Green Pesticides Handbook
Essential Oils for Pest Control
Leo M.L. Nollet, Hamir Singh Rathore

Sandalwood Oil (Santalum album L.): Source of a Botanical Pesticide—Present Status and Potential Prospects

Publication details
https://www.routledgehandbooks.com/doi/10.1201/9781315153131-11
Somnath Roy, Gautam Handique, Ranjida Ahmed, N. Muraleedharan
Published online on: 30 May 2017

11

Sandalwood Oil (*Santalum album* L.): Source of a Botanical Pesticide—Present Status and Potential Prospects

Somnath Roy, Gautam Handique, Ranjida Ahmed, and N. Muraleedharan

CONTENTS

11.1 Introduction

Plant essential oils are naturally occurring volatile components primarily derived from the seeds, stems, bark, and roots of many plants that have been in use for thousands of years in various civilizations for medicinal and health purposes (Jones, 1996). The versatile role of these essential oils ranges from personal beauty care and household cleaning products, aromatherapy, and natural drugs, which comes from the antimicrobial, anti-inflammatory, and antioxidant properties present in them (Anonymous, 2016). These oils are usually present in glandular hairs or secretory cavities of the plant cell wall and as fluid droplets in the bark, flowers, leaves, stems, roots, and/or fruits of diverse plants. The aromatic properties of essential oils execute various functions for the plants, which include attracting or deterring insects, protecting themselves from heat or cold, and utilizing some chemical constituents such as monoterpenes, sesquiterpenes, and phenolics (Bhalla et al., 2013) of the oil as defense materials (Koul et al., 2008).

TABLE 11.1

Geographical Distribution and General Uses of *Santalum* L. (Santalaceae)

Serial No.	Scientific Name	Geographical Distribution	General Uses	Reference
1	*S. album* L.	India, United States, Japan, Germany, Indonesia, France	Flavor component; fragrance; anti-inflammatory, antipyretic, antiulcerogenic, antifungal, antiviral, antibacterial, antioxidant, antispasmodic (muscle relaxant), astringent, diuretic, and anticancerous activities; neuroleptic	Rani et al., 2013; Burdock and Carabin, 2008; Okugawa et al., 1995; Koch et al., 2008; McKinnel, 1990; Baldovini et al., 2010
2	*S. freycinetianum* Gaudich	Sri Lanka, Hawaiian Islands	Perfume, medicinal	Subasinghe et al., 2013; Merlin et al., 2006
3	*S. haleakalae* Hillebr	Sri Lanka	Perfume, medicinal	Subasinghe et al., 2013
4	*S. ellipticum* Gaudich	Sri Lanka, Hawaiian Islands	Perfume, medicinal	Subasinghe et al., 2013; Merlin et al., 2006
5	*S. peniculam* Hook. & Arn.	Sri Lanka	Perfume, medicinal	Subasinghe et al., 2013
6	*S. pyrularium* A. Gray.	Sri Lanka	Perfume, medicinal	Subasinghe et al., 2013
7	*S. involutum* St. John	Sri Lanka	Perfume, medicinal	Subasinghe et al., 2013
8	*S. boniness* (Nakai) Tuyama	Sri Lanka	Perfume, medicinal	Subasinghe et al., 2013
9	*S. insulare* Bertero ex A.DC.	Sri Lanka, France	Perfume, medicinal	Subasinghe et al., 2013; Baldovini et al., 2010
10	*S. austrocaledonicum* Viell.	Sri Lanka, New Caledonia, Vanuatu, France, Fiji	Perfume, medicinal	Subasinghe et al., 2013; McKinnel, 1990; Baldovini et al., 2010; Thomson et al., 2011
11	*S. minutum* N. Halle	Fiji	Perfume, medicinal	Thomson et al., 2011
12	*S. pilosulum* N. Halle	Fiji	Perfume, medicinal	Thomson et al., 2011
13	*S. yasi* Seem.	Sri Lanka, Fiji	Perfume, medicinal	Subasinghe et al., 2013; McKinnel, 1990; Thomson et al., 2011; Huish et al., 2015
14	*S. macgregorii* F. Muell	Sri Lanka, New Guinea	Perfume, medicinal	Subasinghe et al., 2013; McKinnel, 1990
15	*S. obtusifolium* R. Br.	Sri Lanka	Perfume, medicinal	Subasinghe et al., 2013
16	*S. lanceolatum* R. Br.	Australia, Sri Lanka	Perfume, medicinal	McKinnel, 1990; Subasinghe et al., 2013
17	*S. fernanderzianum* F. Phil.	Sri Lanka	Perfume, medicinal	Subasinghe et al., 2013
18	*S. salicifolium* Meurisse	Sri Lanka	Perfume, medicinal	Subasinghe et al., 2013
19	*S. spicatum* (R. Br.) A.DC.	Australia, Sri Lanka, France	Perfume, medicinal	McKinnel, 1990; Subasinghe et al., 2013; Baldovini et al., 2010
20	*S. acuminatum* (R. Br.) A.DC.	Australia	Perfume, medicinal	McKinnel, 1990
21	*S. murrayanum* (T. Mitch) C.A. Gardner	Australia	Perfume, medicinal	McKinnel, 1990

Among the commercially viable essential oils, sandalwood oil is largely used for a variety of purposes. The oil is derived from the genus *Santalum* of the Santalaceae family, which is hemiparasitic in character that includes 15 extant species with approximately 14 varieties, and 1 extinct species, spread all throughout India, Australia, and the Pacific Islands (Table 11.1) to as far as the Juan Fernandez Islands, 600 miles off the coast of Chile, to the northwest of the Bonin Islands, 600 miles south of Honshu province, Japan (van Balgooy, 1960, 1971; van Balgooy et al., 1996).

11.2 Botany of the Plant

Santalum album (East Indian sandalwood or sandal) is a small evergreen plant that can grow up to a height of 4 m in Australia, while in India, it can grow up to 20 m with girth diameter of around 2.4 m and lean, flabby branchlets. The bark may be dark brown, reddish, dark gray, or nearly black; tight, smooth in young trees; and rough with deep vertical cracks in older trees, having a reddish color from within. Leaves are thin, usually opposite, ovate or ovate elliptical, 3–8 to 3–5 cm, glabrous and shining green above, glaucous and slightly paler beneath; tip rounded or pointed; stalk grooved, 5–15 cm long; venation noticeably reticulate. Flowers are small; purplish-brown, straw colored, reddish, green, or violet; about 4–6 mm long; up to six small terminal or axillary clusters, unscented in axillary or terminal; paniculate cymes. Fruit is a globose, fleshy drupe; red, purple to black when ripe; about 1 cm in diameter, with hard ribbed endocarp and crowned with a scar; almost stalkless; smooth; single seeded (Sindhu et al., 2010). The generic name is derived from the Greek *santalon*, meaning "sandalwood," and the species name from the Latin *albus*, meaning "white," alluding to the bark.

S. album forms haustoria root connections with the roots of a wide range of species, including annual and perennial crops (Tennakoon et al., 1997; Tennakoon and Cameron, 2006), and is renowned for its fragrant heartwood (Shea et al., 1997). In general, *S. album* is a small to medium-sized tree that grows to 8–12 m in height and 2.5 m in girth. The tree has many slender drooping branches, and the bark is smooth gray-brown, thinly furrowed, semicoarse. The bark and sapwood are odorless, and the roots and heartwood contain the essential oil (Kirtikar and Basu, 1993). The flowers are small with numerous short stalks (Grieve, 1971). The form of the crown is flat or a dome. It has an inflorescence terminal or axillary panicle or raceme. Flowers are unisexual or hermaphrodite, small, white or yellowish, 4(-5)-merous; the perianth tube is campanulate. Flowering starts at 3–4 year-old plants (Prasetyaningtyas, 2007). Benencia and Courreges (1999) report that the heartwood is yellowish brown and strongly scented. Leaves are 3.8–6.3 by 1.6–3.2 cm, elliptic lanceolate, and subacute glabrous, and the entire thin base is acute. Petioles are 1–1.3 cm long slender flowers, brownish purple induorous, in terminal and auxiliary paniculate cymes shorter than leaves. They also report that perianth has a campanulated limb of four, valvate triangular segments with four stamens, exerted, alternating with four rounded obtuse scales (Vasundhara et al., 2015).

11.3 Methods of Oil Extraction

The sandalwood tree's precious oil is located within the tree's heartwood, and the older the tree, the higher the proportion of its heartwood. As the oil is held tightly within the wood, a distillation process is required, in which the wood is first ground to a powder form. Distillation methods vary, ranging from today's steam distillation to the more traditional hydrodistillation (water), also including CO_2 extraction, absolute extraction, and an array of new technologies (Montoro et al., 2015). The sandalwood industry, however, lacks a universally accepted method to determine the heartwood oil content (Hettiarachchi et al., 2010).

11.3.1 Steam Distillation

Steam distillation is a process in which steam heated at extremely high temperatures (usually around 140°F–212°F) is passed through the powdered wood. The steam then carries the essential oil that is locked within the cellular structure of the wood. The mixture of steam and oil then flows through a condenser and cools, yielding two separate layers of oil and water. The sandalwood essential oil, which separates from the hydrosol (floral water) and ascends to the top, is collected. The distillation process for sandalwood oil takes 14–36 hours, longer than for many other essential oils. Despite the fact that this method requires a longer process than other distillation methods (Kusuma and Mahfud, 2016b), it is known to produce superior quality oil, yielding up to 84.32% santalol. Steam-distilled sandalwood oil is light pale yellow in color (Nautiyal, 2011).

11.3.2 Hydrodistillation

Hydrodistillation (water distillation) is the traditional method of extracting sandalwood essential oil. Hydrodistillation is a widely used oil extraction process to quantify the oil yield and quality (Hettiarachchi et al., 2010). This process produces good-quality oil. Instead of steam passing through the powdered wood, in hydrodistillation the powdered wood is immersed in water to soak. The water is then boiled, often heated in an open fire, and the vapor it carries is collected from the top of the hydrodistiller. The oil is then separated from the hydrosol. Some disadvantages of this method include the fact that it requires heating a large quantity of water, which increases the cost and time needed for sandalwood distillation. Also, the temperature of the boiling water is difficult to control, which causes the rate of distillation to vary and often causes the oil to be "burned," lessening its quality.

11.3.3 CO_2 Extraction

CO_2 extraction, also known as supercritical CO_2 extraction or supercritical fluid CO_2 extraction, is the latest technique of getting essential oil from pure plant parts (Brunner, 2005). CO_2 extracts are similar to essential oils and can be used in aromatherapy or perfumery. For this process, CO_2 is used as the solvent in place of steam or water. The CO_2 extraction method involves impelling pressurized carbon dioxide into a chamber filled with the powdered heartwood of sandalwood. When CO_2 is subjected to high pressure, it attains liquid properties while retaining its gaseous state. Because of these liquid properties of the gas, CO_2 acts as a solvent, releasing the sandalwood oil from the wood. While steam distillation requires temperatures of 140°F–212°F, CO_2 extraction only requires temperatures of around 95°F–100°F. Oil yielded in CO_2 extraction contains about 82.5% santalol, while steam-distilled oil contains about 84.32% santalol, and hydrodistilled oil contains about 52.59% santalol.

11.3.4 Absolute (Solvent) Extraction

Absolute (solvent) extraction is a method of extracting essential oils that are most often used by the perfume industry, due to the strong aroma of the oil extracted by this process. Solvent extraction uses solvents, such as ethanol, methanol, hexane, or petroleum ether to extract the essential oil from the sandalwood plant. The solvent additionally pulls out the chlorophyll and other plant tissues, which results in the formation of a deeply colored and viscous extract of the solvent. This first product is termed as a concrete and contains the concentrated extract of waxes and/or fats, as well as the odoriferous materials from the plant. The concrete is then mixed with alcohol, which helps in extracting the major aromatic components of the material. The final product is known as an absolute. This distillation method is, however, not applied to produce therapeutic oils for aromatherapy, such as sandalwood essential oil, as chemicals such as hexane, acetone, and di-methylene-chloride are used in the process. Absolute extraction is rarely used to extract sandalwood. In a study by Nautiyal (2010), the oil produced through solvent extraction methods was more in quantity than that produced through hydrodistillation and steam distillation, with the highest yield in ethyl alcohol extraction (84% santalol), but three of the four solvent-extracted sandalwood oils were recorded as "less pleasant," indicating the generally inferior note of oil derived from the other methods.

11.3.5 Phytonics Process

The phytonics process is one of the most recently developed technologies for essential oil extraction using nonchlorofluorocarbons (non-CFCs). It is also called florasol extraction, and the oils are referred to as phytols. Advanced Phytonics Limited, Manchester, United Kingdom, developed and patented this method. A recent statement on essential oil extraction processes reports that the oil mostly extracted by this process is biological or phytopharmacological aromatic components of essential oils that can be used directly without further physical or chemical treatments (Handa, 2008). The phytonics process involves the solvent hydrofluorocarbon-134a, which has a boiling point of 25°C (Swapna et al., 2015). Additionally, this solvent is neither toxic nor flammable, and has no negative impact on the ozone layer. By most standards, this substance makes for a "poor solvent," as it does not mix with many other chemicals, such as mineral oils or triglycerides. However, since this solvent also does not dissolve plant wastes, it is perfect for use in the extraction of essential oils. Other advantages of this extraction technology are numerous; for example, unlike other methods, such as steam or water distillation, which employ high temperatures, the phytonics process is "cool and gentle," and the products are not exposed to excess, possibly harmful temperatures. Because the phytonics process also uses minimal electricity and does not release any harmful emissions into the atmosphere, it is thought to be much less threatening to the environment (Handa, 2008).

11.4 Methods of Analysis of Oil

Santalol in sandalwood oil is conventionally analyzed by gas chromatography (GC) (Howes et al., 2004), while those in heartwoods of field-grown trees are analyzed by gas chromatography with mass spectrometry (GC-MS)/MS (Jones et al., 2006). Fourier transform infrared (FTIR) qualitative analysis is also found to be quite interpretative in establishing the sandalwood oil measurement (Nautiyal, 2011). More recently, Misra and Dey (2013) evaluated the oil in high-performance thin-layer chromatography (HPTLC)–derived spectral scans, which could be helpful in the identification of sesquiterpenoids present in the oil.

Panto et al. (2015) used the hyphenation of liquid and gas chromatography techniques for collection of the important sesquiterpene alcohols of sandalwood oil, as reported by the international regulations, and found the following components: (Z)-α-santalol (44.6%), (Z)-α-*trans*-bergamotol (5.9%), (Z)-β-santalol (19.2%), epi-(Z)-β-santalol (3.2%), α-bisabolol (0.7%), (Z)-lanceol (1.4%), and (Z)-nuciferol (4.0%). Furthermore, Nautiyal (2011) used hydrodistillation, steam distillation, solvent extraction, and subcritical carbon dioxide for analysis of oil components and reported that subcritical carbon dioxide yielded oil determined to contain 2.56% santalene and 82.5% santalol, benzene extracted oil contained 9.49% santalene and 42.99% santalol, diethyl ether extracted oil contained 2.04% santalene and 72.19% santalol, ethyl alcohol extracted oil contained 1.56% santalene and 83.56% santalol, hydrodistilled oil contained 3.43% santalene and 52.59% santalol, hydrodistilled (alkaline) oil contained 7.26% santalene and 56.79% santalol, and steam-distilled oil contained 2.57% of santalene and 84.32% santalol. Howes et al. (2004) suggested a specification of >43% Z-α-santalol and >18% Z-β-santalol by GC-MS for sandalwood oil.

11.5 Composition of Oil

Sandalwood oil consists almost exclusively of closely related sesquiterpenoids (Burdock and Carabin, 2008). Four sesquiterpenols, α-, β-, and epi-β-santalol and α-exo-bergamotol, make up approximately 90% of the oil of *S. album* (Diaz-Chavez et al., 2013). These compounds are the hydroxylated analogues of α-, β-, and epi-β-santalene and α-exo-bergamotene. The oil contains other minor components, including sesquiterpene hydrocarbons (~6%) (Burdock, 2002). The sesquiterpene hydrocarbons are mostly α- and β-santalenes and epi-β-santalene, with small amounts of α- and β-curcumenes and possibly β-farnesene and dendrolasin (Burdock and Carabin, 2008). The volatile composition of *S. album* essential oil contains >90% sesquiterpene alcohols. Current International Organization for Standardization (ISO) standards for (Z)-α-santalol must fall within the 41%–55% range, while (Z)-β-santalol must fall within the 16%–24% range of alcohol content. Different authors reported that sandalwood also contains (Z)-α-*trans*-bergamotol, epi-β-santalol, α-bisabolol, (E,E)-farnesol, (Z)-lanceol, (Z)-nuciferol (Howes et al., 2004; Panto et al., 2015), α-bisabalol, *cis*-bergamatol, γ-curcumen-12-ol (Subasinghe et al., 2013), hydrocarbons (santene and nor-tricyclo-ekasantalene), alcohols (santenol and teresantalol), aldehydes (nor-tricyclo-kasantalal), and acids (α- and β-santalic acids and teresantalic acids) (Sindhu et al., 2010). The alcohols α-santalol and β-santalol are mainly responsible for the odor, with α-santalol comprising approximately 7%–60% of the total santalol and β-santalol comprising approximately 7%–33% of the total santalol, depending on the sourced species (Lawrence, 1991). The other constituents reported include dihydro-β-agarofuran, santene, teresantol, borneol, teresantalic acid, tricycloekasantalal, santalone, and santanol (Khan and Abourashed, 2010). The other minor chemical components reported in sandalwood oil are phenols, lactones, and terpenes. Hentriacontan-16-one is reported in one *S. album* oil sample (Anonymous, 1999).

Two minor components, cyclosantalal (0.21%–2.26%) and isocyclo-santalal (0.11%–1.47%), as new sesquiterpene aldehydes were reported. Also, a new acid ketosantalic (as methyl ester) and gamma-L-glutamyl-S-(*trans*-1-propenyl)-L-cysteine sulfoxide, an interesting natural sulfoxide diastereoisomer, have been isolated from sandal (Sindhu et al., 2010). Zhang et al. (2012) detected a total of 66 volatile compounds from the pericarp of sandalwood. The most prominent compounds were found to be oleic and palmitic acids, which represented about 40%–70% of the oil. Many fragrant constituents and biologically active components, such as α- and β-santalol, cedrol, esters, aldehydes, phytosterols, and squalene, are also present in the pericarp oils.

11.6 Physical and Chemical Properties of Oil

The volatile oil derived from the roots and heartwood of *S. album* L. is a somewhat viscous, yellowish liquid of a peculiarly sweet and very lasting odor (Benencia and Courreges, 1999). Vasundhara et al. (2015) reported the physical and chemical properties of *S. album* and found that the refractive index of sandalwood seed oil was 1.4898, and specific gravity was 0.9406. Sandalwood seed oil has a high level of freshness, as it has very low acid value (0.748), and the ester value was 157.108. The specific gravity at 25°C was 0.94061. Further, they reported that the saponification value was 157.856. In addition, Sindhu et al. (2010) reported that volatile oil extracted from *S. album* L. derived from the roots and heartwood is a colorless to yellowish, viscous (reference index 1.499–1.506, specific gravity 0.962–0.985, and rotation 19°–20°) liquid with a peculiar heavy sweet odor, the chief constituent of the oil being santalol.

11.7 General Uses of Oil

Sandalwood oil is used as a flavor component in many food products (Rasor and Dunca, 2014), including alcoholic and nonalcoholic beverages, frozen dairy desserts, candy, baked goods, and gelatin and puddings, at use levels generally below 0.001% (10 ppm), except in hard candy. The highest maximum use level for sandalwood oil in food products is approximately 90 ppm. Sandalwood oil is generally used as a natural flavoring substance (Hall and Oser, 1965) or in conjunction with other flavor (Burdock, 2002). Current interests in sandalwood oil are growing in the aromatherapy, cosmetics, and food industries due to its sedative action and fragrance (Burdock and Carabin, 2008). The Flavor and Extract Manufacturers Association (FEMA) has approved sandalwood oil as a "generally recognized as safe" (GRAS) flavoring ingredient for use in food.

Sandalwood oil is mainly used in the perfume industry. The oil is an excellent base and fixative for other high-grade perfumes. Most top-grade perfumes have sandalwood oil as their base, which, in itself, is an excellent, mild, long-lasting, and sweet perfume, yet the industry finds that it can blend very well with other perfumes and does not impart its fragrance when used as a base. It can also fix better perfumes, which are volatile, for longer hours. From perfumery to joss sticks, there are several hundred products that use sandalwood oil. It is also used in the soap industry (Ral, 1990).

Essential oils obtained from seeds, stem bark, and roots of many plants have been widely used in traditional medicine. Sandalwood oil is used medicinally for common colds, bronchitis, fever, infection of the urinary tract, inflammation of the mouth and pharynx, liver and gallbladder complaints, and other maladies (Kusuma and Mahfud, 2016a). In addition, the main α-santalol component is found to prevent the development of skin tumors in mice and reduce the likelihood of actinic keratosis and skin cancer (Dickinson et al., 2014). Sandalwood is mainly used as a coolant, and also has a sedative effect and astringent activity, making it useful as a disinfectant in the genitourinary and bronchial tracts; it is also a diuretic, expectorant, and stimulant. The same is also used as a tonic for the heart, stomach, and liver; as an antipoison; for fever and memory improvement; and as a blood purifier (Sindhu et al., 2010). Satou et al. (2014) reported that fragranced sandalwood oil has an anxiolytic activity on mice. Sandalwood oil is used as an antiseptic, anti-inflammatory, antiphlogistic, antispasmodic, astringent, cicatrisant, carminative, diuretic, disinfectant, emollient, expectorant, hypotensive, memory booster, sedative, and tonic. Sandalwood oil is an active substance of agreeable odor employed in the treatment of subacute and chronic infections of mucous tissues, particularly gonorrhea after the active symptoms have been mitigated. Chronic bronchitis with fetid expectoration, chronic mucous diarrhea, chronic inflammation of the bladder, and pyelitis are also said to be benefited by it. It occasionally disturbs the gastrointestinal tract, and like copaiba, which it was introduced to supersede, it will cause cutaneous eruptions. The dose ranges from 5 to 20 drops, in capsules or emulsion (Nautiyal, 2011). Sandalwood oil is also used to treat gastric ulcers (Ahmed et al., 2013).

11.8 Pesticidal Uses of Sandalwood Oil

In general, plant essential oils could be good resources in developing insect pest control agents (Batish et al., 2008; Ebadollahi, 2013), as they are reported to have many bioactivities, including insecticidal and repellant activities, and as oviposition deterrent against flies (Kim et al., 2016). Besides other uses, sandalwood oil can also be used as an insecticide. Roh et al. (2011) reported that sandalwood oil and its constituents have considerable acaricidal properties. Sandalwood oil was significantly active against adults of *Tetranychus urticae*, with more than 80% mortality in adults with oviposition-deterring effects of up to 89.3%. A mixture of α- and β-santalol, which are two of the main components of the oil, also demonstrated higher mortality (85.5%) and oviposition-deterrent effects (94.7% reduction in the number of eggs) than the control. From the experiment, it was conclusive that sandalwood oil could likely be used for the sustainable management of *T. urticae* on various greenhouse vegetables and food crops. Similarly, Roh et al. (2015) reported that both sandalwood oil and santalol had significant insecticidal properties (up to 98.8%) against *Aphis gossypii*, which were comparable to that of imidacloprid, a neonicotinoid insecticide. Further, the control efficacies of sandalwood oil (94.0%), α-santalol (84.2%), β-santalol (90.6%), and a mixture of α- and β-santalols (88.7%) against *A. gossypii* infesting hot peppers were also comparable to each other in greenhouse bioassays. Amer and Mehlhorn (2006) reported that sandalwood oil at 50 ppm concentration inflicted 83.3% mortality within 1 hour of application against third-instar larvae of *Aedes aegypti*, and mortality increased to 100% after 12 hours of treatment. Similar trends, in terms of median lethal dose, were also observed in the case of *Anopheles stephensi* and *Culex quinquefasciatus*, ranging from 100 to 50 ppm, respectively, after 1 hour of treatment.

11.9 Advantages as a Pesticide

Natural pesticides based on plant essential oils may represent alternative crop protectants. Many plant essential oils show a broad spectrum of activity against pest insects and plant pathogenic fungi, including insecticidal, antifeedant, repellent, oviposition-deterrent, growth regulatory, and antivector activities (Koul et al., 2008). Plant-derived oils and powders have recently been evaluated and shown to be effective against a number of insect pests (Butler and Henneberry, 1990; Koul et al., 2008; Dhaliwal et al., 2015; Sola et al., 2014). The aromatic characteristics of essential oils provide various functions for the plants, including (1) attracting or repelling insects, (2) protecting themselves from heat or cold, and (3) utilizing chemical constituents in the oil as defense materials (Koul et al., 2008). They are nonenvironmental pollutants, unlike other synthetic pesticides (Isman, 2000). Essential oils are totally nontoxic to other mammals, birds, bees, and even beneficial insects (Anonymous, 2007). One of the most important advantages of essential oils is that they do not leave any residue on the plants (Lokanadhan et al., 2012). Plant-based oils as a natural pesticide are of immense significance in view of the environmental and toxicological implications of the indiscriminate use of synthetic pesticides and overcoming or reducing the problem of increasing pest resistance. It is also obvious that resistance will develop more slowly to essential oil–based pesticides owing to the complex mixtures of constituents that characterize many of these oils (Koul et al., 2008).

11.10 Limitations as a Pesticide

The characteristic features of sandalwood oil indicate that it has potential to be used as a pesticide in a variety of ways to control a large number of pests, some of which remain to be explored. However, the rationality of use of sandalwood oil as a pesticide suffers from a few constraints, primarily the high price of the oil and unavailability of sufficient quantities of plant material. Further, the efficacy of the oil may fall short when compared with synthetic pesticides, although there are specific pest contexts where control equivalent to that with conventional products has been observed. Also, the oil may require somewhat greater application rates and frequent reapplication when used in fields. In general, additional challenges to the commercial application of plant essential oil–based pesticides include standardization and refinement of pesticide products, protection of technology (patents), and regulatory approval (Isman, 2005). In addition, as the chemical profile of plant species can vary naturally, depending on geographic, genetic, climatic, annual, or seasonal factors, pesticide manufacturers must take additional steps to ensure that their products will perform consistently (Koul et al., 2008). Then, data on their bioefficacy, product characterization, efficacy, safety, toxicology, and label claim will have to be generated, before applying for registration. Finally, once all these issues are addressed, regulatory approval is required. Accordingly, regulatory approval continues to be a barrier to commercialization and will likely continue to be a barrier until regulatory systems are adjusted to better accommodate these products (Isman and Machial, 2006).

11.11 Conclusion

In the future, the use of pesticides will be more firmly regulated because of well-documented environmental risks in the use of synthetic chemicals (Ongley, 1996; Koul et al., 2008). This may lead to a growing demand for biological plant protection agents, including plant-based oils. Sandalwood oil has a wide range of applications, ranging from fragrance to medicinal and pesticidal uses. These features indicate that pesticides based on sandalwood oil could be used in a variety of ways to control a large number of key pests. Since several plant-based essential oils have already been researched and reported successfully for their anti-insect properties, it is high time to refocus the attention of researchers toward the development and application of known plant oils to speed up the scaling-up process, enhancing the availability of eco-friendly pest management techniques. A simplified process facilitating the registration of the essential oils having pesticidal properties of these plant-based formulations would ensure future development, improvement, and applications of these potential biopesticides that form a part of the rich floral diversity. In order to derive and implement a comprehensive management strategy, a paradigm shift in the mindset of pesticide users is needed. The mission must facilitate the successful development, commercialization, and adoption of biopesticides in public–private partnership (PPP) mode (Roy et al., 2016). It is expected that such collective efforts would lead to the successful implementation of plant-based oils in the integrated approach in pest management.

References

Ahmed, N., M. S. Ali Khan, A. M. Mat Jais et al. 2013. Anti-ulcer activity of sandalwood (*Santalum album* L.) stem hydroalcoholic extract in three gastric-ulceration models of Wistar rats. *Boletín Latinoamericano y del Caribe de Plantas Medicinales y Aromáticas* 12: 81–91.

Amer, A. and H. Mehlhorn. 2006. Larvicidal effects of various essential oils against *Aedes*, *Anopheles*, and *Culex* larvae (Diptera, Culicidae). *Parasitology Research* 99: 466–472.

Anonymous. 1999. Hentriacontane-1-ol. In *Phytochemical Dictionary: A Handbook of Bioactive Compounds from Plants*, 2nd ed., ed. J. B. Harborne, H. Baxter and G. P. G. Moss, 168–169. Boca Raton, FL: Taylor & Francis, Philadelphia, p. 53.

Anonymous. 2007. Neem benefits: Discover all the benefits of neem oil, leaf, and neem trees. Discover NEEM. http://www.discoverneem.com/neem-benefits.html.

Anonymous. 2016. 101 Essential oil uses & benefits. Dr. Axe Food Is Medicine. https://draxe.com/essential-oil-uses-benefits/.

Baldovini, N., C. Delasalle and D. Jaulain. 2010. Phytochemistry of the heartwood from fragrant *Santalum* species: A review. *Flavor and Fragrance Journal* 26: 7–26.

Batish, D. R., H. P. Singh, R. K. Kohli and S. Kaur. 2008. Eucalyptus essential oil as a natural pesticide. *Forest Ecology and Management* 12: 2166–2174.

Benencia, F. and M. C. Courreges. 1999. Antiviral activity of sandalwood oil against herpes simplex viruses 1 & 2. *Phytomedicine* 6: 119–123.

Bhalla, Y., V. K. Gupta and V. Jaitak. 2013. Anticancer activity of essential oils: A review. *Journal of the Science of Food and Agriculture* 93: 3643–3653.

Brunner, G. 2005. Supercritical fluids: Technology and application to food processing. *Journal of Food Engineering* 67: 21–33.

Burdock, G. A. 2002. *Fenaroli's Handbook of Flavor Ingredients*. 4th ed. CRC Press, Boca Raton, FL, pp. 1684–1685.

Burdock, G. A. and I. G. Carabin. 2008. Safety assessment of sandalwood oil (*Santalum album* L.). *Food and Chemical Toxicology* 46: 421–432.

Butler, Jr., G. D. and T. J. Henneberry. 1990. Pest control on vegetables and cotton with household cooking oils and liquid detergents. *Southwest Entomology* 15: 123–131.

Dhaliwal, G. S., G. A. Burdock, J. Vikas and M. Bharathi. 2015. Crop losses due to insect pests: Global and Indian scenario. *Indian Journal of Entomology* 77: 165–168.

Diaz-Chavez, M. L., J. Moniodis, L. L. Madilao et al. 2013. Biosynthesis of sandalwood oil: *Santalum album* CYP76F cytochromes P450 produce santalols and bergamotol. *PLoS One* 8: e75053. http://journals.plos.org/plosone/article?id=10.1371/journal.pone.0075053.

Dickinson, S. E., E. R. Olson, C. Levenson, J. Janda, J. J. Rusche and D. S. Alberts. 2014. A novel chemopreventive mechanism for a traditional medicine: East Indian sandalwood oil induces autophagy and cell death in proliferating keratinocytes. *Archives of Biochemistry and Biophysics* 558: 143–152.

Ebadollahi, A. 2013. Plant essential oils from Apiaceae family as alternatives to conventional insecticides. *Ecologia Balkanica* 5: 149–172.

Grieve, M. 1971. A modern herbal: The medicinal culinary, cosmetic and economic properties. In *Cultivation and Folk-lore of Herbs, Grasses, Fungi, Shrubs & Trees with All Their Modern Scientific Uses*. Vol. II. United States: Courier Corporation.

Hall, R. L. and B. L. Oser. 1965. Recent progress in the consideration of flavoring ingredients under the food additives amendment. *Food Technology* 19: 151–197.

Handa, S. S. 2008. An overview of extraction techniques for medicinal and aromatic plants. In *Extraction Technologies for Medicinal and Aromatic Plants*, ed. S. S. Handa, S. P. S. Khanuja, G. Longo and D. D. Rakesh, 21–54. Trieste, Italy: International Centre for Science and High Technology, pp. 21–54.

Hettiarachchi, D. S., M. Gamage and U. Subasinghe. 2010. Oil content analysis of sandalwood: A novel approach for core sample analysis. *Sandalwood Research Newsletter* 25: 1–4.

Howes, M. J. R., M. S. J. Simmonds and G. C. Kite. 2004. Evaluation of the quality of sandalwood essential oils by gas chromatography–mass spectrometry. *Journal of Chromatography A* 1028: 307–312.

Huish, R. D., T. Fakaosi, H. Likiafu, J. Mateboto and K. H. Huish. 2015. Distribution, population structure, and management of a rare sandalwood (*Santalum yasi*, Santalaceae) in Fiji and Tonga. *Pacific Conservation Biology* 21: 27–37.

Isman, M. B. 2000. Plant essential oils for pest and disease management. *Crop Protection* 19: 603–608.

Isman, M. B. 2005. Problems and opportunities for the commercialization of botanical insecticides. In *Biopesticides of Plant Origin*, ed. C. Regnault-Roger, B. J. R. Philogene and C. Vincent, 283–291. Paris: Lavoisier.

Isman, M. B. and C. M. Machial. 2006. Pesticides based on plant essential oils: From traditional practice to commercialization. In *Naturally Occurring Bioactive Compounds*, ed. M. Rai and M. C. Carpinella, 29–44. The Netherlands: Elsevier Science.

Jones, C. G., E. L. Ghisalberti, J. A. Plummer and E. L. Barbour. 2006. Quantitative co-occurrence of sesquiterpenes: A tool for elucidating their biosynthesis in Indian sandalwood, *Santalum album*. *Phytochemistry* 67: 2463–2468.

Jones, F. A. 1996. Herbs—Useful plants: Their role in history and today. *European Journal of Gastroenterology and Hepatology* 8: 1227–1231.

Khan, I. A. and E. A. Abourashed. 2010. *Leung's Encyclopedia of Common Natural Ingredients*. New York: John Wiley & Sons Inc.

Kim, S., H. Lee, M. Jang, C. Jung and I. Park. 2016. Fumigant toxicity of Lamiaceae plant essential oils and blends of their constituents against adult rice weevil *Sitophilus oryzae*. *Molecules* 21: 1–10.

Kirtikar, K. R. and B. D. Basu. 1993. Santalum album. In *Indian Medicinal Plants.* Vol. 3, 2nd ed. Allahabad, India: L. M. Basu, pp. 2184–2188.

Koch, C., J. Reichling, J. Schneele and P. Schnitzler. 2008. Inhibitory effect of essential oils against herpes simplex virus type 2. *Phytomedicine* 15: 71–78.

Koul, O., S. Walia and G. S. Dhaliwal. 2008. Essential oils as green pesticides: Potential and constraints. *Biopesticide International* 4: 63–84.

Kusuma, H. S. and M. Mahfud. 2016a. Preliminary study: Kinetics of oil extraction from sandalwood (*Santalum album*) by microwave-assisted hydro-distillation. Paper presented at the International Conference on Innovation in Engineering and Vocational Education, Bandung, Indonesia.

Kusuma, H. S. and M. Mahfud. 2016b. The extraction of essential oil from sandalwood (*Santalum album*) by microwave air-hydrodistillation method. *Journal of Materials and Environmental Science* 7: 1597–1606.

Lawrence, B. M. 1991. Recent progress in essential oils. *Perfumer & Flavorist* 16: 49–58.

Lokanadhan S., P. Muthukrishna and S. Jeyarama. 2012. Neem products and their agricultural application. *Journal of Biopesticides* (Supplementary): 72–76.

McKinnell, F. H. 1990. Status of management and silviculture research on sandalwood in western Australia and Indonesia. https://www.fs.fed.us/psw/publications/documents/psw_gtr122/psw_gtr122_mckinnell.pdf (accessed September 22, 2016).

Merlin, M. D., L. Thomson and C. R. Elevitch. 2006. *Santalum ellipticum*, *S. freycinetianum*, *S. haleakalae*, and *S. paniculatum* (Hawaiian sandalwood) Santalaceae (sandalwood family). http://www.doc-development-durable.org/file/Arbres-Bois-de-Rapport-Reforestation/FICHES_ARBRES/Arbres-non-classes/Santalum-Haw-sandalwood.pdf (accessed September 22, 2016).

Misra, B. B. and S. Dey. 2013. Developmental variations in sesquiterpenoid biosynthesis in East Indian sandalwood tree (*Santalum album* L.). *Trees* 27: 1071–1086.

Montoro, P., M. Masullo, S. Piacente and C. Pizza. 2015. Extraction, sample preparation and analytical methods for quality issues of essential oils. In *Aromatherapy: Basic Mechanisms and Evidence Based Clinical Use*, ed. G. Bagetta, M. Cosentino and T. Sakurada, 105–149. Boca Raton: CRC Press/Taylor & Francis.

Nautiyal, O. H. 2010. Subcritical carbon dioxide and conventional extraction techniques of sandalwood oil: An industry project. *Sandalwood Research Newsletter* 25: 5–7.

Nautiyal, O. H. 2011. Analytical and Fourier transform infrared spectroscopy evaluation of sandalwood oil extracted with various process techniques. *Journal of Natural Products* 4: 150–157.

Okugawa, H., R. Ueda, K. Matsumoto, K. Kowanishi and A. Kato. 1995. Effect of α-santalol and β-santalol from sandalwood on the central nervous system in mice. *Phytomedicine* 2: 119–126.

Ongley, E. D. 1996. Control of water pollution from agriculture- FAO irrigation and drainage paper 55. http://www.fao.org/docrep/w2598e/w2598e00.htm#Contents (accessed September 22, 2016).

Panto, S., D. Sciarrone, M. Maimone et al. 2015. Performance evaluation of a versatile multidimensional chromatographic preparative system based on three-dimensional gas chromatography and liquid chromatography-two-dimensional gas chromatography for the collection of volatile constituents. *Journal of Chromatography A* 1417: 96–103.

Prasetyaningtyas, M. 2007. *Santalum album* L. Seed leaflet 116. http://curis.ku.dk/ws/files/20495554/santalum_album.pdf (accessed October 15, 2016).

Ral, S. N. 1990. Status and cultivation of sandalwood in India. https://www.fs.fed.us/psw/publications/documents/psw_gtr122/psw_gtr122_rai.pdf (accessed October 15, 2016).

Rani, A., P. Ravikumar, M. D. Reddy and A. Kush. 2013. Molecular regulation of santalol biosynthesis in *Santalum album* L. *Gene* 527: 642–648.

Rasor, A. S. and S. E. Dunca 2014. Fats and oils—Plant based. In *Food Processing: Principles and Applications*, ed. S. Clark, S. Jung and B. Lamsal, 457–480. New York: John Wiley & Sons Ltd.

Roh, H. S., J. Kim, E. S. Shin, D. W. Lee, H. Y. Choo and C. G. Park. 2015. Bioactivity of sandalwood oil (*Santalum austrocaledonicum*) and its main components against the cotton aphid, *Aphis gossypii*. *Journal of Pest Science* 88: 621–627.

Roh, H. S., E. G. Lim and J. Kim. 2011. Acaricidal and oviposition deterring effects of santalol identified in sandalwood oil against two-spotted spider mite, *Tetranychus urticae* Koch (Acari: Tetranychidae). *Journal of Pest Science* 84: 495–501.

Roy, S., G. Handique, N. Muraleedharan, K. Dashora, S. M. Roy, A. Mukhopadhyay and A. Babu. 2016. Use of plant extracts for tea pest management in India. *Applied Microbiology and Biotechnology* 100: 4831–4844.

Satou, T., M. Miyagawa, H. Seimiya, H. Yamada, T. Hasegawa, and K. Koike. 2014. Prolonged anxiolytic-like activity of sandalwood (*Santalum album* L.) oil in stress-loaded mice. *Flavour and Fragrance Journal* 29: 35–38.

Shea, S. R., A. M. Radomiljac, J. Brand, and P. Jones. 1997. An overview of sandalwood and the development of sandal in farm forestry in western Australia. Paper presented at the International Seminar on Sandal and Its Products, Canberra, Australia.

Sindhu, R. K., A. K. Upma, and S. Arora. 2010. *Santalum album* Linn: A review on morphology, phytochemistry and pharmacological aspects. *International Journal of Pharm Tech Research* 2: 914–919.

Sola, P., B. M. Mvumi, J. O. Ogendo, O. Mponda, J. F. Kamanula, S. P. Nyirenda, S. R. Belmain, and P. C. Stevenson. 2014. Botanical pesticide production, trade and regulatory mechanisms in sub-Saharan Africa: Making a case for plant-based pesticidal products. *Food Security* 6: 369–384.

Subasinghe, U., M. Gamage, and D. S. Hettiarachchi. 2013. Essential oil content and composition of Indian sandalwood (*Santalum album* L.) in Sri Lanka. *Journal of Forestry Research* 24: 127–130.

Swapna, G., T. Jyothirmai, V. Lavanya, S. Swapnakumari, and P. A. Sri Lakshmi. 2015. Extraction, and characterization of bioactive compounds from plant extracts: A review. *European Journal of Pharmaceutical Science and Research* 2: 1–6.

Tennakoon, K. U. and D. D. Cameron. 2006. The anatomy of *Santalum album* (sandalwood) haustoria. *Canadian Journal of Botany* 84: 1608–1616.

Tennakoon, K. U., J. S. Pate, and D. Arthur. 1997. Ecophysiological aspects of the woody root hemiparasite *Santalum acuminatum* (R. Br.) A. DC and its common hosts in south western Australia. *Annals of Botany* 80: 245–256.

Thomson, L. A. J., J. Doran, D. Harbaugh, and M. D. Merlin. 2011. Farm and forestry production and marketing profile for sandalwood (*Santalum* species). http://pacificschoolserver.org/content/_public/Local%20Topics/Pacific%20Islands/Agriculture%20for%20Islands/Specialty%20crops/Sandalwood.pdf (accessed October 15, 2016).

van Balgooy, M. M. J. 1960. Preliminary plant-geographic analysis of the Pacific. *Blumea* 10: 385–430.

van Balgooy, M. M. J. 1971. Plant genera of the Pacific as based on a census of Phanaerogam genera. *Blumea* 6: 1–222.

van Balgooy, M. M. J., P. H. Hovenkamp and P. C. van Welzen. 1996. Phytogeography of the Pacific: Floristic and historical distribution patterns in plants. In *The Origin and Evolution of Pacific Island Biotas, New Guinea to Eastern Polynesia: Patterns and Processes*, ed. A. Keast and S. E. Miller, 191–213. Amsterdam: SPB Academic Publishing.

Vasundhara, M., B. S. Thara, B. Radhika, A. Jayaram, and R. Priyanka. 2015. Assessment of Indian sandalwood (*Santalum album* L.) seeds for seed oil production and fatty acid methyl esters. *World Journal of Pharmaceutical Research* 4: 1416–1425.

Zhang, X. H., J. A. da Silva, Y. X. Jia, J. T. Zhao, and G. H. Ma. 2012. Chemical composition of volatile oils from the pericarps of Indian sandalwood (*Santalum album*) by different extraction methods. *Natural Product Communications* 7: 93–96.

Taylor & Francis
Taylor & Francis Group
http://taylorandfrancis.com