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Insecticidal and antifungal chemicals produced by plants. A review

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ABSTRACT

Leaf-cutting ants (tribe of Attini) are one of the most important pest species of agricultural and forestry productions in the New World and economic losses caused by these ants were estimated at several million dollars per year. These ants need to live in symbiosis with a basidiomycete fungus, and due to their mutualistic interaction with the symbiotic fungus, management of Attini ants may be considered at the insecticidal or at the fungicidal level, individually, or as a combination of both strategies to increase the efficiency of an integrated control. Until now, synthetic pesticides were the main control mean for these ants, but with high injurious effects on the environment. Very few studies deal with alternative methods for the control of leaf-cutting ants including the use of insecticidal and fungicidal plants extracts. There is then a need of knowledge on phytochemicals and plants that can be possibly used as general insecticides and fungicides.

Here we review chemicals of plant origin and species with insecticidal and fungicidal activities in order to establish a listing of plants and phytochemicals, which can possibly manage leaf-cutting ants, but also other groups of insects that utilize fungus-based agriculture or any insects or fungi pests. An exhaustive literature search of 1965 references (from 1923 to 2010) was conducted using scientific databases, chemical databases, botanical databases and books to identify published papers related to insecticidal and fungicidal chemical compounds stemmed from plant species. The major points are the following: 1) 119 and 284 chemical compounds have been cited in the literature as to have respectively insecticidal and fungicidal activities; 2) 656 and 1064 plant species where identified as to have respectively significant insecticidal and fungicidal activities; 3) 3 main chemical classes were most cited for these activities: alkaloids, phenolics, and terpenoids; 4) 20 interesting chemicals with the both activities were found; and 5) 305 plant species containing these chemicals were cited.
In conclusion, the data presented in this study showed that 20 interesting chemicals (caryophyllene oxide, cinnamaldehyde, eugenol, helenalin, linalool, menthone, myristicin, pulegone, thymol, anethole, anisaldehyde, elemicin, isopimpinellin, plumbagin, podophyllotoxin, psoralen, xanthotoxin, anonaine, solamargine, and tomatine), 2 notable plant families (Lamiaceae and Apiaceae), and 17 species of these families were particularly interesting for leaf-cutting ants’ pest-management.

**Key Words**
Insecticide, fungicide, plants phytochemicals, natural pesticides, *Attini* ants, integrated pest management, environmental chemistry, green chemistry.
1. Introduction

1.1 Consequences of synthetic chemical pesticides

Insect pest management is nowadays a worldwide ecological challenge mainly due to environmental pollution caused by extensive use of synthetic chemical pesticides (Rattan 2010). Synthetic pesticides have been used since 1945 in order to reduce crop damages due to plant pathogens. However, the use of pesticides has some detrimental consequences on environment, such as groundwater pollution, river eutrophication, soil erosion, excessive water use, and the development of weeds and diseases resistant to chemical control (Lichtfouse et al. 2009). It also has negative impact on health with human poisonings and their related illnesses. In 1997, the United Nations Environmental Program estimated that 26 million persons suffer from pesticide poisoning each year, around 3 million persons were hospitalized due to pesticides, and about 220,000 persons died due to pesticide poisonings (Paolletti and Pimentel 2000). In the French West Indies, organochlorine insecticides that were used to control banana weevils (Cosmopolites sordidus) and leaf-cutting ants (Acromyrmex octopinosus) were responsible for long-term pollution of soils, river water, wild animals, and vegetables cultivated in polluted zones. These pesticides also were shown to cause hepatic tumors in laboratory and probably increased the risk of prostate cancer (Multigner et al. 2010).

1.2 Major herbivores in the Neotropics: leaf-cutting ants

Ants represent the half of the global insect biomass and leaf-cutting ants are a high percentage of the worldwide ant societies (Benckiser 2010). Leaf-cutting ants, also called ‘Gardening ants’ (tribe Attini, genera Acromyrmex and Atta) (photo 1), are among the most damaging invertebrates in the Neotropics (Fowler 1978). Their geographic distribution ranges from southern United States to northern Argentina, including the West Indies (Bacci et al. 2009). Because of their voraciousness and the large amount of plant material they collect, these ants cause substantial losses to agricultural and forestry productions. Some nests of the Attini tribe may contain millions of workers and consume hundreds of kilograms of leaves per year (Mikheyev 2008). Economic losses caused by these ants were estimated at several million dollars per year (Bacci et al. 2009). Consequently, they are considered as the major herbivore in the Neotropics, the main agricultural pest of the New World and the most important pest species in South America (Mikheyev 2008; Erthal et al. 2004).

Photo 1 Workers of a leaf-cutting ant, Acromyrmex octopinosus (Reich) (left to right: minor, medium and major workers). © I. Boulogne
There is a binding mutualistic symbiosis between *Attini* ants and a Basidiomycota fungus cultivar (Mikheyev 2008). Several authors suggested that a unique fungus species (*Leucocoprinus gongylophorus* (Heim) Moeller) (photo 2) is cultivated by the *Attini* according to observations on *Acromyrmex* and *Atta* nests and DNA analysis studies (Silva-Pinhati et al. 2004; Silva-Pinhati et al. 2005). The fungus grows inside the nests on parts of plants (leaves, flowers,...) collected by the ants. This is an obligate relationship where the fungus metabolizes polysaccharides, such as xylan, starch, pectin, and cellulose, derived from the plants, into nutrients assimilable by the ants; in return, the ants protect the fungus from parasites and potential competitors. The fungus is the unique food source for the ant queens, male ants, larvae and nymphs and supplements the plant sap diet of adult workers (Silva et al. 2006). A colony of ants is composed of various castes of workers, which cooperate, in the nest, in an ‘assembly line’ mode. The major workers cut and bring the vegetation back to the nest. They are also known as foragers and porters. The medium-sized workers cut the plant material into smaller pieces. The smallest workers (the gardeners) implant fungal strands by applying their own fecal material on these pieces of plant material and care for the fungus as it grows. Strong relationships between ants and fungus are obvious; they are schematized in figure 1.

**Photo 2** Symbiotic fungus of leaf-cutting ants, *Leucocoprinus gongylophorus* (Heim) Moeller. © I.Boulogne

**Figure 1** Relationships between ants and symbiotic fungus (*Leucocoprinus gongylophorus*) in leaf-cutting ants (*Acromyrmex* and *Atta*) nests.
Synthetic chemical pesticides have been used worldwide, and some are still recommended, for the control of leaf-cutting ants, with no success in eradication of the pest, but causing irreversible environmental injuries (Antunes et al. 2000). Pesticides against these leaf-cutting ants have essentially focused on the use of insecticides targeted at the major ant workers. Among these pesticides, we can quote perchlordecone, sulfluramid, heptachlor, malathion, chlorpyrifos, sulfluramid and fipronil (Paoletti et al. 2000; Camargo et al. 2006; Forti et al. 2007). Some of them like sulfluramid and fipronil are still frequently and worldwide used despite of their impact on human health and environment.

1.3 Natural pesticides

Many plants produce biologically active metabolites. Some of which are useful as, for example, insecticide agent or insect control agent. Thus, plants constitute a vast untapped reservoir for discovering new active natural products. Applying biopesticides should decrease both pest development and the use of toxic pesticides (Lichtfouse et al. 2009). Natural products are known to be environmentally safe; they can be then a viable alternative to the use of synthetic products that can be harmful toward the environment (Regnault-Roger et al. 2003). Because of their non-phytotoxicity and systemicity as well as biodegradability, plant-derived products can be potent and valuable reagents in pest management (Javaid et al. 2006; Xuan et al. 2006; Ameziane et al. 2007). These phytochemicals are mainly biodegradable and, more importantly, they are renewable. The efficient use of such renewable natural resources is becoming increasingly an important worldwide concern (Kubo 1993) and nowadays, the green and environmental chemistry has an international success (Lichtfouse et al. 2011). Applying these biopesticides should also be an economical strategy for farmer because besides being less pollutant, they are less expensive than synthetic pesticides.

Natural insecticides and fungicides may serve as alternatives to synthetic compounds to develop safer control agents of leaf-cutting ants, as shown by some precedent studies conducted on lignans of Myristicaceae (Pagnocca et al. 1996), ricine of *Ricinus communis* (Bigi et al. 2004), amides of Piperaceae (Pagnocca et al. 2006; De Paula et al. 2000), rotenoids of *Lonchocarpus* sp (Petit 2004) or TRAMIL’s plant extracts (Boulogne 2011; Boulogne et al. 2011).

Due to their mutualistic interaction with the symbiotic fungus, management of *Attini* ants may be considered at the insecticidal or at the fungicidal level, individually, or as a combination of both strategies to promote a more efficient integrated control. In the literature, there is a lack of information available on molecules and plants that can be possibly used as general insecticides and fungicides. The aim of this paper was to establish a list of plants and chemicals that can possibly be used for best management of leaf-cutting ants, based on the literature available. Plant species with both insecticidal and antifungal chemicals properties were voluntarily favored here. The present work, which lies within the scope of sustainable development, aim at selecting plants whose chemicals can be potentially used to control leaf-cutting ants that devastate the crops in many tropical areas. This review could also help for management of other groups of insects that utilize fungus-based culture like ambrosia beetles and termites or any insects and fungi pests. It deals with ecological pest control and biopesticides from plants origin.

An exhaustive literature search of 1965 references (from 1923 to 2010) was conducted using scientific databases (Sciencedirect, Springerlink and Wiley), chemical databases (Amicbase 2010; Duke 2010), botanical databases (Tropicos 2010) and books (Duke 1992; Bruneton 1999) to identify published papers related to insecticidal and fungicidal chemical compounds stemmed from plant species. Information was further analyzed to select plant species, plant families and chemicals worthy in pest-management of leaf-cutting ants.

2. Insecticidal Activity

2.1 Chemical Compounds
So far, 119 chemical compounds have been cited in the literature as to have an insecticidal activity. These chemicals compounds were distributed in 11 types (Figure 2). Among these 11 types, 3 were identified as holding strong insecticidal activity: the terpenoids (43 chemical compounds), the alkaloids (38 chemical compounds), and the phenolic compounds (21 chemical compounds) counting for 37, 30, and 20% of the chemicals cited, respectively (Table 1).

**Figure 2** Frequency (%) of chemical compounds types in plants with insecticidal activity (data obtain from literature search of 1965 references). Terpenoids, alkaloids and phenolic compounds were the most regularly cited as holding insecticidal activity with respectively 37, 30, and 20% of the chemicals.

**Table 1**: Terpenoids, alkaloids and phenolic compounds produced by plants with insecticidal activity (data obtain from literature search of 1965 references).

| Terpenoids       | Alkaloids       | Phenolic compounds |
|------------------|-----------------|--------------------|
| β-amyrine        | 5-hydroxytryptamine | methole           |
| β-asarone        |aconine          |anisaldehyde       |
| α-pinene         |aconitine        |asarin              |
| α-terpinene      |ajaxonine        |bergapten           |
| α-terpineol      |anabasine        |caneline            |
| α-thujone        |anonaime         |deguelin            |
| 10-hydroxy-asimicine | aphylline    |deoxyxpodophyllotoxin |
| 24-methylene-3,22-dihydroxycholesterol | aristolochine |deoxyxpodophyllotoxin |
| 24-methylene-cholesta-3-ol | atropine     |dillapiol           |
| absinthin        |benzaconine      |elemicin            |
| apiole           |caffeine         |isopimpinellin      |
| ascaridol        |camptothecin     |mannmein            |
| asimicine        |castanospermine  |methyl-chavicol     |
| azadirachtin     |celabenzine      |methyl-cinnamate    |
| bisabolangelone  |cevadine         |plumbagin           |
| Carvone | Ephedrine | Podophyllotoxin |
|---------|-----------|-----------------|
| Delcosine | Delsoline | Psoralen |
| Caryophyllene-oxide | Donaxerine | Rotenone |
| Cinnamaldehyde | Galanthamine | Rutin |
| Estragole | Gramine | Xanthotoxin |
| Eugenol | Hyppaconitine | |
| Gedunine | Jervine | |
| Geranyl-linalool | Mescanitine | |
| Glucarubrinone | Myosmine | |
| Helenalin | Napelline | |
| Himachalol | Neoline | |
| Iridomyrmecin | Neopelline | |
| L-carvone | Nicotine | |
| Limonene | Physostigmine | |
| Limonene-oxide | Piperine | |
| Linalool | Ricinine | |
| Menthone | Solamargine | |
| Myristicin | Solasonine | |
| Nerifolin | Sparteine | |
| Ocimene | Tomatine | |
| Picrotoxinin | Wilfordine | |
| Piperitenone-oxide | Wilforine | |
| Pulegone | | |
| Quassin | | |
| Terpineol | | |
| Thymol | | |
| Zingiberene | | |

2.2 Plant Families

Similarly, 656 plant species worldwide, distributed into 110 families, where identified as to have a significant insecticidal activity. The most cited family is the Lamiaceae, with 181 species distributed into 48 genera, counting for 28% of the plant families with an insecticidal activity (Figure 3). Within this family nine genera were the most often cited: *Pycnanthemum, Teucrium, Thymus, Satureja, Micromeria, Origanum, Mentha, Monarda*, and *Ocimum*.

**Figure 3** Frequency (%) of plant families with insecticidal activity (plants families presented have a frequency over or equal to 1%). The most cited family is the Lamiaceae counting for 28% of the plant families cited.
3. Fungicidal Activity

3.1 Chemical Compounds

From the literature, 284 chemical compounds distributed in 11 types have fungicidal activity. Of these chemical compounds types, three were the most regularly cited: the phenolic compounds (47% of the chemicals cited), the terpenoids (29% of the chemicals cited), and the alkaloids (11% of the chemicals cited) (Figure 4).

123 phenolic compounds, eighty terpenoids and thirty alkaloids with fungicidal activity were mentioned in the literature (Table 2).

Figure 4 Frequency (%) of chemical compounds types with fungicidal activity (data obtained from literature search of 1965 references). Phenolic compounds (47%), terpenoids (29%), and the alkaloids (11%) were the most regularly cited.
Table 2: Terpenoids, alkaloids and phenolic compounds produced by plants with fungicidal activity (data obtained from literature search of 1965 references)

| Phenolic compounds | Terpenoids | Alkaloids |
|--------------------|------------|-----------|
| ε-viniferin        | α-bisabolol| α-chaconine|
| 2,6-dimethoxy-p-benzoquinone | α-hederin | α-solanine |
| 2′-hydroxygenistein | β-ionone | 4-methoxybrassinin |
| 5-methoxy-psoralen  | α-phellandrene | actidione |
| 6-α-hydroxyzaackiain | β-phellandrene | alstonine |
| 6-α-hydroxymedicarpin | 1-tuliposide-B | amphibine |
| 8-methoxy-psoralen  | 1,8-cineole | anonaine |
| aloe-emodin         | 1-tuliposide-A | arecoline |
| amentoflavone       | acetophenone | berberastine |
| anacardic acid      | agropyrene | berberine |
| anethole            | alantolactone | canthin-6-one |
| anisaldehyde        | anemonin | chelestrychine |
| baicalein           | arteannuin-B | dehydroglucine |
| benzoic-acid        | asarone | dictamine |
| biochanin-A         | ascaridole | emetine |
| caffeic-acid        | atractyloid | frangufoline |
| cajinin             | bayogenin | isoboldine |
| catechin            | borneol | jatrohrrhizine |
| chavicol            | butyl-phthalide | liriodenine |
| chlorogenic acid    | camphor | methoxybrasitin |
| chrysarobin         | capsidiol | reticulin |
| chrysin             | carene | rubijervine |
| chrysophanic acid   | carnosol | sanguinarine |
| chrysophanic-acid-9-anthrole | carvacrol | serpentine |
| Chemical Name                  | Chemical Name                  | Chemical Name                  |
|-------------------------------|-------------------------------|-------------------------------|
| cinnamic acid                 | caryophyllene                 | solamargine                   |
| cis-3,5,4′-trihydroxy-4-isopentenylstilbene | caryophyllene-oxide          | solanine                       |
| cis-resveratrol               | casabene                      | theaflavin                     |
| coumestrol                    | cinnamaldehyde                | solasodine                     |
| curcumin                      | cis-octimene                  |                              |
| cyclopentetrene               | citral                        | tomatine                       |
| daidzein                      | citronellal                   | tryptanthrin                   |
| daidzin                       | citronellol                   |                              |
| demethylyvesotrol             | cnidilide                     |                              |
| dihydropinansylvic            | coniferyl-alcohol             |                              |
| elemicin                      | cornellamarosite              |                              |
| esculetin                     | cuminaldehyde                 |                              |
| falcariindiol                 | dehydroisoeugenol             |                              |
| ferulic acid                  | epipolygodial                 |                              |
| flavone                       | escin                         |                              |
| formononetin                  | eugenol                       |                              |
| furocoumarin                  | fulvoplumierin                |                              |
| genistein                     | gentiopicroxin               |                              |
| genistin                      | geraniol                     |                              |
| glyceollin-I                  | glutinosone                   |                              |
| glycitein                     | gossypol                     |                              |
| herniarin                     | hardwickic acid               |                              |
| homogentisic acid             | hederagenin                   |                              |
| homopisatin                   | hederasin-p-C                |                              |
| honokiol                      | helenanin                    |                              |
| humulone                      | isosalantolactone             |                              |
| hydroxyphaseollin             | kawain                         |                              |
| isoliquiritin                 | linalol                       |                              |
| isomucronulatol               | medicagenic-acid              |                              |
| isopimpinellin                | menthone                      |                              |
| isoxanthohumol                | methyl Eugenol                |                              |
| juglone                       | muzigadial                    |                              |
| kaempferol                    | myrcene                       |                              |
| kievitone                     | myristicin                    |                              |
| kuwanon-G                     | nimbidin                      |                              |
| kuwanon-H                     | nimbin                        |                              |
| lapachol                      | paeonol                       |                              |
| lawsone                       | parthenolide                  |                              |
| licoisoflavone-A              | patchouli-alcohol             |                              |
| liquiritiginin               | p-cymene                      |                              |
| liquiritin                    | perillaldehyde                |                              |
| lupulone                      | perillyl-alcohol              |                              |
| magnolol                      | pinene                        |                              |
| mangostin                     | plumericine                   |                              |
| medicagol                     | pogostone                     |                              |
| medicarpin                    | protoanemomin                  | 
| Methyl-salicylate  | Pulegone       |
|-------------------|-------------|
| Naringenin        | Rishitin     |
| Nepodin           | Sclareol     |
| Noblethin         | Solavetivone |
| O-coumaric acid   | Terpinolene  |
| Odoratol          | Thymol       |
| Oxypeucedanin     | Tuliposide-C |
| P-coumaric acid   | Vanillin     |
| Phaseol           | Witherin-A   |
| Phaseolladin      |              |
| Phaseollin        |              |
| Phenol            |              |
| Phloroglucinol    |              |
| Phylloquinone     |              |
| Piceatinol        |              |
| Piceid            |              |
| Pimpinellin       |              |
| Pinocembrin       |              |
| Pinostrobin       |              |
| Pinosylvin        |              |
| Pisatin           |              |
| Plumbagin         |              |
| P-methoxy-cinnamic acid |          |
| Podophyllotoxin   |              |
| Protocatechuic acid |            |
| Prunetin          |              |
| Prunin            |              |
| Psoralen          |              |
| Psoralidin        |              |
| Pyrogallol        |              |
| Quercetin         |              |
| Resorcinol        |              |
| Resveratrol       |              |
| Rhein             |              |
| Sakuranatin       |              |
| Scopoletin        |              |
| Seselin           |              |
| Sinapic acid      |              |
| Sinensetin        |              |
| Tangeretin        |              |
| Taxifolin         |              |
| Tectorigenin      |              |
| Tetrahydroxystilbene |            |
| Trans-3,5,4'-trihydroxy-4'-isopentenylstilbene | |
| Trans-resveratrol |              |
| Trichocarpin      |              |
3.2 Plant Families

From the literature, 1064 plant species worldwide, distributed into 150 families, have fungicidal activity. The families most often cited are the Lamiaceae and the Fabaceae, representing 19 and 18% of the plant families with a fungicidal activity, respectively (Figure 5). Within the Lamiaceae, 196 species with a fungicidal activity are distributed into 48 genera. Among these genera, 9 were regularly cited: *Teucrium*, *Pycnanthemum*, *Thymus*, *Satureja*, *Origanum*, *Micromeria*, *Mentha*, *Monarda*, and *Ocimum*. Similarly, within the Fabaceae 190 species with a fungicidal activity are distributed into 94 genera. Among of them, 8 were most often cited: *Genista*, *Rhynchosia*, *Canavalia*, *Trifolium*, *Acacia*, *Chamaecytisus*, *Cytisus*, and *Vigna*.

Figure 5 Frequency (%) of plant families with fungicidal activity (plants families presented have a frequency over or equal to 1%). The families most often cited are the Lamiaceae and the Fabaceae, representing respectively 19 and 18% of the plant families.

4. Chemicals and plants species of interest for management of leaf-cutting ants

This literature review pointed out that twenty chemical compounds are of particular interest in the perspective of management of *Attini* ants, as they showed both strong insecticidal and fungicidal activities. Nine of these chemical compounds are from the terpenoid family (caryophyllene oxide, cinnamaldehyde, eugenol, helenalin, linalool, menthone, myristicin, pulegone and thymol), eight from the phenolic family (anethole, anisaldehyde, elemicin, isopimpinellin, plumbagin, podophyllotoxin,
psoralen, and xanthotoxin) and three from the alkaloid family (anonaine, solamargine, and tomatine) (Table 3, Figure 6).

Table 3: Twenty chemical compounds (phenolics, alkaloids, and terpenoids) produced by plants with both insecticidal and fungicidal activity and that have particular interest in the perspective of management of *Attini* ants. Some insects and fungi tested, methods of extraction and method of identification most cited were also given.

| Chemicals         | Insects                                                                 | Fungi                                                                 | Extraction          | Identification                  |
|-------------------|-------------------------------------------------------------------------|----------------------------------------------------------------------|---------------------|----------------------------------|
| Anethole (Phenolics) | tobacco cutworm, Spodoptera litura (Akhtar and Isman, 2003), Blattella germanica (Chang and Ahn 2002) | *Aspergillus parasiticus* (Karapinar 1990) | hydro-distillation  | gas chromatography–mass spectrometry (GC-MS) (Osei-Safo et al. 2010) |
| Anisaldehyde (Phenolics) | larvae of Lycoriella ingenua (Park et al. 2006) | blue mould of pear, *Penicillium expansum* (Neri et al. 2005) | hydro-distillation  | GC-MS (Park et al. 2006)         |
| Anonaine (Alkaloids) | black bean aphid, chrysanthemum aphid and the aphid *Macroisaphis solanifolii* (Harper et al, 1947), *Callosobruchus chinensis* (Kotkar et al. 2002) | *Candida* spp (Agnihotri et al. 2008) | hexane and MeOH purified by preparative thin-layer chromatography (TLC) (Simas et al. 2001) |
| Caryophyllene oxide (Terpenoids) | termite *Coptotermes formosanus* (Cheng et al. 2004) | white-rot fungi : *Lenzites betalina, Pycnoporus coccineus, Trametes versicolor* and *Laetiporus sulphureus* (Cheng et al. 2004) | hydro-distillation  | GC-MS (Cheng et al. 2004)       |
| Cinnamaldehyde (Terpenoids) | stored product beetle, *Callosobruchus maculatus* (Hubert et al. 2008; Islam et al. 2009), Formosan subterranean termite, *Coptotermes formosanus* (Zhu et al. 2001) | *Malassezia furfur, Candida albicans* (Ferhout et al. 1999) | hydro-distillation  | GC-MS (Islam et al. 2009)       |
| Elemicin (Phenolics) | Coleopterans (Paneru et al. 1997) | yeasts, dermatophytes and *Aspergillus* spp (Tavares et al. 2008) | hydro-distillation  | GC-MS (Tavares et al. 2008)     |
| Eugenol (Terpenoids) | maize weevil, red flour beetle, grain weevil and larger grain borer (Huang et al. 2002), american cockroach *Periplaneta americana* (Ngoh et al. 1998) | wood-rot fungi (Basidiomycetes), yeasts belonging to *Candida* species (Saccharomyces), *Penicillium* sp (Ascomycetes) and other dermatophyte fungi (Vasquez et al. 2001; Gayoso et al. 2005; Cheng et al. 2008; Jianhua and Hai, 2001) | methanol (Zhu et al. 2001; Borg-Karlson et al. 2006) | GC-MS (Zhu et al. 2001; Borg-Karlson et al. 2006) |
| Helenalin (Terpenoids) | vector of Chagas' disease (Maya et al. 2007) | yeasts (Ascomycetes) (Picman 1984) | chloroform spectrophotometric, RPLC, GC, and GC–MSD and NMR spectroscopy (Staneva et al. 2010) | (Staneva et al. 2010) |
| Isopimpinellin (Phenolics) | African Cotton Leafworm, *Spodoptera littoralis* (Hadaeeck et al. 1994) | *Cladosporium herbarum, Botrytis cinerea, Alternaria brassicicola, Dreschlera sorkiniana, Alternaria spp* Bipolaris spp and (Hadaeeck et al. 1994) | Petroleum ether-diethyl ether or hexane-diethyl ether-thin-layer chromatography (TLC) and high-performance liquid and gas chromatography–mass spectrometry (GC-MS) (Osei-Safo et al. 2010) | spectrophotometric, RPLC, GC, and GC–MSD and NMR spectroscopy (Staneva et al. 2010) |

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| Chemical          | Source                                                                 | Method                                      |
|-------------------|------------------------------------------------------------------------|---------------------------------------------|
| Linalool          | Adult coleopteran (Shaaya et al. 1991), Mediterranean fruit fly (Salvatore et al. 2004), mosquito Culex pipiensi molestus (Traboulsi et al. 2002) | Several species of Aspergillus, Cladosporium, Penicillium, Trichoderma, Chaetomium, Paecilomyces and Stachybotrys (Rakotonirainy and Lavedrine 2005) |
| Menthol           | Red flour beetle, Tribolium castaneum, rice weevil, Stiophilus oryzae, sawtoothed grain beetle, Oryzaephilus surinamensis, house fly, Musca domestica and German cockroach, Blattella germanica (Lee et al. 2003) | Fusarium verticillioides (Daferera et al. 2003) hydro-distillation (Daferera et al. 2003) |
| Myristicin        | Fly, aphid, beetle, and caterpillar species (Dussourd 2003); coconut leaf beetle, Brontispa longissima (Qin et al. 2010) | Soil fungus, Gaeumannomyces graminis (Monsalvez et al. 2010) hydro-distillation (Monsalvez et al. 2010; Qin et al. 2010) |
| Plumbagin         | Subterranean termite, Odontotermes obesus (Ganapathy et al. 2004; Adfa et al. 2010), larvae of Aedes aegypti (Sreelatha et al. 2010) | Aspergillus fumigatus, Aspergillus flavus, Aspergillus niger, Candida parapsilosis, Candida tropicalis, C. albicans, C. neoformans, T. mentagrophytes, S. schenckii, Trichoderma viride, Microsporum gypseum, Absidia ramosa, Pseudallescheria boydii and Saccharomyces (Mishra et al. 2010) chloroform (Ganapathy et al. 2004), petroleum ether and ethanol (Mishra et al. 2010) characterized by its EI mass spectra, H NMR spectra, IR data, and melting point and identified by a search in AntiBase (Ganapathy et al. 2004) |
| Podophyllotoxin   | Vinegar fly Drosophila melanogaster, diamondback moth Platellia xylostella and common house mosquito Culex pipiensi pallens, silkworm Bombyx mori and cabbage butterfly Pieris rapae (Di et al. 2010); northern armyworm Mythimna separata (Xu and He 2010); larvae of Pieris rapae (Gao et al. 2004) | Aspergillus niger, Geotrichum flavo-bunneum, Microsporum canis, Fusarium culmorum, Trichophyton erinacei (Figgitt et al. 1989) hydro-distillation (Gawde et al. 2009) |
| Psoralen          | Beet armyworm Spodoptera exigua (Diawara et al. 1993) | Fusarium oxysporum, Fusarium solani, Penicillium digitatum, Penicillium italicum (Asthana et al. 1993); Alternaria alternata, ethanol (Bafi-Yeboa et al. 2005) HPLC (Bafi-Yeboa et al. 2005) |
| Compound               | Targets                                                   | Method                   | Instruments                  |
|------------------------|-----------------------------------------------------------|--------------------------|------------------------------|
| Pulegone (Terpenoids)  | Aspergillus fumigatus, Microsporum gypseum, Pseudallescheria boydii, Rhizopus sp., Trichophyton mentagrophytes, Candida albicans, Cryptococcus neoformans, Wangiella dermatitidis (Bafl-Yeboa et al. 2005) | scab of cucurbit, an Ascomycota (Dancewicz et al. 2008) | hydro-distillation (Vagionas et al. 2007) |
| Solamargine (Alkaloids)| Ascomycetes plant pathogenic fungi (Fewell et al. 1994)  | methanol and purified by different procedures (Venel et al. 1999) | purity was verified by high-performance liquid chromatography (HPLC) (Hall et al. 2006) |
| Tomatine (Alkaloids)   | Fusarium solani, Nomuraea rileyi (Gallardo et al. 1990); Fusarium oxysporum (Ito et al. 2007) | ethanol (Nenaah 2010) | TLC, NMR and MS (Nenaah 2010) |
| Thymol (Terpenoids)    | 17 phytopathogenic fungi (Kordali et al. 2008), Penicillium sp (Vasquez et al. 2001) and Candida sp (Braga et al. 2008) | hydro-distillation (Vokou et al. 1998) | GC-MS (Vokou et al. 1998) |
| Xanthotoxin (Phenolics)| Spodoptera litura, S. exigua, Trichoplusia ni (Akhtar and Isman 2004) | Cladosporium herbarum, Botrytis cinerea, Alternaria brassicicola, Drechslera sorkiniana, Fusarium spp. and Alternaria spp. (Al-Barwani and Eltayeb 2004) | petroleum ether-diethyl ether or hexane-diethyl ether-methanol (HPLC) (Hadacek et al. 1994) |

Pulegone: A terpenoid with activity against a variety of fungal, yeast, and mold species, including Aspergillus fumigatus, Microsporum gypseum, Pseudallescheria boydii, Rhizopus sp., Trichophyton mentagrophytes, Candida albicans, Cryptococcus neoformans, and Wangiella dermatitidis.

Solamargine: An alkaloid with activity against Ascomycetes plant pathogenic fungi.

Tomatine: An alkaloid with activity against Fusarium solani, Nomuraea rileyi, Fusarium oxysporum.

Thymol: A terpenoid with activity against 17 phytopathogenic fungi, Penicillium sp, and Candida sp.

Xanthotoxin: A phenolic with activity against Spodoptera litura, S. exigua, and Trichoplusia ni.
**Figure 6** Twenty chemical compounds produced by plants with insecticidal and fungicidal activities that have particular interest in the perspective of management of *Atta* ants: anethole (a), anisaldehyde (b), anonaine (c), caryophyllene oxide (d), cinnamaldehyde (e), elemicin (f), eugenol (g), helenalin (h), isopimpinellin (i), linalool (j), menthone (k), myristicin (l), plumbagin (m), podophyllotoxin (n), psoralen (o), pulegone (p), solamargine (q), tomatine (r), thymol (s) and xanthotoxin (t).
Because of the co-dependence of leaf-cutting ants and its basidiomycete fungus, it was important to our study to find interesting plant species, which contained chemicals with the both activities. Our literature search displayed 305 worldwide plant species, which contained chemicals with both insecticidal and fungicidal activity; among these plant species, 148 species belong to the Lamiaceae family and 24 species belong to the Apiaceae family. Twenty-one plant species contained from four to seven chemicals compounds with both insecticidal and fungicidal activities. Eleven of these twenty-one species belong to the family of Lamiaceae and six belong to the family of Apiaceae (Table 4).

Table 4 Plant families, plant species and their chemical compounds with both insecticidal and fungicidal activity. In bold, plant wich contained from 4 to 7 chemical compounds with both insecticidal and fungicidal activities.

| Plant Families | Plant species                     | Chemicals                                      |
|----------------|-----------------------------------|------------------------------------------------|
| Acoraceae      | *Acorus calamus* L.               | eugenol, elemicin, menthone                    |
| Amaranthaceae  | *Chenopodium album* L.            | xanthotoxin                                    |
| Amaryllidaceae | *Narcissus tazetta* L.            | eugenol                                        |
|                | *Polianthes tuberosa* L.          | eugenol                                        |
| Annonaceae     | *Annona cherimola* Mill.          | anonaine                                       |
|                | *Annona glabra* L.                | anonaine                                       |
|                | *Annona montana* L.               | anonaine                                       |
|                | *Annona reticulata* L.            | anonaine                                       |
|                | *Annona squamosa* L.              | anonaine                                       |
|                | *Cananga odorata* (Lam.) Hook. f. & Thomson | eugenol                                      |
|                | *Rollinia mucosa* (Jaq.) Baill.   | anonaine                                       |
| Apiaceae       | *Ammi majus* L.                   | xanthotoxin, isopimpinellin                    |
|                | *Ammi visnaga* (L.) Lam.          | xanthotoxin, isopimpinellin                    |
|                | *Anethum graveolens* L.           | eugenol, elemicin, myristicin, anethole        |
|                | *Angelica archangelica* L.        | xanthotoxin, psoralen, isopimpinellin          |
|                | *Angelica daharica* Benth & Hook. | xanthotoxin, psoralen                          |
|                | *Apolium graveolens* L.           | eugenol, thymol, menthone, myristicin, xanthotoxin, psoralen, isopimpinellin |
|                | *Carum carvi* L.                  | myristicin                                      |
|                | *Coriandrum sativum* L.           | myristicin, psoralen                           |
|                | *Cuminum cyminum* L.              | eugenol, caryophyllene oxide, anisaldehyde     |
|                | *Ferula alliacea* Boiss.          | eugenol, elemicin, caryophyllene oxide, myristicin, isopimpinellin, xanthotoxin |
|                | *Ferula assa-foetida* L.          | isopimpinellin                                 |
|                | *Pastinaca sativa* L.             | myristicin, isopimpinellin, psoralen, xanthotoxin |

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**Petroselinum crispum** (Mill.) Fuss

*Pimpinella anisum* L.

*Trachyspermum ammi* (L.) Sprague

**Aristolochiaceae**

*Asarum canadense* L.

*Asiasarum heterotropoides* (F. Schmidt) F. Maek.

**Asparagaceae**

*Hyacinthus orientalis* L.

**Asteraceae**

*Achillea millefolium* L.

*Ageratum conyzoides* L.

*Arnica montana* L.

*Artemisia annua* L.

*Artemisia capillaris* Thunb.

**Artemisia dracunculus** L.

*Artemisia herba-alba* Asso.

**Cnicus benedictus** L.

*Cynara cardunculus subsp. cardunculus* L.

*Eupatorium perfoliatum* L.

*Helianthus annuus* L.

*Helichrysum angustifolium* DC.

*Inula helenium* L.

**Berberidaceae**

*Podophyllum hexandrum* Royle

*Podophyllum peltatum* L.

*Podophyllum pleianthum* L.

**Burseraceae**

*Boswellia sacra* Flueck

*Canarium indicum* L.

*Commiphora myrrha* (T. Nees) Engl.

**Cannabaceae**

*Humulus lupulus* L.

**Cistaceae**

*Cistus ladaniferus* L.

*Juniperus communis* L.

**Cucurbitaceae**

*Citrullus colocynthis* (L.) Schrad.

**Cupressaceae**

*Juniperus virginiana* L.

**Droseraceae**

*Dionaea muscipula* E.

**Ericaceae**

*Vaccinium corymbosum* L.

*Vaccinium macrocarpon* Aiton

**Euphorbiaceae**

*Croton eluteria* (L.) W. Wright

**Fabaceae**

*Acacia farnesiana* (L.) Willd.

*Copinaea spp*

**Glycyrrhiza glabra** L.

*Myroxyylon balsamum* (L.) Harms

*Psoralea corylifolia* L.

*Tamarindus indica* L.

*Trifolium pratense* L.

**Geraniaceae**

*Pelargonium graveolens* L'Hér.

**Ginkgoaceae**

*Ginkgo biloba* L.

**Iridaceae**

*Iris x germanica* L.

**Juglandaceae**

*Juglans regia* L.

**Lamiaceae**

*Acinos alpinus var. meridionalis* (Nyman) P. W. Ball

*Acinos suaveolens* G. Don

**Podophyllum peltatum** L.

**Podophyllum pleianthum** L.

**Podophyllum hexandrum** Royle

**Podophyllum peltatum** L.

**Podophyllum pleianthum** L.

**Podophyllum hexandrum** Royle

**Podophyllum peltatum** L.

**Podophyllum pleianthum** L.

**Podophyllum peltatum** L.

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**Podophyllum pleianthum** L.

**Podophyllum peltatum** L.

**Podophyllum pleianthum** L.

**Podophyllum peltatum** L.

**Podophyllum pleianthum** L.
Agastache foeniculum (Pursh) Kuntze
Agastache pallidiflora (A. Heller) Rydb.
Agastache rugosa (Fischer & C. Meyer) Kuntze
Agastache urticifolia (Benth.) Kuntze
Calamintha nepeta (L.) Savi

Calamintha nepeta subsp. glandulosa (Req.) P.W. Ball

Collinsonia canadensis L.
Coridothymus capitatus (L.) Rchb. f.
Cunila origanoides (L.) Britton
Draecocephalum thymiflorum L.

Elsholtzia blanda (Benth.) Benth.
Elsholtzia eriostachya var. pusilla
Elsholtzia pilosa (Benth.) Benth.
Elsholtzia polystachya Benth.

Galeopsis tetrahit L.
Hedeoma drummondii Benth.
Hedeoma pulegioides (L.) Pers.
Hyptis suaveolens (L.) Poit.
Hyptis verticillata Jacq.

Hyssopus officinalis L.
Isanthus brachiatus (L.) Bsp
Lavandula angustifolia Miller

Lavandula latifolia Medik.
Lavandula x intermedia Ernério ex Loisel.
Leonotis leonurus (L.) R. Br.
Lepechinia calycina Epling
Lycopus europaeus L.
Lycopus virginicus L.
Melissa officinalis L.
Mentha aquatica L.

Mentha arvensis var. piperascens Malinv. ex Holmes

Mentha longifolia (L.) Huds.

Mentha pulegium L.

Mentha spicata L.

Mentha x piperita L.

Mentha x rotundifolia (L.) Huds.

Micromeria congesta Boiss. & Hausskn.
Micromeria croatica (Pers.) Schott
Micromeria dalmatica Benth.
Micromeria fruticosa Druce

Micromeria fruticosa subsp. barbata (Boiss. & Kotschy) P.H. Davis
Micromeria juliana (L.) Bentham ex Reichb.

Micromeria myrtifolia Boiss. & Hohen.

Micromeria thymifolia Fritsch

Minthostachys mollis (Kunth) Griseb.

Anisaldehyde
Pulegone, menthone
Anisaldehyde
Pulegone, menthone
Pulegone, menthone
Eugenol, pulegone, thymol, menthone
Elemicin
Thymol
Pulegone, caryophyllene oxide, menthone
Eugenol
Caryophyllene oxide
Thymol
Pulegone, menthone
Thymol
Caryophyllene oxide
Cinnamaldehyde
Eugenol, caryophyllene oxide
Cinnamaldehyde
Pulegone, menthone
Pulegone, menthone
Thymol, caryophyllene oxide
Pulegone
Thymol, caryophyllene oxide
Pulegone, caryophyllene oxide, menthone
Eugenol, pulegone, thymol, anisaldehyde
Pulegone, thymol, caryophyllene oxide, menthone
Pulegone, thymol, caryophyllene oxide
Pulegone, menthone
Eugenol, pulegone, thymol, menthone
Pulegone, caryophyllene oxide, menthone
Pulegone
Eugenol, pulegone, thymol, menthone
Pulegone, caryophyllene oxide, menthone
Pulegone, menthone
Eugenol, pulegone, thymol, menthone
Pulegone, caryophyllene oxide, menthone
Pulegone, menthone
Moldavica thymiflora (L.) Rydb.
Monarda citriodora Cerv. ex Lag.
Monarda clinopodia L.
Monarda didyma L.
Monarda fistulosa L.
Monarda media Willd.
Monarda punctata L.
Monarda russeliana Nutt. ex Sims
Nepeta cataria L.
Nepeta racemosa Lam.

_Ocimum basilicum_ L.
Ocimum canum Sims
Ocimum gratissimum L.
Ocimum kilimandscharicum Baker ex Gürke
Ocimum sanctum L.
Ocimum suave Willd.
Ocimum tenuiflorum L.
Origanum majorana L.
Origanum minutiflorum O. Schwarz & P.H. Davis
Origanum onites L.
Origanum syriacum L.
Origanum vulgare L.
Origanum vulgare subsp. hirtum Ietsw.
Origanum vulgare var. hirtum (Schar) Soó
Origanum vulgare var. viride Boiss.
Perilla frutescens (L.) Britton

_Pogostemon cabiln_ (Blanco) Benth.
Pycnanthemum albescens Tott. & A. Gray
Pycnanthemum beardlei _(_Small_)_ Fernald
Pycnanthemum californicum Tott. ex Durand
Pycnanthemum clinopodioides Tott. & A. Gray
Pycnanthemum incanum (L.) Michx.
Pycnanthemum loomisii Nutt.
Pycnanthemum montanum Michx.
Pycnanthemum muticum (Michx.) Pers.
Pycnanthemum nudum Nutt.
Pycnanthemum pilosum Nutt.
Pycnanthemum pycnanthemoides (Leaverw.) Fernald
Pycnanthemum setosum Nutt.
Pycnanthemum tenuifolium Schrad.
Pycnanthemum torreyi Benth.
Pycnanthemum verticillatum (Michx.) Pers.
Pycnanthemum virginianum (L.) Durand & Jackson
Rosmarinus eriocalyx Jordan & Fourn.
Rosmarinus officinalis L.
Rosmarinus tomentosus Huber
Rosmarinus x lavandulaeus De Noe

Pulegone, caryophyllene oxide, menthone
Thymol
Pulegone
Pulegone, thymol
Thymol
Pulegone, thymol
Pulegone, thymol
Pulegone, thymol, caryophyllene oxide
Pulegone, thymol
eugenol, thymol, caryophyllene oxide,
menthone
eugenol
eugenol, thymol
eugenol
caryophyllene oxide
eugenol
eugenol, thymol, caryophyllene oxide
linalool, thymol
thymol, caryophyllene oxide
eugenol, thymol, caryophyllene oxide
thymol
thymol
elemicin, myristicin
eugenol, caryophyllene oxide,
cinnamaldehyde
pulegone, menthone
pulegone, menthone
pulegone, menthone
pulegone, menthone
pulegone, menthone
pulegone, thymol
pulegone, menthone, anisaldehyde
pulegone, menthone
eugenol, pulegone, menthone
pulegone, carophyllene oxide, menthone
pulegone, menthone
pulegone, carophyllene oxide, menthone
| Plant Name                         | Chemicals Contained                  |
|-----------------------------------|--------------------------------------|
| Rosmarinus x mendizabalii Sagredo Ex Rossa | Caryophyllene oxide                  |
| Salvia canariensis L.              | Thymol, Caryophyllene oxide          |
| Salvia dorisiana Standl.           | Caryophyllene oxide                  |
| Salvia gillesii Benth.             | Caryophyllene oxide                  |
| Salvia officinalis L.              | Thymol, Caryophyllene oxide          |
| Salvia sclarea L.                  | Caryophyllene oxide                  |
| Satureja ciliaca P.H. Davis        | Pulegone, Thymol                     |
| Satureja cuneifolia Ten.           | Thymol                               |
| Satureja douglasii (Benth.) Briq.  | Pulegone, Thymol, Menthone           |
| Satureja glabella (Michx. ) Briq.  | Pulegone, Menthone                   |
| Satureja grandiflora (L.) Scheele   | Thymol                               |
| Satureja hortensis L.              | Thymol, Caryophyllene oxide          |
| Satureja montana L.                | Thymol, Caryophyllene oxide          |
| Satureja obovata Lag.              | Thymol                               |
| Satureja odora (Griseb.) Epling    | Pulegone, Menthone                   |
| Satureja parvifolia (Phil.) Epling | Thymol                               |
| Satureja subspicata subsp. liburnica Silic | Caryophyllene oxide |
| Satureja thymbra L.                | Menthone                             |
| Scutellaria churchilliana Fernald  | Caryophyllene oxide                  |
| Scutellaria galiyriculata L.       | Thymol                               |
| Scutellaria parvula Michx.         | Thymol, Anethole                     |
| Sideritis alba Papanicolau & Kokkini | Caryophyllene oxide |
| Sideritis scardica Griseb.         | Caryophyllene oxide                  |
| Tescrum arduini L.                 | Thymol                               |
| Tescrum asiaticum L.               | Caryophyllene oxide                  |
| Tescrum cyprium Boiss.             | Thymol                               |
| Tescrum divaricatum var. canescens (Čelak.) Holmboe | Thymol, Caryophyllene oxide, Anethole |
| Tescrum gnaphalodes L’Hér.         | Thymol                               |
| Tescrum kotschyanum Pooch          | Thymol, Caryophyllene oxide, Anethole |
| Tescrum micropodioidei Rouy        | Thymol                               |
| Tescrum oxylepis fo. marianum Ruiz Torre & Ruiz Cast. | Thymol |
| Tescrum oxylepis subsp. oxylepis Font Quer | Thymol |
| Tescrum polium L.                  | Pulegone                             |
| Tescrum valentinum Schreb.         | Thymol                               |
| Tescrum pseudocorodononia Desf.    | Thymol                               |
| Tescrum salvistrum Schreb.         | Thymol                               |
| Tescrum scorodonia L.              | Thymol                               |
| Thymus brousseonetti Boiss.        | Thymol                               |
| Thymus capitatus (L.) Hoffmanns. & Link | Eugenol, Thymol, Caryophyllene oxide |
| Thymus cicalicus Boiss. & Balansa   | Eugenol, Caryophyllene oxide         |
| Thymus funkii Coss.                | Eugenol, Linalool, Thymol            |
| Thymus longicaudis C. Presl        | Thymol                               |
| Thymus mastichina L.               | Caryophyllene oxide                  |
| Thymus orospedamus Huguet de Villar | Thymol, Caryophyllene oxide          |
| Thymus riatarum Humbert & Maire    | Thymol                               |
| Thymus saturejoides Coss.          | Thymol                               |
| Thymus serpyllum L.                | Thymol, Eugenol, Thymol, Menthone, Anethole |
| **Thymus vulgaris L.**              | Thymol                               |
| Thymus x citriodorus Schreb.       | Thymol                               |
| Thymus zygis L.                    | Thymol                               |
| Family                        | Species                                      | Constituents                                      |
|-------------------------------|----------------------------------------------|---------------------------------------------------|
| Lauraceae                     | Thymus zygis subsp. sylvestris Brot. ex Cout. | thymol                                            |
|                               | Trichostemma dichotomum L.                   | caryophyllene oxide                               |
|                               | Vitex agnus-castus L.                        | caryophyllene oxide                               |
|                               | Cinnamomum aromaticum Nees                  | eugenol, cinnamaldehyde                           |
|                               | Cinnamomum camphora (L.) J. Presl            | eugenol                                           |
|                               | Cinnamomum verum J. Presl                   | eugenol, caryophyllene oxide, cinnamaldehyde     |
|                               | Laurus nobilis L.                            | eugenol, elemicin, caryophyllene oxide            |
|                               | Litsea glancescens var. glancescens         | caryophyllene oxide                               |
|                               | Persea americana Miller                      | anethole                                          |
|                               | Sassafras albidum (Nutt.) Nees              | eugenol, elemicin, myristicin, anethole           |
|                               | Uncellularia californica (Hook. & Arn.) Nutt.|                                                  |
| Magnoliaceae                  | Magnolia denudata Desr.                     | carophyllene oxide                                |
|                               | Magnolia kobus DC.                           | eugenol, anethole                                 |
|                               | Magnolia officinalis Rehder & E.H. Wilson   | anonaine                                          |
| Malvaceae                     | Hibiscus sabdariffa L.                      | anisaldehyde                                     |
|                               | Tilia sp.                                   | eugenol                                           |
|                               | Ficus carica L.                             | psoralen, xanthotoxin                              |
|                               | Morus alba L.                               | eugenol                                           |
|                               | Myristicafragrans Hout.                     | eugenol, elemicin, myristicin                     |
|                               | Eucalyptus citriodora Hook.                 | eugenol                                           |
|                               | Melaleuca bracteata F. Muell.               | eugenol, cinnamaldehyde                           |
|                               | Melaleuca viridiflora Sol. ex Gaertn.       | eugenol                                           |
|                               | Myrtus communis L.                           | eugenol, caryophyllene oxide, cinnamaldehyde, caryophyllene oxide |
|                               | Pimenta dioica (L.) Merr.                   | eugenol                                           |
|                               | Pimenta racemosa (Mill.) J.W. Moore         | carophyllene oxide                                |
|                               | Psidium guajava L.                          | eugenol, caryophyllene oxide                      |
|                               | Syzygium aromaticum (L.) Merr. & L.M. Perry | cinnamaldehyde                                   |
| Nelumbonaceae                 | Nelumbo nucifera L.                         | anonaine                                          |
| Oleaceae                      | Jasminum officinale L.                      | eugenol                                           |
|                               | Ligustrum japonicum Thunb.                  | eugenol                                           |
|                               | Syringa vulgaris L.                          | elemicin, anisaldehyde                            |
| Orchidaceae                   | Vanilla planifolia Andrews.                 | eugenol, anisaldehyde                             |
|                               | Vanilla tahitensis J.W. Moore               | anisaldehyde                                      |
| Passifloraceae                | Turnera diffusa Willd. ex Schult.           | thymol                                            |
| Pinaceae                      | Pinus mugo Turra                            | anisaldehyde                                      |
|                               | Pinus sylvestris L.                         | anisaldehyde                                      |
| Piperaceae                    | Piper betel L.                              | eugenol                                           |
|                               | Piper nigrum L.                             | eugenol, caryophyllene oxide, myristicin          |
| Poaceae                       | Cymbopogon winterianus Jovitt ex Bor        | eugenol                                           |
|                               | Zea mays L.                                 | eugenol, thymol, xanthotoxin                      |
| Rosaceae                      | Prunus cerasus L.                           | eugenol                                           |
|                               | Prunus dulcis (Mill.) D.A. Webb             | eugenol                                           |
|                               | Rosa centifolia L.                          | eugenol                                           |
|                               | Rosa damascena Mill.                        | eugenol, cinnamaldehyde                           |
Chemical compounds of the Lamiaceae family appear to be the most promising for management of leaf cutting ants (Figures 3 and 5). Indeed, several authors cited this family as one of the dominant families among aromatic plants with antifungal and insecticidal activities (Vokou et al. 1998; Kokkini et al. 1988; González et al. 2011). The specific advantages of these plants are their secondary metabolites, such as terpenoids and phenolics, which are known to have strong plant chemical defense activity against insects, bacteria and fungi (Karamanoli et al. 2000). Other studies revealed that species of the Apiaceae family possess chemical compounds with diverse biological activities such as apoptosis inducers, antibacterial, antifungal, phytotoxic activity, and cyclooxygenase inhibitory (Meepagala et al. 2005) that may potentially be used for pest management.

Phenolic compounds can be divided into simple phenols, phenolic acids, quinones, flavones, flavonoids, flavonols, tannins and coumarins (Murphy Cowan 1999). The sites and number of hydroxyl groups on the phenolic compounds are thought to be related to their relative toxicity to fungi (Geissman 1963). Terpenoids occur as diterpenes, triterpenes, tetraterpenes, hemiterpenes and sesquiterpenes (Murphy Cowan 1999). Their mechanism of action against fungi is speculated to involve membrane disruption by the lipophilic compounds (Mendoza et al. 1997). Alkaloids are heterocyclic nitrogen compounds. Their antimicrobial mechanism of action is attributed to their ability to intercalate with DNA (Phillipson an O’Neil 1987).
Phytochemicals from plants include substances that are potentially useful as insect control. While synthetic insecticides have neurotoxic mode of action and promoted the rapid development of cross-resistance in insect population; phytochemical insecticides have emphasized non-neurotoxic modes-of-action such as antifeedant action, inhibition of molting, growth reduction, loss of fecundity, respiratory inhibition, etc. Standardized plant extracts containing a mixture of active phytochemicals should reduce the rate of evolution of conventional resistance compared to the selection pressure exerted by single pure toxin (Arnason et al. 1993). Studies, on relationships between chemicals structure and activity in phytochemical compounds, revealed that one important factor of insecticidal activities is related to the number of hydroxyl functions available compared to the degree of polymerization of the molecule (Regnault-Roger et al. 2003).

A choice must also be made for extraction type and solvent used. The choice would be influenced most by the degradability of total plant extract obtained. Water seems to be the best solvent. All the molecules with hydroxyl or glycated functions were water-soluble. Alkaloids were also miscible in aqueous solvents, but which have acid pH. Being naturally evolved ingredients such as plants and water have at least an advantage over synthetic molecules in term of ecological suitability. Their development as successful pest control products can also be economically feasible, especially if the source materials and solvent are available in abundance or with lower price (e.g., common plants with a wide distribution and water which is the least expensive extraction solvent).

Among methods for controlling Attini ants, the use of toxic baits is probably the most efficient. These baits should contain an active ingredient used on adult ant workers (Camargo et al. 2006). Thus, with our perspective to find efficient natural method to control leaf-cutting ants, the ingestion baits containing water plant extracts with an effective fungicidal and insecticidal action could be tested and then used.

5. Conclusion

In this study based on exhaustive literature review, we have identified twenty chemical compounds and seventeen plant species from the Lamiaceae and Apiaceae families with potential to achieve efficient pest management of leaf cutting ants. These seventeen species include four to seven chemical compounds with both insecticidal and fungicidal activities. Further biological bioassays will be conducted to evaluate the experimental effect of extracts from the plant species extracts identified from this review on Attini ants and their symbiotic fungus.

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