0971-4693/94 US $ 5.00
Allelopathy Journal 25 (2): 313-330 (2010) *International Allelopathy Foundation* 2010
Tables: 5, Fig : -

Chemistry and bioactivity of Eucalyptus essential oils

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(Received in revised form: November 23, 2009)

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ABSTRACT

The essential oils obtained from the eucalyptus have many medicinal and commercial uses. The oils possess many bioactivities (antimicrobial, antiviral, fungicidal, insecticidal and herbicidal activities). The commercial uses of essential oils have increased the research on their extraction, chemical composition, bioactivity and mode of actions. Eucalyptus species differs in their chemical composition. The bioactivity of essential oils is highly associated with their unique chemical composition. The novel biological functions of eucalyptus essential oils suggest research on all eucalyptus species to fully exploit their commercial benefits. This review, discusses the recent progresses in above research areas and future research prospects.

Keyword: Allelopathy, bioactivity, chemical composition, essential oils, eucalyptus.

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1. INTRODUCTION

Eucalyptus (family *Myrtaceae*) is native to Australia, however, its few species are indigenous to neighbouring countries (30). It grows over wide range of soils and climates, hence, has been introduced into North and South Africa, Asia and Southern Europe (3). The interspecific hybrids are grown in Brazil, Congo, China, Indonesia and South Africa and small plantations in Phillippines, Vietnam, Thailand and Malaysia and South Americas (Argentina, Chile, Paraguay and Uruguay) (35). There are approximately 700 species worldwide and only about 1% are used for industrial purposes (76). Its timber is now used for fuel, shelterbelts, windbreaks and for hardwood fibre (86).

Its essential oils have many medicinal and commercial uses (47). They can be used as folk medicine and are anesthetic, anodyne, antiperiodic, antiphlogistic, antiseptic, astringent, deodorant, diaphoretic, disinfectant, expectorant, febrifuge, fumigant, hemostat, inhalant, insect repellant, preventitive, rubefacient, sedative yet stimulant, suppurative, tonic, and vermifuge (34). Its 9-species are used for medicinal and commercial purposes (Table 1). Besides, *E. cinerea* and *E. cneorifolia* also possess medicinal value and *E. macarthurii* in perfumery.

Table 1. Cultivated Eucalyptus species

Uses	Species	Country
Medicinal	*Eucalyptus globulus* Labill.	China, Portugal, Spain, India, Brazil, Chile,Bolivia, Uruguay, Paraguay
	E. smithii R. Baker	South Africa, Swaziland, Zimbabwe
	E. polybractea R. Baker (syn. *E. fruticetorum* F. Muell. ex Miq.)	Australia
	E. exserta F. Muell.	China
	E. radiata Sieber ex DC. (syn. *E. australiana, E. radiata var. australiana)*	South Africa, Australia
	E. dives Schauer	Australia
	E. camaldulensis Dehnh. (syn. *E. rostrata* Schldl.)	Nepal
Perfumery	*E. citriodora* Hook.	China, Brazil, India
	E. staigeriana F. Muell. ex Bailey	Brazil

Source : 38

Growth inhibition of plants by other plants in their vicinity has been known for a long time. The chemical interaction between plants is referred to as allelopathy (80). Intensive allelopathy research has been conducted in recent decades and progress has made in analysis and identification of allelochemicals (10,37,42,51,84,116). The rapid advances in the identification of bioactive allelochemicals in eucalyptus oils have prompted research into potential natural herbicidal compounds for weed management in agriculture (16,17,81).

Owing to the wide range of traditional uses and potential commercial prospects of eucalyptus oils, extensive research on yield and chemical composition of oils has been undertaken, as well as development of extraction and analytical techniques. This paper reviews the progress on isolation, identification, bioactivity and mode of actions of essential eucalyptus oils.

2. ESSENTIAL OIL CHEMISTRY

2.1. Extraction methods

Essential oils are secondary metabolites produced by plants in response to stress, infection or parasitic attack. Eucalyptus oils are volatile organic compounds found in fruits, flowers, bark, seeds, wood and roots. However, they are mainly extracted from leaves (3,20). There are 5-extraction methods (11,19,43,45,82,90) :

(i). **Hydrodistillation:** It involves placing plant material and water in a container and heating from below. The heat releases the aromatic vapour, which is condensed into liquid containing little hydrosol (water). Total oil yield increases with increase in distillation time, but the principle component (%) reduces accordingly (11).
(ii). **Steam distillation:** It involves placing the plant material in a flask and forcing steam through the plant material to vaporize the volatile oils. It is similar to hydrodistillation, but higher oil yield is obtained (90).

(iii). **Vacuum distillation:** To extract essential oils from many eucalyptus species, vacuum distillation is done at lower temperatures, avoiding the change in essential oil chemical composition during distillation(19).

(iv). **Supercritical fluid extraction (SFE):** It uses the ability of certain gases (generally CO_2 is used) to act as non-polar solvents at certain temperature and pressure. It is more efficient and faster than hydrodistillation (82).

(v). **Subcritical-water extraction (SWE):** It uses hot water (100-374^{o}C) as extractant and high pressure. It is faster and efficient than hydrodistillation (45). The advantages are shorter extraction time, high quality of extract, lower costs of extracting agent and environmental friendly (43).

2.2. Essential oils Yields

The yields of eucalyptus oils from leaves depends on the species studied and varies from 0.10 to 9.0 % on dry weight basis (Table 2). Several factors affect the eucalyptus oils yields: tree age (5), leaf age (39,96), altitude (62), season (77), harvest time (32) and fertilizer application (61). Young leaves contains more oil than old leaves (39), while leaves from older trees gave slightly higher yield (5). However, oil production is more influenced by altitude than age (62). Oil content also fluctuates with season. *E. citriodora* leaves collected in Pakistan in April-May contained 0.9% oil than 1.3% in December (77). Good eucalyptus oil yields in central Thailand were obtained between January to July (32). Application of nitrogen, phosphorus and potassium fertilizers increased the production of essential oils (61).

Table 2. Yields of eucalyptus essential oils

Species	Yield [a] (%)	Reference
E. bakeri	1.8-3	22
E. brachycorys, E. crucis	0.75-3.75	19
E. caesia	0.97	7
E. camaldulensis	0.39 [b]	113
E. camaldulensis	0.25-0.46	39
E. cinerea	1.2-2.3	39
E. citriodora	0.6	16
E. citriodora	0.9-1.3	77
E. crebra	0.29-1.33	3
E. dunnii	3.67	112
E. globulus	1.3-2.7 [b]	96
E. grandis	0.36% [b]	113
E. microtheca, E. spahulata	0.38-1.88	88
E. nitens, E. denticulata	0.7-0.8	54
E. porosa	0.57	6
E. propinqua, E. pulverulenta	0.22-3.56	120
E. radiata ssp. *robertsonii*	6.7-8.4	97
E. radiate ssp. *radiata, E. smithii*	6.0-9.0	28
E. remophil, E. oleosa, E. patellaris, E. ranscontienalis, E. salubris	0.1-5.3	36
E. tereticornis	1.57-2.09	94
E. viminalis	0.5-1.2	39

[a]Dry weight basis; [b]Fresh weight basis.

2.3. Chemical composition

The oil composition of different eucalyptus species has been reviewed till 1998 (30). This current review collates the research advances from 1999 (Table 3). The number of components identified and main components in essential oils from different eucalyptus species are presented in increasing order of 1,8-cineole content. The main components are monoterpenes (1,8-cineole, *p*-cymene, citronellal, citronellol, limonene, α-phellandrene, β-phellandrene, α-pinene, β-pinene, *trans*-pinocarveol, terpinolene, α-terpineol, α-thujene) and sesquiterpenes (β-caryophyllene, β-eudesmol, globulol, spathulenol and virdiflorol).

The chemical profile and main components of oils from eucalyptus leaves varied significantly between species (88,120). For example, the main components of *E. largiflorens* oil were 1,8-cineole (37.5%), *p*-cymene (17.4%), *neo*-isoverbenol (9.1%), limonene (6.5%) and spathulenol (6.7%), while those of *E. spathulata* oil were 1,8-cineole (72.5%), α-pinene (12.7%) and *trans*-pinocarveol (3.3%), with the absence of *neo*-isoverbenol, limonene and spathulenol or at lower amounts (88). The monoterpenes, 1,8-cineole and α-pinene, are the main components in most species, while, *E. citriodora* is rich in citronellal (49.5-87%) and citronellol (8-20%). The content of 1,8-cineole in eucalyptus oils ranges from 10-90%. Generally, the content of α-pinene is below 20%. The composition of eucalyptus oils differs even between the trees of same species in different periods, sites (25) and extraction method/time (11,90).

Table 3. Chemical composition of eucalyptus essential oils

Species	Number of components	Major components (% of total essential oils)						Other components (%)	Reference
		1,8-Cineole	α-Pinene	*p*-Cymene	Limonene	Citronellal	α-Thujene		
E. kochii	63	92.3	0.6	0.9	0.9			α-Terpineol (0.6)	115
E. horistes	63	90.2	1.8	1.0	1.6			α-Terpineol (0.7)	115
E. cinerea	83	87.8	5.2	1.2	0.5				120
E. polybracteata	63	87.3	1.5	1.4	2.1			β-Pinene (0.7), α-terpineol (0.6)	115
E. baueriana	83	87.1		4.1	0.3				120
E. amaldulensis	5	85.7							68
E. leucoxylon	7	85.5							89
E. smithii	83	83.2	4.7	0.9	2.3				120
E. bridgesiana	83	82.6	5.2	2.1	3.0				120
E. intertexta	10	80.6							89
E. microtheca	83	80.3	9.4	3.6	0.9				120
E. foecunda	83	75.5	17.3	0.9	3.1				120
E. sargentii	17	75.5	8.3					β-Eudesmol (4.1)	89
E. pulverulenta	83	75.1	4.6	2.0	2.1			α-Copane (4.8)	120
E. globulus	15	74.8	6.3		5.7				11
E. stricklandii	17	71.2	9.2						2
E. spathulata	21	72.5	12.7					*trans*-Pinocarveol (3.3)	88
E. tricklandii	17	71.2	9.2						2
E. caesia	21	69.4	9.3					*trans*-Pinocarveole (2.4), caryophyllene (6.1), globulol (2.8)	7
E. propincua	83	67.5	2.4	16.1	3.2			*trans*-Pinocarveole (2.2)	120
E. loxophleba	63	64.9	13.0	1.3	3.2			4-Methyl-2-pentyl acetate (6.1), α-terpineol (1.2)	115
E. kruseana	15	63.3	5.9					α-Phellandrene (0.6-8.0)	2
E. porosa		58.6	12.8					Nopinone (3.11)	6
E. sargentii	16	56.7	4.9					β-Eudesmol (6.0)	2
E. crebra		11.9-43.8	1.6-18.2		2.7			α-Phellandrene (0.6-8.0), careen (1.3-5.6), β-pinene (0.5-2.1)	18
E. platypus	18	41.5	26						89
E. largiflorens	15	41.3						Spathulenol (11.6), viridiflorol (15.9)	2
E. largiflorens	26	37.5		17.4	6.5			*neo*-Isoverbenol (9.1), spathulenol (6.7%)	88

Table 3. Contd.

Species	Number of components	Major components (% of total essential oils)						Other components (%)	Reference
		1,8-Cineole	α-Pinene	*p*-Cymene	Limonene	Citronellal	α-Thujene		
E. microtheca	13	35.2							68
E. microtheca	22	34	10.7	12.4				β-Pinene (10.5)	88
E. camaldulensis	62	29.6	9.7		15.2			Terpinolene (3.0), β-pinene (9.9)	106
E. camaldulensis	24	26.1	12.6	14.4				Spathulenol (13.2), β-phellandrene (9.2)	89
E. grandis	65	19.8	11.4	2.1	4.7			α-Terpinyl acetate (12.8), α-terpineol (5.0)	106
E. brockwayi	25	17.8	14.0					*trans*-Pinocarveole (12), β-pinene (7.5), *rho*-cymene (5.3)	2
E. urophylla	51	13.9	1.8	22.3				γ-Terpinene(26.2)	106
E. alba	32	13.3	0.7	12.9			32.9	β-Caryophyllene (7.8%), α-terpineol (2.6%), spathulenol (1.8%), caryophyllenoxide (1.8%)	71
E. saligna	25	12.2		0.6	4.8		63.8	α-Terpineol (3.6%), terpinolene (2.7)	71
E. citriodora	35	1.9	1.3			49.5		Citronellol (11.9), β-pinene (2.2)	106
E. citriodora	6					67-87		Citronellol (8-20), isopulegol (1.6-3.3)	25
E. citriodora	17					52.2		Citronellol (12.3), isoisopulegol (11.9)	16
E. decaisneana	49		2.2	20.8	2.8			α-Phellandrene (31.1), γ-terpinene (11.7)	67

3. ESSENTIAL OIL BIOACTIVITY

Eucalyptus essential oil has range of bioactivity [antimicrobial (53,56,107), antiviral (26), fungicidal (92,93), insecticidal (57,63), anti-inflammatory (95), antinociceptive activity (55), antioxidant capacity (104,119) and phytotoxic (91) activity] (Tables 4,5).

3.1. Bioactivity on organisms

3.1.1. **Antimicrobial activity**: Sumitra and Sharma (107) reported that *E. teriticornis* essential oils had antibacterial activity against six bacteria (*Staphylococcus aureus, Bacillus cereus, Escherichia coli, Micrococcus luteus, Proteus mirabilis* and *Alcaligenes faecalis*). Cermelli *et al.* (26) showed that *Haemophilus influenzae, Haemophilus parainfluenzae* and *Stenotrophomonas maltophilia* were the most susceptible to *E. globulus* essential oils, followed by *Streptococcus pneumoniae* and *Streptococcus agalactiae*. The highest activity was found at 1.25µl ml^{-1} for *H. influenzae, H. parainfluenzae* and *S. maltophilia*. Antiviral activity assays using virus yield experiments indicated mild activity on the mumps virus (26).

3.1.2. Antifungal activity: *E. citriodora* essential oil is effective against *Microsporum nanum*, *Trichophyton mentagrophytes* and *Trichophyton rubrum* (93). Pure oil controlled *M. nanum* in 20 s and *T. mentagrophytes* and *T. rubrum* in only 15 s. It was more effective than prevalent synthetic antifungal drugs (Dactrine, Nizral and Tenaderm) without any adverse side effects on mammalian skin up to 5% concentration. *E. citriodora* oil has also clinical value in dermatophytoses, when used as a broad spectrum antimycotic ointment. *E. robusta, E. rostrata, E. camaldulensis, E. tereticornis, E. globulus* and *E. citriodora* oils are antibacterial (66,83) and antifungal (53,56,103).

3.1.3. Insecticidal activity: *E. globulus* essential oil has high insecticidal activity against *Aphis gossypii* (63). *E. grandis* and *E. globulus* oils are resistant to termite followed by *E. citriodora* and *E. urophylla* oils (57).

3.1.4. Antioxidant: Eucalyptus oils also antioxidant, due to the presence of phenolic compounds (104,119) and their radical scavenging properties (119). They can also trigger a series of induced chemical defence responses (21,110).

3.2. Bioactivity on weeds and crops

Volatile allelochemicals derived from eucalyptus oils also have herbicidal activity against many weed species (13,16,17,79,91). Volatile essential oils from *E. citriodora* was phytotoxic to *Bidens pilosa, Amaranthus viridis, Rumex nepalensis* and *Leucaena leucocephala*, with no germination occurring at 0.06% eucalypt oil concentration under laboratory conditions (91). Essential oils from *E. nicholii* strongly inhibited the germination of *Amaranthus retroflexus, Portulaca oleracea* and *Acroptilon repens* (79).

Table 4. Bioactivity of eucalyptus essential oils on organisms

Species	Bioactivity	Reference
A. Antimicrobial activity		
E. camaldulensis, E. tereticornis	Antimicrobial activity	27
E. citriodora	Antibacterial activity against *Escherichia coli, Staphylococcus aureus, Proteus mirabilis, Pseudomonas aeruginosa, Proteus vulgaris*.	66
E. citriodora	Antimicrobial activity against *Trichophyton rubrum, Histoplasma capsulatum, Candida albicans, E.coli and Mycobacterium smegmatis*	60
E. globulus	Antimicrobial activity against *S. aureus, E. coli*	4
E. maidenii	Antimicrobial activity against 12 bacteria	41
E. robusta, E. saligna	Antimicrobial activity against *S. aureus, E. coli and C. albicans*	83
E. teriticornis	Antibacterial activity against *S. aureus, Bacillus cereus, E. coli, Micrococcus luteus, P. mirabilis* and *Alcaligenes faecalis*	107
E. globulus	Antiviral activity	26
B. Antifungal activity		
E. camaldulensis, E. tereticornis	Antifungal activity	27
E. citriodora	Antifungal effects against mildew and wood decay fungi	106
E. dalrympleana	Antifungal agent against *Epidermophyton floccosum, Microsporum gypseum* and *T. rubrum*	92
E. globulus	Antifungal effects against three *Candida* species	56
E. rostrata, E. camaldulensis	Fungitoxic properties against four human pathogens: *Trichophyton mentagrophytes, Epidermophyton floccosum* and *Microsporum canis*	103
C. Insecticidal activity		
E. globulus	Insecticidal activity against *Aphis gossypii* adults	63
E. globulus	Fumigant toxicities	53
E. globulus, E. citriodora	Repellent effects against adults *Apriona germarii, Psacothea hilaris* and *Monochamus alternatus*	117
E. grandis	Larvicidal activity	59
E. saligna	Repellent effects against *Sitophilus zeamais* and *Tribolium confusum*	111
E. urophylla, E. citriodora	Antitermite activity	57
D. Antioxidant		
E. camaldulensis	Antioxidative activities	104
E. staigeriana	Antioxidant capacity	119
D. Others		
E. camaldulensis	Antinociceptive properties	55
E. citriodora, E. tereticornis, E. globulus	Anti-inflammatory and analgesic effects	95
E. tereticornis	Relaxant effects on guinea-pig tracheal smooth muscle	29

Table 5. Biological activity of eucalyptus essential oils on plants

Eucalyptus species	Bioactivity	Reference
Crops		
E. camaldulensis	Growth inhibition against *Allium cepa, Spinacia oleracea, Lepidium sativa, Zea mays* and *Lycopersicon esculentum*	64
E. citriodora	Phytotoxicity against crops (*Triticum aestivum* and *Oryza sativa*)	17
E. exserta, E. urophylla	Growth inhibition against *Raphanus sativus* and *Lactuca sativa*	118
Weeds		
E. camaldulensis	Growth inhibition against *Echinochloa crus-galli, Avena fatua* and *Rumex acetosella.*	64
E. citriodora	Inhibition on germination and growth against *Cassia occidentalis* and *E. crus-galli*	16
E. citriodora	Phytotoxicity against weeds (A*maranthus viridis* and *E. crus-galli*)	17
E. citriodora	Herbicidal activity against *Anagallis arvensis, Chenopodium album* and *Spergula arvensis*	65
E. citriodora	Herbicidal activity against *Bidens pilosa, A. viridis, Rumex nepalensis* and *Leucaena leucocephala*	91
E. citriodora	Germination inhibition in *Parthenium hysterophorus*	100
E. globulus	Germination inhibition in *Amaranthus retroflexus* and *Portulaca oleraceae*	9
E. globulus	Germination inhibition in *P. hysterophorus*	49
E. nicholii	Herbicidal activity against *A. retroflexus, P. oleracea* and *Acroptilon repens*	79

The eucalyptus oils are also herbicidal against *Parthenium hysterophorus*, *Cassia occidentalis*, *Echinochloa crus-galli* and *A. viridis* (16,17,100). Thus compounds in eucalyptus oils have potential for further use as natural herbicides.

However, the phytotoxic activity of eucalyptus oils can also cause damage to some crops (64,118). Batish *et al.* (13,17) found that eucalyptus oils from *E. citriodora* not only inhibited weed (*A. viridis and E. crus-galli)* growth, but also caused injuries to wheat (*Triticum aestivum),* maize (*Zea mays*), radish (*Raphanus sativus*) and rice (*Oryza sativa*). It is therefore critical to maximise the herbicidal activity of eucalyptus oils against weeds but at the same time to minimise the negative impact of crop growth.

3.3. Mechanism of oil bioactivity

Antibacterial and antifungal compounds may target various cell structures or chemical pathways, such as cell wall degradation, membrane damage, dissipation of the proton motive force, decrease in extracellular protease activity, o-lipopolysaccharide rhamnose content, ergosterol content or unsaturated fatty acids (23,44,72,73). However, research data are very limited on the mechanism of antimicrobial and antifungal activity of eucalyptus oils. The mode of actions of essential oils and chemical compounds from other plant species may assist the understanding of the possible mechanism involved in eucalyptus oil bioactivity.

Cox *et al.* (31) reported that tea tree (*Melaleuca alternifolia*) essential oils inhibited the growth of *E. coli* through reduction in glucose-dependent respiration and enhanced leakage of intracellular K^+. Cytoplasmic membrane damage was reported in *S. aureus* after treatment with tea tree oil or its main monoterpene components, leading to lysis, the loss of 260-nm-absorbing material and the loss of tolerance to NaCl (24). It was shown that the oils of *E. citriodora* exerted its antimicrobial activity through the synergistic action of citronellal and citronellol (58).

The antifungal mechanism of *Thymus spp.* essential oils against yeasts and filamentous fungi was identified due to the inhibition of germ tube formation (74), with additional impairment of ergosterol biosynthesis in some strains (75). Rapid propidium iodide (PI) penetration into cells detected by flow cytometry assays indicates that the fungicidal effect is through primary cell membrane damage rather than secondary membrane damage caused by metabolic impairment. The biochemical nature of the monoterpenes suggests they probably act as a solvent of the cell membrane. The major components of *Thymus spp.* essential oils such as carvacrol, thymol and *p*-cymene exhibited similar fungicidal activity against *Candida* species with synergistic effects noted for thymol/*p*-cymene and thymol/1,8-cineole mixtures (74). The synergism helps explain the differences in bioactivity between essential oils and their pure major compounds.

The bioactivity mechanism of eucalyptus oils on plants reduces cell survival, chlorophyll content, RNA contents, acid soluble carbohydrate and water soluble carbohydrate (50). Moradshahi *et al.* (64) found that the presence of different concentrations of crude volatile oils from *E. camaldulensis* decreased the mitotic index in the root apical meristem of *Allium cepa*, affected the Hill reaction in isolated spinach (*Spinacia oleracea*) chloroplast and reduced peroxidase activity in *Lepidium sativa, E. crus-galli, Avena fatua, Rumex acetosella, Z. mays* and *Lycopersicon esculentum*. Under laboratory conditions, volatile oils from lemon-scented eucalypt (*E. citriodora*) decreased weed emergence and earlier seedling growth by severely inhibiting photosynthetesis and respiration at 0.06% (93) and 0.07% (15) concentration levels. Rapid electrolyte leakage in the leaf tissue suggested that the mode of actions of the eucalyptus oils is a result of the disruption of membrane integrity (15). α-Pinene, one of the common monoterpenoids from eucalyptus oils, has been regarded as a key compound contributing to the disruption effect (102). From these studies, it can be concluded that eucalyptus species suppress the growth of other plant species by affecting several biochemical and physiological processes.

4. RELATIONSHIP BETWEEN BIOACTIVITY AND CHEMICAL COMPONENTS

Progress has been made toward better understanding of relationship between the observed biological activity and the key bioactive chemical components of eucalyptus oils. Major compounds, such as 1,8-cineole, α-pinene, β-pinene, *p*-cymene, limonene, citronellal and citronellol are principle bioactive compounds in essential oils.

Sartorelli *et al.* (83) reported that *E. robusta* oil is more active than *E. saligna* oil against both *E. coli* and *S. aureus* due to the higher concentrations of the monoterpenes α-pinene, β-pinene and limonene. Pure solutions of 1,8-cineole and α-pinene are bioactive against *Pseudomonas tolaasii*, exhibiting bacteriostatic activity at 7.0 $\mu l\ ml^{-1}$ and bactericidal activity at 10.0 $\mu l\ ml^{-1}$ (105). Antibacterial activity of citronellal and citronellol suggest that most monoterpenes in eucalyptus oils are antibacterial (85,87). The relationship between the chemical composition and antifungal activity has also been documented. Su *et al.* (106) reported that the chemical components and antifungal activities varied significantly among *E. urophylla, E. grandis, E. camaldulensis,* and *E. citriodora*, with *E. citriodora* the most effective for controlling mildrew. *E. urophylla*, on the other hand, was least effective, suggesting that antifungal activity is associated with citronellal and citronellol, two major compounds in the essential oils of *E. citriodora*. This conclusion was supported by antifungal tests using the pure citronellal and citronellol compounds (46).

Antitermite properties of eucalyptus oils are conferred by monoterpene α-pinene, followed by monoterpenes *p*-cymene and 1,8-cineole, while the other components in the oils were less effective (57). α-Pinene has stronger larvicidal activity than pure 1,8-cineole, suggesting that α-pinene is a principal larvicidal component of *E. grandis* essential oils (59).

The phytotoxic and herbicidal activities of eucalyptus oils are highly related to chemical composition of essential oils, with *E. citriodora* essential oils being strongly phytotoxic (13,65,100). The monoterpenes (citronellal, citronellol, 1,8-cineole and α-pinene) inhibited the germination and initial seedling growth of *C. occidentalis*, *A. conyzoides, E. crus-galli*, *Cassia obtusifolia* and *Z. mays* (1,81,98,99,102). Singh *et al.* (101) assessed the phytotoxicity of citronellal against *Ageratum conyzoides*, *Chenopodium album*, *P. hysterophorus*, *Malvastrum coromandelianum*, *C. occidentalis* and *Phalaris minor*. Emergence of *A. conyzoides* and *P. hysterophorus* was inhibited by citronellal at a concentration of 50 µg g^{-1} (sand) and the weed emergence and early seedling growth of other species were completely inhibited at 100 µg g^{-1}.

The bioassay results suggest that the bioactivity of eucalyptus oils may be due to their monoterpene components. However, essential oils are a complex chemical mixture and they possess higher activities than their individual components (52). Therefore, total bioactivity of essential oils may be due to the combined effects of several minor components or the synergistic effect of essential oil components (12,52).

5. APPLICATIONS OF EUCALYPTUS ESSENTIAL OILS

Eucalyptus essential oils are widely used in many industries and mainly in therapeutic natural medicine (108).

Eucalyptus is a traditional medicinal plant to treat cold, flue, fever, diabetics and bronchial infections (70,92,95) or to prevent and control other pathogenic diseases (4,109). Eucalyptus oil based products are used as topically applied medication to relieve muscular pain and as solvent/sealer in dentistry (3) and as disinfectant (38). The bioactive components identified from eucalyptus essential oils may develop new classes of analgesic and anti-inflammatory drugs (95).

Similarly, the insecticidal activity of eucalyptus oils could provide opportunities for new biodegradable products for pest control. The oil is used as an insect repellent since 1948 (48) and now many commercial repellents are available in US and China (14). A commercial mosquito repellent has also been developed from *p*-manthane-3,8-diol isolated from *E. citriodora* (14). Kegley *et al.* (48) has reported that eucalyptus oil based products ranked 4th amongst the insecticides used for repelling insects from beehives.

The widespread use of synthetic herbicides has resulted in the rapid evolution of herbicides-resistant weeds and increasing public concern over the impact of synthetic herbicides on human health and the environment (114). Alternative weed management options based on natural products are being sought (33), with essential oils from plants receiving much attention due to their ready availability and low cost (8,33). A commercial herbicide with the active ingredient cinmethylin, has been developed based on the natural chemistry of 1,8-cineole, the major monoterpene in eucalyptus essential oils (40). A myriad of compounds are present in eucalyptus essential oils and determination of their chemical structure and bioactivity may provide novel leads for development of herbicides with new modes of action.

Eucalyptus oils are widely used in fragrance industry (soaps, detergents, creams, lotion, deodorizer, perfumes) and as flavouring agents in food industry (38,69,78). Eucalyptus oils are also used as a flotation agent in the mining industry (3) and as a source of citronellal for the chemical industry (38).

6. CONCLUSIONS

Eucalyptus essential oils are gaining increasing interest due to their varied commercial applications particularly as insect repellents, fragrants and traditional medicines. Despite the commercial prospects, till now only limited eucalyptus species have been studied. Considering that the chemical composition of eucalyptus oils and its associated biological activities varies significantly between species, other species deserves further attention. It should be emphasized that the research into eucalyptus oil chemistry may lead to the development of natural pesticides with new mode of actions.

The relationship between the bioactivity and chemical composition has been reported, yet information on the mode of actions of eucalyptus oils is limited. Modern molecular and biochemical approaches have provided excellent research tools to facilitate the study of mechanisms of action and the biosynthesis of essential oils.

Progress has been made in identification of genes responsible for essential oil biosynthesis in peppermint (*Mentha piperita*), with subsequent metabolic engineering significantly altering essential oil composition and yield. This success in genetic manipulation of essential oil biosynthesis in peppermint suggests similar improvements in eucalyptus essential oil production may be possible. An extensive review on the advances in genetic transformation of eucalypts indicates that significant progress has already been made into understanding eucalyptus genetics. Quantitative trait loci associated with essential oil biosynthesis in *E. grandis* × *E. urophylla* hybrids have already been identified. Future modification of eucalyptus essential oil biosynthesis will require close collaboration between plant biologists, biochemists and molecular biologists as well as plant breeders to develop products for new applications.

ACKNOWLEDGEMENTS

Authors acknowledge the funding support from Meat and Livestock of Australia.

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