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The Use of Essential Oils in Agrochemistry

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Abstract

Every year tons of synthetic products are used in agriculture in order to keep away or kill harmful insects, weed or other pests like fungi or viruses. These substances are harmful towards human health and environment. Essential oils bear a great potential to replace synthetic products or to complement them. Even though they might not be that important in industrialized countries they can be very useful in less industrialized countries where farmers can't afford even less toxic syntheticals, as e. g. in Europe. Essential oils can be used as pesticide, insect repellent, weed management substance, or as inhibitor of fungi and viruses. They also play an important role for stored products.

Zusammenfassung

Jedes Jahr werden Tonnen von synthetischen Substanzen in der Landwirtschaft eingesetzt, um Insekten, Unkraut oder andere Schädlinge, wie Pilze oder Viren, fernzuhalten oder zu töten. Diese Produkte können jedoch auch die Gesundheit und die Umwelt schädigen. Ätherische Öle stellen hier eine gute Alternative dar, um jene schädlichen Substanzen zu ersetzen oder zu ergänzen. Besonders profitieren können dabei allerdings weniger die Industrieländer als die sogenannten „Schwellenländer", in denen sich die Bauern die weniger toxischen Stoffe, die bei uns bereits eingesetzt werden, nicht leisten können. Ätherische Öle können sowohl als Pestizide als auch als Repellent, Unkrautvertilgungsmittel und als Mittel, um Pilze und Viren zu beseitigen, verwendet werden. Sie spielen auch eine wichtige Rolle bei der Verlängerung der Haltbarkeit von gelagerten Produkten.

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1. Introduction

Essential oils play a major role in nature for the plants that produce them in order to protect them against bacteria, fungi, viruses as well as against herbivores and pests. [1] Since pollution of our environment and intoxication of mammalians with pesticides and herbicides is a severe problem all over the world it is necessary to look for healthier alternatives. Especially natural products such as essential oils offer an enormous potential for agricultural usage since most of them are non-toxic to vertebrates and do not harm our ambience. Even though there are so many advantages of essential oils, also some disadvantages must be mentioned, like the slow action and short duration of effectiveness as well as the high quantities needed. The object of this compilation is to review the chances and problems of the use of essential oils in agrochemistry.

Crop protection has always been an important topic in agriculture for thousands of years. Many Greek and Roman authors, for example Theophrastus (371 - 287 B.C.), Cato the Censor (234 - 149 B.C.), Varro (116 - 27 B.C.), Vergil (70 - 19 B.C.), Columella (4 - 70 A.D.) and Pliny the elder (23 - 79 A.D.) wrote about different substances, such as essential oils, to protect plants against pests. Also Chinese literature, such as a survey of the Shengnong Ben Tsao Jing era (25 - 220 A.D.) tells about pesticidal activity of plants. Famous Linnaeus (1752 A.D.) did research about natural pesticides which could be used on caterpillars. During European agricultural revolution in 19th century pyrethrum and rotenone containing powders, which were made of Chrysanthemum flower heads and Derris root, were discovered. But due to high synthetical insecticide useage, many pests nowadays are suspected to have a higher restistance against those products. [2]

Also essential oils have a long history. The first written report on extraction of essential oils was written by Ibn al-Baitar in Andalusia in Spain in the thirteenth century, but they have been used since much longer. [3] They have been used since ancient times as cosmetics and pharmaceuticals and until today they still play a major role in our life. [4] They are also known for their ability to kill bacteria, viruses and fungi, which allows their use as antiseptics. [1] And due to their herbicidal, pesticidal and antimicrobial activity they also can be used in agrochemistry.

2. Essential oils as antipests

Insects form the largest population in the animal kingdom and many of them are harmful towards human beings, since they act as pathogenic vectors and devaster crops. That is why pesticides bear a huge market potential, which can be seen in the regular growth of 7-10% per year. But due to massive use of oil based synthetic molecules as pesticides since the middle of the 20th century there have also been negative side effects reported, such as environmental pollution, toxicity towards mammalians and increased insect resistance. [5] Every year million tons of pesticides are used and harm our environment, because of that it is important to find alternatives which do not damage our environment. [6]

2.1. Health and environmental impact of botanical antipests

Essential oils are natural products, which are an excellent alternative to synthetic products because they reduce negative impacts on human health and the environment. [6] Even though there are a lot of botanical insecticides available, from 1980 to 2000 only one single product was registered in the United States and Europe, which is called Neem. It is obtained by the seeds of the Indian tree *Azadirachta indica*, Meliaceae. In the last few years also essential oils obtained influence as botanical insecticides in the United States. But due to the "relatively slow action, variable efficacy, lack of persistence and inconsistent availability" of natural products, they still cannot compete against synthetic pesticides. On the other hand it is not necessary to kill harmful insects since botanical insecticides, like essential oils, can also be used as repellents against animals. Moreover, those natural pesticides can also be mixed with synthetical products which could lessen the needed quantities of pesticides and improve the environmental problems which are caused by excessive use of synthetic pesticides. Especially developing countries could benefit from the increased use of botanical pesticides, such as essential oils, since human poisoning from pesticides, which can even lead to death, is a severe problem there. The farmers, who use pesticides often do not know about the dangers because many of them do not receive any information and they are often unable to read the official languages in which the instructions are written. [7] In static water eugenol appears to be 1500 times less toxic than pyrethrum, which is also a botanical insecticide, and not more than 15000 times less toxic than the organophosphate insecticide azinphosmethyl. Moreover, eugenol is volatile, that means that its half time is extremely short. After about 2 days there will be no eugenol left which also avoids rare side effects of essential oils. [8] Also the tobacco cutworm, which is a severe problem to vegetable and tobacco crops in Asia, can be killed by compounds of essential oils, namely thymol, carvacrol, pulegone, eugenol and trans-anethole even though it is quite resistant. [9] Many monoterpenes, like (+)-limonene, pinene and Δ3-carene show acaricidal activity. Carvomenthenol and terpinen-4-ol proved to cause highest toxicity against mites. [10] Eucalyptus essential oil was tested on several parasites, such as *Varroa destructor* (Varroa mite), *Tetranychus urticae*, *Phytoseiulus perisimilis* and *Boophilus microplus*. The studies concluded that several *Eucalyptus sp.* (Myrtaceae) essential oils can be used as acaricides. [11] *T. urticae* can be killed by essential oils obtained from *Satureja hortensis* L. (Lamiaceae), *Ocimum basilicum* L. (Lamiacae) and *Thymus vulgaris* L. (Lamiaceae). [12] Essential oils do not only act as deterrents but also as attractants towards insects. Ethanolic extracts of *Rosmarinus officinalis* L. (Lamiaceae) essential oil attracted the moth *Loberia botrana*, a pest of grape berries. [13]

2.2. Pesticidal and repellent action of essential oils

Essential oils are neurotoxic to some pests as some of them interfere with neuromodulator octopamine and others with GABA-gated chloride channel. [14] Octopamine "controls and modulates neuronal development, circadian rhythm, locomotion 'fight or flight' responses, as well as learning and memory“. It activates GTP-binding protein G-coupled receptors which lead to cAMP production or calcium release. [15] Interrupting its function "results in total break down of nervous system in insects". [16] GABA A receptors of insects show similarities as well as differences to vertebrate ones. Activation of insect GABA channels can increase the chloride ion conductance across cell membranes. Insect GABA receptors are also sensitive to benzodiazepines and barbiturates but they are insensitive to antagonists like bicuculline and pitrazepin. The differences of insect and vertebrate GABA channels can be used as targets for pesticides. [17] At high concentrations of essential oils they can also inhibit the acetylcholinesterase activity, but it cannot explain the low-dose pesticidal effect. [18] Moreover, the acetylcholinesterase inhibiting effect could not be seen in-vivo for all monoterpenes. [19] It seems to be a very good idea to use nontoxic substances that only act as deterrents or antifeedants towards insects. This concept obtained influence with the discovery of the antifeedant azadirachtin in the 1970s and 1980s. But even though deterrents and antifeedants were hyped a lot during that time a few problems remain, such as the variability of response - even closely related insects vary in their behaviour towards these substances, some may even get attracted by substances that other insects may find detesting. Furthermore, the deterrent action may change during a period of time and insects can get used to it. [14] The exact mode of action of repellents still could not be explained completely. It is also unclear if there are common mechanisms in different anthropods. Just as insects do on the antennae, "tick detects repellents on the tarsi of the first pair of legs". It is known that hairs on the antennae of mosquitos are used to detect temperature and moisture. Repellents target female mosquito olfactory receptors and block them. As for cockroackes about the method of defence is just known that oleic and linoleic acid cause death recognition and aversion. [16]

Even though single compounds of the essential oil can be isolated and tested for they repellent activity, it has been reported that the synergistic effect of the whole essential oil is more effective. [20]

Table 1: Examples of harmful pests

Name **Family**	**Notes**	**Source**
Acanthoscelides obtectus Bean weevil Coleoptera: Bruchidae	Native to Africa, Europe, America; eats fruits of crops	[21]

Acrolepiopsis assectella Leek moth Lepidoptera: Yponomeutidae	Native to Asia, Europe; eats foliage of crops	[21]
Acyrthosiphon pisum Pea Aphid Hemiptera: Aphididae	Pest of legumes, e. g. alfalfa, clover and peas	[21]
Aedes aegypti Yellow fever mosquito Diptera: Culicidae	Lives in tropics and subtropics; pathogenous	[21]
Anopheles stephensi Diptera: Anophelinae	Vector of malaria disease	[22]
Bemisia tabaci Sweetpotato white fly Homoptera: Aleyrodidae	Polyphageous, pathogenous vector (i.e. cassava mosaic disease); lives in America, Africa, Asia	[21]
Boophilus microplus Ixodida, Ixodidae		[21]
Callosobruchus chinensis Adzuki bean weevil Coleoptera: Bruchidae	Storage pest i. e. in Syria	[21]
Callosobruchus maculatus Cowpea weevil Coleoptera: Bruchidae	Damages cowpeas	[21]
Cryptolestes pusillus Flat grain beetle Coleoptera: Laemophloeidae	Stored grain pest; in temperate climate	[21]
Culex pipiens House mosquito Diptera: Culicidae	Pathogenous vector of diseases	[21]
Culex quinquefasciatus Diptera: Culicidae	Tropical regions; pathogenous vector of diseases	[21]
Delia radicum Cabbage fly Diptera: Anthomyiidae	Native to Asia, Europe and North America; damages crucifers	[21]
Dendroctonus rufipennis Spruce beetle Coleoptera: Scolytidae	Damages spruce trees	[10]
Dendroctonus simplex Eastern larch beetle Coleoptera: Scolytidae	Damages spruce trees	[10]
Dermanyssus gallinae Roost mite Gamasida, Dermanyssoidea, Dermanyssidae	Worldwide; poultry pest; can reduce egg production	[21]
Drosophila auraria	Subgroup of D. melanogaster	[23]
Ephestia kuehniella Mediterranean flour moth Lepidoptera: Pyralidae	Pest of industrial flour mills; lives in temperate climate	[21] [24]
Helicoverpa armigera Cotton bollworm	Pest of maize and other crops; native to Asia and Africa	[21]

Lepidoptera: Noctuideae		
Hyalomma marginatum Acari: Ixodidae	In Europe and Asia	[21]
Hylobius abietis Large pine weevil Coleoptera: Curculionidae	Pest of conifers; in Europe and Asia	[21]
Lasioderma serricorne Cigarette beetle Coleoptera: Anobiidae	Pest of stored food, hoursehold pest; native to America, Asia and Africa	[21]
Leptinotarsa decemlineata Colorado potato beetle Coleoptera: Chrysomelidae	Destroys solanaceous crops; in Europe, North America	[21]
Limantria dispar Gypsy moth Lepidoptera: Lymantridae	Pest of cork oak forests	[25]
Listronotus oregonensis Carrot weevil Coleoptera: Curculionidae	Damages mainly carrots	[21]
Lobesia botrana Grape berry moth Lepidoptera: Tortricidae	Pest of grapes; for example in Jordan and Iran	[21]
Megastigmus pinus Hymenoptera: Torymidae	Destroys white fir trees	[10]
Megastigmus rafini Hymenoptera: Torymidae	Destroys white fir trees	[10]
Musca domestica Housefly Diptera: Muscidae	Feeds on garbage and feces; worldwide	[21]
Oryzaephilus surinamensis Sawtoothed grain beetle Coleoptera: Silvavidae	Stored-product pest	[21]
Papilio demoleus Common lime butterfly Lepidoptera: Papilionidae	Southeast Asia; pest of citrus	[21]
Periplaneta americana American cockroach Blattaria: Blattidae	Household pest; omnivore	[21]
Phytoseiulus persimilis Acarina: Phytoseiidae	Is used to control mite pests in greenhouses; predatory mite	[21]
Pissodes strobi White pine weevil Coleoptera: Curculionidae	Destroys pines, for example Eastern White pine	[21] [10]
Plodia interpunctella Indian meal moth Lepidoptera: Pyralidae	Stored-grain pest; worldwide	[21]
Prays citri (Citrus blossom moth) Lepidoptera: Hyponomentidae	E. g. in Egypt	[21]

Prostephanus truncatus Larger grain borer Coleoptera: Bostrichidae	Pest of maize; especially in tropical regions	[21]
Rhyzopertha dominica Lesser grain Borer Coleoptera: Bostrichidae	Native to America, Africa, Asia; pest of grain	[21]
Sitophilus granarius Granary weevil Coleoptera: Curculionidae	Pest of stored grain	[21]
Sitophilus oryzae Rice weevil Coleoptera: Curculionidae	Pest of stored grain	[21]
Sitophilus zeamays Maize weevil Coleoptera: Curculionidae	Pest of stored grain	[21]
Spodoptera frugiperda Fall armyworm Lepidoptera: Noctuideae	Pest of sugarcane fields and other crops, North and South America	[21]
Spodoptera litura Rice cutworm Lepidoptera: Noctuidae	Native to Australia and Asia; damages legumes and solanaceous crops	[21]
Stegobium paniceum Drugstore beetle Coleoptera: Anobiidae	Temperate and subtropical areas; eats pharmaceutical drugs	[21]
Stephanitis pyri Azalea lace bug Heteroptera: Tingidae	Native to Europe; damages trees	[21]
Tenebrio molitor Yellow mealworm Coleoptera: Tenebrionidae	Stored-product pest	[21]
Tetranychus cinnabarinus Carmine mite Acari: Tetranychidae	Damages soybeans, cotton, plums, citrus, vegetables; in Syria, Saudi Arabia, Lebanon, Jordan;	[21]
Tetranychus urticae Twospotted spider mite Acari: Tetranychidae	Worldwide in temperate and subtropical areas; greenhouse pest	[21]
Thaumetopoea pityocampa Pine processionary Lepidoptera: Thaumetopoeidae	Pest of Pinaceae	[21]
Triatoma infestans Kissing bug Hemiptera: Reduviidae: Triatominae	Pathogeous vectors of Chagas disease in South America	[21]
Tribolium castaneum Red flour beetle Coleoptera: Tenebrionidae	Native to America, Africa and Asia; pest of stored food	[21]
Tribolium confusum Confused flour beetle Coleoptera: Tenebrionidae	Stored food pest, especially flour, difficult to control	[21]

Tyrophagus putrescentiae Mold mite Acaridida: Acaroidea: Acaridae	Eats processed cereals	[21]
Varroa destructor (Varroa jacobsoni) Acari: Varroidae	Pest of honey bees	[21]

2.3. Development and commercialization of botanicals

The utilization of insecticides, both botanicals and synthetics, are handled differently in various countries [14]: In the US many essential oils are registered for agricultural use. Canada has a slightly different law as there are not as many essential oils allowed. Mexico has a similar utilization of essential oils as the United States, but there is no exception of essential oils. The European Union allows the utilization of components of essential oils. Even though, the individual law differs for countries in the European Union. In India more biological pesticides are used than in other countries. In South America pesticide use varies in every region. In Africa there are no real restrictions by law, its local use of various pesticides. In general, countries tend to make law for use of pesticides stricter than they were, because the majority of the population and media is aware of the environmental and health impact the pesticides cause. This is especially the case in wealthier countries, but since developing countries are dependent on selling their products to so-called "first world countries", they also have to meet up with stricter criteria, even though it might not make sense for them. [14] According to Isman three aspects are important for successful commercialisation of pesticides: sustainability of the botanical resource, standardization of the chemically complex extracts and regulatory approval. Sustainability means that the base of the product must be available every time and not only seasonal. Standardization means that there must be a method to investigate analytically the product so that the product obtained from plants will not vary. It will be a problem if the pesticidal action of a substance differs even though it has been cultivated under the same circumstances. Regulatory control is - among those - the most difficult aspect. The profit made by selling botanicals will not be very high in industrialized countries. That is why "green pesticides" might not even reach the market. In industrialized countries it is hard to imagine that botanicals such as essential oils will play a bigger role in the future since synthetic pesticides are affordable and very potent againts various insects. [14]

2.4. Examples of essential oils used as antipests

Table 2: Essential oils that can be used as insecticide and acaricide

Name **Family**	**Constituents**	**Notes**	**Source**
Acorus sp. Acoraceae	β-asarone, acorenone, acoragermacrone		[26]
Artemisia sp. Asteraceae	Limonene, myrcene, α-thujone, β-thujone, caryophellene, sabinyl-acetate		[27]
Baccharis salicifolia (Ruiz&Parvon) Pers Asteraceae	β-Pinene, pulegone, camphene, limonene, α-pinene, pulegone, pulegol, germacrol, germacrone	Insecticidal effect on *T. castaneum*	[28]
Carum sp. Apiaceae	D-Carvone, limonene		[26]
Chenopodium ambrosoides L. Amaranthaceae	α-Terpinene, cymol, cis-β-farnesene, acaridole, carvacrol		[29]
Cinnamomum sp. Lauraceae	Cinnamaldehyde, linalol, β-caryophyllene, eugenol		[26]
Citrus sinensis (L.) Osbeck Rutaceae	Limonene, α-pinene, sabinene, α-terpinene	Repellent against *A. pisum*	[30] [31] [32]
Coriandrum sativum L. Apiaceae	Linalol, α-terpinylacetate, 1,8-cineole, linalyacetate, geranyl acetate, camphor	Active against *S. oryzae*, *R. dominica*, and *C. pusillus*	[26] [33]
Cuminum cyminum L. Umbelliferae	Cuminal, cuminic alcohol, γ-terpinene,	Ovicidal effects on eggs of *E. kuehniella*	[34] [35]

	safranal, p-cymene, β-pinene		
Cymbopogon sp. Poaceae	Citronellal, geraniol, citronellol, citral, limonene	Weed control, antipest; exogenous limonene against insect pests; Acaricidal effect against *T. putrescentiae*	[26] [2] [10] [36]
Elettaria cardamomum (L.) Maton Zingiberaceae	α-Terpinylacetate, 1,8-cineole, linalyacetate	Active against *S. zeamais* and *T. castaneum*, acaricidal	[26] [37] [36]
Eucalyptus sp. Myrtaceae	1,8-Cineole, limonene, α-pinene		[26]
Evodia rutaecarpa Hook f. et Thomas Rutaceae	Limonene, β-elemene, linalool, myrcene, valencene, linalyl acetate, β-caryophyllene	Fumigant against *T. castaneum* and topical insecticide against *S. zeamais*	[38] [39]
Foeniculum vulgare L. Apiaceae	Anethol, fenchone, estragol		[26]
Hedomea mandonianum Wedd. Lamiaceae	Eucalyptol, pulegone, menthone		[40]
Juniperus sp. Cupressaceae	α-Pinene, myrcene, β-pinene, terpinene-4-ol, germacrene D	Toxicity against *D. gallinae*; acaricide against *T. putrescentiae*; controls *A. stephensi*, *A. aegypti* and *C. quinquefascius*	[26] [41] [36] [22]
Lavandula sp. Lamiaceae	Linalol, linalyacetate, fenchone, camphor		[23]
Leptospermum scoparium J.R. et G. Forst. Myrtaceae	Trans-calamenene, δ-cadinene, β-caryophyllene, leptospermone	Highly effective against *D. gallinae*	[42] [43] [44]
Lippia sp. Verbenaceae	Piperitenone-oxide, limonene, thymol, carvacrole, p-cymene, β-caryophyllene and γ-terpinene	Acaricide towards *T. urticae*, repellent activity on *S. zeamais*	[45] [46] [47]
Melaleuca sp. Myrtaceae	Terpinene-4-ol, γ-terpinene, α-terpinene	Fumigant action against *S.*	[26] [48]

		oryzae, *R. dominica* and *T. castaneum*	
Mentha sp. Lamiaceae	Carvone, pulegone, menthol, menthone, menthylacetate		[26] [23]
Micromeria fruticosa L. Lamiaceae	Pulegone, β-caryophyllene, isomenthol, limonene	Effective against *B. tabaci* and *T. urticae*	[49] [50]
Minthostachys andina (Britton) Eppling Lamiaceae	Menthone, pulegone, iso-menthone		[40]
Myristica fragrans Houtt. Myristicaceae	Sabinene, α-pinene, β-pinene, myristicine	Very high mortality rates on *T. putrescentiae*	[26] [36]
Myrtus communis Myrtaceae	1,8-Cineole, α-pinene, limonene, linalol, myrtenol	Highly effective against *E. kuehniella*, *P. interpunctella*, *A. obtectus S. oryzae* and *R. dominica*	[26] [24]
Nepeta racemosa L. Lamiaceae	Nepetalactone, myrtenol, terpinen-4-ol	Effective against *B. tabaci* and *T. urticae*	[51] [50]
Ocimum sp. Lamiaceae	γ-Terpinene, α-terpinene, thymol, carvacrol, linalol, eugenol		[12]
Origanum sp. Lamiaceae	Carvacrole, thymol, γ-terpinene, p-cymene, linalool		[23]
Pelargonium graveolens L‘Hér Geraniaceae	Geraniol, citronellol	Acaricide against *D. gallinae*	[52]
Pimpinella anisum L. Apiaceae	Cis-anethol	Ovicidal effects against eggs of *T. confusum* and *E. kuehniella*	[53] [35]
Piper nigrum L. Piperaceae	β-Caryophyllene, α-pinene, sabinene, limonene	Effective against *T. molitor*	[26] [44]
Rosmarinus officinalis L. Lamiaceae	Limonene, cineol, borneol, terpineol		[23]
Salvia sp. Lamiaceae	Cineol, thujone, camphor, α-pinene, β-pinene	Insecticide against *D. auraria* and *R. dominica*	[23] [54]

Satureja sp. Lamiaceae	Carvacrol, thymol, γ-terpinene, p-cymene		[23]
Syzygium aromaticum (L.) Merr. Et L.M. Perry Myrtaceae	Eugenol, aceteugenol, β-caryophyllene		[26]
Tagetes sp. Asteraceae	Limonene, (*Z*)-β-ocimene, (*Z*)- and (*E*)-ocimenone	Toxic to *V. destructor*, no toxicity towards honey bees; causes repellence to *S. zeamais*	[55] [47]
Tanacetum vulgare L. Asteraceae	α-Pinene, α-terpinene, γ-terpinene, carvone, borneol, β-thujone, camphor	Antifeedant against *L. decemlineata* and acaricide towards *T. urticae*	[27]
Thymbra sp. Lamiaceae	Carvacrole, thymol, γ-terpinene, p-cymene	High mortality rates in *D. gallinae* and *T. cinnabarinus*; Insecticidal activity on *D. auraria*	[52] [56] [23]
Thymus sp. Lamiaceae	Thymol, carvacrole, p-cymene		[26]

Table 3: Effect of limonene application on various pests [10]

Insect species	**Host plant**	**Limonene application**	**Response**
		<u>Reduced activity of pest insect</u>	
Acrolepiopsis assectella (Leek moth)	Leek & onion, all Allium crops	olfactometer with two parallel air currents containing a Y-shaped nylon fibre	limonene shows repellent activity
Delia radicum (Cabbage fly)	Brassicaceae	olfactory stimuli for orientation behaviour	limonene from the surface part of plant host acts as a repellent
Dendroctonus rufipennis, D. simplex (Spruce beetle, eastern larch beetle)	Spruce spp	bioassayed for their toxicity	(+)-limonene at 60 ppm kills 100% of the pests after 24 hours

Hylobius abietis (Large pine weevil)	Pine, Spruce	exposure to limonene vapours	high limonene concentrations shows signs of poisoning within a few hours
Megastigmus pinus, M. rafini (Silver fir seed wasp)	White fir	olfactory responses to pure α-pinene and limonene	limonene significally acts as repellent
Thaumatopoea pityocampa (Pine processionary)	Pine	emulsified with water and sprayed on the foliage of pine seedlings	(+)-limonene reduces the number of egg cluster on plants sprayed with it
		Increased activity of pest insect	
Helicoverpa armigera (Cotton bollworm)	Polyphageous moth (e. g. cotton, tomatoes, conifers, etc)	electroantennography used to investigate electrophysiological responses	attractive to 1-2 days old moths
Papilio demoleus (Common lime butterfly)	Fabaceae	orientation responses to different odours in Olfactory	(-)-limonene shows maximum attraction to the larvae
Prays citri (Citrus blossom moth)	Citrus limonum, C. decuminata, C. aurantium	electroantennogram response to pure limonene	limonene activates oviposition
		No effect	
Hylobius abietis (Large pine weevil)	Pine	exposure to limonene vapours	low limonene levels does not affect feeding activity

Table 4: Effect of Eucalyptus essential oil on various pests [11]

Eucalyptus sp.	**Tested organism**
E. camaldulensis (River red gum E.)	Repels adult females of *Culex pipiens* (common house mosquito); mortality of eggs in *Tribolium confusum* amd *Ephestia kuehniella*
E. citriodora (Lemon scented E.)	Toxicity against *Sitophilus zeamais* (greater rice weevil)

E. globulus (Tasmanian blue gum E.)	Toxic to pupae of *Musca domestica* (housefly) as well as to female *Pediculus humanus* (louse)
E. intertexta *E. sargentii* *E. camaldulensis*	Causes death of adult *Callosobruchus maculatus*, *Sitophilus oryzae* and *Tribolium castaneum*
E. saligna	Repelled *Sitophilus zeamais* and *Tribolium confusum* (confused flour beetle)
E. tereticornis	Pesticidal activity against *Anopheles stephensi*
Eucalyptus sp.	Toxic to *Thaumetopoea pityocampa* (pine processionary)

Rosmarinus officinalis

Rosmarinus officinalis L. (Lamiaceae) can be found in the mediterranean area. The used parts are the fresh flowering tops. The essential oil can be used as antipest due to its effect on beetles, caterpillar larvae and many other insects [2] like *Drosophila auraria* [23], *Sitophilus oryzae*. [57] or *Rhyzopertha dominica*. [54] The microencapsulated essential oil also showed larvicidal effects on *Limantria dispar*. [25] In *Acanthoscelides obtectus* males and females *R. officinalis* volatile oil also caused high mortality rates. [58] Repellent activity was reported against Listronotus oregonensis. [59]

Thymus sp.

Thymus vulgaris L. (Lamiaceae) also grows in the Mediterranean area. Parts used are partial dried or fresh aerial parts. The main components are "available for broad-spectrum insect control in organic farming". [2] The essential oil was tested against *Bemisia tabaci* and caused its death. [12] *T. vulgaris* essential oil also showed toxicity against *Dermanyssus gallinae*, a pathogenic mite on hens. [43][41][52] It also caused high mortality in *Tenebrio molitor* [44] and *Tyrophagus putrescentiae*. [36] *Thymus herba-barona* Loisel. essential oil was microencapsulated and tested on *Limantria dispar*, on which it caused mortality. [25]

Syzygium aromaticum

Syzygium aromaticum (L.) Merr et L. M. Perry (Myrtaceae) [26] grows in tropical areas. Parts used are flower buds, which have been dried. Its field of application is insect pest management as eugenol is toxic to many common pests. [2] In another study conducted by Huang et al. toxicity of eugenol to *Sitophilus zeamais* and *Tribolium castaneum* could be shown. [60] Acaricidal activity against *Tyrophagus putrescentiae* [36] and *Dermanyssus gallinae* [61] could also be confirmed for clove essential oil.

Muña

Muña are Bolivian medical plants and include species of Satureia, Minthostachys, Mentha and Hedomea. They derive their name muña by the Kechuas Indians, who live in the Andean mountains where these plants grow on an altitude between 2500 and 5000 metres. Indians use these plants among others because of their insecticide and repellent activity in order to protect the crops of potatoes against insects and also to prevent the Chagas' disease of which an insect acts as pathogenous vector. Plants used in the study which was conducted by Fournet et al. (1996) were *Minthostachys andina (*Britton) Eppling (Lamiaceae) and *Hedomea mandonianum* Wedd. (Lamiaceae) against *Triatoma infestans*. Essential oil of *M. andina* could significally decrease the number of insects: After 28 days 10 out of 20 insects were found dead. *H. mandonianum* had no such effect. [40]

Eucalyptus sp.

Eucalyptus' essential oil is obtained from the Australian tree *Eucalyptus sp.* that belongs to the Myrtaceae family. It has been known for its antibacterial, antifungal, and antiseptic action for hundreds of years. [11] Toxicity of eucalyptus essential oil towards *Sitophilus oryzae* was reported by Lee et al. It proves to be a promising fumigant to control that pest. [57] Lee et al. reported in another study that several Eucalyptus species were toxic to S. *oryzae,* namely *E. nicholii*, *E. codonocarpa* and *E. blakelyi*. Same species cause mortality in *Tribolium castaneum* and *Rhyzopertha dominica*. [48]

Satureja sp.

Aslan et al. tested the essential oil of *Satureja hortensis* L. (Lamiaceae) against *Bemisia tabaci*. Of three oils (*T. vulgaris* and *O. basilicum*) tested *S. hortensis* essential oil was most toxic to it. [12] *S. thymbra* L. (Lamiaceae) was tested against *Hyalomma marginatum* and was able to kill almost all of the ticks after 24 hours. [62] It also showed toxicity to *Drosophila auraria*. [23] According to Ayvaz et al savory essential oil caused mortality against the pests *Ephestia kuehniella* and *Plodia interpunctella*. [24]

Ocimum sp.

Basil (*Ocimum basilicum* L., Lamiaceae) essential oil was tested against *B. tabaci* and proved to be effective against it. [12] Keita et al. tested the fumigant and contact toxicity of *O. basilicum* and *O. gratissimum* L. on *Callosobruchus maculatus* beetles. Both essential oils showed a high toxicity towards the beetles compared to the control. Also the egg hatch rage was decreased. [63] Another study reports methyleugenol, methylcinnamate, linalool and estragol as main compounds. Estragole was identified as one of the effective compound against *Cryptolestes pusillus* and *Rhyzopertha dominica*, while it was variable against *Sitophilus oryzae*. [33] Basil essential oil showed also very promising results in *Oryzaephilus surinamensis*. [54] *Ocimum kilimandscharicum* Wild. essential oil, with camphor as major compound, was proved to be toxic to four pests, namely *Sitophilus granarius, Sitophilus zeamais, Tribolium castaneum* and *Prostephanus truncatus,* while it also caused repellency in them. Compared with the other three *T. castaneum* is the strongest among them in tolerating fumigation, as it has the lowest mortality rate. [64]

Origanum sp.

Calmasur et al. tested the pesticidal effect of *Origanum vulgare* L. (Lamiaceae) essential oil on two pests, namely *Tetranychus urticae* and *Bemisia tabaci*. They could show that after 120 hours and at a concentration of 2 µl per litre air the mortality rate on B. *tabaci* is 100% and on *Tetranychus urticae* 95%. [50] Oregano essential oil can also be used as acaricide against *Tyrophagus putrescentiae* [36] and as insecticide against *Oryzaephilus surinamensis* [54] and *Drosophila auraria*. *O. dictamnus* L. and O. *majorana* L. were also effective against *D. auraria*. [23] *O. acutidens* essential oil is also effective against *Sitophilus granarius* and *Tribolium confusum*. [65] O. *onites* L. is successful in controlling *T cinnabarinus* as reported by Sertkaya et al. [56] *O. onites* essential oil's compounds were found to be carvacrol, linalol and thymol. Oregano essential oil showed high activity against *Plodia interpunctella* and *Ephestia kuehniella*. [24]

Artemisia sp.

The main constitutents of *Artemisia absinthium* L. (Asteraceae) essential oil are said to be effective against several flea, flies and mosquitoes. In a study conducted by

Chiasson et al. *A. absinthium* essential oil showed toxicity to *T. urticae* [27] and *T. putrescentiae*. [36] When used as fumigant *A. sieberi* Besser essential oil caused mortality in *Callosobruchus maculatus*, *Sitophilus oryzae* and *Tribolium castaneum*. Of all three insects it was most toxic to *C. maculatus,* as it caused 100% mortality at a concentration of 37 µL/L after 12 h. [66] In another study Negahban et al. tested the effect of A. *scoparia* Waldst et Kit essential oil on the same three stored-product pests as mentioned above. At a concentration of 37µL/L 100% mortality of the pests can be observed after one day. It also causes repellent effects on all three insects. [67]

Mentha sp.

Mentha pulegium L. (Lamiaceae) essential oil was tested on *Dermanyssus gallinae*, it showed high toxicity as fumigant against the mite. [43] The same essential oil proved to be active as acaricide against *Tyrophagus putrescentiae*. The same effect can be observed with *M. spicata* L. [36] *M. pulegium* L. and *M. spicata* were very effective against *Drosophila auraria*. [23] Mentha *arvensis var. piperascens* also showed high mortality rates on *Dermanyssus gallinae*. [61] *Mentha microphylla* and *M. viridis* proved to be toxic to *Acanthoscelides obtectus* and they also decreased the number of eggs. [58]

Cinnamomum sp.

Cinnamomum aromaticum Nees, Lauraceae proved to be a contact insecticide to *Tribolium castaneum* and *Sitophilus zeamais*. [68] *C. cassia* and *C. sieboldii* proved to have pesticidal action against *Sitophilus oryzae* and *Callosobruchus chinensis*. [69] Cinnamaldehyde causes acaricidal effects on *Tyrophagus putrescentiae*, especially in closed containers. [70] *C. camphora* (L.) J.Presl causes mortality to *Dermanyssus gallinae* and can be used as acaricide against them. [61]

Acorus sp.

Acorus calamus var angustatus L. and *Acorus gramineus* Sol. showed 100 % mortality at concentrations of 3.5 mg/cm^3 after three days treatment on *Sitophilus oryzae*. Essential oil obtained from *A. calamus var angustatus* was also very potent against *Callosobruchus chinensis*. A mortality rate of 100% after one day could be realized at a concentration of 3.5 mg/cm^3. [69] Another pest that can be controlled by *A. calamus* *var angustatus* is *Dermanyssus gallinae*. [61] *A. gramineus* essential oil shows insecticidal action against *Sitophilus oryzae* and *Callosobruchus chinensis* when directly applied. It can also be used against Lasioderma serricorne, but it works more potent on the first two insects. As fumigant it worked best in closed containers. [71]

Foeniculum vulgare

Fennel essential oil caused 100% toxicity to *Sitophilus oryzae* after exposition for 3 days at concentrations of 3.5 mg/cm^3. The essential oil was even more potent against *Callosobruchus chinensis* because 100% mortality can be realized at the same concentration after one day. [69] Compounds of fennel essential oil were also toxic, as proven in the previous study, to *S. oryzae* and *C. chinensis* and also to *Lasioderma serricorne*. At concentrations of 0.168mg/cm^2 estragole was most toxic to *S. oryzae* after one day, followed by (+)-fenchone and (*E*)-anethol. Against *C. chinensis* (*E*)-anethole was most effective, followed by estragol and (+)-fenchone. After one day (*E*)-anethole was lethal to *L. serricorne*, whereas estragole and (+)-fenchone showed lower toxicity. [72] *F. vulgare* essential oil is also potent in controlling *Dermanyssus gallinae*. [61] Fennel essential oil also showed toxic effects to *Tyrophagus putrescentiae* [73], which can possibly be attributed to fenchone, as the isolated compound also showed high mortality rates. [74]

Lavandula sp.

Lavandula stoechas L. (Lamiaceae) essential oil is effective in killing *Drosophila auraria* in a study conducted by Konstantopoulou et al. In the same study the insecticidal effect of *Lavandula angustifolia* Miller (Lamiaceae), with linalool and linalylacetate as main compounds, could be confirmed as well. [23] *Lavandula hybrida* volatile oil caused fumigant toxicity to *Acanthoscelides obtectus* males and females and lower number of eggs. [58] Lavender essential oil also showed high activity against *Rhyzopertha dominica*. [54]

Carum sp.

Carum carvi L. (Apiaceae) essential oil is able to kill *Sitophilus oryzae*, carvone seems to be the active compound against it. (*E*)-anethole is proven to be effective against *Rhyzopertha dominica*. Limonene and fenchone, for example were active against

Cryptolestes pusillus. [33] *C. copticum* C. B. Clarke volatile oil constituents are thymol, α-terpineol and p-cymene. Especially *S. oryzae* was weak against the fumigant action of the essential oil, but also mortality on *Tribolium castaneum* can be observed. [75]

Chenopodium ambrosoides

At a concentration of 0.4% the essential oil of Chenopodium ambrosoides was able to kill *Callosobruchus chinensis*, *Callosobruchus maculatus* and *Acanthoscelides obtectus* at a high percentage. *Sitophilus granarius* and *Sitophilus zeamais* were totally killed at 6.4%, *Prostephanus truncatus* was least sensitive, as 56% survived. [29]

2.5. Conclusion

The use of essential oils as antipest were presented in this chapter. It could be shown that several essential oils, like *Rosmarinus officinals*, *Thymus vulgaris*, *Eucalyptus* species and *Origanum* species show great potential in controlling several pests, for example *Sitophilus* sp. or *Tetranychus* sp., among many others, both on stored products and in protection of lifestock, bees and crops. Since synthetical pesticides bear a lot of risk towards environment and mammalian health there is a need for natural and healthier alternatives, just like essential oils. Of course, the high volatility is a limiting factor in the use of volatile oils on the field, but in glasshouses or on stored food they bear a great chance to change the current situation.

3. Essential oils as herbicides

Weed control in agriculture is very important as a high percentage of weed causes a high crop reduction, even more than pests. While in ancient times people were dependent on removing weed by hand today's weed control is managed by synthetic and natural substances. Since synthetic substances for weed control cause the same environmental and health problems as synthetic substances for pest control, natural substances such as essential oils seem to be highly preferable. [2]

3.1. Phytotoxicity

Phytotoxicity means the harmful impact of chemical substances on plants which can be seen in many different ways: Their parts can appear to be burned, they can suffer from chlorosis, which colours the leaves yellow, or they can also result in a lack of growth or even an excessive growth. When phytotoxicity of various components of essential oils was tested, pulegone was least and D-carvone most phytotoxic to maize plants. (+)-Limonene appeared most toxic to sugar beet seedlings. Limonene showed toxicity towards strawberry seedlings in preliminary screenings as well as towards cabbage and carrot seedlings. [10]

Almeida et al. found out that essential oils of balm, caraway, hyssop, thyme and vervain showed a 100% inhibition of germination of *Lepidium sativum* (Brassicaceae). *Raphanus sativus*' (Brassicaceae) germination was inhibited by 100% by vervain oil at all concentrations. At low concentrations anise and basil essential oils promoted the germination and radicle growth, while caraway, sage, vervain and marjoram essential oils inhibited the growth of radish. *Lactuca sativa's* (Asteraceae) growth was inhibited by thyme essential oil. Vervain, balm and caravay also had the ability to suppress the growth of lettuce. Generally said, a high level of oxygenated monoterpenes is most harmful towards weed. When it comes to inhibit the seed germination and subsequent growth ketones and alcohol showed the highest activity followed by aldehydes and phenols. [53]

Especially plants from Lamiaceae family can inhibit the growth of several weeds by releasing phytotoxic monoterpenes, namely α-pinene, β-pinene, camphene, limonene, α-phellandrene, p-cymene, 1,8-cineole, borneol, pulegone and camphor. [76] The herbicide effect of 1,4-cineole and 1,8-cineole is also described by Dayan et al. [77]

Plants that are exposed to essential oils often metabolize them. Dayan et al. described the appearance of geraniol, nerol and their acids when citral was added. When citronellal metabolisation was tested citronellol and citronellic acid were formed, for pulegone (iso-)menthone, isopulegol and menthofuran appeared. [78]

It was also reported that essential oils lead to accumulation of H_2O_2 in other plants. That way they increase oxidative stress, which leads to “disruption of metabolic activities in the cell”. Another cause for phytotoxicity is that essential oil destroys the cell membrane of plants and inhibits their enzymes. [51]

Table 5: Examples of tested plants

Name	Common name	Family	Source
Achyranthes aspera	Prickly chaff flower	Amaranthaceae	[32]
Ageratum conyzoides	Billygoat weed	Asteraceae	[32]
Agrostis stolonifera	Creeping bentgrass	Poaceae	[32]
Alcea pallida	Hollyhock	Malvaceae	[32]
Amaranthus hybridus	Smooth amaranth	Amaranthaceae	[32]
Amaranthus retroflexus	Red-root amaranth	Amaranthaceae	[32]
Amaranthus viridis	Slender amaranth	Amaranthaceae	[32]
Ambrosia artemisiifolia	Common ragweed	Asteraceae	[32] [79]
Arabidopsis thaliana	Thale cress	Brassicaceae	[32]
Bromus danthoniae		Poaceae	[32]
Bromus intermedius		Poaceae	[32]
Cassia occidentalis			
Centaurea salsotitialis			
Chenopodium album	Commmon lambsquarters	Amaranthaceae	[32] [79]
Cirsium arvense	Creeping thistle	Asteraceae	[32]
Cynodon dactylon	Bermuda grass	Poaceae	[32]
Cyperus rotundus	Purple nut sedge	Cyperaceae	[32]
Echinochloa crus-galli	Common barnyard grass	Poaceae	[32]
Hordeum spontaneum	Wild barley	Poaceae	[32]
Lactuca sativa	Lettuce	Asteraceae	[32]

Lactuca serriola	Prickly lettuce	Asteraceae	[32]
Lepidium sativum	Garden cress	Brassicaceae	[32]
Lolium multiflorum	Annual ryegrass	Poaceae	[32]
Lolium rigidum	Ryegrass	Poaceae	[32]
Parthenium hysterophorus	Whitetop weed	Asteraceae	[32]
Phalaris canariensis	Canarygrass	Poaceae	[32]
Phalaris minor	Littleseed canarygrass	Poaceae	[32]
Portulaca oleracea	Common purslane	Portulacaceae	[32]
Ranunculus repens	Creeping buttercup	Ranunculaceae	[32]
Raphanus raphanistrum	Wild radish	Brassicaceae	[32]
Raphanus sativus	Radish	Brassicaceae	[32]
Rumex crispus	Curled dock	Polygonaceae	[32]
Rumex nepalensis		Polygonaceae	[32]
Rumex obtusifolius	Broad-leaved dock	Polygonaceae	[32]
Secale cereale	Rye	Poaceae	[32]
Senecio jacobaea	Common ragwort	Asteraceae	[32] [80]
Sinapis arvensis	Wild mustard	Brassicaceae	[32]
Sonchus oleraceus	Common sowthistle	Asteraceae	[32]
Sorghum halepense	Johnsongrass	Poaceae	[32] [79]
Taraxacum sp.	Dandelion	Asteraceae	[32]
Trifolium campestre	Hop trefoil	Fabaceae	[32] [26]
Urtica dioica	Common nettle	Urticaceae	[26]

3.2. Prospects of organic weed control

Organic weed control's problem are the huge quantities that must be applied to harm the weed. This may also cause a large negative impact on the environment and the microbes in the soil. Also the volatility is a problem of essential oils, on account of which they also have to be applied very often, which could be avoided by using microencapsulation of essential oils, because it will decrease their volatility. The third problem is that essential oils can also harm the desired crop and lead to a partly destruction of the culture. Altogether, organic weed control using essential oils does not seem too promising as a future replacement of synthetic products. [2]

3.3. Examples of essential oils in weed control

Table 6: Essential oils that can be used in weed control

Name **Family**	**Constituents**	**Notes**	**Source**
Achillea sp. Asteraceae	Camphor, 1,8-cineole, piperitone, borneol, α-terpineol	Inhibitory effect on germination and seedling growth of *A. retroflexus*, *C. arvense* and *L. serriola*	[81]
Ageratum conyzoides L. Asteraceae	Precocene I and II, β-caryophyllene, γ-bisabolene, fenchyl acetate	Causes phytotoxic effects on radish, mungbean and tomatoes	[82] [32]
Anisomeles indica L. Lamiaceae	Isobornyl-acetate, isothujone, nerolidol, camphene, eugenol	Herbicide against *P. minor*, positive effects on growth of wheat	[83] [84]
Artemisia scoparia Waldst et Kit. Asteraceae	p-Cymene, β-myrcene, (+)-limonene		[85]
Callicarpa japonica Thunb. Verbenaceae	Spathulenol, germacrene B, viridiflorol, globulol	Toxic to *A. stolonifera*, but had no such effect on lettuce	[86]
Carum carvi L. Apiaceae	D-Carvone, limonene	Inhibits germination of *A. retroflexus*, *C. salsotitialis*, *S. arvensis*, *S. oleraceus*, *R. raphanistrum* and *R. nepalensis* and *A. pallida*	[26] [53] [87]
Coriandrum sativum L. Apiaceae	Linalol, α-terpinylacetate, 1,8-cineole, linalyacetate	Effective against *C. salsotitialis*, *S. arvensis*, *S. oleraceus*, *R. raphanistrum* and *R. nepalensis*	[26] [87]
Cymbopogon sp. Poaceae	Citronellal, geraniol, citronellol, citral, limonene		[26] [2]
Eucalyptus sp. Myrtaceae	1,8-Cineole, limonene, α-pinene citronellal,		[26] [88]

	citronellol, linalool, α-terpinene		
Foeniculum vulgare L. Apiaceae	Anethol, fenchone, estragol	Reduces germination rate (under 25%) of *C. salsotitialis*, *S. arvensis* and *R. raphanistrum*	[26] [87]
Hibiscus cannabinus L. Malvaceae	α-Terpineol, myrtenol, limonene, trans-carveol and γ-eudesmol	Controls various weeds e. g. *A. retroflexus* and *L. multiflorum*, at higher concentration effective against lettuce, bentgrass and against one cyanobacterium	[89]
Hyssopus officinalis L. Lamiaceae	β-Pinene, iso-pinocamphone, trans-pinocamphone	Inhibitory effect on germination of wheat seeds	[53] [49]
Juniperus sp. Cupressaceae	α-Pinene, myrcene, β-pinene, terpinene-4-ol, germacrene D	Effective against *S. arvensis*, *T. campestre*, *L. rigidum* and *P. canariensis* causing electrolyte leakage in them	[26] [90]
Lavandula sp. Lamiaceae	Linalol, linalyacetate, fenchone, camphor		[23] [53]
Majorana hortensis L. Lamiaceae	1,8-Cineole, α-pinene, limonene		[53]
Melissa officinalis L. Lamiaceae	Citral, citronellal, carvacrol, iso-menthone	Inhibitory effect on germination of wheat seeds	[26] [53] [49]
Mentha sp. Lamiaceae	Carvone, pulegone, menthol, menthone, menthylacetate		[23] [26]
Micromeria fruticosa Lamiaceae	Pulegone, β-caryophyllene, isomenthol, limonene	Inhibits germination of wheat seedlings	[49]
Nepeta meyeri Benth. Lamiaceae	Nepetalactone, myrtenol, terpinen-4-ol	Inhibits germination of seeds of *B.*	[51]

		danthoniae, *B. intermedius*, *A. retroflexus*, *C. dactylon*, *C. album* and *L. serriola*	
Ocimum sp. Lamiaceae	γ-Terpinene, α-terpinene, thymol, carvacrol, linalool, eugenol, carvone	Inhibits germination of wheat seeds	[12] [53] [49]
Origanum sp. Lamiaceae	Carvacrole, thymol, γ-terpinene, p-cymene, linalool		[23] [53]
Peumus boldus Mol. Monimiaceae	Limonene, 1,8-cineole, p-cymene, ascaridol	Herbicidal activity against *A. hybridus* and *P. oleracea*	[10] [26] [91]
Pimpinella anisum L. Apiaceae	Cis-anethol	Herbicidal effect against *R. raphanistrum*	[53] [87]
Pinus sp. Pinaceae	α-Pinene, β-pinene	Herbicide against various weeds	[26] [2]
Pistacia sp. Anacardiaceae	α-Terpinene, limonene	Completely inhibits germination of dicotyles *S. arvensis* and *T. campestre*, partially germination of monocotyles *L. rigidum* and *P. canariensis*	[90]
Rosa damascena Mill. Rosaceae	Citronellol, geraniol, nerol, linalool		[92] [26]
Rosmarinus officinalis L. Lamiaceae	Limonene, 1,8-cineole, borneol, terpineol	Selective toxicity against *C. album*, *P. oleracea*, *E. crus-galli*, *C. annuum*; good inhibition rates against *C. salsotitialis*, *S. arvensis* and *R. raphanistrum* and wheat seeds	[23] [76] [87] [49]
Ruta graveolens L. Rutaceae	α-Pinene, limonene, 1,8-cineole, nonan-2-one, undecan-2-one	Inhibits germination and radicle elongation of radish	[93]

Salvia officinalis L. Lamiaceae	1,8-Cineole, thujone, camphor, borneol	Lowers germination rate of *S. arvensis* and *R. raphanistrum*; inhibits germination of wheat seeds	[26] [53] [87] [49]
Satureja sp. Lamiaceae	Carvacrol, thymol, γ-terpinene, p-cymene	Damages several weeds, e. g. dandelion leaves, *C. album*, *A. artemisiifolia*, *S. halepense*	[23] [76] [79]
Syzygium aromaticum (L.) Merr et L.M. Perry Myrtaceae	Eugenol, aceteugenol, β-caryophyllene	Damages *Taraxacum sp*, *S. halepense*, *C. album* and *A. artemisiifolia*	[26] [2] [79]
Tagetes minuta L. Asteraceae	Limonene, (*Z*)-β-ocimene, (*Z*)- and (*E*)-ocimenone	Inhibits germination of *E. crus-galli* and *C. rotundus*; inhibits root-growth of *Zea. mays*	[55] [94] [95]
Tanacetum sp. Asteraceae	α-Pinene, α-terpinene, γ-terpinene, carvone, borneol, β-thujone, camphor		[27]
Thymbra sp. Lamiaceae	Thymol, carvacrol	Lowers germination rate to under 5% of *A. retroflexus*, *S. arvensis*, *S. oleraceus* and *R. raphanistrum*	[52] [87]
Thymus vulgaris L. Lamiaceae	Thymol, p-cymene, carvacrol	Inhibits the growth of *P. oleracea*, *E. crus-galli* and *C. album*, lettuce and pepper crops; damages *Taraxacum* sp., *C. album*, *A. artemisiifolia* and *S. halepense*	[26] [53] [72] [79]
Verbena officinalis L. Verbenaceae	Citral, isobornyl formate, linalol, geranial		[53]

Zataria multiflora Boiss. Lamiaceae	Carvacrole, linalool, α-pinene, p-cymene		[96]

Thymus vulgaris

Thymus vulgaris L. belongs to *Lamiaceae* family as well. [53] [76] Angelini et al. observed that thyme essential oil can inhibit the growth of the weeds *Portulaca oleracea*, *Echinochloa crus-galli* and *Chenopodium album*, but also of lettuce and pepper crops. [76] *T. vulgaris* essential oil also causes damage to dandelion (Taraxacum sp., Asteraceae) leaves, Common lambsquarters (*Chenopodium album* L), Common ragweed (*Ambrosia artemisiifolia*) and Johnsongrass (Sorghum halepense L) [79]

Mentha sp.

2-Phenylethyl propionate can be obtained from peppermint oil (*Mentha x piperita*, L., Lamiaceae), it also contains menthol and menthone. [2] *Mentha spicata* L. essential oil contains (-)-carvone and limonene. *M. spicata s*hows good effects against several weeds. It is able to inhibit germination (under 15%) of *Amaranthus retroflexus*, *Centaurea salsotitialis*, *Sinapis arvensis*, *Sonchus oleraceus*, *Raphanus raphanistrum* and *Rumex nepalensis* Spreng. [87] *Mentha longifolia (*L.) Huds and *Mentha officinalis* can be used as herbicide as they are able to inhibit germination of wheat seeds. This must be considered if the crop happens to be wheat. [49]

Cymbopogon sp.

Besides its mosquito-repellent actions lemongrass oil can also be used as herbicide and *Cymbopogon citratus* (DC) Stapf (Poaceae) as weed control and antipest. It is used as contact herbicide, since limonene is able to "remove the waxy cuticular layer from leaves" which leads to death by dehydration. Limonene can be used as pesticide as well as herbicide. [2] *Cymbopogon winterianus* essential oil shows toxicity towards several weeds, namely *Senecio jacobaea* L, *Ranunculus repens* L, *Rumex obtusifolius* L and *Urtica dioica* L. When sprayed on trees it causes damage to the foliage but it does not inhibit their growth. [80] The mode of action of citral is probably that it causes disruption of microtubuli polymerization in weeds, as could be proved in *Arabidopsis thaliana* seedlings. [77] The effect of *C. citratus* essential oil was also proved by Dudai et al.. The essential oil proves to be one of the most effective ones, as it is able to inhibit germination sooner (0% germination at 80nl/ml) than most other essential oils tested. [49]

Eucalyptus sp.

Species of *Eucalyptus* (Myrtaceae), such as *Eucalyptus citriodora* and *Eucalyptus tereticornis,* can be used for weed control, because they could reduce growth, chlorophyll and water content when used as fumigant. It also reduced the cellular respiration of *Parthenium hysterophorus (Asteraceae)*. After about two weeks injuries like necrosis or wilting could be observed. [2] [11] Moreover, the essential oil of *E. citriodora* can also inhibit its seed germination. The suspected mode of action is the inhibition of mitosis. [97] The essential oil obtained from *E. tereticornis* showed a higher toxicity than that of *E. citriodora*, because of a slightly different composition of the essential oil. In another study E. *citriodora* essential oil was tested on crops, namely *Triticum aestivum*, *Zea mays* and *Raphanus sativus*, and weeds, namely *Cassia occidentalis*, *Amaranthus viridis* and *Echinochloa crus-galli*. It could be shown that the essential oil was more toxic to small-seeded crops such as *A. viridis*. When *Eucalyptus* essential oil was tested on *P. hysterophorus* and *Phalaris minor*, the herbicidal effect could also be confirmed. [11] The herbicidal effect of *E. citriodora* on *P. minor* was examined in another study by Batish et al. They found out that the concentration of lemon scented eucalytus oil is important for inhibiting the growth. The inhibition is higher at higher concentrations. The mode of action is more the inhibition of growth of seedlings than inhibition of germination; *E. citriodora* also lessens the chlorophyll content and the respiratory activity of the weed and causes an ion leakage in membranes. [98] The herbicidal effect of *E. citriodora* was also mentioned by Dudai et al. when they examined the inhibition of germination of wheat seeds. [49] *E. camaldulensis* also showed promising effects in controlling *Amaranthus hybridus* and *Portulaca oleracea*, because it inhibits seedling growth as well as germination in both of them. Its main compound is identified as spathulenol. [99]

Lavandula sp.

When tested on various weeds by Azirak et al. *Lavandula stoechas* was not able to significally inhibit the germination (under 25%) of most of the weed plants. It showed an effect on a few of them, namely *Centaurea salsotitialis*, *Sinapis arvensis* and *Raphanus raphanistrum*. [87] *Lavandula x intermedia* cv Grosso was tested on *Lolium rigidum* by Haig et al. It showed a high phytotoxicity when it comes to inhibiting root growth. [100]

Origanum sp.

An author group found out that the composition of oregano was different compared to literature because other authors named p-cymene as main compound. [53] O. *onites* L. essential oil proved to be effective against several weeds, namely *Amaranthus retroflexus*, *Centaurea salsotitialis*, *Sinapis arvensis*, *Sonchus oleraceus* and *Raphanus raphanistrum*, as they lower germination rate to less than 20%. [87] O. *majorana* L. is also able to significally inhibit germination of wheat seeds. [49] *O. acutidens* is able to inhibit germination and seedling growth of *Amaranthus retroflexus*, *Chenopodium album* and *Rumex crispus*. [65]

Artemisia scoparia

Artemisia scoparia Waldst. & Kit. (Asteraceae) was tested on *Achyranthes aspera* L, *Cassia occidentalis* L, *Echinochloa crus-galli* (L) P. Beauv., *Parthenium hysterophorus* L and Ageratum conyzoides L. The inhibitory effect on seedling growth was greatest in the latter two weeds. When the essential oil was used on the weeds it caused wilting and necrosis of sprayed parts. Also a decreasing chlorophyll amount and ion leakage can be observed. This effect was greatest in *E. crus-galli* and *P. hysterophorus*. *A. scoparia* essential oil's main constitutents are p-cymene, β- myrcene and (+)-limonene. [85]

Zataria multiflora

Two different ecotypes of *Zataria multiflora* Boiss, Lamiaceae, were tested in the study conducted by Saharkhiz et al. Ecotype B had similar constituents but in lower concentrations, this also explains why ecotype A was more successful in inhibiting the germination and growth of the tested weeds, which were *Hordeum spontaneum* Koch, *Secale cereale*, *Amaranthus retroflexus* and *Cynodon dactylon*. [96]

Tanacetum sp.

Tanacetum aucheranum and *Tanacetum chiliophyllum var chiliophyllum,* Asteraceae, are common in Europe and western Asia. The essential oils were tested about their potential to inhibit germination and seedling growth of *Amaranthus retroflexus, Chenopodium album* and *Rumex crispus,* in which they were very successful. Besides their herbicidal effect, they also have an antibacterial and antifungal activity. [101]

3.4. Conclusion

Weeds are a severe problem for agriculture today as they lead to decreased yields in crops. Essential oils, like those obtained from *Cymbopogon* sp., *Eucalyptus* sp., *Origanum* sp. and *Thymus vulgaris* have been proven to be very potent inhibitors of both germination and seedling growth of various weeds. Although two limiting factors must be mentioned: First the high volatiliy of essential oils, and second the fact that some essential oils do not only inhibit the growth of weeds, but also that of crops. More research needs to be done on which weeds and crops are influenced by different volatile oils.

4. Essential oils as inhibitors of various pests

Volatile oils can also be used in controlling various other pests like bacteria, viruses, fungi and nematodes. Their application and potential will be discussed in the following section.

Table 7: Essential oils with effect on bacteria, viruses, fungi and nematodes

Name **Family**	**Constituents**	**Notes**	**Source**
Aloysia triphyllata Verbenaceae	α-Thujone, cis-carveol, carvone, limonene	Nematicide	[45]
Artemisia sp. Asteraceae	Limonene, myrcene, α-thujone, β-thujone, caryophellene, sabinyl-acetate	Fungicide Nematicide	[27]
Calamintha nepeta Lamiaceae	Limonene, menthone, pulegone, menthol	Bactericide	[10]
Carum carvi L. Apiaceae	D-Carvone, limonene	Nematicide	[26]
Cinnamomum zeylanicum Lauraceae	Cinnamaldehyde, linalol, β-caryophyllene, eugenol	Fungicide	[26]
Coridothymus sp. Lamiaceae	Carvacrole, thymol, γ-terpinene, p-cymene	Nematicide	[23]
Cotinus coggygria Scop. Anacardiaceae	Limonene, (*Z*)-β-ocimene, (*E*)-β-ocimene, β-caryophyllene	Bactericide	[102]
Cymbopogon sp. Poaceae	Citronellal, geraniol, citronellol	Virucide Bactericide Fungicide	[26]
Ducrosia anethifolia (DC.) Boiss Apiaceae	α-Pinene, myrcene, limonene, terpinolene, (*E*)-β-ocimene	Bactericide	[10]
Echinophora tenuifolia Apiaceae	α-Phellandrene, eugenol, p-cymene	Bactericide	[92]
Elettaria cardamomum (L.) Maton Zingiberaceae	α-Terpinylacetate, 1,8-cineole, linalyacetate	Fungicide	[26]
Eucalyptus sp. Myrtaceae	1,8-Cineole, limonene, α-pinene	Bactericide Fungicide Nematicide	[26]

Foeniculum vulgare L. Apiaceae	Anethol, fenchone, estragol	Bactericide Fungicide Nematicide	[26]
Hibiscus cannabinus L. Malvaceae	α-Terpineol, myrtenol, limonene, trans-carveol and γ-eudesmol	Fungicide	[89]
Juniperus sp. Cupressaceae	α-Pinene, myrcene, β-pinene, terpinene-4-ol, germacrene D	Bactericide	[26]
Laurus nobilis L. Lauraceae	1,8-Cineole, linalool, terpineol acetate, methyleugenol, linalyacetate, eugenol	Fungicide	[103]
Lavandula sp. Lamiaceae	Linalol, linalyacetate, fenchone, camphor	Bactericide	[23]
Lippia sp. Verbenaceae	Piperitenone-oxide, limonene	Nematicide	[45]
Melaleuca alternifolia (Maiden et Betche) Cheel Myrtaceae	Terpinene-4-ol, γ-terpinene, α-terpinene	Virucide	[26]
Mentha sp. Lamiaceae	Carvone, pulegone, menthol, menthone, menthylacetate	Nematicide Bactericide	[23] [26]
Micromeria fruticosa Lamiaceae	Pulegone, β-caryophyllene, isomenthol, limonene	Nematicide	[49]
Ocimum sp. Lamiaceae	γ-Terpinene, α-terpinene, thymol, carvacrol, linalol, and eugenol	Nematicide	[12]
Origanum sp. Lamiaceae	Carvacrole, thymol, γ-terpinene, p-cymene, linalool	Fungicide Bactericide Nematicide	[23]
Pelargonium graveolens L'Hér. Geraniaceae	Geraniol, citronellol	Nematicide	[52]
Peumus boldus Mol. Monimiaceae	Limonene, 1,8-cineole, p-cymene	Bactericide	[10] [26]
Pinus sp. Pinaceae	α-Pinene, β-pinene	Fungicide	[26]
Rosa damascena Mill. Rosaceae	Citronellol, geraniol, nerol, linalool	Bactericide	[92] [26]
Rosmarinus officinalis L. Lamiaceae	Limonene, cineol, borneol, terpineol	Bactericide	[23]
Salvia fruticosa Miller Lamiaceae	Cineol, thujone, camphor, α-pinene, β-pinene	Fungicide	[23]
Satureja thymbra L. Lamiaceae	Carvacrol, thymol, γ-terpinene, p-cymene	Fungicide	[23]
Syzygium aromaticum (L.) Merr. et L.M. Perry	Eugenol, aceteugenol, β-caryophyllene	Fungicide	[26]

Myrtaceae			
Tagetes minuta L. Asteraceae	Limonene, (*Z*)-β-ocimene, (*Z*)- and (*E*)-ocimenone	Bactericide	[55]
Thymbra sp. Lamiaceae	Thymol	Fungicide	[52]
Thymus sp. Lamiaceae	Thymol, carvacrole, p-cymene	Bactericide Fungicide	[26]
Xylopia longifolia A. DC. Annonaceae	α-Phellandrene, limonene, p-cymene, spathulenol	Bactericide	[104]

4.1. Effect on bacteria

Essential oils also have the potential to kill bacteria. Since they are lipophile themselves they can pass through the membrane of cells and cause cytotoxicity. [1] On one hand they „inhibit the respiration and increase the permeability of bacterial cytoplasmatic membranes“ of bacteria, and on the other hand they cause potassium leakage. [10] According to Burt other mechanisms that cause the bactericidal effects are depletion of proton motive force, damage to membrane proteins as well as to the to the cytoplasmatic membrane and degradation of the cell wall. [105] E. g., the essential oil of *Cymbopogon densiflorus (Poaceae)*, whose main compounds are limonene, cymenene, p-cymene, carveol and carvone, were active against Gram-negative as well as Gram-positive bacteria. [10] Another essential oil with effect against bacteria is that of *Eucalyptus sp. (Myrtaceae)*, which mostly contains 1,8-cineole, linalool, citronellal and limonene. [11] The essential oil of *Calamintha nepeta (Lamiaceae)*, which contains limonene, menthone and pulegone, showed high activity against Salmonella. Of all the constituents pulegone was the most effective. The essential oil from *Peumus boldus (Monimiaceae)* contains mainly monoterpenes, especially limonene and was also highly efficient against Gram- negative and Gram-positive bacteria. Also the essential oils of *Foeniculum vulgare (*Apiaceae*)* - mostly sweet fennel, *Rosmarinus officinalis (*Lamiaceae*)* and *Thymus vulgaris (*Lamiaceae*)* showed high activity against bacteria. Other essential oils with activity against bacteria are those obtained from *Tagetes minuta (*Asteraceae*)*, *Xylopia longifolia (*Annonaceae*)*, *Cotinus coggygria* Scop. *(*Anacardiaceae*)* and *Ducrosia anethifolia*. [10] Essential oils obtained from *Origanum* *onites* (Lamiaceae), *Rosa damascena* (Rosaceae), *Mentha piperita* (Lamiaceae), *Echinophora tenuifolia* (Apiaceae), *Lavandula hybrida* (Lamiaceae) and *Juniperus exalsa* (Cupressaceae) were tested on various bacteria. *Origanum onites*' essential oil was reportet to elicit biggest effect. [92]

4.2. Effect on fungi

Volatile oils are also capable of killing fungi that harm crops, because they cause the increasing of plasma membrane permability. Several monoterpenes like isopulegol, (*R*)-carvone and iso-limonene seemed to be very efficient against *Candida albicans*. The essential oils obtained from *Foeniculum vulgare (*Apiaceae*)* proved to be very active against *Aspergillus niger*. Also essential oils of citrus fruits (other than limonene) were tested against several *Penicillum* species and they were highly efficient. Unlike many other essential oils, volatile compounds which can be found in tomato leaves were able to inhibit the growth of hyphes of *Alternaria alternata*. Cardamom oil, linalool, limonene, and cineole showed the highest toxicity against fungi. [10] Another essential oil that is able to kill harmful fungi like *Aspergillus* sp., *Penicillum* sp., *Fusarium* sp. and *Mucor* sp. is that of *Eucalyptus* sp., which mostly contains 1,8-cineole, citronellal, limonene and linalool. It is able to inhibit the growth of mycel as well as spore production and germination. [11] *Pinus roxburghii (*Pinaceae*)* essential oil was able to kill *Aspergillus sp., Cymbopogon pendulus* (Poaceae) and can inhibit the mycelium growth of *Microsporum gypseum* and *Trichophyton mentagrophytes*. Moreover, essential oils of *Eucalyptus amygdalia (*Myrtaceae*)* and *Eucalyptus panciflora* which showed activity against *Erysiphe cichoracearum*. Moreover, essential oils obtained from *Thymbra spicata*, *Satureja thymbra*, *Salvia fruticosa*, *Eucalyptus sp.*, and *Origanum minitiflorum* (Lamiaceae) were tested on several fungi. Most toxic to those fungi were the essential oils of *T. spicata*, *S. thymbra* and *O. minitiflorum*. [106] Origanum, cassia and red thyme essential oils are able to inhibit fungi that destroy wood. [107] *Origanum acutidens* (Lamiaceae) essential oil shows antifungal activity as well, for example, against several fungi of *Fusarium* and *Botrytis* family. [65] Against *Botrytis cinerea* essential oil from *Cymbopogon martini* (Poaceae), *Thymus zygis* (Lamiaceae), *Cinnamomum zeylanicum* (Lauraceae) and *Syzygium aromaticum* (Myrtaceae) showed high activity as well. Especially C. *martini* and *T. zygis* were very effective in inhibiting spore germination, followed by *S. aromaticum* essential oil. [108] Laurel oil (*Laurus nobilis* L., Lauraceae) showed antifungal activity against *Rhizoctonia solani* and *Sclerotinia sclerotiorum*. [103] Essential oil of *Hibiscus cannabinus* L. (Malvaceae) was effective against fungi of *Colletotrichum* species, even though the antifungal effect was weak. [89] Essential oils from *Artemisia dranunculus*, *Artemisia absinthium*, *Artemisia santonicum* and *Artemisia spicigera*, all of them Asteraceae, were tested against various fungi and showed to be effective against them. [109]

4.3. Effect on viruses

Essential oils have also be found to be active against viruses. The tobacco mosaic virus, which is an important pest in agrochemistry is weakly resistant to lemongrass essential oil. [107] But also essential oil of *Melaleuca alternifolia (Myrtaceae)* resulted in less lesions caused by tobacco mosaic virus for at least 10 days. [110]

4.4. Effect on nematodes

The population of nematodes (*Heterodera schachtii*) could be decreased down to less than 3% of the control within 3 months using (+)-limonene. Also menthol proved to be very efficient against nematodes. [10] Essential oil of *Ocimum sanctum* L. (Lamiaceae) and eugenol as main compound was tested on *Caenorhabditis elegans* and showed an anthelmintic effect. [111] Another essential oil that is very promising in nematode control is *Eucalyptus sp.* essential oil. It proved to be toxic to *Meloidogyne incognita* and *Meloidogyne exigua*. [11] *Ocimum basilicum* L. (Lamiaceae) and *Ocimum sanctum* L. (Lamiaceae), as well as their main compounds linalol and eugenol, are effective in killing larvae of *M. incognita*. [112] Pandey et al. reported that several *Eucalyptus* and *Mentha* species as well as *O. basilicum*, as proven in the previous study, and *Pelargonium graveolens* L'Hér (Geraniaceae) volatile oils act nematicidal on *M. incognita*, too. [113] Another study conducted on *Meloidogyne sp.* shows that *Aloysia triphyllata* (Verbenaceae), *Lippia juneliana* (Verbenaceae) and *Lippia turbinata* (Verbenaceae) have a nematocidal effect. The main components are α-thujone, cis-carveole, carvone and limonene in *A. triphyllata*; Piperitenone oxide, limonene and camphor in *L. junelia* and limonene and piperitenone oxide in *L. turbinata*. [45] Oka et al. examined the effect of essential oil on *M. javanica*. Essential oils that significally inhibited its mobility (more than 80%) were *Artemisia judaica*, *Carum carvi*, *Coridothymus capitatus*, *Coridothymus citratus*, *Foeniculum vulgare*, *Mentha rotundifolia*, *Mentha spicata*, *Micromeria fruticosa*, *Origanum syriacum* and *Origanum vulgare*. Essential oils that lowered the egg hatching rate to less than 2% were *Artemisia judaica*, *Carum carvi*, *Foeniculum vulgare* and *Mentha rotundifolia*. [114] *Ocimum gratissimum*, with eugenol and 1,8-cineole as main compounds, was reported to have anthelmintic activity on *Haemonchus contortus* as it decreases the egg hatch rate. [115]

Table 8: List of various pests in agrochemistry, including post-harvest food pathogens and soil microbes

Name	**Notes**	**Group**	**Source**
Aeromonas hydrophila	Spoils meat	Bacterium	[105]
Alternaria alternata		Fungus	
Arthrobacter sp.	Can use essential oil as carbon source	Bacterium	[116]
Aspergillus flavus	Storage fungus, can produce toxic aflatoxines	Fungus	[106] [117]
Aspergillus niger	Post-harvest pathogen	Fungus	[118]
Aspergillus parasiticus	Can produce toxic aflatoxines	Fungus	[117]
Bacillus cereus	Food pathogen	Bacterium	[105]
Botrytis cinerea	Post-harvest pathogen	Fungus	[118]
Caenorhabditis elegans		Nematode	
Candida albicans		Fungus	
Cladosporium herbarum	Post-harvest pathogen	Fungus	[117]
Clostridium botulinum	Spoils food, produces neurotoxins	Bacterium	[119] [120]

Colletotrichum coccodes	Postharvest pathogen	Fungus	[118]
Erysiphe cichoracearum	Phytopathogenous funghus	Fungus	[106]
Eurotium sp.	Spoils food, i. e. bakery products	Fungus	[121]
Fusarium oxyporum f sp. dianthi	Phytopathogenous fungus	Fungus	[122]
Haemonchus contortus	Gastrointestinal parasite of ruminants	Nematode	[115]
Heterodera schachtii	Infects various plants i. e. sugarbeet	Nematode	[10]
Liseria monocytogenes	Spoils food	Bacterium	[119]
Meloidogyne exigua Root-knot nematode	Damages plant roots	Nematode	[11]
Meloidogyne incognita Root-knot nematode	Damages plant roots	Nematode	[11]
Meloidogyne javanica Root-knot nematode	Damages plant roots	Nematode	[114]
Methylosinus trichosporium	Consumes methane in soils	Bacterium	[123]
Microsporum gypseum		Fungus	
Monilinia laxa	Post-harvest pathogen	Fungus	[103]
Mucor sp.		Fungus	
Nitrosomonas sp.	Oxydize ammonia	Bacterium	[124]
Nitrosospira sp.	Oxydize ammonia	Bacterium	[124]
Nocardia sp.	Can use essential oils as carbon source	Bacterium	[116]
Penicillium digitatum	Spoils food, i. e. bakery products	Fungus	[121]
Polysphondylium pallidum	Cellular slime mold, feeds on bacteria in forest soils	Fungus	[125]
Pseudomonas sp.		Bacterium	
Rhizoctonia solani	Post-harvest fungus	Fungus	[103]
Rhizopus stolonifer	Spoils food	Fungus	[118]
Salmonella enteritidis	Spoils food, especially raw food	Bacteria	[120]
Sclerotinia sclerotiorum	Phytopathogenous fungus	Fungus	[122]
Sclerotium cepivorum	Phytopathogenous fungus	Fungus	[122]
Trichophyton mentagrophytes		Fungus	

4.5. Conclusion

This section gave a short overview about various pests that play a role in agrochemistry. The bactericidal and fungicidal effect of various essential oils, like *Cymbopogon* sp., *Thymus* sp., *Eucalyptus* sp. and *Foeniculum vulgare* among many others has been known for quite a long time. This effect has been studied in many different publications and many facts about the mode of action and the different effects are known already. But essential oils already show virucidal and nematocidal effects as well. An agrochemical relevant virus is the tobacco mosaic virus, for example, that causes big losses every year. An essential oil that could be of use in killing the virus is *Cymbopogon* sp. Also nematodes, like the root-knot nematode, can be contolled by essential oils, for example by several *Mentha* species.

5. Effect of essential oils on the condition of the soil

5.1. Effects of essential oils on microorganisms and soil

Successful biodegradation is influenced by several factors, namely soil water, oxygen, redox potential, pH, nutrient status and temperature. [126] Essential oils are not only capable of destroying microorganisms but they can also be used as carbon and energy source if they have been exposed to it recently. That way some micoorganisms can actually be activated by essential oils. This applies mostly to bacteria that have lived in Mediterranean areas where also many plants that contain essential oils are. That way they were able to make fast use of the offered essential oil, that was added. [127] Especially bacteria like *Arthrobacter* sp. and *Nocardia* sp. have been reported to use essential oils as carbon source. Also several *Pseudomonas* species have been detected to use α-pinene as energy source. [128] [116] Essential oils tested by Voukou et al. were *Origanum vulgare subsp. hirtum (Lamiaceae)*, *Rosmarinus officinalis (Lamiaceae)*, *Mentha spicata (Lamiaceae)* and *Coridothymus capitatus (Lamiaceae)* as well as *Lavandula angustifolia (Lamiaceae)*. [127] In another study Voukou et al. observed the effect of essential oils obtained from *Lavandula stoechas (Lamiaceae)*, *Satureia thymbra (Lamiaceae)*, or fenchone [129] They were all able to increase the CO_2 emission of the soil and the microbial population, even though some substances had not been in previous contact with the soil sample before. [127] According to Hassiotis et al. the deciding factor if essential oils act as inhibitors or not is the concentration of the essential oil applied. At lower lower concentrations they can induce bacterial growth, at higher decisions most likely they inhibit bacterial action. [130] The only difference between the essential oils was the time after they showed an effect. While some were immediately effective others needed more time to work. Gram-positive as well as Gram-negative bacteria were able to use monoterpenes or oxygenated products. [129] This effect is also enhanced by the ability of essential oils to kill harmful fungi and their spores. As one can see, plants that contain essential oils can influence the condition of the soil by activating the soil respiration through increasing the microbial growth. The plants must be native to the soil's place to achieve that effect. If essential oils are tested on soil where they do not belong to they appear to be less or noneffective. [127] Amaral et al. found out that several monoterpenes, especially (-)-α-pinene, were able to inhibit the atmospheric methane consumption by forest soils. Essential oils can kill *Methylosinus trichosporium*, a methanotrope bacterium, and they are also said to be able to inhibit the nitrification of forest soils. In the same way as the nitrogen cycle also the carbon cycle is affected by essential oils. [123] Generally said, terpenes, alcohols and esters can be degraded by bacteria in a very fast way, while it takes a lot longer for ketones. [116] Another interesting question is how essential oils affect *Polysphondylium*, a cellular slime mold, that feeds on bacteria in forest soils. (*R*)-(-)-limonene, (-)-camphene and (*S*)-(+)-carvone as well as (-)-menthone and (+)-β-pinene inhibited growth of *Polysphondylium pallidum*. [125]

5.2. Examples of essential oils with an effect on soil condition

Table 9: Essential oils that can influence condition of the soil

Name **Family**	**Constituents**	**Notes**	**Source**
Cymbopogon sp. Poaceae	Citronellal, geraniol, citronellol		[26]
Laurus nobilis L. Lauraceae	1,8-Cineole, linalool, terpineol acetate, methyleugenol, linalyacetate, eugenol		[103]
Lavandula sp. Lamiaceae	Linalol, linalyacetate, fenchone, camphor		[23]
Mentha spicata L. Lamiaceae	Carvone, pulegone, menthol, menthone, menthylacetate		[23] [26]
Myrtus communis L. Myrtaceae	1,8-Cineole, α-pinene, limonene, linalol, myrtenol		[26]
Origanum sp. Lamiaceae	Carvacrole, thymol, γ-terpinene, p-cymene, linalool	Activates soil respiration	[23] [127] [129]
Rosmarinus officinalis L. Lamiaceae	Limonene, 1,8-cineol, borneol, terpineol, camphor	Activates soil respiration	[23] [127] [129]
Salvia sp. Lamiaceae	Cineol, thujone, camphor, α-pinene, β-pinene		[23]

Satureja thymbra L. Lamiaceae	Carvacrol, thymol, γ-terpinene, p-cymene	Activates soil respiration	[23] [129]
Thymbra capitata (L.) Cav. Lamiaceae	Carvacrole, thymol, γ-terpinene, p-cymene	Activates soil respiration	[52] [129]

Mentha spicata

Mentha spicata's (Lamiaceae) main compounds are (*R*)-(-)-carvone, limonene and 1,8-cineole. [129] Chalkos et al. evaluated the ability of *M. spicata* composted plants to increase growth of tomato crops and avoids weed growth. It has also a postive effect on the bacterial and fungal population in the soil. The bacteria *Nitrosomonas* and *Nitrosospira* are still oxidizing ammonia in the soil despite adding the compost. Among all these effects the compost of *M. spicata* was able to increase the pH. A long time after adding *M. spicata* to the soil compounds of the essential oil can be found, but in another composition than the original essential oil. Carvone, for example, makes up 50% of the essential oil in the beginning but after some time in the soil the concentration lowers to 1%, while other monoterpenes are gone completely. Sesquiterpenes, which act as allelochemicals, on the other hand can be found at the same or even higher concentrations than in the original oil. [124]

Lavandula sp.

Lavender oil (*Lavandula angustifolia* Mill., Lamiaceae) mainly contains linalool and linalyl acetate. Its natural habitat is also the Mediterranean area. [129] Spanish or French lavender oil (*L. stoechas* L., Lamiaceae), as it is also called, is obtained from *L. stoechas* and consists of fenchone. [129] Other compounds are camphor, p-cymene and 1,8-cineole. In a study by Hassiotis et al. the bacterial growth stimulating effect could be shown. [116] [130] In another study *L. stoechas*' essential oil degradation was examined. Highest essential oil degradation was in October, November and December. During the hot summer months the essential oil decrease was not very high, this indicates that bacteria are the reason for the loss and not evaporation. After seventeen months only camphene, 1,8-cineole and camphor remained. [116]

Salvia sp.

Adding *Salvia fruticosa* Mill. (Lamiaceae) compost to soil decreases the high C:N rates and raises the pH of the soil. Moreover, it increases the number of microbes in the soil, such as bacteria and fungi. [124] S. *sclarea* (Lamiaceae) volatile oil's compounds are linalyl acetate, linalool, geranyl acetate and α-terpineol. The essential oil is able to cause fungicidal activity on *Sclerotinia sclerotiorum*, a soil-borne pathogen. It also inhibits growth of *Sclerotium cepivorum* and *Fusarium oxysporum f sp. dianthi*. [122]

Myrtus communis

Hassiotis et al. examined the bacterial population growth during degradation of *Myrtus communis* L. (Myrtaceae) essential oil. It could be shown that the bacterial population was able to grow and use myrtle essential oil, whose compounds were decreasing over the time, as energy source. At the end of the study only low percentages of 1,8-cineole and camphene could be detected. [128]

Laurus nobilis

Laurus nobilis showed inhibition of bacterial activity and lowered the number of colonies as well as soil respiration rate. This is because 1,8-cineole as well as eugenol are known for their bactericidal effects. [130]

Cymbopogon sp.

Malkomes tested the dihydrogenasis activity in soil with and without dung and the addition of citronella (*Cymbopogon* sp., Poaceae) oil. A low concentration of citronella oil caused a decreasing stimulation of the activity of dihydrogenasis. In the soil, in which no dung was added, citronella oil also stimulated the CO_2 production from the very beginning in the soil, in which dung was added, the CO_2 production decreased at first, but after three weeks it started to increase. [131]

5.3. Conclusion

The bactericidal action of essential oils has been known for quite a long time, but they can also be used as energy source for bacteria and activate them. That way they can increase the quality of the soil because CO_2 production is stimulated and pathogenous microorganisms are killed. Several essential oils, namely *Mentha spicata*, *Lavandula* sp. and *Cymbopogon* sp., bear great potential to be used as dung and control of soil microbes in the future.

6. Essential oils used in post-harvest disease control

Food safety is a very important topic. Even though there is an increased hygiene during food production still 30% of people suffer from food poisoning every year and as a result two million people worldwide still die. A lot of people nowadays also want their food to have less synthetic food additives in it, therefore there is a need to find natural substances which can replace them. [105]
Insects and mites that damage food and act as pathogens, are also a major problem in food storage, especially in developing countries, Essential oils which can be used as acaricides and insecticides are explained in the first chapter.

6.1. Effects of essential oils on stored product pests

In order to keep the concentration of health damaging effects low it is important to find out on the benefits of essential oils on stored products. Essential oils that have proven themselves to be useful against postharvest pathogens, namely the fungi *Botrytis cinerea*, are red thyme oil, clove oil, and cinnamon oil. Essential oils of *Monarda citriodora (Lamiaceae)* and *Melaleuca alternifolia (Myrtaceae)* showed an antifungal effect against many different fungi. Tea tree oil also works as inhibitor on bacteria. [119] The effect of anethole, carvacrol, cinnamaldehyde, eugenol, and safrole were tested against fungi of *Mucor*, *Aspergillus* and *Rhizopus* species. Against most *Rhizopus* and *Mucor* species carvacrol proved itself to be most effective. Against *Aspergillus* species both carvacrol and eugenol showed best results. [132] Carvacrole is also able to inhibit toxins, that are produced by *Bacillus cereus* in various dishes. [105]
Against bacteria, that damage stored products, cedar, eucalyptus, thyme and chamomile oils proved themselves useful, especially when used against pathogenous bacteria B. *cereus*, *Clostridium botulinum* and *Listeria monocytongenes*. [119]
Generally said, essential oils with a high percentage of phenolic compounds seem to be more effective against pathogens that damage food. Moreover, essential oils have a bigger effect on Gram-positive bacteria than on Gram-negative. [105]

But it must be mentioned that the effect of essential oils was tested in laboratories and not in the commercial field and that many essential oils only show a fungistatic effect, which means that the fungi will start growing again after the essential oil vapour is gone. [119] Moreover, a higher concentration of essential oils – up to 100 times as much in soft cheese - is needed to inhibit bacteria in food than in vitro. The chemical environment of the the food is also important for the effect, e. g. the bactericide effect increases when the pH decreases, also the concentration of the fat in the food is plays a major role because essential oils lose their ability to harm bacteria with increasing fat concentration. [105]

6.2. Examples of essential oils used on stored products

Table 10: Essential oils that can be used to preserve stored products

Name **Family**	**Constituents**	**Notes**	**Source**
Artemisia sp. Asteraceae	Limonene, myrcene, α-thujone, β-thujone, caryophellene, sabinyl-acetate, camphor, 1,8-cineole, borneol, terpinen-4-ol, bornyl acetate	Very strong antifungal activity	[27] [109]
Cinnamomum sp. Lauraceae	Cinnamaldehyde, linalol, β-caryophyllene, eugenol		[26]
Coriandrum sp. Apiaceae	Linalool, α-terpinyl acetate, 1,8-cineole, linalyl acetate	Can be used to preserve meat products from bacteria	[26] [105]
Cymbopogon sp. Poaceae	Citronellal, geraniol, citronellol		[26]
Eucalyptus sp. Myrtaceae	1,8-Cineole, limonene, α-pinene	Against browning of mushrooms in plastic bags, antibacterial	[26] [119]

Laurus nobilis L. Lauraceae	1,8-Cineole, linalool, terpineol acetate, methyleugenol, linalyacetate, eugenol		[103]
Melaleuca alternifolia (Maiden et Betche) Cheel Myrtaceae	Terpinene-4-ol, γ-terpinene, α-terpinene	At 500 ppm it is able to kill 100% of the fungi *Botrytis* sp on grapes	[26] [119]
Mentha piperita L. Lamiaceae	Carvone, pulegone, menthol, menthone, menthylacetate	Is able to kill *Salmonella enteritidis* in several foods	[23] [26] [133]
Monarda citriodora Lamiaceae	Thymol, thymol methylester, α-terpinene, p-cymene	Antifungal activity on most post-harvest fungi e.g. *Alternaria*, *Fusarium* and *Rhizopus* species	[134] [119] [135]
Origanum sp. Lamiaceae	Carvacrole, thymol, γ-terpinene, p-cymene, linalool	Inhibits bacterial growth on meat, fish and vegetable products	[23] [105]
Satureja hortensis Lamiaceae	Carvacrol, thymol	Inhibitor of *Aspergillus parasiticus* (can produce aflatoxines)	[117]
Syzygium aromaticum (L.) Merr. Et L.M. Perry Myrtaceae	Eugenol, aceteugenol, β-caryophyllene	Eugenol shows high activity against *A. flavus*; is antibacterial; inhibits *L. monocytogenes* and *A. hydrophila*	[26] [119] [106] [105]
Thymus zygis L. Lamiaceae	Thymol, carvacrole, p-cymene	Protects meat products against *L. monocytogenes* and *A. hydrophila*; also against *Salmonella* species	[26] [119] [105]
Zizyphus jujuba Rhamnaceae	Eugenol, isoeugenol, caryophyllene, eucalyptol, caryophyllene oxide	Active acainst *Listeria monocytogenes*	[136]

Thymus zygis

Main components of thyme (*Thymus zygis* L., Lamiaceae) oil are thymol and p-cymene. Its home is the Mediterranean area. [119] Thyme oil can be used to protect meat products from two bacteria, namely *Listeria monocytogenes* and *Aeromonas hydrophila*. Thymol also showed activity against several Salmonella species. [105]

Cinnamomum sp.

Cinnamon oil (*Cinnamomum zeylanicum* J.Presl, Lauraceae) consists mainly of cinnamaldehyde. [119] It can be used to preserve dairy products but it also proved to be successful in defeating several *Salmonella* bacteria on vegetables. [105] Guynot et al. tested Cinnamon essential oil on *Eurotium* sp., *Aspergillus* sp. and *Penicillium* sp. to preserve bakery products. [121]

Cymbopogon citratus

*Cymbopogon citratus (*Poaceae*)* was able to kill *Aspergillus flavus* to 100%, a fungus that harms stored products. It has to be applied at about 1000 ppm to inhibit *Aspergillus flavus*. Besides *A. flavus* it has the ability to kill many other fungi as well for about 210 days in storage. The essential oil of *Cymbopogon citratus*, especially if it was produced between May and November, also appeared to be more successful in fighting fungi than several synthetic products. [137] Lemongrass essential oil also showed activity against colony development of *Cladosporium herbarum* and *Rhizopus stolonife*r. A concentration of 500 ppm was lethal for *Colletotrichum coccodes*, *Cladosporium herbarum*, *Rhizopus stolonifer* and *Aspergillus niger*. The fungal colony growth of *Botrytis cinerea* was only inhibited up to 60%. The fungal spore production could be inhibited of all these five fungi. [118] Lemongrass essential oil can also be used against *A. flavus*, a fungus that can produce aflatoxines in parboiled rice. It causes fungistatic and fungicidal effects. [138]

Laurus nobilis

Essential oil of *Laurus nobilis* L., Lauraceae, showed good effects in the protection of the harvested fruits of kiwi and peach against the post-harvest fungi *Monilinia laxa*, *Botrytis cinerea* and *Penicillium digitatum*. The fungistatic effect is very high in *M. laxa* and *B. cinerea* but *P. digitatum* can not be completely killed. [103]

6.3. Conclusion

The protection of stored food against pathogens like bacteria, fungi, insects and mites is a big challenge especially in developing countries. Especially volatile oils obtained from *Cinnamomum* sp., *Cymbopogon* sp. and *Syzygium aromaticum* (earlier known as Eugenia caryophyllata) bear great potential. One thing that should be considered is that they have a strong taste themselves, therefore not every essential oil can be used in every dish as the flavors might not match very well. But overall adding essential oils to food helps preserve it and seems to be a good idea since many essential oil plants are alraedy used as spices throughout the world and most of them do not have any known toxic effects. But of course, studies must be conducted to make sure adding volatile oils do not lead to yet unknown side effects.

7. Conclusion

Essential oils can be used in various fields of application and one of them is in agrochemistry. Until now agrochemistry is dominated by synthetic products in order to control various pests, weed and soil condition but essential oils bear great potential to replace or complement those substances. In insect pest control essential oils proved to be very promising as they have great potential for killing various harmful insects. Especially in developing countries they might play a bigger role in the future as they are very cheap and can be combined with synthetic products to minimize their toxicity. When it comes to repellent activity, essential oils might not be that useful as only some insects will be deterred while others can be attracted by them. When it comes to weed control essential oils do not seem as promising because of the high quantities needed and the frequent application, which might also lead to negative environmental effects. Moreover, the possibility that the applied essential oils might damage the wanted crops can not be excluded. Volatile oils are also able to kill various pests, namely bacteria, fungi and viruses as well as mites and nematodes. Especially in the control of tobacco mosaic virus essential oils might become very important. More research needs to be done in this field of application. Furthermore, essential oils are also able to improve the condition of the soil because if exposed to the oils earlier, bacteria can use them as carbon source. That way the respiration of the soil can be activated. Finally, a very interesting aspect of essential oils is to use them in post harvest pest management and against fungi and bacteria on stored products. Especially in developing countries the insect and other pest management on stored products might become very useful. But also in industrialized countries there is some use for them, for example in supermarkets on fruits and vegetables to make them less perishable.

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