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Review paper

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A mini-review of essential oils in the South Pacific and their insecticidal properties

R.R. Chand (*), A.D. Jokhan, R.D. Gopalan

Faculty of Science, Technology and Environment, The University of the South Pacific, Private Mail Bag, Suva, Fiji.

Key words: essential oils, insecticidal activities, traditional medicinal plants.

Abstract: Studies on traditional medicinal plants (TMPs) found in the South Pacific that holds potential for the insect controls have been reviewed. Few TMPs are known to have insecticidal properties, however many of those are still unknown in the South Pacific. The information on plants were collected using online databases such as Science Direct, PubMed, Google Scholar, Scopus and Springer Open in order to confirm the studies that support the insecticidal properties of plants present in the South Pacific. The following study confirmed that there is a potential for the selected TMPs suggesting enough evidence for their usage in the insecticidal activities. These plants would represent an alternative in crop protection due to its novel, safe and eco-friendly substitutes for its effective insecticidal properties.

(*) **Corresponding author:**
s11074077p@gmail.com

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All relevant data are within the paper and its Supporting Information files.

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The authors declare no competing interests.

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1. Introduction

Agricultural and animal origin stored products are destroyed by more than 600 species of beetle pests, 70 species of moths and about 355 species of mites (Rajendran and Sriranjini, 2008). These insect pests have greatly affected the food commodities and resulted in one of major problem to the food industries (Isman, 2006). There are many concerns raised with the usage of synthetic chemicals for pest control. According to the Food and Agriculture Organization of the United Nations (FAO, 2015), the consequences of high usage of synthetic pesticides in the Pacific Island Countries (PIC) has led to threats to human health and the environment. Chemical pollution is a major concern to the environment and human body through food chains, which results in severe physiological disorders and diseases (Oliva *et al.*, 2001; Baldi *et al.*, 2003; Briggs, 2003; Saiyed *et al.*, 2003; Lemaire *et al.*, 2004).

The investigation in the area of natural resources have dramatically increased when it comes to public concern for the long term health and environmental effect of synthetic chemicals (Coats, 1994; Regnault-Roger and Hamraoui, 1995; Lee *et al.*, 1997; Akhtar and Isman, 2004; Ukeh and Umoetok, 2011; Khani and Heydarian, 2014; Pandey *et al.*, 2014). For example, the massive use of chemical compound phosphine has led to environmental issues due to its insect resistance/ineffectiveness in the agricultural fields of some countries (Opit *et al.*, 2012). Likewise, the use of methyl bromide for the fumigation has been reported as ozone-depleting substance and therefore removed completely from its use in some countries (Rajendran and Sriranjini, 2008). In view of the problems with current synthetic chemicals, there is a global interest in the search of alternative strategies and among them is the use of plant extracts.

Traditional aromatic plants have a wide impact on the agriculture, since plant derivatives are considered an integral source of pesticides. It represents a total of US $700.00 million market value with a total production of 45000 tons (Tripathi *et al.*, 2009). The science of natural products has advanced significantly in recent years benefiting humankind in the form of food, clothing, shelter, tools, medicines and crop protectant agents (Copping and Duke, 2007). The TMPs are the mainstay for treatment of illness in the Pacific for years. According to Dasilva *et al.* (2004), traditional medicines hold a natural treasury that clearly depicts that Pacific is rich in plant biodiversity. However, many plants in the Pacific are yet to be exploited for their right purpose. Hence, the present paper emphasizes on the insecticidal properties of essential oils from potential medicinal plants found in the South Pacific.

2. Overview of essential oils

Essential oils are diverse groups of natural products which are mainly produced by plants for defence, signalling or derive from their secondary metabolism (Charles and Simon, 1990; Bakkali *et al.*, 2008). These oils are volatile liquids which have a lower density than water (Bakkali *et al.*, 2008). Essential oils are also known as 'essence' that are strong-smelling liquid components found in aromatic plants, grasses and trees (Ríos, 2016). Essential oils are mostly formed in plants such as from flowers, leaves, buds, fruits, seeds, bark and roots (Isman, 2000; Ríos, 2016). The synthesised essential oils are mostly kept in secondary cell cavities, epidermal cells, canals or glandular trichomes (Nazzaro *et al.*, 2013).

The extraction of essential oils can be divided into conventional and recently developed methods. The conventional methods include; hydro-or steam distillation, solvent extraction and cold pressing. Hydro-distillation being one of the oldest methods, dating back to 5000 years. While the recent methods for extracting essential oils include; supercritical fluid extraction and microwave-assisted extraction. The quality and quantity of chemical compounds are depended on different extraction method (Fig. 1).

Essential oils containing between 20-60 components at different concentrations are considered to be very complex natural mixtures (Pandey *et al.*, 2014). Essential oils are characterized by two or more major compounds with few trace compounds. For instance, the GC-MS analysis of *Ocimum tenuiflorum* L. essential oils showed eugenol (58.20%), germacrene D (11.68%), *cis*-β-ocimene (10.79%) and β-caryophyllene (4.31%) as major compounds and terpinen-4-ol (1.01%), α-copaene (1.98%), δ-cadinene (1.44%) and few others as trace compounds (Chand *et al.*, 2016). The percentage composition of essential oils may vary with plants, environmental conditions, soil types and nutrients (Masotti *et al.*, 2003; Erbil *et al.*, 2015).

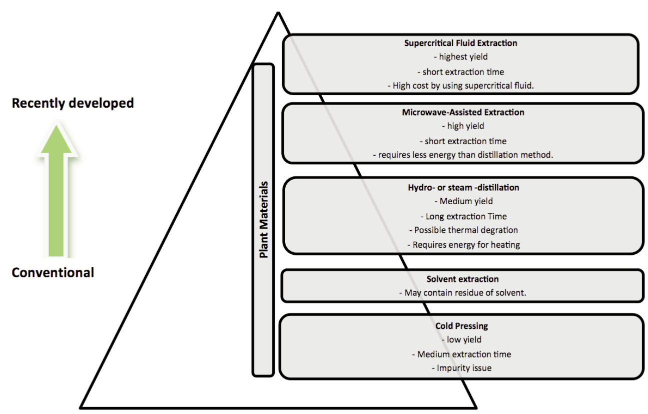

Fig. 1 - Overview of essential oil extraction methods (Park and Tak, 2015).

Formation of essential oils

Essential oils mostly have a high constituent of terpenes (Farag *et al.*, 1989). The other composition of essential oils include aromatic and aliphatic constituents that have different function to perform in relation to plants and animals (Bakkali *et al.*, 2008; Chamorro *et al.*, 2012; Hossain *et al.*, 2012; Hrckova and Velebny, 2012; Tongnuanchan and Benjakul, 2014). For instance, monoterpenes are used by plants for defence against pathogens, aid in seed dispersal and allelochemical functions, while alcohol groups have bactericidal, anti-infective and repellent properties (Table 1).

Terpenes are usually formed using mevalonate pathways. Mevalonate pathway is also known as isoprenoid pathway which occurs in all higher eukaryotes (Corsini *et al.*, 1993). This biosynthetic pathway

Table 1 - Composition of essential oils with their general function in plants and animals

Group	Sub-group	General functions in relation to plants and animals	Reference
Terpene Hydrocarbon	Monoterpenes ($C_{10}H_{16}$)	Producing defense against pathogens, help in the pollination, seed dispersal and allelochemical functions between plants and herbivores	(Lee *et al.*, 1997; Choi *et al.*, 2006; Ibanez *et al.*, 2012)
Terpene Hydrocarbon	Sesquiterpenes ($C_{15}H_{24}$)	Contact irritant effects on insects	(Gonzalez-Coloma *et al.*, 2013)
Terpene Hydrocarbon	Sesquiterpenes ($C_{15}H_{24}$)	Also used as analgesic, spasmolytic agents, calming, slight hypotension and anti-inflammatory	(Chaichana, 2009)
Terpene Hydrocarbon	Diterpenes ($C_{20}H_{22}$)	Are known to have insecticidal, antimicrobial and anti-inflammatory properties	(de Oliveira *et al.*, 2008; Gonzalez-Coloma *et al.*, 2013)
Terpene Hydrocarbon	Triterpenes ($C_{20}H_{22}$)	Components of the surface waxes that accumulate in the intra-cuticle layers of stems and leaf surface for protection against dehydrations and herbivores	(Thimmappa *et al.*, 2014)
Terpene Hydrocarbon	Triterpenes ($C_{20}H_{22}$)	Wide ranges of application of these compounds are in food, health, and industrial biotechnology sector	(Thimmappa *et al.*, 2014; Hadjimbei *et al.*, 2015).
Oxygenated Compounds	Alcohols	These compounds have bactericidal, anti-infective and repellent properties	(Ukeh and Umoetok, 2011)
Oxygenated Compounds	Phenols	Have strong toxic effects, antiseptic and insecticidal properties	(Akhtar and Isman, 2004; Romero *et al.*, 2013, cited in Pinheiro *et al.*, 2015)
Ethers	-	Severely affects the speed of germination, seedling growth and chlorophyll content	(He *et al.*, 2009)
Aldehydes	-	Used for antiviral, anti-inflammatory, hypotensive, vasodilators and antipyretic activities	(Dorman and Deans, 2000; Djilani and Dicko, 2012)
Ketones	-	Toxic effects to a number of pests	(Kordali *et al.*, 2007)
Ketones	-	Other uses of these compounds include anticoagulant, anti-inflammatory and digestant	(Peixoto *et al.*, 2015).
Organic acids and esters	-	Special properties such as anti-fungal, anti-inflammatory and antispasmodic	(Chaichana, 2009)
Organic acids and esters	-	Have potential antimicrobial properties	
Oxides	-	Used in aromatherapy, pharmaceuticals and agriculture	(Chaichana, 2009)

is used to produce dimethyl allyl pyrophosphate (DMAPP) and isopentenyl pyrophosphate (IPP). These two compounds serve as the basis for the biosynthesis of molecules in diverse processes of terpene synthesis, protein prenylation, cell membrane maintenance, hormones, *N*-glycosylation and protein anchoring (Chaichana, 2009; Cooper and Nicola, 2014).

Terpene biosynthesis involves addition of isopentenyl diphosphate (IPP; C_5) to its isomer dimethylallyl diphosphate (DMAPP; C_5 - can also form hemiterpenes) synthesizing geranyl diphosphate (GPP; C_{10}) which is a precursor for synthesis of monoterpenes. GPP and FPP form monoterpenes and sesquiterpenes skeleton respectively. Further condensation of enzyme-bound geranyl diphosphate (GPP; C_{10}) with addition of IPP units forms farnasyl diphosphate (FPP; C_{15}). Geranylgeranyl diphosphate (GGPP; C_{20}), that goes through series of reactions such as cyclization, rearrangement or coupling to form diterpenes and polyterpenes (Figure 2 shows the parental precursors to synthesise terpenes).

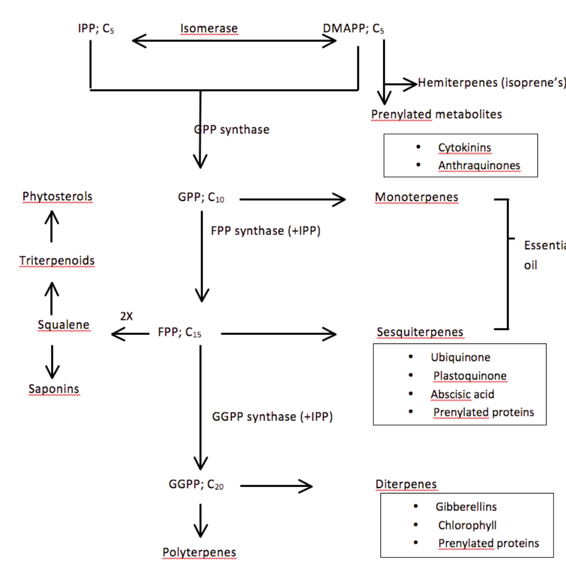

Fig. 2 - Synthesis of different classes of terpenes in plants. DMAPP - Dimethylallyl diphosphate; IPP - Isopentenyl diphosphate; FPP - Farnesyl diphosphate; GPP - Geranyl diphosphate; GGPP - Geranylgeranyl diphosphate.

Medicinal plants and their insecticidal properties

Insect control using plant materials is an ancient practice all over the world (Gonzalez-Coloma *et al.*, 2013). This review is focused on nineteen different families of TMPs commonly found in the South Pacific that are known to have essential oils (World Health Organization, 1998).

These selected plants exhibit insecticidal properties that are traditionally used in form of medicines in the South Pacific (Table 2). The general characteris-

Table 2 - Selected medicinal plants reported for its efficiency against the insects

Family	Scientific names	Common English name	Plant part used	*Traditional Uses in the South Pacific (Treatment)	Active Constituents/Compounds	Efficiency against insects	References
Lamiaceae	*Ocimum tenuiflorum* L.,	Holy or sacred basil	Essential oils from leaves	Earache, nasal infections, cough, colds, stomach ache, hair lice, gastric, ulcer, flu, fevers, sore throat, and filariasis	-	Fumigant and repellent toxicity against the *Aleurodicus Dispersus* Russell (Spiralling whiteflies)	(Chand *et al.*, 2016)
Lamiaceae	*Ocimum basilicum* Linn. var. pilosum (willd)-Benth	Holy or sacred basil	Leaf extract	Earache, nasal infections, cough, colds, stomach ache, hair lice, gastric, ulcer, flu, fevers, sore throat, and filariasis	4h-1-Benzopyran-4-one, 5-hydroxy-6,7-dimethoxy-2-(4-methoxyphenyl)-, catechol and Monoacetin	Repellency against the 3N7H and 3Q8I of *Anopheles gambiae* (African malaria mosquito)	(Gaddaguti *et al.*, 2016)
Lamiaceae	*Ocimum tenuiflorum* var. CIM AYU	Holy or sacred basil	Leaf extract	Earache, nasal infections, cough, colds, stomach ache, hair lice, gastric, ulcer, flu, fevers, sore throat, and filariasis	2-hexadecen-1-ol, phytol, DL-alpha-tocopherol, phenol-2-methoxy-3-(2-propenyl)-lycopersin, gamma-sitosterol, benzene, 1, 2-dimethoxy-4-(2-Propenyl)	Repellency against the 3N7H and 3Q8I of *Anopheles gambiae* (African malaria mosquito)	(Gaddaguti *et al.*, 2016)
Mimosaceae	*Adenanthera pavonina* L.	Holy or sacred basil	Seed extract	Leprosy	Trypsin inhibitor (ApTI)	Inhibitory activity of papain by trypsin inhibitor (ApTI) in *Callosobruchus maculatus* (Cowpea weevil)	(Macedo *et al.*, 2004)
Mimosaceae	*Adenanthera pavonina* L.	Holy or sacred basil	Seed extract	Leprosy	Trypsin inhibitor (ApTI)	Inhibitory activity of papain by trypsin inhibitor (ApTI) in *Diatraea saccharalis* (Sugarcane borer)	(da Silva *et al.*, 2012)
Asteraceae	*Ageratum conyzoides* L.	Goat weed	Canopy of plant species (above ground plant parts)	Infective hepatitis, eczyma, epilepsy, dizziness, diarrhoea, dysentery, sore, eyes, fever, headaches, intestinal worms, filariasis, vomiting, nausea, wounds and cuts	5, 6, 7, 8, 3', 4', 5'-Heptamethoxyflavone and coumarin	Insecticidal activity of hexane extracts against the *Rhyzopertha dominica* (F.) (Lesser grain borer)	(Moreira *et al.*, 2007)
Asteraceae	*Ageratum conyzoides* L.	Goat weed	Crude hexane extract of aerial parts of *A. conyzoides*	Infective hepatitis, eczyma, epilepsy, dizziness, diarrhoea, dysentery, sore, eyes, fever, headaches, intestinal worms, filariasis, vomiting, nausea, wounds and cuts	-	Repellent, antifeedant and toxic effects against *Helicovepra armigera* (Hübner) (Cotton bollworm)	(Ragesh *et al.*, 2016)
Asteraceae	*Ageratum conyzoides* L.	Goat weed	Crude petroleum ether extract aerial parts of *A. conyzoides*	Infective hepatitis, eczyma, epilepsy, dizziness, diarrhoea, dysentery, sore, eyes, fever, headaches, intestinal worms, filariasis, vomiting, nausea, wounds and cuts	Chromene precocene II, two flavonoids: eupalestin and lucidin dimethyl ether	Insecticidal activity against *Musca domestica* (house-fly-third instar larvae), *Cynthia carye* third, (butterfly-fourth and fifth instar larvae) and *Acanthoscelides obtectus* (Bean weevil)	(Calle *et al.*, 1990)
Agavaceae	*Aloe vera* L.	Aloe, aloe vera	Leaf extract	Treat wounds and burns, sun burns, rashes, x-ray burns and stomach ache	-	Larvicidal activity on first to fourth instars larvae of *Aedes aegypti* (Yellow fever mosquito)	(Subramaniam *et al.*, 2012)
Agavaceae	*Aloe vera* L.	Aloe, aloe vera	Leaf extract	Treat wounds and burns, sun burns, rashes, x-ray burns and stomach ache		Mosquitocidal activity against the *Anopheles stephensi* (Malaria vector)	(Dinesh *et al.*, 2015)

To be continued

Table 2 - Selected medicinal plants reported for its efficiency against the insects (continued)

Family	Scientific names	Common English name	Plant part used	*Traditional Uses in the South Pacific (Treatment)	Active Constituents/Compounds	Efficiency against insects	References
Agavaceae	*Aloe vera* L.	Aloe, aloe vera	Acetone, ethyl acetate, water, and ethanol extracts	Treat wounds and burns, sun burns, rashes, x-ray burns and stomach ache	-	Acaricidal activity against female adults of *Tetranychus cinnabarinus* (Carmine spider mite)	(Wei *et al.*, 2011)
Annonaceae	*Annona muricata* L.	Soursop, custard apple	Crude ethanoic seed extract	Treating stomach ailments	-	Insecticidal activity against the *Spodoptera litura* (leafworm moth) and *Trichoplusia ni* larvae (Cabbage looper)	(Leatemia and Isman, 2004)
Annonaceae	*Annona muricata* L.	Soursop, custard apple	Fruit (pericarp) extract	Treating stomach ailments	Acetogenins -annonacin, annonacin A and annomuricin A.	Cytotoxicity towards the cell line U 937 (model cell line used in biomedical research)	(Jaramillo *et al.*, 2000)
Annonaceae	*Annona muricata* L.	Soursop, custard apple	Ethanoic seed extract	Treating stomach ailments	-	Insecticidal activity against the *Trichoplusia ni* (cabbage looper) and *Myzus persicae* (Green peach aphid)	(Ribeiro *et al.*, 2014)
Meliaceae	*Azadirachta indica* A. Juss.	Margosa, neem, Indian Lilac	Seed water extract	For diabetes, skin diseases, asthma, syphilis and used as insecticide	-	Insecticidal activity against the *Trogodarma granariun* (Khapra beetle)	(Satti *et al.*, 2010)
Meliaceae	*Azadirachta indica* A. Juss.	Margosa, neem, Indian Lilac	Neem oil from seeds	For diabetes, skin diseases, asthma, syphilis and used as insecticide	-	Insecticidal activity against the *Maruca testulalis* Geyer (Mung moth)	(Jackai and Oyediran, 1991)
Meliaceae	*Azadirachta indica* A. Juss.	Margosa, neem, Indian Lilac	Crude ethanol extracts of leaves	For diabetes, skin diseases, asthma, syphilis and used as insecticide	-	Insecticidal activity to adult *Tribolium confusum* (Flour beetle)	(Williams and Mansingh, 1993)
Annonaceae	*Cananga odorata* (Lam.) Hook. F. & Thoms.	Ylang-ylang, Kenanga	Essential oil extracts from flowers	Earaches, toothaches, headaches, stomach aches, boils, skin irritation, coughs and dizziness	-	Fumigant and Repellent toxicity against the *Aleurodicus Dispersus* Russell (Spiralling whiteflies)	(Chand *et al.*, 2016)
Annonaceae	*Cananga odorata* (Lam.) Hook. F. & Thoms.	Ylang-ylang, Kenanga	Essential oil extracts from the leaves	Earaches, toothaches, headaches, stomach aches, boils, skin irritation, coughs and dizziness	-	Insecticidal activity (contact and fumigant toxicity) to *Sitophilus zeamais* (Greater grain weevil)	(Cheng *et al.*, 2012)
Annonaceae	*Cananga odorata* (Lam.) Hook. F. & Thoms.	Ylang-ylang, Kenanga	Essential oil extracts from the leaves	Earaches, toothaches, headaches, stomach aches, boils, skin irritation, coughs and dizziness	-	Insecticidal activity against larvae of *Aedes aegypti* (Yellow fever mosquito)	(Vera *et al.*, 2014)
Solanaceae	*Capsicum frutescens* L.	Chili pepper, red pepper, paprika	Methanol extract of fruits and leaves	Skin tuberculosis, mild conjunctivitis and jaundice, boils and cough	-	Insecticidal activity to 2^{nd} and 3^{rd} instar larvae of *Aedes aegypti* (Yellow fever mosquito)	(Vinayaka *et al.*, 2010)
Solanaceae	*Capsicum frutescens* L.	Chili pepper, red pepper, paprika	Powdered fruits	Skin tuberculosis, mild conjunctivitis and jaundice, boils and cough	-	Discouraging oviposition and minimising damage to leaves of cowpea seeds	(Onu and Aliyu, 1995)

To be continued

Table 2 - Selected medicinal plants reported for its efficiency against the insects (continued)

Family	Scientific names	Common English name	Plant part used	*Traditional Uses in the South Pacific (Treatment)	Active Constituents/Compounds	Efficiency against insects	References
Solanaceae	*Capsicum frutescens* L.	Chili pepper, red pepper, paprika	Ethanolic extract of fruit	Skin tuberculosis, mild conjunctivitis and jaundice, boils and cough	-	Larvicidal activites against *Aedes aegypti* (Yellow fever mosquito) and *Aedes albopictus* (Asian tiger mosquito)	(Alvarez *et al.*, 2015)
Caricacea	*Carica papaya* L.	Papaya, Pawpaw	Hexanic, acetonic and methanolic extracts of seed	Sores, high blood pressure and treat diarrhea	-	Insecticidal activity against the *Spodoptera frugiperda* (Fall armyworm)	(Figueroa-Brito *et al.*, 2011)
Caricacea	*Carica papaya* L.	Papaya, Pawpaw	Leaf extract	Sores, high blood pressure and treat diarrhea	-	Insecticidal toxicity against the *Lipaphis Erysimi* Kal. (Mustard aphids)	(Ujjan *et al.*, 2014)
Caricacea	*Carica papaya* L.	Papaya, Pawpaw	Chloroform seed extract	Sores, high blood pressure and treat diarrhea	Palmitic acid, oleic acid, or stearic acid	Insecticidal and insectistatic activities against the *Spodoptera frugiperda* (Fall armyworm)	(Pérez-Gutiérrez *et al.*, 2011)
Caricacea	*Carica papaya* L.	Papaya, Pawpaw	Chloroform seed extract	Sores, high blood pressure and treat diarrhea	Palmitic acid, oleic acid, or stearic acid	Insecticidal and insectistatic activities against the *Spodoptera frugiperda* (Fall armyworm)	(Pérez-Gutiérrez *et al.*, 2011)
Caricacea	*Carica papaya* L.	Papaya, Pawpaw	-	-	-	Larvicdial and pupicidal activity to the Chikungunya vector, *Aedes aegypti* (Yellow fever mosquito)	(Kovendan *et al.*, 2012)
Fabaceae (Caesalpiniaceae)	*Cassia alata* L (Senna alata)	Ringworm bush, roman candle tree	Ethanoic extracts of leaves	Skin diarrhoea, worms, purifies blood and scabies	-	Acaricidal activity to *Rhipicephalus (Boophilus) annulatus* (Blue cattle tick)	(Ravindran *et al.*, 2012)
Fabaceae (Caesalpiniaceae)	*Cassia alata* L (Senna alata)	Ringworm bush, roman candle tree	Solvent extract of fruits	Skin diarrhoea, worms, purifies blood and scabies	-	Toxic effects against the *Callosobruchus chinensis* L. (Adzuki bean weevil)	(Upadhyay *et al.*, 2011)
Fabaceae (Caesalpiniaceae)	*Cassia alata* L (Senna alata)	Ringworm bush, roman candle tree	Leaf and stem extract	Skin diarrhoea, worms, purifies blood and scabies	-	Larvicidal effect on *Anopheles gambiae* (African malaria mosquito), *Culex quinquefasciatus* (Southern house mosquito) and *Aedes aegypt* (Yellow fever mosquito)	(Edwin *et al.*, 2013)
Apiaceae	*Centella asiatica* (L.) Urban	Indian pennywort, Asiatic pennywort	Leaf extract	Dysentery, fever, headache, diarrhea, pimples, rashes, itchy lumps, Fractures, migraines and boils	-	Larvicidal and Adult emergence Inhibition Effect against Mosquito *Culex quinquefasciatus* Say (Southern house mosquito)	(Rajkumar and Jebanesan, 2005)
Apiaceae	*Centella asiatica* (L.) Urban	Indian pennywort, Asiatic pennywort	Leaf extract	Dysentery, fever, headache, diarrhea, pimples, rashes, itchy lumps, Fractures, migraines and boils	-	Larvicidal and adulticidal activities against the Malarial Vector - *Anopheles stephensi* (Asian malaria mosquito)	(Senthilkumar *et al.*, 2009)
Apiaceae	*Centella asiatica* (L.) Urban	Indian pennywort, Asiatic pennywort	Leaf extract (hexane, diethyl ether, dichloromethane, and methanol)		-	Larvicidal activities against different strains of *Aedes aegypti* (Yellow fever mosquito) and *Anopheles stephensi* (Asian malaria mosquito)	(Nair *et al.*, 2014)

To be continued

Table 2 - Selected medicinal plants reported for its efficiency against the insects (continued)

Family	Scientific names	Common English name	Plant part used	*Traditional Uses in the South Pacific (Treatment)	Active Constituents/Compounds	Efficiency against insects	References
Rutaceae	*Citrus aurantium* L.	Seville or sour orang	Fruit extract	Headache, abdominal pain and urinary tract infections	-	Insecticidal activity against the adult *Bactrocera oleae* (Gmelin) (Olive fruit fly)	(Siskos *et al.*, 2007)
Rutaceae	*Citrus aurantium* L.	Seville or sour orang	Leaf extract	Headache, abdominal pain and urinary tract infections	-	Insecticidal activity against the adult *Bactrocera oleae* (Gmelin) (Olive fruit fly)	(Siskos *et al.*, 2007)
Rutaceae	*Citrus aurantium* L.	Seville or sour orang	Shoot extract	Headache, abdominal pain and urinary tract infections	-	Insecticidal activity against the adult *Bactrocera oleae* (Gmelin) (Olive fruit fly)	(Siskos *et al.*, 2007)
Rutaceae	*Citrus sinensis* (L.) Osbeck	orange, sweet orange	Essential oils from fruits	Sickness, abdominal pains and remedies for internal ailments	D-limonene	Larvicidal and pupicidal activities against *Musca domestica* L. (Housefly)	(Kovendan *et al.*, 2012)
Rutaceae	*Citrus sinensis* (L.) Osbeck	orange, sweet orange	Peels from fresh oranges	Sickness, abdominal pains and remedies for internal ailments	-	Insecticidal activity against mosquito, cockroach and housefly	(Ezeonu *et al.*, 2001)
Rutaceae	*Citrus sinensis* (L.) Osbeck	orange, sweet orange	Essential oils from the seeds	Sickness, abdominal pains and remedies for internal ailments	-	Insecticidal activity against the *Tribolium Castaneum (Herbst)* (Red flour beetle)	(Hussain *et al.*, 2013)
Zingiberaceae	*Curcuma longa* L.	turmeric	Leaf essential oils	Painful skin, sores and rashes in infant, sprains, bruises, eye diseases and open wounds, Colds and runny nose, dysentery and infected puncture wounds	-	Contact and fumigant toxicity against *Rhyzopertha dominica* F. (Lesser grain borer), *Sitophilus oryzae* L. (Rice weevil), and *Tribolium castaneum* Herbst (Red flour beetle)	(Tripathi *et al.*, 2002)
Zingiberaceae	*Curcuma longa* L.	turmeric	Turmeric rhizome oils	Painful skin, sores and rashes in infant, sprains, bruises, eye diseases and open wounds, Colds and runny nose, dysentery and infected puncture wounds	-	Repellency and feeding deterrent effects of Turmeric oils against the *Rhyzopertha dominica* (F.) (Lesser grain borer)	(Jilani and Saxena, 1990)
Zingiberaceae	*Curcuma longa* L.	turmeric	Leaves		α-turmerone and β-turmerome	Larvicidal activity on *Anopheles gambiae* (African malaria mosquito)	(Ajaiyeoba *et al.*, 2008)
Zingiberaceae	*Curcuma longa* L.	turmeric	Rhizomes			Larvicidal activity on *Anopheles gambiae* (African malaria mosquito)	(Ajaiyeoba *et al.*, 2008)
Fabaceae	*Erythrina variegata* L.	Coral tree	Ethanoic extracts from root and bark	Filariasis, stomach ache and fever	-	Contact toxicity and antifeedant activities against the *Spodoptera exigua* (Beet armyworm)	(Feng *et al.*, 2012)
Fabaceae	*Erythrina variegata* L.	Coral tree	Leaf extract using solvents	Filariasis, stomach ache and fever	-	Antifeedant and toxicity against the *Spodoptera litura* (Fab) (Taro caterpillar)	(Thushimenan *et al.*, 2016)

To be continued

Table 2 - Selected medicinal plants reported for its efficiency against the insects (continued)

Family	Scientific names	Common English name	Plant part used	*Traditional Uses in the South Pacific (Treatment)	Active Constituents/Compounds	Efficiency against insects	References
Fabaceae	*Erythrina variegata L.*	Coral tree	Methanoic leaf extracts	Filariasis, stomach ache and fever	-	Larvicidal activity of *Culex quinquefasciatus* (Southern house mosquito)	(Nazar *et al.*, 2009)
Cucurbitaceae	*Momordica charantia* L.	Bitter gourd, balsam pear, balsam apple	Leaf extract	Leprosy and malignant ulcers, stomach worms, fever, hypertension, diabetes and dysentery	-	Insecticidal activities of *Sitophilus zeamais* (Greater grain weevil)	(Adesina, 2013)
Cucurbitaceae	*Momordica charantia* L.	Bitter gourd, balsam pear, balsam apple	Acetone, *n*-hexane, and methanol extract of leaves	Leprosy and malignant ulcers, stomach worms, fever, hypertension, diabetes and dysentery	-	Toxicity and repellent activity against the *Callosobruchus maculatus* (Fab.) (Cowpea weevil). The order of extract toxicity was *n*-hexane> methanol >acetone	(Ajayi, 2015)
Cucurbitaceae	*Momordica charantia* L.	Bitter gourd, balsam pear, balsam apple	Methanoic fruit extracts	Leprosy and malignant ulcers, stomach worms, fever, hypertension, diabetes and dysentery	-	Larvicidal effects on *Culex pipiens* (Northern house mosquito)	(Nagappan and Gomathinayagam, 2014)
Passifloraceae	*Passiflora foetida* (L.) var. *hispida* (DC.) Killip	Wild passion fruit	Leaves and the sterm	Improve fertility in women	-	Repellent effect against the hematophagous insects	(Obico and Ragragio, 2014)
Psilotaceae	*Psilotum nudum* (L.) P. Beauv.	Psilotum	Aerial extract	Pain relief and remedy for thrush and the spore	Psilotin [6-(4'-β glucopyranosyloxyphenyl)-5,6-dihydm-2-oxo-2H-pyran]	Feeding deterrent and growth reducer to *Ostrinia nubilalis* (European corn borer)	(Arnason *et al.*, 1986)
Verbenaceae	*Vitex trifolia* L.	Vitex	Leaf extract	Stomach pains and mouth infections	-	Larvicidal activity on *Culex quinquefasciatus* (Southern house mosquito)	(Kannathasan *et al.*, 2007)
Verbenaceae	*Vitex trifolia* L.	Vitex	Hexanic and dichloromethanic (DCM) extracts of leaves and stems	Stomach pains and mouth infections	-	Antifeeding activity against the insect pest *Spodoptera frugiperda* (Fall armyworm)	(Hernández *et al.*, 1999)
Verbenaceae	*Vitex trifolia* L.	Vitex	Leaves and stem bark extracts	Stomach pains and mouth infections	-	Larvicidal activity on *Anopheles gambiae* (African malaria mosquito)	(Nyamoita *et al.*, 2013)

tics of most active families are discussed below.

Lamiaceae family. Lamiaceae family is also known as mint family that has strong aromatic essential oils, tannins, saponins and organic acids (Raja, 2012). Numerous insecticidal properties on a wide range of insect species have been reported from extracts obtained from the Lamiaceae family. For instance, biological activities of *Ocimum basilicum* L., *Mentha rotundifolia* L., *Origanum vulgare* L. ssp. vulgare, *Rosmarinus officinalis* L. and *Thymus vulgaris* L. have been reported against the first instar larvae of *Tribolium castaneum* Herbst (Coleóptera, Tenebrionidae) (Clemente *et al.*, 2003). Likewise, the extracts of *Plectranthus glandulosus* against the *Callosobruchus maculatus* in cowpea showed 100% mortality at 4 g/kg, within 7 days with LC_{50} of 0.39 g/kg (Danga *et al.*, 2015). The leaf extracts from Lamiaceae family have also shown post-harvest grain protectants efficacy (Nukenine *et al.*, 2007; 2011; 2013). Similarly, Bekircan *et al.* (2014) reported the antifeedant activity of *T. transcaucasicus* , *T. pseudopulegioides*, *T. leucotrichus* and *Teucrium poli-*

um L., against *Agelastica alni* L. (Coleoptera: Chrysomelidae larvae). Overall, the Lamiaceae family has an extensive range of biological activities including cytotoxic, antimicrobial, antioxidant, anti-inflammatory, hypotensive and insecticidal properties (Božović *et al.*, 2015).

Annonaceae family. Annonaceae is the largest family in the order Magnoliales and consist of 2500 species and 130 genera (Pirie *et al.*, 2005; Westra and Maas, 2012). The Annonaceae family has drawn attention since 1980s among the terrestrial plant families as a result of acetogenins that are known for a broad range of insecticidal bioactivities (Isman and Seffrin, 2014). The species of Annonaceae family such as *Asimina triloba*, *Annona muricata*, and *A. squamosa* L. are frequently considered for insecticidal activities against *Spodoptera frugiperda*, *Plutella xylostella*, *Aedes aegypti*, and stored grain insects (Isman and Seffrin, 2014). The fruit extract of *Xylopia aethiopica* and *Dennettia tripetala* were reported to have an insecticidal effect against *Sitophilus oryzae* (Coleoptera: Curculionidae). The larvicidal, ovicidal and pupicidal properties against *Aedes aegypti* have been reported using benzene, chloroform, ethyl acetate and methanol extracts of *A. reticulata* L. Nevertheless, the leaf and stem extracts of *A. coriacea* Mart., *A. crassiflora* Mart., *Duguetia furfuracea* (A. St.-Hil.) Saff. and *Xylopia aromatica* L. were reported for their phytotoxic effects on germination of lettuce, tomato and onion seeds (Novaes *et al.*, 2016).

Rutaceae family. Murraya koenigii (L) Spreng leaf extract resulted in high mortality, population reduction with delay in development of *Tribolium castaneum* - pest of stored wheat (Gandhi *et al.*, 2010). Furthermore, as reported by Arivoli *et al.* (2015), the hexane extracts of *M. koenigii* showed not only larvicidal activitiy against the vector mosquito's i.e., *A. aegypti*, *Anopheles stephensi* and *Culex quinquefasciatus* but also they demonstrated that one of the six fractions obtained from the residue of hexane extract, had an effect against the third instar larvae of *A. aegypti, C. quinquefasciatus* and *A. stephensi* with a percentage of mortality of 100.0, 97.6 and 99.2%. The methanolic leaf extracts of *Atlantia monophylla* were evaluated for pupicidal activities against *C. quinquefasciatus, A. stephensi, and A. aegypti* under laboratory conditions and the respective lethal values corresponding to LC_{50} of 0.07, 0.05, and 0.07 mg/l (Sivagnaname and Kalyanasundaram, 2004). The *Zanthoxylum rhoifolium* leaves also showed insecticidal activities in *Bemisia tabaci* populations (Christofoli *et al.*, 2015). Phytochemical survey of Rutaceae family reveals the presence of flavonoids, alkaloids, limonoids, coumarins and volatile oils, of which some are associated with insecticidal activity (Rajkumar and Jebanesan, 2008; Emam *et al.*, 2009; Supabphol and Tangjitjareonkun, 2014).

Meliaceae family. Natural products of Meliaceae family such as Limonoids have biological activities against several insects. One compound widely known and commercialised is azadirachtin reported to hold antifeedant and growth-regulating properties (Champagne *et al.*, 1989). The azadirachtin compound inhibits the feeding, growth and survival of the variegated cutworm such as *Peridroma saucia*, with an EC_{50} and LC_{50} of 0.36 and 2.7 ppm in diet (Champagne *et al.*, 1989). The fruit extracts of *Trichilia elegans* and *T. catigua* revealed insecticidal activity on *Spodoptera frugiperda* (fall armyworm) (Matos *et al.*, 2009). *Azadirachta indica* A. Juss (neem derivatives) was known to used traditionally as an insecticide in the South Pacific (World Health Organization, 1998).

Modes of action of plant extract components

Natural plant products show different mode of actions mainly due to chemical components acting differently, resulting into contact toxicity, stomach poison and systemic activities if used in soils or injected on plants (Upadhyay, 2016). For instance, different plant extracts such as armoise, clary sage, oregano, lemongrass, niaouli, spearmint, cassia especial, dalmatian sage, red thyme, bay, garlic, pennyroyal, cassia pure, white thyme, cassia redistilled, star anise, peppermint, wintergreen, and cinnamon bark oils have shown potent fumigant toxicity against the *C. corticalis* (Kim *et al.*, 2012). These volatile substances affect the insect's nervous system. The nervous system is the control center of the body that transduces the activity of nerves into behaviour. The nerve cells act upon external cues (smell, taste, touch, hearing and light) as well as internal inputs from sources such as hormones, body temperature and limb position sensors in order to create control coordination in insects behaviour (Salgado, 2013). The fine-tuned control system of these insects is disrupted by the volatile nature of plant extracts when applied.

The plants extract lead to the poisoning of insects whereby certain cells show alternation of staining properties; while some cells can breakdown (cytolysis) in tissues. Similarly, within the nucleus the chromatin granules result into pyknosis (clump together) and the Nissl bodies (granular substances) which dissolves the nerve cells (Tanada and Kaya, 1993; Satar *et al.*, 2008). The symptoms of nerve poisons are divided in four stages: excitation, convulsion, paralysis and death. The neurotoxic fumigant results only in three stages: excitation, paralysis and death (Tanada and Kaya, 1993). The disturbance of nervous system in the insects often affects the respiratory, muscular and circulatory systems. As a result of disturbance or malfunction in the metabolic system the insect dies. In addition, the two common potential mode of action of essential oil components are discussed below.

Acetylcholinesterase. Acetylcholine (ACh) is one of the major compounds that are responsible for transmitting nerve impulses from different nerve cells and involuntary muscles. Acetylcholine is denatured by the enzyme Acetylcholinesterase (AChE) to choline and acetate and when Ach is released from synaptic vesicles depolarises the postsynaptic cell membrane. A result of the AChE activity is the regulation of the nerve impulse across the cholinergic synapses (Siegfried and Scott, 1992; López and Pascual-Villalobos, 2010). In other words, the inhibition activity of AChE activity generates the accumulation of neurotransmitters acetylcholine in neuronal synapses which creates a state of permanent stimulation resulting into lack of coordination in the neuromuscular system followed by the subsequent death of insect (Fig. 3) (Dambolena *et al.*, 2016).

Monoterpenoids were the first inhibitors that were considered to have the anticholinesterasic properties. The inhibition of AChE in stored-product insect pests, *Sitophilus oryzae* L. (Coleoptera: Curculionidae), *Rhyzopertha dominica* Fabricius (Coleoptera: Bostrichidae) and *Cryptolestes pusillus* Schönherr (Coleoptera: Cucujidae) is a possible mode of action from monoterponoids such as linalool, camphor, γ-terpinene, geraniol, *S*- carvone, *E*-anethole, fenchone and estragole (López and Pascual-Villalobos, 2010). For instance, 1,8-cineole (monoterpene) is found to be the best inhibitor of Acetylcholinesterase activity (IC_{50} values 0.015 - 0.05 mg/mL) (Picollo *et al.*, 2008; Dambolena *et al.*, 2016).

Octopaminergic sites. Octopamine, phenolic analogue of noradrenaline, is also present in the nervous system of the arthropods. There is some evidence that octapamine plays a role in neuromuscular transmission or rather possess a modulating influence on the nerve-muscle interaction (Candy, 1978; Enan, 2001). Octapamine act as neurotransmitters, neurohormones and neuromodulators in nervous system of inverterbrates (Kostyukovsky *et al.*, 2002). In insects, octopamine induces hyperextension of legs and abdomen due to the increased frequency of excitatory postsynaptic potentials from abdominal motor neurons (Harris-Warrick *et al.*, 1980; Livingstone *et al.*, 1980). Octopamine is likely to be involved in the regulation of heartbeats in insects since it is released in the axon terminals of pericardial organs (Evans *et al.*, 1976).

Octopamine exerts the effects through octopamine-1 and octopamine-2 receptors throughout their union with G-protein-coupled receptors (Dambolena *et al.*, 2016). For instance, carvacrol compound was found to change the conformation of the endogenous G-protein by increasing the affinity (Dambolena *et al.*, 2016). Likewise, a blockage of octopamine receptors binding sites was noted at the lowest concentration of the eugenol, α-terpineol and cinnamic alcohol resulting in decreased biding of $[^3H]$octopamine to its receptors (Enan, 2001).

The compounds such as octopamine and acetylcholine (accumulated in the nerves) in insects have diverse biological roles. Octopamine and acetylcholine compounds function as neurotransmitters (Fig. 3). If these compounds get interrupted by any

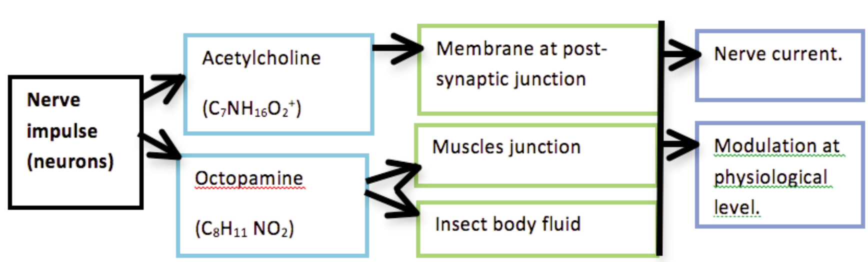

Fig. 3 - Target sites in insects as possible neurotransmitter mediated toxic action of volatile plant extracts. Adapted from: Tripathi *et al.* (2009)

chance, then it results in the damage of nervous system of the insects.

Plant extracts have long been touted as a potential alternative to synthetic insecticides presumably because of less environmental and human health impacts (Kostyukovsky *et al.*, 2002). The extracts form an impermeable film when applied on crops, which covers the insect from the air. The formation of the covering results in suffocation with the consequent death in insects (Li *et al.*, 2014). In addition, Tripathi *et al.* (2009) reported that volatile components of plant extracts such as monoterpenes have cytotoxic effects on tissues of living organisms. For example, the reduction in the intact mitochondria and golgi bodies, impairing respiration and reducing cell membrane permeability. The overall effect of plant extracts led to disruption, dissolution of cell membranes, and blockage of tracheal system of insects (Isman and Machial, 2006; Tehri and Singh, 2015).

3. Conclusions

Bio-control has been long touted as an attractive alternative over synthetic methods for the insect management. The current review has showed that out of the 19 plants selected, only *Azadirachta indica* A. Juss (neem derivatives) was known to be used traditionally as an insecticide in the South Pacific (World Health Organization, 1998).

Although essential oils are gaining momentum in market due to their environmental friendly pesticidal properties, there are few disadvantages of essential oils. Firstly, the use of essential oil in industrial farming may be not very popular mainly due to essential oils being more expensive and its less available. Secondly, the effect of separate chemical composition of essential oils is studied and trialled on insects, however, every little study concerning combined effects of essential oils is known mainly due to high level of difficulty in identifying the effectiveness (Regnault-Roger *et al.*, 2012). Thirdly, the use of essential oils for pest control is known from ancient times however only few are known to be available in commercialized market (Park and Tak, 2015).

Nevertheless, essential oils play a very important role in non-synthetic farming where the environmental safety is the primary concern (Isman, 2000). Although economically, synthetic chemicals are more often used then the plant extracts, these botanicals have the potential of providing efficient and safer approach for the environment as well as for humans (Nerio *et al.*, 2010; Pandey *et al.*, 2014).

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