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Eucalyptus essential oil as a natural pesticide

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ABSTRACT

Eucalyptus (family Myrtaceae), an Australian native, represented by around 700 species is a genus of tall, evergreen and magnificent trees cultivated world over for its oil, gum, pulp, timber, medicine and aesthetic value. Among the various wood and non-wood products, essential oil found in its foliage is the most important one and finds extensive use in food, perfumery and pharmaceutical industry. In addition, the oil possesses a wide spectrum of biological activity including anti-microbial, fungicidal, insecticidal/insect repellent, herbicidal, acaricidal and nematicidal. The present paper discusses this environmentally benign pest control using eucalyptus oils against bacteria, fungi, insects, nematodes, weeds and mites. The use of eucalyptus oil as a natural pesticide is of immense significance in view of the environmental and toxicological implications of the indiscriminate use of synthetic pesticides and overcoming/reducing the problem of increasing pest resistance.

1. Introduction: rationale and objectives

Since antiquity humans have been dependent upon natural ecosystems for marketable commodities such as food, fodder, fuelwood, timber and medicines. However, until recently, very little significance was given to the natural, hidden, life-supporting services of the natural ecosystems. It is only when the disruption/loss of these natural resources poses/results in a severe threat to the very existence of human civilization, these intrinsic values have been highlighted. In fact, these services are ignored largely due to their non-marketable potential and a negligible role in modern trade-based economy. Nevertheless, during the last decade the importance of these natural benefits has been highlighted and the perils linked to their loss realized. The phrase '*ecosystem services*' has been widely used for these underpinned natural environmental benefits (Ehrlich and Ehrlich, 1981) and considered as '*world's natural capital*' (Costanza et al., 1997).

Majority of the ecosystems services', particularly intangible, provided by nature are complex, interwoven and intricately related. However, some of the ecosystem services include simple products such as fodder, fuelwood, oil, and resins that are commercially marketed. Ecosystem services have been recognized since ancient times. For example, Plato (ca. 400 B.C.) based on his direct observation concluded that deforestation leads to soil erosion and results in drying up of springs. Ecosystem services have been grouped into five categories—provisioning (food, fuel, fodder, essential oil), regulating (carbon sequestration, nutrient cycling), supporting (purification, cleansing, pest control), cultural (spiritual, recreational and aesthetic) and preserving (biodiversity protection) services (Millennium Ecosystem Assessment, 2005). Of late, these intrinsic services of nature have been recognized as an important tool for conservation and resource management (Reid, 2006). As per report of the World Bank (2006), more than one billion people are directly dependent upon ecosystem services. It is very difficult and *more so* debatable to assess the ecosystem services in monetary terms or market-economy; however, some estimates have been made. Costanza et al. (1997) opined that monetary value of global ecosystem services is in the range of US$ 16–54 trillion (10^{12}) per year with an average value of US$ 33 trillion per year. Looking at the importance of ecosystem services to mankind, it is worthwhile to explore environmental benefits of the natural products to mankind.

Among the variety of nature's ecosystem services, the natural pest control is an important aspect. DeBach (1974) reported that ~99% of the crop pests are controlled by natural enemies such as birds, spiders, parasitic wasps, viral diseases and other organisms. In fact, natural pest control not only minimizes the use of synthetic chemicals, protects crops, but also saves huge amount of money spent on chemical compounds (Naylor and Ehrlich, 1997). It is thus pertinent to explore the pesticidal activity of natural products.

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World over, pests (especially weeds, pathogens and insects) are the largest competitor of agricultural crops and severely reduce the crop production in the range of 25–50% (Pimentel et al., 1991; Oerke, 2006). Among the pests, weeds alone are held responsible for nearly 34% reduction in crop yield (Oerke, 2006). To protect agricultural crops enormous amount of synthetic pesticides are used world over. As per Agrow (2007) report, the total value of world's agrochemical market was between US$31–35 billion and among the products herbicides accounted for 48% followed by insecticides (25%) and fungicides (22%).

However, the excessive use of synthetic pesticides in the croplands, urban environment, and water bodies to get rid of noxious pests has resulted in an increased risk of pesticide resistance, enhanced pest resurgence and development of resistance/cross-resistance, toxicological implications to human health and increased environmental pollution. In fact, combating of environmental pollution and its ill-effects on the life and life-support systems is one of the most serious challenges before the present day world. Efforts are thus being made world over to replace these synthetic chemicals with alternatives, which are safer and do not cause any toxicological effects on the environment. The natural pest and disease control either directly or indirectly using natural plant products/botanicals, including essential oils, holds a good promise (Regnault-Roger, 1997; Isman, 2000, 2006; Bakkali et al., 2008). Among essential oils, Eucalyptus oil, in particular, is more useful as it is easily extractable commercially (industrial value) and possesses a wide range of desirable properties worth exploiting for pest management (Boland et al., 1991; FAO, 1995; Barton, 2000). We refer it as a provisioning ecosystem service since the oil is commercially important product of the tree. Our objective in the present context is to review its use as a natural pesticide, which could be another supporting ecosystem service.

2. Essential oils: their characteristics and potential

Plant essential oils are obtained from non-woody parts of the plant, particularly foliage, through steam or hydrodistillation. They are complex mixture of mainly terpenoids, particularly monoterpenes (C10) and sesquiterpenes (C15), and a variety of aromatic phenols, oxides, ethers, alcohols, esters, aldehydes and ketones that determine the characteristic aroma and odour of the donor plant. Presence of volatile monoterpenes or essential oils in the plants provides an important defense strategy to the plants, particularly against herbivorous insect pests and pathogenic fungi (Langenheim, 1994). These volatile terpenoids also play a vital role in plant–plant interactions and serve as attractants for pollinators (Tholl, 2006). They act as signaling molecules and depict evolutionary relationship with their functional roles (Theis and Lerdau, 2003).

Aromatic plants and their essential oils have been used since antiquity in flavor and fragrances, as condiment or spice, in medicines, as antimicrobial/insecticidal agents, and to repel insect or protect stored products (Dorman and Deans, 2000; Isman and Machial, 2006; Bakkali et al., 2008). These constitute effective alternatives to synthetic pesticides without producing adverse effects on the environment (Isman, 2000; Isman and Machial, 2006). However, the attempts to characterize their pest control activity under *in vitro* conditions started in 1900s (Dorman and Deans, 2000). Moreover, the interest in essential oils has regained momentum during the last decade, primarily due to their fumigant and contact insecticidal activities and the less stringent regulatory approval mechanisms for their exploration due to long history of use (Isman, 2006). Of late, the essential oils are being tried as potential candidates for weed (Singh et al., 2003; Batish et al., 2004, 2007), and pest and disease management (Isman, 2000; Pawar and Thaker, 2006; Abad et al., 2007). It is primarily because essential oils are easily extractable, ecofriendly being biodegradable and get easily catabolized in the environment (Zygadlo and Grosso, 1995), do not persist in soil and water (Misra and Pavlostathis, 1997; Isman, 2000, 2006), possess low or no toxicity against vertebrates—fishes, birds and mamamals (Enan et al., 1998) and play an important role in plant protection against pests (Isman, 2000; Isman and Machial, 2006; Bakkali et al., 2008). All these benign properties of essential oils permit their use even in sensitive areas such as schools, restaurants, hospitals and homes.

3. Eucalyptus essential oils as pesticide—Why?

Among various aromatic plants, genus *Eucalyptus* L′ Herit (Family Myrtaceae and a native of Australia) represented by over 700 species distributed throughout the world (Brooker and Kleinig, 2006) is one of the most-extensively planted pulpwood species (Zobel, 1988). It consists of tall, magnificent and evergreen trees with fragrant foliage rich in oil glands and is an excellent source of commercially important eucalyptus oil that finds extensive use in pharmaceutical, perfumery and industry (Brooker and Kleinig, 2006). The common oil yielding *Eucalyptus* species include: lemon or lemon-scented eucalyptus (*E. citriodora*), Tasmanian blue gum (*E. globulus*), blue mallee (*E. polybractea*), and River red gum (*E. camaldulensis*). As per a report, essential oil from Eucalyptus species are among the world's top traded oils and oil extracted from *E. citriodora* is one of the world's major oil in terms of trade volume (Green, 2002).

Eucalytpus species not only provide fuel biomass and reduce atmospheric carbon dioxide levels directly (Barton, 2000; Martin, 2002), but also perform a variety of indirect services through their essential oil used as insect/pest repellent and as a pesticidal agent (Barton, 2000). In fact, eucalyptus oil has been known for hundreds of years as antibacterial, antifungicidal and antiseptic in nature (Brooker and Kleinig, 2006). Eucalyptus oil ranks superior in quality and has advantages over essential oil from other tree crops, since it has multipurpose uses in perfumery, pharmaceutical and other industries (Boland et al., 1991; FAO, 1995).

Under natural conditions, essential oil of *Eucalyptus* is also known to provide allelopathic property to the tree (Kohli, 1990; Liu et al., 2008). Essential oil emanated from its foliage has been demonstrated to retard the growth of associated vegetation (del Moral and Muller, 1969; Kohli, 1990; May and Ash, 1990; Liu et al., 2008). Additionally, the presence of essential oil also provides defense advantage to *Eucalytpus* leaves against herbivory and attack by harmful insects (Brooker and Kleinig, 2006). In general, the plant secondary metabolites including phenolics, tannins and even monoterpenes are considered to have co-evolved with herbivory (Vourc'h et al., 2002; Bailey et al., 2004; Foley and Moore, 2005). However, whether herbivory and presence of essential oil in *Eucalyptus* species has any evolutionary relationship is not clearly understood. Anyhow, a strong genetic basis has been established for the resistance of *E. globulus* to marsupial herbivory largely due to presence of sideroxylonal (O'Reilly-Wapstra et al., 2004).

Eucalyptus oil has been placed under GRAS (Generally Regarded as Safe) category by Food and Drug Authority of USA and classified as non-toxic (USEPA, 1993). Even the Council of Europe has approved use of eucalyptus oil as a flavouring agent in foods (≤5 mg/kg) and candies and confectionery items (≤15 mg/kg) (Council of Europe, 1992). At low concentrations, it is also used extensively in soaps, detergents and perfumes (Furia and Bellanca, 1971). Currently, three to five thousand tonnes of Eucalyptus oil are traded every year in international markets and around two-third of this is produced by Australia (Barton, undated).

Table 1
Major constituents of the essential oil with pesticidal activity extracted from *Eucalyptus* species

Eucalyptus sp.	Major constituents	Reference
E. camaldulensis	Eucamalol	Watanabe et al. (1993)
E. citriodora	Citronellal	Ramezani et al. (2002b), Batish et al. (2006), Su etal. (2006)
E. globulus	1,8-Cineole	Yang etal. (2004)
E. grandis	α-Pinene, 1,8-cineole	Lucia etal. (2007)
E. robusta	α-Pinene	Sartorelli et al. (2007)
E. saligna	α-Pinene (during blossoming), *p*-cymene (at vegetative phase)	Ceferino et al. (2006), Sartorelli et al. (2007)
E. urophylla	γ-Terpinene,	Su et al. (2006)
E. camaldulensis, *E. grandis*	1,8-Cineole	Su et al. (2006)
E. cinerea, *E. viminalis*	1,8-Cineole	Ceferino et al. (2006)
E. grandis × *E. urophylla*	Alloocimene, α-pinene	Liu etal. (2008)
E. alba, *E. camaldulensis*, *E. citriodora*, *E. deglupta*, *E. globulus*, *E. robusta*, *E. saligna*, *E. tereticornis*	Cineole, α-pinene, *p*-cymene	Cimanga et al. (2002)
Eucalyptus sp.	*p*-Menthane-3,8-diol (PMD)	Trigg (1996a,b), Trigg and Hill (1996)
Eucalyptus sp.	1,8-Cineole	Saad et al. (2006)

4. Nature and composition of eucalyptus essential oils

The eucalyptus oil is a complex mixture of a variety of monoterpenes and sesquiterpenes, and aromatic phenols, oxides, ethers, alcohols, esters, aldehydes and ketones; however, the exact composition and proportion of which varies with species (Brooker and Kleinig, 2006). The pesticidal activity of eucalyptus oils has been due to the components such as 1,8-cineole, citronellal, citronellol, citronellyl acetate, *p*-cymene, eucamalol, limonene, linalool, α-pinene, γ-terpinene, α-terpineol, alloocimene, and aromadendrene (Watanabe et al., 1993; Li et al., 1995, 1996; Cimanga et al., 2002; Duke, 2004; Batish et al., 2006; Su et al., 2006; Liu et al., 2008). The major components identified in essential oil with pesticidal activity extracted from various *Eucalyptus* species are given in Table 1. However, the bioactivity of the essential oil depends upon the type and nature of the constituents and their individual concentration. It further varies with species, season, location, climate, soil type, age of the leaves, fertility regime, the method used for drying the plant material, and the method of oil extraction (Brooker and Kleinig, 2006).

The various components of eucalyptus essential oil act synergistically (and not additively) to bring the overall pesticidal activity (Cimanga et al., 2002). Among the various components of eucalyptus oil, 1,8-cineole is the most important one and, in fact, a characteristic compound of the genus *Eucalyptus*, and is largely responsible for a variety of its pesticidal properties (Duke, 2004).

Table 2
Insecticidal activity of essential oil from some *Eucalyptus* species

Eucalyptus sp.	Tested organism	Reference
E. camaldulensis	Repels adult females of *Culex pipiens*	Erler et al. (2006)
E. camaldulensis	Egg mortality in *Tribolium confusum* and *Ephestia kuehniella*	Tunç et al. (2000)
E. citriodora	Toxicity against *Sitophilus zeamais*	Tinkeu et al. (2004)
E. globulus	Repellent in action, reduced fecundity, decreased egg hatchability, increased neonate larval mortality and adversely influenced offspring emergence in *Acanthoscelides obtectus*	Papachristos and Stamopoulos (2002, 2004)
E. globulus	Kills pupae of *Musca domestica*	Abdel Halim and Morsy (2005)
E. globulus	Ovicidal and adulticidal against female *Pediculus humanus capitis* De (human body lice)	Yang et al. (2004)
E. globulus	Toxic to *Aedes aegypti* larvae	Lucia et al. (2007)
E. intertexta, *E. sargentii* and *E. camaldulensis*	Kills 1–7 days adults of *Callosobruchus maculatus*, *Sitophilus oryzae* and *Tribolium castaneum*	Negahban and Moharramipour (2007)
E. nicholii, *E. codonocarpa*, *E. blakelyi*	*Sitophilus oryzae*, *Tribolium castaneum* and *Rhyzopertha dominica*	Lee et al. (2004)
E. saligna	Repellent activity against *Sitophilus zeamais* and *Tribolium confusum*	Tapondjou et al. (2005)
E. tereticornis	Larvicidal, pupicidal and adulticidal activity towards *Anopheles stephensi*	Nathan (2007)
Eucalyptus sp.	Rice weevil *Sitophilus oryzae*	Lee et al. (2001)
Eucalyptus sp.	Toxic to larvae of pine processionary moth *Thaumetopoea pityocampa*	Kanat and Alma (2003)
Eucalyptus sp.	Mushroom fly *Lycoriella mali*	Choi et al. (2006)
Eucalyptus sp.	Larvicidal activity against 4th instar stage larvae of *Aedes albopictus*, *A. aegypti* and *Culex pipiens pallens*	Zhu et al. (2006)
Eucalyptus sp.	*Tribolium castaneum*, *Rhyzopertha dominica*, *Sitophilus oryzae* and *Sitophilus zeamais*, *Corcyra cephalonica* and *Sitotroga cerealella*	Rajendran and Sriranjini (2008)

5. Insecticidal/insect-repellent activity of eucalyptus oils

Eucalyptus oil can directly act as a natural insect repellent to provide protection against mosquitoes and other harmful arthropods or serves antifeedant activity against herbivores. Some of the examples of use of eucalyptus oil for insecticidal activity are listed in Table 2.

Yang et al. (2004) reported that essential oils from *E. globulus* and its major monoterpene 1,8-cineole showed toxicity against human head lice, *Pediculus humanus capitis*. The pediculicidal activity of essential oil and its major component 1,8-cineole was more than that of commercially used pediculides—delta-phenothrin or pyrethrum. The LT_{50} value of essential oil was 0.125 mg/cm^2 compared to 0.25 mg/cm^2 of commercial pediculides (Yang et al., 2004). Of late, Ceferino et al. (2006) demonstrated the fumigant toxicity/repellent activity of essential oil from *E. cinerea*, *E. viminalis* and *E. saligna*, against permethrin-resistant human head lice with KT_{50} (time for 50% knockdown) values of 12.0, 14.9 and 17.4 min, respectively. Based on the study, these workers concluded that these essential oils could be used for the development of new products for control of human head lice (Ceferino et al., 2006).

Eucalyptus oil has also been used as an antifeedant, particularly against biting insects (Trigg, 1996a,b; Trigg and Hill, 1996; Chou et al., 1997; Thorsell et al., 1998). Trigg (1996a,b) reported that eucalyptus based products used on humans as insect repellent can protect from biting insects up to 8 h depending upon the concentration of the essential oil. Further, the insect-repellent activity could be extended up to 8-days, when eucalyptus essential oils are applied on the clothes (Mumcuoglu et al., 1996). Later, Fradin and Day (2002) reported that 30% eucalyptus oil can prevent mosquito bite for 2 h; however, the oil must have at least 70% cineole content. Lucia et al. (2007) demonstrated that essential oil from *E. globulus* are toxic to *Aedes aegypti* larvae and showed LC_{50} of 32.4 ppm. Seyoum et al. (2003) reported that burning of leaves of *E. citriodora* provides a cost-effective method of household protection against mosquitoes in Africa. It is particularly significant for providing protection against mosquito bites during the evenings before going to bed (Seyoum et al., 2003). Of late, CDC (Center for Disease Control and Prevention, USA) recommended the use of lemon eucalyptus oil (with *p*-menthane-3,8-diol, PMD, as active ingredient) for protection against West Nile virus that causes neurological disease or even death and is spread by mosquitoes (Kuehn, 2005).

Table 3
Antimicrobial (against fungi and bacteria) activity of essential oils from some Eucalyptus species

Oil source	Microbe (s)	Reference
E. camaldulensis	*Penicillium digitatum* causing fruit rot of mandarin *cv.* Kinnow under both *in vitro* and *in vivo* conditions	Dhaliwal et al. (2004)
E. camaldulensis	Dermatophytes—*Microsporum canis*, *Microsporum gypseum*, *Trichophyton rubrum*, *Trichophyton schoenleinii*, *Trichophyton mentagrophytes* and *Epidermophyton floccosum*	Falahati et al. (2005)
E. camaldulensis	Seed-borne fungi – *Colletotrichum graminicola*, *Phoma sorghina*, and *Fusarium moniliforme* – of sorghum without any negative effect on *Sorghum*	Somda et al. (2007)
E. citriodora	Human pathogens *Microsporum nanum*, *Trichophyton mentagrophytes* and *T. rubrum*	Shahi et al. (1999)
E. citriodora	Mycelial growth and germination of spores of *Didymella bryoniae*	Fiori et al. (2000)
E. citriodora	Radial growth and dry weight of rice pathogens, *Helminthosporium oryzae* and *Rhizoctonia solani* DC	Ramezani et al. (2002a,b)
E. citriodora	*Aspergillus* sp., *Penicillium* sp., *Fusarium* sp. and *Mucor* sp.	Alfazairy (2004)
E. citriodora	Phytopathogenic fungi, postharvest pathogenic fungi, *Botrytis cinerea* and three soil-borne pathogenic fungi, *Fusarium oxysporum*, *Pythium ultimum* and *Rhizoctonia solani*	Lee et al. (2007)
E. citriodora	*Candida* sp.	Dutta et al. (2007)
E. citriodora	*Phytophthora cactorum*, *Cryphonectria parasitica* and *Fusarium circinatum*	Lee et al. (2008)
E. citriodora	*Botrytis cinerea*	Tripathi et al. (2008)
E. dives	Gram-positive and Gram-negative bacteria and *Saccharomyces cerevisiae*	Delaquis et al. (2002)
E. globulus	Spore germination and radial growth of *Pythium aphanidermatum* Edson	Oluma and Garba (2004)
E. globulus	*Escherichia coli* O157:H7	Moreira et al. (2005)
E. globulus, *E. maculata* and *E. viminalis*	Fungus *Trichophyton mentagrophytes*	Takahashi et al. (2004)
E. robusta and *E. saligna*	*Staphylococcus aureus*, *Escherichia coli* and *Candida albicans*	Sartorelli et al. (2007)
E. tereticornis	*Staphylococcus aureus*, *Bacillus cereus*, *Escherichia coli*, *Micrococcus luteus*, *Proteus mirabilis* and *Alcaligenes faecalis*	Singh and Sharma (2005)
Eucalyptus grandis × *E. urophylla*	Pathogenic fungi *Fusarium oxysporum*, *Pyricularia grisea*, *Gloeosporium musarum* and *Phytophthora capsici*	Liu et al. (2008)
Eucalyptus sp.	Dermatophytes—*Candida* spp. and *Pityrosporum orbiculare*	Kothavade et al. (1997)
Eucalyptus sp.	Mycelial dry weight of *Penicillium aurantiogriseum* and *P. viridicatum*	Khaddor et al. (2006)
Eucalyptus sp.	Spores of bacteria *Clostridium botulinum* 62A and *Bacillus cereus* T	Chaibi et al. (1997)
Eucalyptus sp.	Colony forming units of *Staphylococcus aureus* ATCC-25923	Donoyama and Ichiman (2006)
Eucalyptus sp.	Gram-positive and Gram-negative bacteria and fungi	Pattnaik et al. (1996)

6. Antifungal and antimicrobial activity of eucalyptus oils

Eucalyptus essential oils and their major constituents possess toxicity against a wide range of microbes including bacteria and fungi, both soil-borne and post-harvest pathogens. They have been found to reduce mycelial growth (Fiori et al., 2000), and inhibit spore production and germination (Fiori et al., 2000; Oluma and Garba, 2004). Some of the studies of antimicrobial effects of eucalyptus oils are listed in Table 3.

Ramezani et al. (2002a,b) showed that volatile oil from lemon-scented eucalyptus and its major constituent monoterpene citronellal possessed a wide spectrum of fungicidal activity and inhibited the radial growth and dry weight of six phytopathogenic fungi. Recently, Lee et al. (2007) demonstrated that lemon-scented eucalyptus oil (at 10 $\mu l\,l^{-1}$ air) controlled the apple gray mold by ~70%. Cermelli et al. (2008) screened *E. globulus* oil against 120 isolates of *Streptococcus pyogenes*, 20 isolates of *S. pneumoniae*, 40 isolates of *S.agalactiae*, 20 isolates of *Staphylococcus aureus*, 40 isolates of *Haemophilus influenzae*, 30 isolates of *H. parainfluenzae*, 10 isolates of *Klebsiella pneumoniae*, 10 isolates of *Stenotrophomonas maltophilia* and a strain each of adenovirus and mumps virus and reported that *H. influenzae*, *H. parainfluenzae*, and *Stenotrophomonas maltophilia* and *Streptococcus pneumoniae* are very susceptible. The study concluded that eucalyptus oil could be used for the control of respiratory tract bacteria.

Su et al. (2006) demonstrated the antifungal activity of essential oils from *Eucalyptus grandis*, *E. camaldulensis*, and *E. citriodora* against the mildew and wood rot fungi *viz. Aspergillus clavatus*, *A. niger*, *Chaetomium globosum*, *Cladosporium cladosporioides*, *Myrothecium verrucaria*, *Penicillium citrinum*, *Trichoderma viride*, *Trametes versicolor*, *Phanerochaete chrysosporium*, *Phaeolus schweinitzii* and *Lenzites sulphureus*. Based on the study, the authors opined that essential oil from *E. citriodora* could be an excellent choice as a wood preservative and preservation of leather goods and wood artifacts.

Cimanga et al. (2002) demonstrated the antibacterial activity of essential oil extracted from *Eucalyptus camaldulensis*, *E. tereticornis*, *E. alba*, *E. citriodora*, *E. deglupta*, *E. globulus*, *E. saligna*, and *E. robusta* against *Pseudomonas aeruginosa*. They concluded that composite essential oils were more effective than the additive activity of their major constituents such as 1,8-cineole, α-pinene, and *p*-cymene.

Recently, Tzortzakis (2007) demonstrated that essential oil vapours from *E. globulus* offer a good choice for maintaining postharvest freshness and firmness of strawberry and tomato during storage and transit. Further, no change was observed in sweetness, and organic acid and total phenolic content upon exposure to oil vapours (Tzortzakis, 2007).

Further, studies have also documented that eucalyptus essential oils are effective even against resistant strains of microbes. For example, Sherry et al. (2001) demonstrated that a topical application of eucalyptus oil can effectively remove the methicillin resistant *Staphylococcus aureus* infection. Trivedi and Hotchandani (2004) showed that strains of *Klebsiella* spp., *Proteus* spp., *Pseudomonas* spp., *Escherichia coli*, and *Staphylococcus aureus* resistant to conventional antimicrobials (tobramycin, gentamicin, amikacin, ciprofloxacin, chloramphenicol and cefotaxime) were inhibited by the commercially available eucalyptus oil containing 63% 1,8-cineole. Eucalyptus oils not only show toxicity against a wide range of fungi and bacteria but also possess antiviral activity. For example, Schnitzler et al. (2001) reported that eucalyptus oil exhibits *in vitro* anti-herpes virus activity.

7. Herbicidal activity of eucalyptus oils

Essential oil extracted from *Eucalyptus* species exhibit phytotoxicity against weeds and have a great potential for weed management (Kohli et al., 1998; Singh et al., 2005; Batish et al., 2007; Setia et al., 2007).

Kohli et al. (1998) reported that essential oil from *E. tereticornis* and *E. citriodora* when applied in vapour form significantly decrease the germination of noxious weed *Parthenium hysterophorus*. Further, fumigation of mature plants with eucalyptus oil vapours reduced growth, chlorophyll and water content, and decreased cellular respiration. The inhibitory activity of oil was time-dependent and gradual decline in weed growth was observed with increasing period of oil exposure. Fifteen days after fumigation, plants showed various levels of visible injury in terms of chlorosis, necrosis, and tissue damage, and even complete wilting that varied with source of oil and period of exposure (Kohli et al., 1998). The essential oil from *E. citriodora* was more toxic than that of *E. tereticornis* and it was attributed to the variability in their chemical constitution. The study concluded that eucalyptus oil is promising for weed management provided the economics of their extraction and application are thoroughly worked out (Kohli et al., 1998). However, they did not evaluate the toxicity against other associated plants and non-target organisms.

Further studies were conducted to determine the impact of essential oil extracted from *E. citriodora* against several crops such as *Triticum aestivum*, *Zea mays*, *Raphanus sativus*, and weed plants *Cassia occidentalis*, *Amaranthus viridis* and *Echinochloa crus-galli* (Batish et al., 2004). It was demonstrated that eucalyptus oil exhibit a species-specific toxicity and the toxic effect was more on small-seeded crops like *A. viridis* compared to large-seeded *R. sativus*. Further, when the toxicity of oil was evaluated against 4-week-old weeds under greenhouse conditions, it was observed that growth reduction was more in broad-leaved *C. occidentalis* than in grassy weed—*E. crus-galli*. A higher toxicity of eucalyptus oil from *E. citriodora* was not surprising since citronellal (a major component of *E. citriodora* essential oil; Batish et al., 2006) is more toxic against broad-leaved (dicot) weeds than towards grassy (monocot) weeds (Singh et al., 2002, 2006).

Later, the herbicidal potential of eucalyptus oil (0–100 $\mu l\,ml^{-1}$) used as a spray treatment was evaluated against *P. hysterophorus* (Singh et al., 2005) and *Phalaris minor* (Batish et al., 2007) under screenhouse studies. It was observed that at lower concentrations ($\leq$50 $\mu l\,ml^{-1}$) the toxic effect was less and reversible, whereas at higher concentrations ($\geq$50 $\mu l\,ml^{-1}$) it was irreversible especially at concentrations $\geq$100 $\mu l\,ml^{-1}$. The plants visibly looked wilted initially and exhibited complete mortality with passage of time. The oil treated plants showed a significantly higher degree of ion leakage indicating a loss of membrane permeability and leading to severe plant damage. The authors concluded that eucalyptus essential oil possess herbicidal potential and could be incorporated as a bioherbicide under Integrated Weed Management Programmes (IWMPs).

Though studies described above have evaluated phytotoxic/herbicidal potential of eucalyptus oil against weeds, yet much needs to be done as far as commercialization of this oil is concerned. There are many constraints such as: inconsistency in the amount of oil that varies with season, changing climate, species and even with age (Batish et al., 2006), volatililty of the oil and its components, lipophilicity, difficulty in plant uptake, effectivity under field conditions and toxicity towards non-target plants. Nevertheless, the oil could be a viable option to replace synthetic herbicides under sustainable organic farming practices.

8. Acaricidal activity of eucalyptus oils

Essential oils and their components can be effectively used to dispel ticks and mites, both parasitic and free-living (Yatagai, 1977; Saad et al., 2006). Eucalyptus oils rich in cineole have been shown to be effective against varroa mite, *Varroa jacobsoni*—an important parasite of honeybee (Calderone and Spivak, 1995), *Tetranychus urticae* and *Phytoseiulus persimilis* (Choi et al., 2004) and *Dermatophagoides pteronyssinus* (Saad et al., 2006). Based on their study, Choi et al. (2004) concluded that eucalyptus essential oils could be used as a natural acaricide for the control of *T. urticae*. Chagas et al. (2002) evaluated the biocidal activity of essential oils from *Eucalyptus citriodora*, *E. globulus* and *E. staigeriana* against the tick—*Boophilus microplus* and concluded that eucalyptus oils could be used as an ecologically and environmentally safer acaricide. Gardulf et al. (2004) demonstrated the Citriodiol®, a Eucalyptus essential oil based commercially available product, significantly reduced the number of tick bites in humans and concluded that it could be used to reduce tick-borne infections.

9. Nematicidal activity of eucalyptus oils

Plant-parasitic nematodes are another major group of plant pests and infest all the food crops including vegetables and cause huge economic loss due to reduced yield and unmarketable produce. As per an estimate, the annual global crop loss due to parasitic nematodes is in the order of US$ 78 billion. Eucalyptus oils have also been shown to possess nematicidal activity. Pandey et al. (2000) demonstrated that essential oil (at 250 ppm) from *E. citriodora* and *E. hybrida* was highly toxic to *Meloidogyne incognita* and inhibited the growth of root-knot nematode at 250 ppm. Salgado et al. (2003) showed that essential oils from *Eucalyptus camaldulensis*, *E. saligma*, *E. urophylla* cause mortality and hatching of second stage-juveniles (J2) of *Meloidogyne exigua* of coffee and concluded that essential oil contain nematicidal compounds. Recently, Ibrahim et al. (2006) reported that eucalyptus essential oil is toxic to the second-stage juveniles (J2s) of root-knot nematode *Meloidogyne incognita*.

10. Toxicological and commercialization concerns

As regards the toxicity of eucalyptus oils, not much is known; however, they have been categorized as GRAS by USEPA. Further, the oral and acute LD_{50} of eucalyptus oil and 1,8-cineole to rat is 4440 mg/kg bodyweight (BW) and 2480 mg/kg BW (Regnault-Roger, 1997), respectively, making it much less toxic than pyrethrins (LD_{50} values 350–500 mg/kg BW; USEPA, 1993) and even technical grade pyrethrum (LD_{50} values ~1500 mg/kg BW) (Casida and Quistad, 1995).

Since eucalyptus oils possess a wide spectrum of biological activity and are regarded as *safer compounds*, there have been attempts to commercialize and market the insecticides/repellent products containing eucalyptus oil as such or based upon them. Crude eucalyptus oil was first registered as an insecticide and miticide in US in 1948 and 29 such compounds have been registered in US till the year 2007 for use as natural insecticide/insect repellent/germicide (Kegley et al., 2007). Of these, only 4 products have been active and 25 have been cancelled (Kegley et al., 2007). These include Citriodiol®, Repel essential insect repellent lotion (2 variants), Repel essential insect repellent pump spray and Repel insect repellent 30 by the United Industrial Corp., USA (Kegley et al., 2007). In the year 2005, eucalyptus oil ranked 4th (~50 pounds) among the largely used insecticides for repelling insects from beehives (Kegley et al., 2007).

Quwenling is another *Eucalyptus*-based product that has been successfully marketed as an insect-repellent in China (Trigg, 1996a). It provides protection against *Anopheles* mosquitoes parallel to DEET (*N*,*N*-Diethyl-*meta*-toluamide) and has, in fact, replaced the widely used synthetic repelleant dimethyl phthalate. Quwenling contains a mixture of *p*-menthane-3,8-diol (PMD), citronellol and isopulegone (Trigg, 1996a). Mosiguard Natural is another eucalyptus oil based repellent that is marketed and contains 50% eucalyptus oil (Trigg and Hill, 1996). Buzz Away is another commercially available repellent based on citronellal and is marketed in China (Chou et al., 1997). MyggA® Natural is another mosquito repellent product based on PMD from lemon eucalyptus and is shown to repel ticks (Jaenson et al., 2006). In fact, lemon eucalyptus oil and PMD are two plant based insect-repellents approved by USEPA for protection against mosquitoes (USEPA, 2007). PMD is a volatile compound naturally occurring in lemon eucalyptus plants and now chemically synthesized. It has been used on human clothes and skin to repel insects such as mosquitoes, biting flies, and gnats (USEPA, 2000). It has no or very little toxicity to the environment and poses no risks to humans and animals. It has been developed and registered for use against public health pests and is available as a spray and lotion (USEPA, 2000).

Though no herbicide containing eucalyptus oil has been introduced/commercialized; yet, a natural herbicide cinmethylin based on the chemistry of 1,8-cineole, one of the major constituent monoterpenes, has been manufactured and marketed as Cinch® (Grayson et al., 1987).

The lesser number of commercialized products based on eucalyptus oil in spite of the huge scope and market for the natural pesticides is largely due to strict market regulations including actual toxicological evaluation against non-target organisms, product standardizations due to variation in quality of available plant material, intellectual property right (IPR) concerns, and regulatory approvals that limit their commercialization (Isman, 2006). Further, registration of new products involves highly expensive regulatory approval procedures that cannot be met by small profits made from the use of these pesticides in greenhouses under organic farming practices (Isman, 2006). Additionally, the issues of product refinement and standardization also limit the potential of essential oil based pesticides, because the quality of the essential oils varies with season, climate, age, geographical region, and genetic makeup of the plant (Isman, 2000, 2006).

Another drawback of these essential oils is that they volatilize quickly in the environment and do not persist for longer duration unlike synthetic pesticides. It results in their continuous reapplications to get the desired results and thus limiting their potential use as pesticides. Anyhow, their use is likely to be more effective under long-term basis since insect pests have developed resistance against synthetic pesticides. Rather, the essential oils have been found useful against those species of pests, which are resistant towards synthetic pesticides. Moreover, since these essential oils are a complex mixture of components including minor constituents, in contrast to synthetic pesticides based on single products, they act synergistically within plant as a defense strategy, it is likely that they are more durable towards evolving pest resistance (Feng and Isman, 1995). However, due to their largely environment friendly nature, they can be efficiently used for pest management in urban areas, homes and other sensitive areas such as schools, restaurants and hospitals (Isman, 2006). More so, the real benefit of these natural pesticides could be harnessed by the farmers in developing countries who cannot afford costly synthetic pesticides and those involved in organic farming and greenhouse production systems (Isman, 2006).

11. Conclusions and way forward

From the above discussion, it is clear that eucalyptus essential oils possess a wide spectrum of biological activity against fungi, bacteria, insects, mites, and weeds and provides a simple, inexpensive, and environment friendly (non-polluting and lesser or no toxicological concerns) alternative pest control. Since eucalyptus oils have a strong toxicity in the vapour form against a wide range of microbes and insects, they could be commercially exploited as a fumigant for stored products and also impregnated into packaging thus preventing the insect infestation. However, the effects on other non-target microorganisms including pollinators, honeybees and natural predators/enemies have not been yet evaluated. Further, experiments are needed to evaluate its economic aspects and activity under field conditions. The volatility and water-insolubility renders the utilization of eucalyptus oils to control nematodes, soil-borne pathogens and weeds under field conditions less appealing. However, it could be overcome by emulsifying the oil with the help of surfactants or using adjuvants for better plant adsorption and improving efficiency.

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