonia solani* and *Helminthosporium oryzae* was done. The radial growth and dry weight of both the test fungi were drastically reduced in response to the volatile oils. A complete inhibition of *R. solani* and *H. oryzae* was observed at 10 and 20 ppm, respectively. Based on the study, it was concluded that *Eucalyptus* volatile oils have potential for the suppression of phytopathogenic fungi [84].

22. *Eugenia caryophylata (Myrtaceae)*

The *Eugenia caryophylata* (Myrtaceae) oleoresin at 0.2 to 0.8% (v/v) was used against the test microorganisms such as *Candida albicans, Pencillium citrinum* and *Aspergillus niger*. It was highly effective against *Candida albicans*. *P. citrinum* and *A. niger* were relatively more resistant. Clove oleoresin was first dispersed in sugar solution and then used for antifungal testing [85].

23. *Foeniculum vulgare (Apiaceae*)

The oil of *Foeniculum vulgare* (Apiaceae) was toxic against *Aspergillus flavus* [62]. The oil from seeds of this plant showed the toxicity against *Alternaria tenuis, Aspergillus oryzae* and *Penicillium chrysogenum* [46]. Its oil was reported to be toxicity against *Alternaria* sp., *Aspergillus candidus, A. flavus, A. fumigatus, A. nidulans, A. niger, Cladosporium herbarum, Caninghamella echinulata, Fusarium moniliforme, F. oxysporum, Helminthosporium sacchari, Mucor mucedo, Penicillium digitatum, Rhizopus* sp., and *Trichothecium roseum* [19,48]. The toxicity of this oil was also recorded against *A. fumigatus, A. niger, Candida tropicalis* and *Rhizopus oryzae* [30]. The fungitoxic factor of the oil was thermostable and remained active during storage upto 365 days. The antifungal efficacy of the oil was not affected when the inoculum density of *Penicillium italicum* was increased [86].

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The oil at 1.5 x 10^3 µl/l completely inhibited the mycelial growth of *Alternaria alternata, A. tenuissima, Aspergillus awamori, A. ochraceus, A. parasiticus, A. sydowi, A. tamarii, A. terreus, Botryodiplodia theobromae, Colletotrichum capsici, Curvularia lunata, C. pallascens, Drechslera hawaiiensis, D. oryzae, Epicoccum nigrum, Fusarium acuminatum, F. equiseti, F. semitectum, F. udum, Macrophomina phaseolina, Mwemnoniella echinata, Nigrospora oryzae, Penicillium chrysogenum, Penicillium citrinum* and *Rhizopus nigricans* and enhanced the seed germination of *Arachis hypogeal* [87]. The chemical composition of the flower and unripe and ripe fruits from fennel (bitter) (*Foeniculum vulgare* ssp. *piperitum*) by gas chromatography and gas chromatography-mass spectrometry. The main identified components of the flower and unripe and ripe fruit oils were estragole (53.08%, 56.11%, and 61.08%), fenchone (13.53%, 19.18%, and 23.46%), and α-phellandrene (5.77%, 3.30%, and 0.72%), respectively. Minor qualitative and major quantitative variations for some compounds of essential oils were determined with respect to the different parts of *F. vulgare*. The oils exerted varying levels of antifungal effects on the experimental mycelial growth of *Alternaria alternata*, *Fusarium oxysporum*, and *Rhizoctonia solani*. The 40 ppm concentrations of fennel oils showed inhibitory effect against mycelial growth of *A. alternaria*, whereas 10 ppm levels were ineffective. The analyses show that fennel oils exhibited different degrees of fungistatic activity depending on the doses [88].

24. *Lantana camara* (*Verbinaceae)*

The seed oil of *Lantana camara* (Verbinaceae) was toxic to *Candida albicans, Curvularia lunata* and *Fusarium oxysporum* [89]. Oil also showed toxicity against *Alternaria* sp., *Aspergillus candidus, A. flavus, A. fumigatus, A. nidulans, A. niger, Cladosporium herbarum, Cunninghamella echinulata, Fusarium moniliforme, Helminthosporium sacchari, Mucor mucedo, Penicillium digitatum, Rhizopus* sp., and *Trichothecium roseum* [19].

25. *Melaleuca leucadendron (Myrtaceae)*

The leaf oil of *Melaleuca leucadendron* (Myrtaceae) was fungistatic to *Colletotrichum capsici, Curvularia lunata, Helminthosporium oryzae, Pyricularia oryzae, Pythium aphanidermatum, P. debaryanum, Rhizoctonia solani and Syncephalastrum* sp. at 0.05 x 10^3 µl/l but at 0.5 x 10^3 µl/l it turned fungicidal. However at 0.5 x 10^3 µl/l the oil was proved to have no adverse effect on seed germination and seedling growth of *Phaseolus aureus* [90]. The essential oil from leaves showed toxicity against *Aspergillus flavus* at 2.0 x 10^3µl/l dose [31].

26. *Mentha arvensis (Lamiaceae*)

The oil of *Mentha arvensis* (Lamiaceae) was fungitoxic [91]. Later it was shown that the oil was toxic against *Alternaria tenuis, Diplodia metalensis, Penicillium digitatum* and *P. italicum* [21,92,93]. The toxicity of oil was also recorded against *Aspergillus* sp., *Curvularia lunata,* and *Helminthosporium oryzae* [18,28,49].This oil showed toxicity against *Aspergillus flavus, A. fumigatus* and *Fusarium oxysporum* [77]. The oil at 2.0 x 10^3 µl/l was fungicidal to *Absidia ramose, Alternaria brassicae, A. raphani, A. solani, Aspergillus niger, A. lindemuthianum, C. tinosporae, Fusarium monoliforme, F. solani, Paecilomyces fusisporus, Talaromyces* sp. and *Trichoderma viride*. It was found to be superior over the synthetic fungicides tested and showed a broad fungitoxic spectrum against *A. niger, A. fumigatus, Botryodiplodia theobromae, Cladosporium cladosporioides, Fusarium oxysporum, Helminthosporium oryzae, Macrophomina phaseolina* and *Sclerotium rolfsii* at 0.10 mg mL^{-1}. The oil completely inhibited the aflatoxin B1 production by the toxigenic strain of *A. flavus* at 0.05 mg mL^{-1}. Moreover, the *Mentha* oil also exhibited potent antioxidant activity in 2,2′-azino-bis-3-ethylbenzothiazoline-6-sulphuric acid (ABTS) bioassay. Keeping in mind the side effects of synthetic pesticides and the global interest in botanical pesticides for plant protection due to their biodegradable nature, *M. arvensis* oil may be used as a botanical fungitoxicant against fungal attack to stored food commodities. The antiaflatoxigenic and antioxidant nature of the oil suggest the possibility of its exploitation for enhancing the shelf life of stored food commodities [94,95].

27. *Murraya exotica (Rutaceae)*

The leaf oil of *Murraya exotica* (Rutaceae) was found to be toxic against *Alternaria alternaria, A. solani, Aspergillus flavus, A. fumigatus, A. nidulans, A. niger, Cladosoporium herbarum, Cunninghamella* sp., *Fusarium moniliforme, Helminthosporium* sp., *Penicillium digitatum, P. italicum, Rhizopus nigricans* and *Trichothecium roseum* [96]. This oil was also toxicity against *Cunninghamella echinulata, Fusarium moniliforme, F. oxysporum* and *Rhizopus* sp [97].

28. *Nardostachys jatamansi (Valerianaceae)*

The oil of *Nardostachys jatamansi* (Valerianaceae) was toxic against *Alternaria helianthi, Colletotrichum capsici, Fusarium solani, Helminthosporium oryzae, H. turcicum, Pyricularia setareae, Pythium vexans, Rhizoctonia bataticola* and *R. solani* [98].

It was found that the oil at 1.0 x 10^3 µl/l conc. inhibited the growth of *Aspergillus flavus, A. niger* and *Fusarium oxysporum.* The oil also proved effective against six other fungi at the same conc. and did not adversely affect seed germination and seedling growth of *Cicer arietinum* and *Cajanus cajan* [99].

29. Ocimum gratissimum (Lamiaceae)

Thirty fungal species were to be associated with the stored kernels of cashewnut *(Anacardium occidentale* L.), chironjee/cuddapah almond *(Buchanania lanzan* Spreng.), walnut (*Juglans regia* L.), dried fruits of cardamom *(Elettarra cardomomum* Matan), and raisin *(Vitis vinifera* L.). Because of their wide distribution, high incidence as well as enormous potential to produce mycotoxins, *Aspergillus flavus* Link: Fr. and *A. ochraceous* Wilhelm were selected as test fungi for antifungal screening of leaf extracts of 126 species of higher plants belonging to 45 families of angiosperms. *Ocimum gratissimum* exhibited the strongest bioactivity. Minimum inhibitory concentrations (MIC) of the volatile antifungal oil fraction against *A. flavus and A. ochraceous* were found to be 400 ppm and 700 ppm, respectively; higher concentrations (>900 ppm) were fungicidal and not fungistatic. The toxicity of the oil did not change even with high inoculum density during storage periods of 270 days, at its exposure to 100ºC, and on autoclaving [100].

30. Ocimum basilicum (Lamiaceae)

The oil of *Ocimum basilicum* (Lamiaceae) showed toxicity against *Alternaria tenuis, Aspergillus oryzae* and *Penicillium chrysogenum* [46]. The toxicity of this oil was also recorded against *Aspergillus niger, Candida albicans, C. utilis* and *Penicillium notatum* [75,101].The oil was toxic to *Aspergillus fumigatus, A. niger, Chrysosporium tropicum* and *Penicillium lilacinum* [102] while inhibition of *Diplodia metalensis, Penicillium digitatum* and *P. italicum* was also reported [21,93]. The cineole, linalool, methyl chavicol and eugenol were probably the active constituents of the oil which completely inhibited the growth of *D. metalensis* and *Fusarium oxysporum* [103]. The essential oil completely inhibited the mycelial growth of 22 species of fungi including mycotoxin producing strains of *Aspergillus flavus* and *A. parasiticus* at 1.5 x 10^3µl/l concentration. It also exhibited significant insect repellent activity against *Allacophora foveicollis* [104].

31. Ocimum canum (Lamiaceae)

The leaf oil of *Ocimum canum* (Lamiaceae) was toxic to *Candida albicans, Cephalosporium sacchari, Ceratocystis paradoxa, Curvularia lunata, Fusarium moniliforme, Helminthosporium sacchari, Physalospora tucumanensis* and *Sclerotium rolfsii* [10]. 1.4% of the oil was isolated from leaves and its toxicity was recorded against *Aspergillus flavus* and *A. versicolor* at 3.0xl0^3 µl/l [105]. The oil was fungistatic nature at 3.0x10^3 µl/l which become fungicidal at 6.0x10^3 µl/l concentration [106]. The toxicity of the oil was thermostable, which remained active during storage up to 390 days [56]. The oil successfully prevented fungal deterioration of *Foeniculum vulgare* and *Coriandrum sativum* during storage without showing any phytotoxic effect on the treated commodities [107,90]. The essential oil isolated from leaves showed its toxicity against *Aspergillus flavus* at 2000 ppm (2.0xl0^3 µl/l) [31]. Linalool isolated from *Ocinum canum* oil was toxic against *Rhizoctonia solani* and *Fusarium solani* [108].

32. Ocimum gratissimum (Lamiaceae)

The oil of *O. gratissimum* (Lamiaceae) showed toxicity against *Penicillium notatum* [101,109]. This oil also showed toxicity against *Alternaria alternata, Colletotrichum capsici* and *Sclerotium rolfsii* at 0.25x10^3 µl/l, 0.5x10^3 µl/l conc. respectively. They further reported that the oil possessed fungistatic nature at lower doses but became fungicidal at higher doses and when chemically analyzed yielded myrcene, b-pinene, p-cymene, linalyl acetate, terpineol, terpinyl acetate, linalool, geranial, citroneollol and eugenol each exhibiting toxicity against *A. alternata, C. capsici* and *S. rolfsii* at different doses [110]. Eugenol was isolated from the oil and it was reported that the oil as well as eugenol can be used to prevent bakery bread from fungal deterioration during storage [111]. The essential oil was isolated from the leaves and was reported its to be toxic against *Aspergillus flavus* at 2000 ppm [31]. The eugenol the main constituent the *Ocimum* oil was isolated [108] and 0.1% of eugenol inhibited the radial growth of *Sclerotium rolfsii, Rhizoctonia* sp. and *Alternaria alternata. O. gratissimum* was found to exhibit absolute toxicity against the tested fungi *A. flavus* and *A. niger*. It was also reported that the oil from leaves of *Ocimum sanctum* (Lamiaceae) showed absolute toxicity against *A. flavus* but was moderately active against *A. niger* [100].

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33. Syzygium aromaticum (Myrtaceae)

The toxicity of the oil of *Syzygium aromaticum* (Myrtaceae) was recorded against *Aspergillus niger* [62]. Further the flower bud extract of *Syzygium aromaticum* exhibited absolute toxicity against *Aspergillus niger* and *Curvularia ovoidea,* inhibiting the mycelial growth completely [112].

34. Thymus striatus (Lamiaceae)

The essential oil composition from *Thymus striatus* was collected from Mountain Orjen (Montenegro) by gas chromatography-mass spectrometry. Thymol, ϒ-terpinene and p-cymene were found to be the major components. Furthermore, the oil and its major component, thymol, were analysed for potential antifungal activity against plant, animal and human pathogenic fungi from different genera by a macrodilution test. The oil exhibited a strong inhibitory effect against all fungi investigated [113].

35. Trachyspermum ammi (Apiaceae)

The *Trachyspermum ammi* essential oil (TAEO) was examined against *Aspergillus flavus*, aflatoxin B_1 (AFB_1) contamination, and its mechanism of action using biochemical and computational approaches. The GC–MS result revealed the chemical diversity of TAEO with the highest percentage of γ-terpinene (39 %). The TAEO exhibited minimum inhibitory concentration against *A. flavus* growth (0.5 µL/mL) and AFB_1 (0.4 µL/mL) with radical scavenging activity (IC_{50} = 2.13 µL/mL). The mechanism of action of TAEO was associated with the alteration in plasma membrane functioning, antioxidative defense, and carbon source catabolism. The molecular dynamic result shows the multi-regime binding of γ-terpinene with the target proteins (*Nor1, Omt1*, and *Vbs*) of AFB_1 biosynthesis. Furthermore, TAEO exhibited remarkable in-situ protection of *Sorghum bicolor* seed samples against *A. flavus* and AFB_1 contamination and protected the nutritional deterioration. Hence, the study recommends TAEO as a natural antifungal agent for food protection against *A. flavus* mediated biodeterioration [114]. Later it was reported that the oil of *Trachyspermum ammi* (Apiaceae) was toxic to *Fusarium tenuis* [115]. Further it was recorded that the oil was inhibitory to *Alternaria* sp., *Aspergillus candidus, A. flavus, A. fumigatus, A. nidulans, A. niger, Candida tropicalis, Cladosporium herbarum, Cunninghamella echinulata, Fusarium moniliforme, F. oxysporum, Helminthosporium sacchari, Mucor mucedo, Penicillium digitatum, Rhizopus oryzae* and *Trichothecium roseum* [48,19,30].

The toxicity of the dethymolysed oil was reported against *Alternaria brassicae, A. solani, Cephalosporium sacchari, Cladosporium cladosporioides, Colletotrichum falcatum, C. lindemuthianum, C. tinosporae, Cornespora casicola, Fusarium solani, Helminthosporium oryzae, Paecilomyces* sp., *Talaromyces* sp. and *Trichoderma viride* [116]. The nature of the oil was reported to be fungicidal against *Alternaria alternata, A. solani, Aspergillus flavipes, A. flavus, A. niger, A. ochraceus, A. sydowi, A. tamarii, A. terreus, A. versicolor, Botrytis cinerea, Colletotrichum capsici, C. falcatum, Curvularia lunata, C. pallescens, Chaetomium globosum, Fusarium semitectum, Monilia pruinosa* and *Penicillium funiculosum* at 800 ppm (0.8 x 10^3 µl/l). They further added that the fungitoxic factor remained unaffected by temperature treatment up to 100°C and storage at room temperature up to 365 days. The seeds of *Arachis hypogea* when dressed at 5000 ppm ($5.0x10^3$ µl/l) of the oil and stored for 12 months showed no fungal contamination indicating the grain protection efficacy of the oil. Thymol and p-cymene were isolated as antifungal principles of the oil and reported to possess toxicity against *Aspergillus flavus* and *A. niger* at $1.0x10^3$µl/l concentration [117].

III. Mechanism Of Action Of Essential Oils Against Storage Fungi

Essential oils exhibit antifungal activity against storage fungi through multiple biochemical and cellular mechanisms. Their bioactive constituents, particularly phenols, terpenoids, aldehydes, and alcohols, interact with fungal cell membranes, disrupting membrane integrity and increasing permeability. This causes leakage of essential intracellular components, including ions, proteins, and nucleic acids, ultimately leading to cellular dysfunction and death. Major compounds such as thymol, carvacrol, eugenol, and cinnamaldehyde interfere with ergosterol biosynthesis, impairing membrane stability and functionality. Essential oils also inhibit key metabolic enzymes, mitochondrial respiration, ATP production, and fungal spore germination. Furthermore, they induce oxidative stress through excessive generation of reactive oxygen species (ROS), resulting in lipid peroxidation, protein denaturation, and DNA damage. Some essential oil constituents additionally suppress fungal growth by inhibiting hyphal elongation, sporulation, and mycelial development. Their combined effects lead to fungistatic or fungicidal activity, depending on concentration, chemical composition, and fungal species.

Thus, essential oils represent promising natural alternatives to synthetic fungicides for controlling post-harvest fungal contamination and maintaining the quality and shelf life of stored agricultural commodities.

IV. Conclusion

The green plants are the reservoir of effective chemotherapeutants and can provide reversible source of useful pesticides. Tropical floras, in contrast to their temperate zone counterparts, have developed a more efficient and varied defense mechanism because of the far severe conditions for survival. They, thus provide a rich and intriguing source for isolating natural secondary plant metabolites, which exhibit interesting antimicrobial properties. Although only some 15,000 secondary plant metabolites have been chemically identified, their total number may exceed 4,000,000. They are vast cornucopia of defense chemicals. Among various fungicides gaseous forms of fungicides are expected to be the best to control storage fungi as they get more uniformly dispersed than spray, dip, wash or dust treatments. The vapour action gives complete coverage and deep penetration following application, due to which labour cost will be reduced comparatively thus more cost effective or economically viable. However, fumigation is not widely practiced because of lack of suitable fumigants. An ideal fumigant should be reasonably volatile to be effective against microorganisms causing deterioration. Volatiles of higher plants obtained in the form of essential oils, as above, have been tested against a number of storage fungi. It is heartening that the essential oils of some plants have been proved to be more efficacious than some of the prevalent synthetic fumigants in the control of fungal deterioration.

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