horticulturae

Review

Apiaceae Family as a Valuable Source of Biocidal Components and their Potential Uses in Agriculture

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Abstract: Synthetic chemicals are used to protect crops and agricultural products, thereby producing high yields. However, intensive use of these synthetic chemicals significantly affects the environment and sustainable agriculture production. Moreover, direct or indirect exposure to these synthetic chemicals may cause acute or chronic toxicity in humans and animals. Due to their biodegradability, low toxicity, and being environmentally friendly, secondary metabolites derived from plant sources are being studied as a sustainable approach. Apiaceae family crops are a good source of bioactive phytochemicals. Many studies have found that Apiaceae extracts and essential oils possess various biocidal activities: antibacterial, antifungal, herbicidal, insecticidal or repellent, and larvicidal activities, among others. These various potent bioactivities make the Apiaceae an excellent alternative source for synthetic chemicals. In this context, the present review highlights the biocidal activities of some Apiaceae species and their potential applications in agriculture to protect the plant and agricultural products against pests, weeds, phytopathogens, and foodborne and food spoilage microorganisms.

Keywords: Antibacterial; antifungal; biocides; essential oil; herbicides; insecticides; pesticides; phytopathogens; Umbelliferae

Citation: Thiviya, P.; Gunawardena, N.; Gamage, A.; Madhujith, T.; Merah, O. Apiaceae Family as a Valuable Source of Biocidal Components and their Potential Uses in Agriculture. *Horticulturae* **2022**, *8*, 614. https://doi.org/10.3390/horticulturae8070614

Academic Editor: Stefania Galletti

Received: 1 June 2022
Accepted: 5 July 2022
Published: 7 July 2022

1. Introduction

Apiaceae (formerly Umbelliferae) is one of the largest plant families in the order Apiales. Commonly known as parsley or carrot family, it consists of nearly 3780 species belonging to 434 genera distributed throughout many regions in the world [1]. The Apiaceae family includes some of the widely used vegetables and aromatic herbs such as carrot (*Daucus carota*), parsnip (*Pastinaca sativa*), celery (*Apium graveolens*), Gotu kola (*Centella asiatica*), parsley (*Petroselinum crispum*), coriander (*Coriandrum sativum*), dill (*Anethum graveolens*), fennel (*Foeniculum vulgare*), cumin (*Cuminum cyminum*), anise (*Pimpinella anisum*), caraway (*Carum carvi*), as well as poisonous species like water hemlock (*Cicuta maculata*), northern water hemlock (*Cicuta virosa*), poison hemlock (*Conium maculatum*), *Aethusa cynapium* (fool's parsley), and hemlock water-dropwort (*Oenanthe crocata*). Plants of the Apiaceae family are grown, not only as a nutritional source, but also as a source of flavour, fragrance, and medicine. Different parts, such as the root, leaf, leaf stalk, pseudo-bulb, and seed, serve these purposes. All parts of Apiaceae plants contain secretory glands that are important in storing essential oils (EOs), giving rise to the distinct flavour of each species [2–4]. Moreover, EO plays a vital role in plants: defence against bacteria, viruses, fungi, insects, and herbivores, and as an attractant to pollinators [5].

Agrochemicals, such as pesticides, fertilizers, and chemical growth agents are widely used to increase crop yield and manage weeds, pests, and diseases. Extensive use of these synthetic agrochemicals poses potential risks to human health and the environment, including agrochemical poisoning, negative impact on biocontrol agents, reduced biodiversity and ecosystem functions, residues in the environment and water and soil pollution, food, and drinking water, accumulation in the food chain, high and acute toxicity in humans, occupational and non-occupational health impacts, and pest-resistance development. Therefore, the development of non-toxic, biodegradable, and eco-friendly natural agrochemicals as an alternative to synthetic biocides gained much attention [6–8].

In recent years, the extraction of active compounds (secondary metabolites) from plant sources gained interest among scientists. Plants synthesize secondary metabolites in response to defence mechanisms against biotic or abiotic stress. These secondary metabolites protect plants from phytopathogens (fungi, bacteria, viruses, nematodes, protozoa), predators, UV-B radiation, and drought, and play a role in growth and development. Plants produce several secondary metabolites, such as phenolics, terpenes, carotenoids, alkaloids, and other nitrogen/sulphur-containing compounds [9,10]. Various plant extracts and secondary metabolites are known to have various bioactivities, such as herbicidal, insecticidal, and antimicrobial activities [11]. Medicinal aromatic plants contain high concentrations of these secondary metabolites or bioactive compounds and can be used in pharmaceuticals, agrochemicals, food additives, and as ingredients in cosmetics [11].

Apiaceae species are a good source of secondary metabolite compounds with diverse biological activities, such as apoptosis inducers, antibacterial, antifungal, phytotoxic activities, and cyclooxygenase inhibitory activity [12,13]. Thus, Apiaceae can be used in agriculture as a biopesticide, sprouting inhibitor, antifungal agent, and insect repellent [14]. In this respect, this current review focuses on the Apiaceae as a source of biocidal components and their potential uses in agriculture. Relevant articles published in English were searched in different databases, specifically, Google Scholar, Scopus, Wiley Online Library, Semantic Scholar, and Pub Med. This review cites data from 150 articles, published between 2005 and 2021, and compiles the biocidal potential of 54 Apiaceae species.

2. Phytochemicalsin Apiaceae Extracts

Several Apiaceae species are an excellent source of EOs, which contain more than 760 different chemical components [1,2]. The chemical composition varies with the plant part used for extraction, various extraction methods, phenological stages of the plant, harvesting season, plant age, soil nature, and environmental conditions. These variations in chemical composition have a direct effect on their biological activities [15,16]. Knowledge of these chemical constituents is vital to make use of this economically important plant family, not only for medicinal benefits, but also for environmental applications. Essential oils and their components, mainly monoterpenoids and sesquiterpenoids, show antimicrobial, repellent, chemosterilant, antifeeding, and other biocidal activities [17,18]. Table 1 shows some Apiaceae species and their major components, while Figure 1 shows the chemical structure of several main components.

Table 1. Phytochemicals in Apiaceae plant extracts.

Botanical Name	Common Name	Part	Extract	Main Compounds with Biocidal Activity	Reference
Aegopodium podagraria	Goutweed Ground Elder	Leaf	Ethanolic extracts	Quercetin-3-O-glucoside (399 mg/kg), apigenin (1.3 mg/kg), rutin (0.7 mg/kg)	[19]
Ammi visnaga	Toothpick weed, Khella	Seeds	Ethanolic extracts	Quercetin-3-O-glucoside (49.5 mg/kg), rutin (24 mg/kg), kaempferol (11 mg/kg), biochanin A (40 mg/kg), genistein (23 mg/kg)	[19]
Ammodaucus leucotrichus	Woolly Cumin	Aerial parts	Essential oil	Perillaldehyde (58.3%), D-limonene (23.33%), α-pinene (5.74%), β-pinene (2.26%)	[20]
Anethum graveolens	Dill	Seeds	Essential oil	Carvone (42%), limonene (32%), dill ether, α-phellandrene (14.2), cymene (2%)	[21]
				Carvone (55.2%), limonene (16.6%), dill apiole (14.4%), linalool (3.7%)	[22]
Angelica archangelica	Garden Angelica	Root	Essential oil	α-Pinene (29.7%), δ-3-carene (14.2%), β-phellandrene + limonene (13.2%)	[23]
Angelica sylvestris	Wild angelica	Leaf	Ethanolic extract	Quercetin 3-O-glucoside (20.5 mg/kg), rutin (136 mg/kg), formononetin (12.4 mg/kg)	[19]
Anthriscus cerefolium	Chervil	Leaf	Ethanolic extract	Naringin (6.5 mg/kg), quercetin 3-O-glucoside (5.3 mg/kg)	[19]
Anthriscus sylvestris	Cow parsley, Wild chervil	Leaf	Ethanolic extract	Rutin (8.0 mg/kg), quercetin 3-O-glucoside (3.8 mg/kg)	[19]
Apium graveolens	Celery	Leaf, Root	CO_2-extract	Leaf: Limonene (32.16%)Root: Limonene (21.87%), carvone (17.71%)	[24]
Apium graveolens	Celery	Leaves	Essential oil	β-Pinene (39.63%), limonene (15.11%), cis-ocimene (16.18%), γ-terpinene (7.73%), β-selinene (3.81%)	[25]
Apium nodiflorum	Water celery	Aerial parts	Essential oil	Myristicin (47.0%), limonene (16.7%), terpinolene (9.9%), (Z)-β-ocimene (6.1%)	[26]
Azorella cryptantha		Aerial parts	Essential oil	α-Pinene (9.6–21.9%), α-thujene (5.7–12.5%), β-pinene (1.5–5.9%)	[27]
Carum carvi	Caraway	Seeds	Essential oil	Carvone (70.1%), γ-terpinene (12.6%), limonene (5.1%)	[28]
				Carvone (66.4%), limonene (32.5%)	[29]
				γ-Terpinene (31.03%), β-pinene (18.77%), p-cymene (17.16%), carvone (12.20%)	[30]

Table 1. *Cont.*

Botanical Name	Common Name	Part	Extract	Main Compounds with Biocidal Activity	Reference
Carum carvi	Caraway	Fruits	Essential oil	2-Caren-10-al (34.03%), anethole (28.46%), d-terpinene (16.06%), p-cymene (5.59%), limonene (3.55%)	[31]
				Carvone (50.6%), limonene (46.48%)	[32]
				(R)-Carvone (37.98%), D-limonene (26.55%), α-pinene (5.21), cis-carveol (5.01%), β-myrcene (4.67%)	[33]
				Carvone (46.62%), limonene (45.49%)	[34]
Carum nigrum		Seeds	Essential oil	Dillapiole (29.9%), germacrene B (21.4%), β-caryophyllene (7.8%)	[35]
Carum copticum	Ajowan	Fruits	Essential oil	Thymol (63.17%), p-cymene (21.4%), d-terpinene (13.76%)	[31]
Centella aciatica	Gotu Kola, Centella, Indian penny	Leaves	Essential oil	α-Humulene (21.06%), β-caryophyllene (19.08%), bicyclogermacrene (11.22%), germacrene B (6.29%), myrcene (6.55%), γ-terpinene (5.77%)	[36]
Chaerophyllum aromaticum		Root	Essential oil and methanolic extract	Viridiflorol (22.2%), germacrene d (5.1%), m-cresol (1.6%), limonene (2.1%), α-pinene (0.8%)	[37]
Chaerophyllum aureum	-	Fruits and aerial parts	Essential oil	Sabinene (18.5–31.6%), p-cymene (7.9–25.4%) and limonene (1.9–10.9%)	[38]
Chaerophyllum crinitum	-	Aerial parts	Essential oil	α-Terpinolene (20.3%), α-terpineol (7.2%), limonene (5.8%)	[39]
Chaerophyllum macropodum	-	Aerial parts	Essential oils and hexane extracts	Trans-β-ocimene (21.2–22.8%), cis-β- ocimene (8.5–10.0%), p-cymene (1.4–10.3%), β-phellandrene (5.1–7.5%), γ-terpinene (1.1–9.2%), β-pinene (2.3–7.1%), (+) spathulenol (4.4–6.0%)	[40]
Coriandrum sativum	Coriander	Seeds	Essential oil	Linalool (40.9%), geranyl acetate (12.8%), γ- terpinene (10.6%)	[28]
				Linalool (66.8%), α-pinene (7.79%), camphor (6.46%), terpinene (3.97%), limonene (3.79%)	[41]
				Linalool (57.57%), geranyl acetate (15.09%), Camphor (3.02%), p-cymene (2.52%)	[42]

Table 1. *Cont.*

Botanical Name	Common Name	Part	Extract	Main Compounds with Biocidal Activity	Reference
				Linalool (58.80%), menthol (12.89%), α-pinene (5.29%), γ-terpinene (4.76%)	[43]
				Linalool (76.41%), γ-terpinene (5.35%), α-pinene (4.44%), Camphor (2.20%)	[30]
Coriandrum sativum	Coriander	Fruits	Essential oil	Linalool (70.9%), α-pinene (4.17%), p-cymene (3.63%)	[32]
Crithmum maritimum	Sea Fennel	Aerial parts	Essential oil	γ-Terpinene (33.6 %), sabinene (32.0 %), thymol methyl ether (15.7 %)	[44]
				β-myrcene (13.66%), p-cymene (11.67%), β-phellandrene (6.57%), α-pinene (5.51%), camphene (5.16%)	[45]
Crithmum maritimum	Sea Fennel	-	Essential oil	Sabinene (49.45%), γ-terpinene (31.37%), pinenes (9.57%), limonene (2.73%)	[46]
Crithmum maritimum	Sea fennel	Aerial parts and seeds	Essential oil	Dillapiole (55.7 and 39.9%), myristicin (4.4 and 12.8%), γ-terpinene (14.0 and 21.2%), thymol methyl ether (11.8 and 11.1%), α-pinene (2.3 and 4.7%), sabinene (4.7 and 1.6%), p-cymene (3.5 and 4.6%), respectively.	[47]
Crithmum maritimum	Sea fennel	Seeds	Essential oil	Dillapiol (39.9%), γ-terpinene (21.2%), myristicin (12.8%), thymol methyl ether (11.1%), α-pinene (4.7%), p-cymene (4.6%)	[48]
Crithmum maritimum	Sea fennel	Leaves	Essential oil	α-Phellandrene (71.05%), dill ether (10.83%), limonene (10.74%), p-cymene (2.12%)	[25]
Cuminum cyminum	Cumin	Seeds	Essential oil	β-Pinene, p-cymene, γ-terpinene, cuminal, α-terpinen-7-aI and γ-terpinen-7-a	[16]
				γ-Terpinen-7-al (35.3%), cumin aldehyde (21.8%), α-terpinen-7-al (15.4%), γ-terpinene (12.5%), β-pinene (6.4%)	[49].
				Cuminaldehyde (30.42–33.24 %), γ-terpinen-7-al (20.54–28.36 %), α-terpinen-7-al (about 13 %), γ-terpinene (6.15–12.60 %), β-cymene (4.19–5.38 %), β-pinene (3.10–5.36 %)	[50]

Table 1. *Cont.*

Botanical Name	Common Name	Part	Extract	Main Compounds with Biocidal Activity	Reference
Cuminum cyminum	Cumin	Fruits	Essential oil	Cuminaldehyde (25.17%), p-cymene (17.5%), β-pinene (13.56%)	[32]
Daucus carota	Wild carrot	Leaf	Ethanolic extract	Quercetin-3-O-glucoside (68.4 mg/kg), rutin (9.5 mg/kg)	[19]
Deverra scoparia		Aerial parts	Essential oil	α-Pinene (31.95%), sabinene (17.24%), Δ 3 -carene (16.85%), ocimene (9.75%), myrcene (3.46%), terpinene-4-ol (2.84%), eugenol (1.8%)	[51]
Echinophora spinosa	Prickly Parsnip	Air dried plants	Essential oil	$δ^3$-carene (60.86%), α-phellandrene (7.12%), p-cymene (6.22%), myrcene (4.82%), β-phellandrene (2.73%)	[52]
Eryngium alpinum	Alpine Sea Holly	Aerial parts	Essential oil	Caryophyllene oxide (27.9%), bicyclogermacrene (13.2%), germacrene D (8.2%)	[53]
Eryngium amethystinum	Amethyst Sea Holly	Aerial parts	Essential oil	β-Caryophyllene (15.2%), α-pinene (10.2%), 2,3,6-trimethylbenzaldehyde (9.3%)	[53]
Eryngium triquetrum	Choukzerk	Flowers	Essential oil	Pulegone (50.6%), piperitenone (30.5%), menthone (7.0%), limonene (1.3%)	[54]
Eryngium triquetrum	Choukzerk	Aerial parts	Essential oil	Falcarinol (74.8%), octane (5.6%)	[55]
Ferula orientalis		Aerial parts	Essential oil	α-Pinene (75.9%), camphene (3.4%), p-cymene (2.2%)	[56]
Ferulago sandrasica		Roots	Essential oil	Limonene (28.9%), α-pinene (15.6%), terpinolene (13.9%)	[56]
Ferulago angulata		Seeds	Essential oil	(Z)-β-Ocimene (19.93%), α-pinene (15.50%), p-cymene (7.67%), sabinene (7.49%), β-phellandrene (5.5%), α-phellandrene (4.95%), γ-terpinene (3.3%)	[57]
Ferulago cassia		Root	Dichloromethane (CH_2Cl_2) extract	Coumarins; peucedanol, suberosin, grandivitinol, umbelliferone	[58]
Ferulago trachycarpa		Rhizomes of plant	Dichloromethane, n-hexane, and methanolic extract	Coumarins; crenulatin, suberosin, marmesin senecioate	[59]
Ferulago trifida		Flowers	Essential oil	(E)-β-Ocimene (37.3%), α-pinene (16.3%), bornyl acetate (9.4%), cis-verbenol (8.6%), γ-terpinene (7.5%), α-limonene (4.3%), β-myrcene (2.8%)	[60]

Table 1. *Cont.*

Botanical Name	Common Name	Part	Extract	Main Compounds with Biocidal Activity	Reference
		Stems		α-Pinene (22.6%), (E)-β-ocimene (20.7%), trans-verbenol (22.1%), bornyl acetate (8.5%), α-limonene (3.3%)	
		Leaves		(E)-β-Ocimene (22.6%), α-pinene (19.6%), bornyl acetate (16.7%), cis-verbenol (10.4%), β-myrcene (3.2%)	
		Fruits		(E)-β-Ocimene (30.5%), α-pinene (18.0%), bornyl acetate (11.0%), α-terpinolene (9.4%)	
Foeniculum vulgare	Fennel	Seeds	Essential oil	Estragole (50.1%), limonene (20.2%)	[28]
			Essential oil	Trans-anethole (65.1%), fenchone (25.6%), methyl chavicol (3.4%), α-pinene (1.5%), limonene (1.3%)	[21]
			Essential oil	Trans-anethole, fenchone, anisketone, p-anisaldehyde, d-limonene, estragol, estragol, carvone	[61]
			Essential oil	Estragole (71.64%)	[62]
			Essential oil	E-Anethol (76.22%), estragole (9.54%), fenchone (10.91%)	[43]
			Essential oil	Estragole (43.38%), anethole (29.34%), fenchone (15.16%), Limonene (5.02%)	[63]
			Ethanolic extract	Rutin (62 mg/kg), quercetin 3-O-glucoside (60.0 mg/kg)	[19]
Foeniculum vulgare	Fennel	Fruits	Essential oil	Trans-Anethole (64.42%), fenchone (14.59%), methyl cavicol (6.62%), limonene (3.37%)	[31]
Foeniculum vulgare	Fennel	Leaves	Essential oil	E-Anethol (41.18%), z-anethol (26.49%), β-phellandrene (5.38%), fenchone (2.46%)	[25]
Heracleum anisactis		Aerial parts	Essential oil	Myristicin (95.15%)	[64]
Heracleum transcaucasicum		Aerial parts	Essential oil	Myristicin (96.87%)	[64]
Hippomarathrum microcarpum		Aerial parts	Essential oil	β-Caryophyllene (31.4%), caryophyllene oxide (23.1%), β-phellandrene (4.6%), Germacrene D (4.2%), α-pinene (3.0%)	[56]
Levisticum officinale	Lovage	leaf and seed	Essential oil	γ-Terpinene (14.52% and 12.37%), β-phellandrene (13.85% and 15.54%), (Z)-β-ocimene (12.91% and 23.70%)	[65]

Table 1. *Cont.*

Botanical Name	Common Name	Part	Extract	Main Compounds with Biocidal Activity	Reference
Ostericum sieboldii	Water Dropwort			Myristicin (30.31%), α-terpineol (9.92%), α-cadinol (7.29%), β-farnesene (6.26%), linalool (5.94%)	[66]
Pastinaca sativa	Wild parsnip	Leaf	Ethanolic extract	Rutin (652 mg/kg), quercetin 3-O-glucoside (517 mg/kg)	[19]
Petroselinum hortense	Parsley	Seeds	Essential oil	α-Pinene (42.15%), β-pinene (30.21%), β-phellandrene (6.03%), myristicine (4.37%), limonene (2.02%), sabinene (2.26%), myrtenal (2.14%)	[43]
Pimpinella anisum	Anise	Seeds	Essential oil	E-Anethol (76.56%), estragole (13.01%), linalool (7.42%)	[43]
			Essential oil	Trans-anethole (80.8%), 1,8-cineol (4.7%), linalool (1.5%)	[21]
			Essential oil	(E)-Anethole (93%)	[49].
			Ethanolic extract	Rutin (13.0 mg/kg), quercetin 3-O-glucoside (6.5 mg/kg)	[19]
Pimpinella saxifraga	Burnet saxifrage	Leaf	Ethanolic extract	Quercetin 3-O-glucoside (421.2 mg/kg), rutin (205.2 mg/kg), apigenin (62.0 mg/kg), quercetin (20.4 mg/kg)	[19]
Prangos peucedanifolia		Flower	Essential oil	β-pinene (35.58%), α-pinene (22.13%), β-phellandrene (12.54%), myrcene (8.27%), γ-terpinene (5.97%), α-phellandrene (3.23%)	[67]
		Leaves	Essential oil	m-Cresol (50.38%), trans-p-menth-2-en-1-ol (6.63%), γ-terpineol (3.9%), α-terpinen-7-al (3.83%), and β-pinene (3.63%)	[67]
Seseli gummiferum	Moon Carrot	Aerial parts	Methanolic and water extracts	Chlorogenic acid (211 and 199 µg/g), Gallic acid (37.81 and 22.27 µg/g), p-coumaric acid (18.69 and 27.16 µg/g), rutin (15.22 and 14.42 µg/g)	[68]
Sison amomum	Stone Parsley	Flowering aerial parts	Essential oil	Sabinene (54.4%), β-phellandrene (16.6%), germacrene D (6.7%), terpinen-4-ol (3.8%), γ-terpinene (2.4%), myrcene (2.0%)	[69]
Smyrnium olusatrum	Alexander, Horse parsley	Roots	Essential oil	Furanoeremophilone (31.5%), furanodiene (19.1%), (E)-β-caryophyllene (11%), β-pinene (3%)	[55]
Trachyspermum ammi	Ajwain, Ajowan caraway	Seeds	Essential oil	Thymol (63.4%), p-cymene (19%), γ -terpinene (16.9%)	[70]

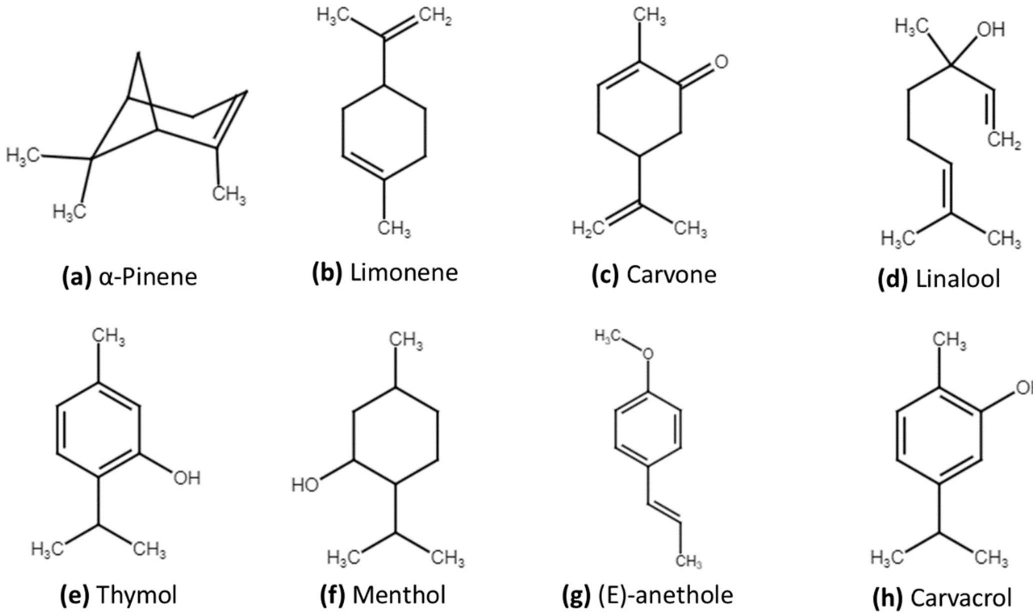

Figure 1. Chemical structure of several major components with potential biocidal activity;

3. Biocidal Effects of Apiaceae Extracts

The biocidal activities of phytochemicals, such as monoterpene, phthalides, terpenoids, phenylpropanoids (coumarins and phenylpropenes), and polyacetylenes, are commonly found in Apiaceae plants [4,5]. Compared with single components, oil in its complete composition showed high antimicrobial activity due to the synergistic effect of minor and major constituents of oil [21]. Table 2 highlights the biocidal potential of several Apiaceae species.

Table 2. Phytochemical constituents of Apiaceae plant extracts.

Botanical Name	Common Name	Biocidal Effect	Results/Mechanisms	References
Actinolema macrolema		Antibacterial activity (*Staphylococcus epidermidis*) Antifungal activity (*Candida albicans*)	MIC using microdilution broth assay 62.5 (*S. epidermidis*) 125 (*C. albicans*) μg/mL.	[71]
Aegopodium podagraria	Goutweed Ground Elder	Antibacterial activity (*Enterobacter cloacae*, *Klebsiella pneumonia*, *Pseudomonas fluorescens*, *Bacillus subtilis*, *Bacillus mycoides*, *Staphylococcus aureus*)	MIC using tube dilution method 1.25–5.00 mg/mL (in ethanol extract).	[72]
Ammi visnaga	Toothpick Weed, Khella	Larvicidal activity (*Culex quinquefasciatus*)	LD_{50} = 9 ppm.	[73]
		Insecticidal activity (*Toxoptera aurantii*)	LD_{50} of seed extract 0.054 ng/aphids	[74]
		Larvicidal activity (*Aedes aegypt*)	Khellin, a major compound showed 100% and 93% mortality at 1 μg/μL and at 0.5 μg/μL.	[75]
		Insecticidal activity (*Schistocerca gregaria*)	LC_{50} of ethanol, petroleum ether and n-butanol extracts (21.0, 12.0 and 22.5%, respectively.	[76]

Table 2. *Cont.*

Botanical Name	Common Name	Biocidal Effect	Results/Mechanisms	References
Ammodaucus leucotrichus	Wooly Cumin	Antibacterial (*Klebsilla pneumonia*) and Antifungal (*Trichophyton rubrum*, *Candida albicans*) activities	Inhibition zones in disc diffusion method 6–20 mm.	[77]
Anethum graveolens	Dill	Insecticidal activity (*Tribolium castaneum*)	Fumigant toxicity (LC_{50} 14.78 µL), repellency, and reduces oviposition potential.	[78]
		Insecticidal activity (*Lymantria dispar*)	Antifeedant activity at concentration of 0.5 and 1% of EO (Tot = 59.18 and 56.12, respectively).	[79]
		Antifungal activity (*Candida* spp.)	MIC and MFC were 0.63–2.5 mg/mL and 1.25–5 mg/mL, respectively.	[21]
		Antifungal activity (*Penicillium citrinum*, *Penicillium veridicatum*, *Aspergillus flavus*, *Aspergillus terreus*, *Aspergillus niger*, *Fusarium graminearum*), antibacterial activity (*Staphylococcus aureus*, *Bacillus subtilis*, *Pseudomonas aeruginosa*, *Salmonella typhi*, *Escherchia coli*, *Bacillus cereus*)	Antifungal activity by inverted petri dish method 27.5–100% at 6 µL. Inhibition zones determined by agar well diffusion method 13.2–25.3 mm (bacteria).	[22]
Angelica archangelica	Garden Angelica	Antibacterial activity against *Staphylococcus aureus* and *Escherichia coli*	MIC using broth microdilution method = 14.2 µL/mL (*S. aureus*) and 28.4 µL/mL (*E. coli*).	[23]
Angelica sylvestris	Wild Angelica	Larvicidal activity (*Culex pipiens*)	LC_{50} > 150 mg/L.	[80]
Anthriscus cerefolium	Chervil	Insecticidal activity (wheat granary weevil *Sitophilus granaries*)	Repellent (62%) and lethal activity (54%).	[81]
Apium graveolens	Celery	Antibacterial activity (*Staphylococcus aureus*, *Salmonella typhi*)	MIC 0.12 µg/mL (*S. aureus*) and 0.5 µg/mL (*S. typhi*).	[82]
		Insecticidal activity against *Pseudaletia unipuncta* (Armyworm)	Antifeedant/feeding deterrence index (84%), growth inhibitory (91%), fumigant and contact toxicant action (100% after 24 h).	[83]
		Antibacterial activity against *Bacillus cereus*, *Staphylococcus aureus*, *Listeria monocytogenes*, *Enterococcus faecalis*	11.5–40 mm inhibition zone in agar diffusion method.	[24]
Azilia eryngioides		Insecticidal activity (*Sitophilus granaries*, *Tribolium castaneum*)	Fumigant toxicity 24-LC_{50} were 20.05 µL/L (*S. granaries*) and 46.48 µL/L (*T. castaneum*).	[84]

Table 2. *Cont.*

Botanical Name	Common Name	Biocidal Effect	Results/Mechanisms	References
Azorella cryptantha		Repellent activity on *Triatoma infestans*, insecticidal activity against *Ceratitis capitata*, antifungal (dermatophytes *Microsporum gypseum*, *Trichophyton rubrum*, *Trichophyton mentagrophytes*), antibacterial (*Escherichia coli* and *Yersinia enterocolitica*)	Repellent activity (92–100%), insecticidal contact toxicity (LD_{50} at 72 h <11 mg/fly), MIC (microbroth dilution method) of dermatophytes and bacteria 125–1000 µg/mL.	[27]
		Antibacterial activity (*Escherichia coli*, *Salmonella enteritidis*)	MIC (microbroth dilution method) values of *S. enteritidis* and *E. coli* 125–250 µg/mL and 500 µg/mL, respectively.	[85]
Carum carvi	Caraway	Antifungal activity (*Aspergillus flavus*) and inhibition of aflatoxin production	Complete inhibition of *A. flavus* growth and afltoxin B_1 production at 1000 ppm caraway EO.	[28]
		Insecticidal activity (African cotton leafworm *Spodoptera littoralis*)	Fumigant toxicity LD_{50} 41.45 µL/L air.	[86]
		Insecticidal activity against *Sitophilus zeamais* and *Tribolium castaneum*	Contact (LD_{50} 3.07 and 3.39 µg/adult) and fumigant (LC_{50} 3.37 and 2.53 mg/L air) toxicity against *S. zeamais* and *T. castaneum*, respectively, and may be attributed to strong contact and fumigant toxicity of (R)-carvone and D-limonene.	[33]
		Herbicidal activity against barnyard grass *Echinochloa crus-galli*	Causing leaf injuries and reduction in biomass, impaired photosynthetic activity and plant metabolism.	[29]
		Antibacterial (*S. epidermidi*, *S. aureus*, *M. luteus*, *E. faecalis*, *B. cereus*, *E. coli*, *L. monocytogenes*, *S. typhimurium*) Antifungal (*C. albicans*, *C. glabrata*, *C. parapsilosis*, *C. kruse*, *S. cerevisae*)	Inhibition zone 11.00 to 25.00 mm diameter in disc-diffusion assay. MIC = 0.059 to 1.875 mg/mL (bacteria), 0.029–0.059 mg/mL (fungi). AChE inhibition (IC_{50} = 0.82 mg/mL) α-Glucosidase inhibition (IC_{50} = 6.83 mg/mL).	[30]
Carum copticum	Ajowan	Antifungal activities against *Penicillium digitatum* and *Alternaria alternata*	Mycelial growth inhibition 67.78% (*A. alternata*) and 44.88% (*P. digitatum*). Thymol may cause severe damage to cell walls, cell membranes and cellular organelles, such as mitochondria in fungi.	[31]

Table 2. *Cont.*

Botanical Name	Common Name	Biocidal Effect	Results/Mechanisms	References
Carum nigrum		Antifungal activity (*Penicillium citrinum*, *Penicillium purpurogenum*, *Aspergillus flavus*, *Aspergillus terreus*, *Aspergillus niger*, *Fusarium graminearum*), antibacterial activity (*Staphylococcus aureus*, *Bacillus subtilis*, *Pseudomonas aeruginosa*, *Salmonella typhimurium*, *Escherichia coli*, *Bacillus cereus*)	Antifungal activity by inverted petri dish method 34–100% at 3000 ppm. Inhibition zones determined by agar well diffusion method 17.9 mm to complete inhibition at 3000 ppm (bacteria).	[35]
Centella asiatica	Gotu Kola, Centella, Indian penny	Larvicidal activity (*Culex quinquefasciatus*)	Larvicidal activity (24 h-LC_{50} was 1.12–6.84 ppm at the temperatures of 31–19 °C) and acts as adult emergence inhibitor.	[87]
		Antibacterial activity (*Bacillus subtilis*, *Staphylococcus aureus*, *Escherichia coli*, *Pseudomonas aeruginosa*, *Shigella sonnei*)	MIC using microplate dilution method ranging from 1.25 to 0.039 mg/mL.	[36]
		Antifungal (*Aspergillus niger*) and Antibacterial (*Bacillus subtilis*) activity	6.3–15.4 mm (*A. niger*) and 8.4–16.4 mm (*B. subtilis*) inhibition zone in disc diffusion method.	[88]
Chaerophyllum aromaticum		Antibacterial activity	Bactericidal activity of Root EO against *Bacillus spizizenii* and *Staphylococcus aureus* (diameter of zone of inhibition 17 mm and 35 mm). BChE inhibitory activity of EO from root (47.65%) and aerial (50.88%).	[37]
Chaerophyllum aureum		Antibacterial activity (*Staphylococcus aureus*, *Staphylococcus epidermidis*, *Micrococcus luteus*, and *Escherichia coli*)	10.0–22.3 mm inhibition zone in agar diffusion method. Mechanisms of inhibition may be attributed to cell membrane damage due to hydrophobicity and impairment of bacterial enzyme.	[38]
Chaerophyllum crinitum		Antifungal (*Candida tropicalis*) and antibacterial (*Acinetobacter baumannii*, *Staphylococcus aureus*) activities	Inhibition zone 16–10 mm diameter in disc diffusion method.	[39]
Chaerophyllum macropodum		Antibacterial activity (*Escherichia coli*, *Salmonella typhi*)	Inhibition zone 6–12 mm diameter in disc diffusion method.	[89]

Table 2. *Cont.*

Botanical Name	Common Name	Biocidal Effect	Results/Mechanisms	References
		Antibacterial activity against *Staphylococcus epidermidis*, *Bacillus subtilis*, *Staphylococcus aureus*, *Escherichia coli*	Inhibition zone 10.7–18.1 mm diameter in agar disc diffusion method.	[40]
Coriandrum sativum	Coriander	Antifungal activity (*Aspergillus flavus*) and inhibition of aflatoxin production	Complete inhibition of *A. flavus* growth and afltoxin B_1 production at 1000 ppm coriander EO.	[28]
		Acaricidal and insecticidal activities (*Plodia interpunctella*, *Sitotroga cerealella* and *Tyrophagus putrescentiae*)	Fumigant toxicity (LD_{50} 4.19–18.76 μg/cm^3), contact toxicity (LD_{50} 19.29 μg/cm^2 for *T. putrescentiae*).	[41]
		Insecticidal activity (*Callosobruchus maculatus*, *Tribolium confusum*)	Insect mortality LC_{50} of *C. maculatus* and *T. confusum* were 1.34 and 318.02 μL/L air, respectively.	[42]
		Antibacterial activity (*Staphylococcus aureus*, *Bacillus spp.*, *Escherichia coli*, *Salmonella typhi*, *Klebsiella pneumonia*, *Proteus mirabilis*)	MIC 108–217 mg/mL.	[90]
		Antibacterial (*S. epidermidi*, *S. aureus*, *M. luteus*, *E. faecalis*, *B. cereus*, *E. coli*, *L. monocytogenes*, *S. typhimurium*) Antifungal (*C. albicans*, *C. glabrata*, *C. parapsilosis*, *C. kruse*, *S. cerevisae*)	Inhibition zone 8.33 to 21.66 mm diameter in disc diffusion assay. MIC = 0.234 to 1.875 mg/mL (bacteria), 0.234–0.469 mg/mL (fungi). AChE inhibition (IC_{50} = 0.68 mg/mL) α-Glucosidase inhibition (IC_{50} = 6.24 mg/mL).	[30]
Crithmum maritimum	Sea Fennel	Antiparasitic activity (*Trypanosoma cruzi*)	EC_{50} = 17.7 μg/mL.	[91]
		Antifungal properties against *Candida albicans*, *Cryptococcus neoformans* and several dermatophytes and *Aspergillus* spp.	*C. neoformans* 260 μg/mL (MIC), *C. albicans* (Inhibition of biofilm formation and germ tube formation).	[44]
		Larvicidal (*Spodoptera littoralis*; tobacco cut worm), AChE inhibitory activities	Toxicity 62.3–71.7 μg/larva (LD_{50}). AChE inhibitory activity 7.4 mg/mL (IC_{50}).	[47]
Cuminum cyminum	Cumin	Insecticidal activity (*Sitophilus zeamais*)	Contact (LC_{50} 0.246 μL/cm^2 area) and fumigant (LC_{50} 0.346 μL/cm^3 air) toxicity, inhibition of AChE activity.	[92]
		Antifungal activity (*Candida albicans*, *Lachancea thermotolerans*, *Metschnikowia pulcherrima*)	MIC $\leq$ 0.5 mg/mL.	[16]

Table 2. *Cont.*

Botanical Name	Common Name	Biocidal Effect	Results/Mechanisms	References
		Insecticidal activity against peach-potato aphid (*Myzus persicae*), tobacco cutworm/cotton leaf worm (*Spodoptera littoralis*), and two insect vectors, common housefly (*Musca domestica*) and lymphatic filariasis and Zika virus vector *Culex quinquefasciatus*	LD_{50} = 3.2 mL/L (*M. persicae*), 100 µg/larva (*S. littoralis*), 31.8 µg/adult (*M. domestica*), 40.5 µL/L (*C. quinquefasciatus*).	[49].
Daucus carota	Wild Carrot	Insecticidal activity (*Tribolium confusum*)	100% efficacy in dose of 1 mL.	[93]
		Antibacterial activity (*Agrobacterium tumefaciens*, *Erwinia carotovora*, *Pseudomonas fluorescens*, *Pseudomonas glycinea*)	28.66–100% of antibacterial activities in disc diffusion method.	[13]
Deverra scoparia		Acaricidal activity against *Tetranychus urticae* (two-spotted spider mite)	Toxicity LD_{50} 1.79 mg/L and decreased fecundity.	[51]
Echinophora spinosa	Prickly Parsnip	Antibacterial (*Escherichia coli*, *Pseudomonas aeruginosa*) and antifungal activity (*Trichoderma viride*)	MIC in microdilution technique were 0.0625 (*E. coli*), 0.25 (*P. aeruginosa*), and 0.0625 (*T. viride*) mg/mL.	[52]
		Antibacterial (*Bacillus subtilis*, *Escherichia coli*, *Proteus mirabilis*) and antifungal activity (*Candida albicans*, *Aspergillus niger*)	Inhibition zone 2–30.5 mm diameter in disc diffusion assay.	[94]
		Insecticidal activity (*Culex quinquefasciatus*, *Spodoptera littoralis*, *Musca domestica*)	Toxicity LC_{50} 15.7 mg/L (*C. quinquefasciatus*), LD_{50} 38.3 µg/adult (*M. domestica*), 86.3 µg/larva (*S. littoralis*).	[95]
Eryngium alpinum	Alpine Sea Holly	Antibacterial (*Escherichia coli*, *Staphylococcus aureus*), antifungal (*Candida albicans*, *Microsporum gypseum*)	MIC 0.08–1.94 mg/mL using microdilution assay.	[53]
Eryngium amethystinum	Amethyst sea holly	Antibacterial (*Escherichia coli*, *Staphylococcus aureus*), antifungal (*Candida albicans*)	MIC 0.06–1.94 mg/mL using microdilution assay.	[53]
Eryngium foetidum	Culantro, Mexican coriander, long coriander	Antibacterial activity against *Bacillus subtilis*, *Staphylococcus aureus*, *Escherichia coli*, *Pseudomonas aeruginosa*, antifungal activity against Candida albicans	Inhibition zone 12–28 mm in agar well diffusion method MIC 1.56–200 µg/mL in microbroth dilution method.	[96]
		Larvicidal activity (Aedes albopictus)	24 h-LC_{50} s 33.3 ppm.	[97]
Eryngium triquetrum	Choukzerk	Antibacterial (*Staphylococcus aureus*, *Staphylococcus epidermidis*, *Bacillus subtilis*) and antifungal (*Candida albicans*) activities	MIC using broth dilution method = 6.25–25 µg/mL.	[54]

Table 2. *Cont.*

Botanical Name	Common Name	Biocidal Effect	Results/Mechanisms	References
		Herbicidal activity (*Lepidium sativum*), antibacterial activities against *Pectobacterium atrosepticum* (potato blackleg disease), and Gram-negative soil bacterium (*Pseudomonas cichorii*) Antifungal and fumigant activity against *Fusarium graminearum* (cereal fusarium) and *Botrytis cinerea* (grey rot in tomatoes, strawberries)	Inhibition of germination, growth, and photosynthesis (43%) of *L. sativum*, inhibition of 85% *Pectobacterium*, 100% *Pseudomonas*, fumigant toxicity with lack of growth on *F. graminearum* and moderate inhibition (43%) on *B. cinerea.*	[55]
Falcaria vulgaris		Antifungal (*Aspergillus fumigatus*)	0.140 mg/mL (MIC using microdilution method). Cholinesterase inhibition (AChE and BChE).	[98]
Ferula caspica		Antibacterial activity (*Staphylococcus aureus*, *Enterococcus faecalis*)	MIC in broth microdilution method 32–64 µg/mL.	[99]
Ferula orientalis		Antibacterial (*Staphylococcus aureus*) and antifungal (*Candida albicans*) activities	Determined by direct bioautography	[56]
Ferula pseudalliacea		Insecticidal activity (*Varroa destructor*)	Highest (30.72%) mortality was at 36 h.	[100]
Ferula rigidula		Antifungal activity (*Aspergillus ochraceus*, *Trichoderma viride*), Antibacterial (*Pseudomonas aeruginosa*)	MIC determined by microdilution method were 0.27 (bacteria) and 0.10 (fungi) mg/mL. Enzymatic inhibitory activities against AChE, BChE, tyrosinase, α-amylase, and α-glucosidase.	[101]
Ferulago angulata		Antibacterial activity against *Bacillus thuringiensis*, *Erwinia amylovora*, *Xanthomonas oryzae* Antifungal activity against *Colletotrichum tricbellum*, *Fusarium oxysporum*	MIC = 8 (*B. thuringiensis*), 12.5 (*E. amylovora*), and 12 (*X. oryzae*) µL/mL. 47.8–100% fungal growth inhibition in agar dilution method 52.5–100% in disc diffusion method at concentration of 800 µL/L.	[57]
Ferulago cassia		Anticholinesterase activity	Cholinesterase inhibition (AChE and BChE).	[58]
Ferulago sandrasica		Antibacterial (*Staphylococcus aureus*) and antifungal (*Candida albicans*) activity	Determined by direct bioautography.	[56]

Table 2. *Cont.*

Botanical Name	Common Name	Biocidal Effect	Results/Mechanisms	References
Ferulago trachycarpa		Antibacterial activity against *Staphylococcus aureus* and *E. faecalis* (dichloromethane and n-hexane extract), Antifungal activity against *Candida albicans*, *Candida tropicalis*, *Candida parapsilosis* (all extracts)	MIC in microdilution method 3.9–625 mg/L.	[59]
Ferulago trifida		Larvicidal activity (*Anopheles stephensi*) cytotoxic activity and inhibition of AChE activity	LC_{50} = 116.54 ppm.	[60,102]
Foeniculum vulgare	Fennel	Insecticidal activity (*Sitophilus granaries*, *Sitophilus oryzae*)	Fumigation toxicity 27.3 µL/L air (*S. granaries*) and 44.16 µL/L air (*S. oryzae*) (LC_{50}).	[103]
		Insecticidal activity (African cotton leafworm *Spodoptera littoralis*)	Fumigant toxicity LD_{50} 51.2 µL/L air.	[86]
		Larvicidal, pupicidal, and insecticidal activity (*Culex quinquefasciatus*)	Larvicidal activity with LC_{50} = 0.10 mg/mL, LD_{50} = 7.52/min.	[104]
		Larvicidal and ovicidal activities (*Culex pipiens*)	Larvicidal activity with 24 h-LC_{50} = 148.3 µg/mL.	[105]
		Insecticidal activity (*Lymantria dispar*)	Antifeedant activity at concentration of 1% EO (77.68 Tot).	[79]
		Insecticidal activity (*Sitophilus granaries*, *Tribolium castaneum)*	100% (*T. castaneum*) and 43.58% (*S. granaries*) fumigant toxicity.	[62]
		Antifungal activities against *Penicillium digitatum* and *Alternaria alternata*	Mycelial growth inhibition 13.94% (*A. alternata*) and 55.39% (*P. digitatum*).	[31]
		Insecticidal activity against *Tribolium castaneum* and *Sitophilus oryzae*	Fumigant toxicity [91.28 and 254.71 µL/L air, respectively (LC_{50})] and repellency effects.	[43]
		Herbicidal activity against weeds of wheats (*Phalaris minor*, *Avena ludoviciana*, broad-leaved weeds, *Rumex'dentatus*, and *Medicago denticulate*)	Inhibition of germination and seedling.	[63]
Heracleum anisactis		Antibacterial activity (*Escherichia coli*, *Staphylococcus epidermidis*, *Staphylococcus aureus*)	11–13 mm inhibition zone in agar disc diffusion method, MIC in broth dilution method 1.1–1.5 *v*/*v*.	[106]
Heracleum persicum	Persian Hogweed	Larvicidal activity (*Anopheles stephensi*)	24 h-LC_{50} = 26–336 ppm	[107]

Table 2. *Cont.*

Botanical Name	Common Name	Biocidal Effect	Results/Mechanisms	References
		Insecticidal (*Callosobruchus maculatus*)	Fumigant toxicity 24 h-LC_{50} = 136.4 µL/L air and higher oviposition deterrence property.	[108]
Hippomarathrum microcarpum		Antibacterial (*Staphylococcus aureus*) and antifungal (*Candida albicans*) activity	Determined by direct bioautography.	[56]
Levisticum officinale	Lovage	Insecticidal activity (*Tribolium confusum*)	100% efficacy in dose of 2 mL.	[93]
Myrrhis odorata	Sweet Cicely	Antifungal activity (*Cladosporium cladosporioides*, *Aspergillus niger*, *Aspergillus flavus*, *Trichoderma viride*)	MIC for fungi were 0.5–1.0 mg/mL in microdilution test.	[109]
Ostericum sieboldii	Water Dropwort	Insecticidal activity against the red flour beetle (*Tribolium castaneum*) and maize weevil (*Sitophilus zeamais*)	Contact toxicity against *T. castaneum* and *S. zeamais* with LD_{50} values of 8.47 and 13.82 µg/adult, respectively. Fumigant toxicity LC_{50} values of 20.92 and 27.39 mg/L air, respectively.	[66]
Pastinaca sativa	Parsnip	Antibacterial activity (*Bacillus cereus*)	MIC in microwell dilution assay 0.72 mg/mL.	[110]
Petroselinum crispum	Parsley	Insecticidal activity against *Pseudaletia unipuncta* (Armyworm)	Antifeedant/feeding deterrence index (99.7%), and contact toxicant action (93% after 48 h).	[83]
Peucedanum ostruthium	Masterwort	Phytotoxic activity (*Lolium multiflorum*, *Echinochloa oryzoides*), nematicidal (*Panagrolaimus rigidus*)	Decreased germination and significant impact on *L. multiflorum* root and shoot growth. Nematicidal activity of leaves extract: 85.6% and 90.5% mortality of larvae and adults of *P. rigidus*.	[111]
Pimpinella anisum	Anise	Insecticidal activity (*Lymantria dispar*)	Antifeedant activity at concentration of 1% EO (Tot 119.26).	[79]
		Antibacterial (*Bacillus subtilis*, *Klebsiella pneumonia*) and antifungal (*Aspergillus niger*, *Candida albicans*) activities	11–40 mm inhibition in cup plate–agar diffusion method.	[112]
		Insecticidal activity against *Tribolium castaneum* and *Sitophilus oryzae*	Fumigant toxicity [43.75 and 292.04 µL/L air, respectively (LC_{50}), and repellency effects.	[43]

Table 2. *Cont.*

Botanical Name	Common Name	Biocidal Effect	Results/Mechanisms	References
		Insecticidal activity against peach-potato aphid (*Myzus persicae*), tobacco cutworm/cotton leaf worm (*Spodoptera littoralis*), and two insect vectors, common housefly (*Musca domestica*) and lymphatic filariasis and Zika virus vector *Culex quinquefasciatus*	*M. persicae* (4.3 mL/L), *S. littoralis* (57.3 µg/larva), *M. domestica* (54.8 µg/adult), *C. quinquefasciatus* (25.4 µL/L) (LD_{50}).	[49].
Prangos peucedanifolia		Antifungal (*Trichophyton rubrum*) and antibacterial activities (*Streptococcus mutans*, *Streptococcus pyogenes*, and *Staphylococcus aureus*)	MIC determined by twofold serial broth dilution method were 2000 (*T. rubrum*) and ≤1.19 (bacteria) µg/mL.	[67]
		Antibacterial activity (*Pseudomonas aeruginosa*, *Escherichia coli*, *Bacillus cereus*, *Listeria monocytogenes*, *Salmonella typhimurium*), Antifungal activity (*Aspergillus ochraceus*, *Trichoderma viride*, *Aspergillus versicolor*), inhibition of α-glucosidase	MIC determined by microdilution method were 0.27–0.56 (bacteria) and 0.22–0.27 (fungi) mg/mL. Enzymatic inhibitory activities against AChE, tyrosinase, α-amylase, and α-glucosidase.	[101]
Seseli gummiferum	Moon Carrot	Antibacterial action against *Staphylococcus lugdunensis*	Enzymatic inhibitory activities against AChE, BChE, tyrosinase, and α-amylase MIC = 0.025–0.5 mg/mL.	[68]
Sison amomum	Stone Parsley	Antibacterial (*Staphylococcus aureus*, *Klebsiella pneumonia*, *Acinetobacter baumannii*)	MIC using microdilution method = 2.0–4.1 mg/mL.	[69]
Smyrnium olusatrum	Alexanders, Horse Parsley	Herbicidal activity (*Lepidium sativum*) Antifungal activity against *Fusarium graminearum* and *Zymoseptoria tritici* Fumigant toxicity (*Fusarium graminearum*, *Botrytis cinerea*)	Inhibition of germination, growth, and photosynthesis (74%) of *L. sativum*, lack of growth on *F. graminearum* and 83% inhibition on *Z. tritici* mycelial growth at low concentration 0.142 µL/mL air. Fumigant toxicity with lack of growth on *F. graminearum* and 48% inhibition on *B. cinerea* at 0.142 µL/mL air.	[55]
Trachyspermum ammi	Ajwain, Ajowan caraway	Antibacterial activity (*Bacillus cereus*, *Staphylococcus aureus*, *Listeria monocytogenes*, *Salmonella typhimurium*, *Escherichia coli*), Antifungal activity (*Penicillium citrinum*, *Penicillium chrysogenum*, *Aspergillus flavus*, *Aspergillus niger*, *Aspergillus parasiticus*)	Inhibition zone in disc diffusion method = 34–39 mm (bacteria) and >80 mm (fungi). MIC using broth microdilution method = 500 ppm (bacteria) and 1000–2000 ppm (fungi).	[70]

Table 2. *Cont.*

Botanical Name	Common Name	Biocidal Effect	Results/Mechanisms	References
		Insecticidal activity (*Tribolium castaneum*)	Fumigant toxicity (LC_{50} 11.6 µL), repellency, and reduces oviposition potential.	[78]
		Insecticidal activity against rice weevil (*Sitophilus oryzae*),	Repellent activity (95% at 1.2% EO), fumigant toxicity [0.37 µL/cm^3 (LC_{50})], AChE inhibition.	[15]
		Insecticidal activity (*Plodia interpunctella*) Antibacterial activity *S. aureus*, *E. coli*, *P. vulgaris*, *B. subtilis*, *K. pneumoniae*, and *B. megaterium*	Fumigant toxicity (LC_{50} 4.33 µL/L air) MIC (dilution method) = 8–14 µL at 25% *v*/*v* EO.	[113]
		Insecticidal activity (maize weevil *Sitophilus zeamais*)	Repellent activity, fumigation (LC_{50} 0.385 µL/cm^3 air), contact toxicity (0.317 µL/cm^2), and oviposition inhibitory effect.	[114]
		Insecticidal activity (*Aethina tumida*)	Contact (LD_{50} 66.64 µg/adult) and fumigant (LC_{50} 89.03 mg/L air) toxicity may be attributed to the presence of thymol compound.	[115]

AChE, acetylcholinesterase; BChE, butyrylcholinesterase; LC_{50}, median lethal concentrations; LD_{50}, median lethal doses; MIC, minimum inhibitory concentration; EC_{50}, half maximal effective concentration or concentration that reduces the infection in 50%; IC_{50}, 50% inhibition of the AChE activity; Tot, total deterrence coefficients; MFC, minimum fungicidal concentration.

Botanical insecticides affect the pest with little or no side effects. These botanical insecticides kill the insects or affect their physiology in various ways, such as survival, behaviour, development, reproduction, and metabolic pathways [7].

The mechanism of insecticidal activity in secondary metabolites, including EOs, occurs via fumigant, contact, repellent, antifeedant, ovicidal, oviposition deterrent and larvicidal activity, and by inhibiting/altering neurotransmitters [acetylcholinesterase enzymes (AChE) and octopamine) and the neurotransmitter inhibitor (γ-aminobutyric acid (GABA)], impairment of the antioxidative defence systems, and cellular respiration [116–119]. Several earlier studies reported the inhibition of AChE by plant EOs. EOs components such as α-pinene and β-pinene, β-phellandrene, carvacrol, limonene, menthol, menthone, 1,8-cineole, cis-ocimene, niloticin, and (L)-fenchone inhibited the AChE of insect pests [7,117]. Thymol and eugenol disrupt the functions of GABA and octopamine [118].

Phytotoxic plant extracts or metabolites delay or inhibit seed germination, as well as retarding the growth of weeds. The phytotoxic or herbicidal effect of EOs is associated with various mechanisms, including inhibition of DNA synthesis and cell proliferation, decreasing mitochondrial respiration, inducing reactive oxygen species (ROS) production, inhibition of enzymes, photosynthesis, seed germination, and seedling growth, altering membrane permeability and respiration. Oxygenated monoterpenes play a major role in most of the mechanisms. Monoterpenes, 1,8-cineole and camphor inhibit DNA synthesis, cell proliferation, and elongation [120–122].

The common antimicrobial mechanism of many EOs is attributed to the effect of membrane permeability or functioning, leading to cell death in fungi or bacteria. Other than these, antifungal mechanisms of secondary metabolites, including EOs, involve inhibiting the fungi cell wall formation, inhibiting the mitochondrial electron transport, cell division, RNA or DNA and/or protein synthesis, and efflux pumps [123]. The sites and number of hydroxyl groups on the phenolic compounds (simple phenols, phenolic acids, quinones, flavones, flavonoids, flavonols, tannins, and coumarins) may be related to their relative toxicity to fungi. The antifungal mechanism of terpenoids (diterpenes, triterpenes, tetraterpenes, hemiterpenes, and sesquiterpenes) is related to membrane disruption by the lipophilic compounds, while the mechanisms of alkaloids (heterocyclic nitrogen compounds) are attributed to their ability to intercalate with DNA [12].

4. Potential Use of Apiaceae Extracts as Agrochemicals

Synthetic agrochemicals are used to manage weeds, pests, and phytopathogens, thus increasing productivity and food safety. However, long-time usage of these synthetic chemicals may lead to environmental contamination, accumulation of toxic residues and biomagnification through the food chain, development of insect resistance, and threats to humans and non-target organisms [9,103]. These synthetic chemicals produce acute or chronic toxicity in living beings, depending on physicochemical characteristics, concentration and exposure time, route of entry, toxicodynamics and toxicokinetics (absorption, distribution, half-life, metabolism, and elimination), a combination of various pesticides, and the components of their formulation [9]. Secondary metabolites, including EOs, from aromatic plants, drew much attention due to their low toxicity to animals and non-target insects, fast degradation in the environment, and local availability. Other than the many health benefits, the biocidal potential of Apiaceae has great importance in agriculture for use as a natural pesticide, herbicide or phytotoxin, and antimicrobial [124].

4.1. Insecticidal Activity for Crops and Stored Producs Protection

4.1.1. Insecticidal Activity to Protect Crops

Several Apiaceae genera are toxic to various insects [124]. *Tuta absoluta*, a major pest of tomato cropping, can be controlled by the EO of *Carum capticum* (Ajwain) [7]. Thymol, γ-terpinene, and ρ-cymene are the major components of *C. capticum* oil that showed AChE inhibition [7].

Ammi visnaga (toothpick-plant) seeds possess acaricidal activity against *Tetranychus urticae* Koch, which is a polyphagous species causing damage to numerous plants (around 1200 species), including major food crops and ornamental plants [125].

Cotton leafworm, *Spodoptera littoralis*, causes serious damage to important economic crops, such as maize, cotton, cereals, potatoes, tobacco, tomato, vegetables, and ornamental plants [47,86]. Apiaceae species, *C. carvi*, *F. vulgare*, *C. cyminum*, *C. caraway*, *C. sativum*, *D. carota* [86], *Helosciadium nodiflorum* (water celery) [126], and *Crithmum maritimum* [47] were demonstrated to possess toxicity against *S. littoralis* larvae. Benelli et al. [49] also suggest that cumin (*C. cyminum*) and anise (*P. anisum*) EOs can be used to protect crops from pests or to control insect vectors, as they have potential insecticidal activity against the peach-potato aphid (*Myzus persicae*) and the tobacco cutworm/cotton leafworm (*S. littoralis*), and insect vectors, such as the common housefly (*Musca domestica*). The crop pest *Spodoptera litura* is a threat to many crops and develops resistance to synthetic pesticides. This pest can be counteracted by sea fennel (*C. maritimum*) EOs [48].

4.1.2. Insecticidal Activity to Protect Stored Products

Several species of storage insect pests infest agricultural products and stored granaries, causing substantial weight losses (around 10%) and quality [15]. They may carry pathogens and contaminate food [127]. *Sitophilus oryzae* (rice weevil), *Sitophilus zeamais* (maize weevil), *Tyrophagus putrescentiae* (mould or cheese mite), *Tribolium confusum* (confused flour beetle), *Callosobruchus maculatus* (cowpea weevil), *Periplaneta americana* (American cockroach), *Tribolium castaneum* (red flour beetle) are some of the pests that affect stored cereals, grains, flour, and other dried products [127]. Research is focused on producing safe and low-risk natural compounds for pest control [43]. Several Apiaceae species were reported to carry insecticidal activities and have potential to protect stored grains from insect infestation.

Monoterpenes, such as (S)-(−)-linalool and (S)-(−)-menthone showed the most contact toxicity and fumigant activities, respectively, while α- pinene, menthone, citronellal, and linalool exhibited repellent activities against the rice weevil (*S. oryzae*) [128]. Cuminaldehyde and (S)-carvone showed strong repellent activities, fumigation toxicity, and AChE inhibition [129].

Apiaceae species were demonstrated to possess insecticidal and repellent activity. EOs from *F. vulgare*, *Petroselinum hortense*, *C. sativum*, and *P. anisum* showed stronger fumigant toxicity against the storage pest, red flour beetle (*T. castaneum*) than against the rice weevil (*S. oryzae*) [43]. *C. carvi* EO and two isolated main compounds, (R)-carvone and D-limonene, exhibited strong contact and fumigant toxicity against the maize weevil (*S. zeamais*) and the red flour beetle (*T. castaneum*) [33]. *A. graveolens* (dill), *C. cyminum* (cumin), and *P. crispum* (parsley) EOs were reported as having contact toxicity, fumigant, and repellent activities against the stored grain pest *S. zeamais*. Moreover, AChE inhibition was also reported with *P. crispum* and *C. cyminum* EOs [129]. *Trachyspermum ammi* EO also showed repellent and fumigant activity against the rice weevil (*S. oryzae*). In addition, *T. ammi* EO showed significant inhibition of AChE activity in rice weevils [15].

Insecticidal activity of EO derived from *A. graveolens* (dill) seeds was reported against *T. confusum* (confused flour beetle), *C. maculatus* (cowpea weevils), *M. domestica*, *P. americana* (American cockroach), and *T. castaneum* (red flour beetles)] [130].

Plodia interpunctella (Indian meal moth), *Sitotroga cerealella* (grain moth), and *T. putrescentiae* (mould or cheese mite) affecting stored products, such as grains, flours, feeds, dried nuts, and fruits, globally. *P. interpunctella* moth continuously produces a silken web on the food; *S. cerealella* larvae invade grains and complete the larval and pupal stages within the grains, thus decreasing grain weight and nutritional value; and *T. putrescentiae* mites disseminate toxic fungi and induce allergic reactions among workers engaged in agriculture and food industries. Camphor and linalool found in *C. sativum* EO, extracted by steam distillation, exhibited acaricidal and insecticidal properties against *P. interpunctella*, *S. cerealella*, and *T. putrescentiae* [41].

4.2. Herbicidal/Phytotoxic Activity against Weeds

Many studies were undertaken to investigate the herbicidal potential of Apiaceae species against weeds. Enzymes such as α- amylase, catalase, and peroxidase enzymes play a key role in the physiological functions of the seeds and plants. Application of EOs increases oxidative stress in plant cells, which inhibits these enzymes and causes subsequent cell death. Moreover, the detrimental effect on the DNA and RNA of the cell results in decreased cell division, growth, and elongation [63].

Herbicidal effects of EOs derived from *C. sativum*, *C. carvi*, *F. vulgare*, and *P. anisum* were reported against various weeds [122]. *Eryngium triquetrum* EO and its major constituent falcarinol showed strong herbicidal activity against *Lepidium*, while *Smyrnium olusatrum* EO showed moderate herbicidal activity. Therefore, *E. triquetrum* and *S. olusatrum* EOs can be used in crop protection to inhibit photosynthesis in weeds [55].

Caraway (*C. carvi*) EO (oil in water emulsion) are rich in oxygenated monoterpenes and exhibited herbicidal activity against *Echinochloa crus-galli* (barnyard grass, a typical maize weed) [29]. *C. carvi* EO was found to inhibit the germination of seeds of common weeds, including *Amaranthus retroflexus*, *Centaurea salsotitialis*, *Raphanus raphanistrum*, *Rumex nepalensis*, *Sonchus oleraceus*, and *Sinapis arvensis* [131].

Fennel (*F. vulgare*) EO strongly inhibited the seed germination and seedling growth of grass weeds, *Phalaris minor*, *Avena ludoviciana*, broad-leaved weeds, *Rumex dentatus* and *Medicago denticulate*, and can, therefore, be used in the biological management of weeds in wheat (*Triticum aestivum*) crops [63]. Fennel (*F. vulgare*) EO was also reported for its phytotoxic activity against field bindweed (*Convolvulus arvensis*) with significant inhibition of germination and early growth in field bindweed seedlings [132].

4.3. Antimicrobial Activity against Phytopathogens

Plant pathogens, including fungi, bacteria, viruses, oomycetes, and nematodes, can cause diseases or damage to plants and result in significant crop yield and quality losses, of which fungi are the predominant pathogens, causing almost 30% of crop diseases during their cultivation or after harvest. Fungal disease symptoms on fruits, leaves, stems, and other plant parts include scabs, mouldy coatings, rust, smuts, powdery mildew, blotches, and rotted tissues. Plant diseases caused by phytopathogenic bacteria and fungi threaten human health and food security [13,120,133,134].

Various phytopathogenic bacteria, including *Xanthomonas* spp. (bacterial spots and blights), *Erwinia* spp. (soft rot, fire blight), *Pseudomonas* spp. (soft rot, bacterial canker), *Agrobacterium* spp. (crown gall), as well as *Ralstonia solanacearum* (bacterial wilt in banana), affect various agricultural plants [123].

Moreover, *Fusarium oxysporum* (vascular wilt of the banana tree), *Macrophomina phaseolina* (damping-off, seedling blight, and rot in peanuts, cabbage, pepper, chickpeas, soybeans, sweet potatoes, sesame, potatoes, sorghum, wheat, corn, etc.), *Alternaria alternata* (rot), *Penicillium digitatum* (green mould in citrus), and *Aspergillus flavus* (damping-off in peanut) are some of the fungi responsible for many diseases in various plants [134,135].

Apiaceae family plants were widely investigated for their potential biocidal activity against phytopathogens.

Apiaceae, such as Torilis anthriscus, Aegopodium podagraria, D. carota, Heracleum sphondyilium, Pimpinella saxifrage, P. sativa, Angelica silvestris, and F. vulgare exhibited antimicrobial activity against phytopathogenic bacteria Agrobacterium radiobacter pv tumefaciens, Erwinia carotowora, Pseudomonas fluorescens, and Pseudomonas glycinea [13]. The EO of C. maculatum (poison hemlock), a poisonous Apiaceae species, has antibacterial activity against Pseudomonas aeruginosa [136].

E. triquetrum EO exhibited strong antibacterial activities against potato blackleg disease, *Pectobacterium atrosepticum*, and the soil bacterium *Pseudomonas cichorii*, which is responsible for disease in lettuce, celery, and chrysanthemum, while *S. olusatrum* EO showed moderate antibacterial activity [55].

The Apiaceae Ferulago angulate exhibited toxicity in variable degrees against phytopathogenic bacteria (Erwinia amylovora, Xanthomonas oryzae, Pseudomonas syringae, Pectobacterium carotovorum, R. solanacearum, Bacillus thuringiensis), and fungi (A. alternata, Culvularia fallax, M. phaseolina, F. oxysporum, Cytospora sacchari, Colletotrichum tricbellum) [57].

A. alternata and *P. digitatum* are two postharvest pathogens in tomato fruits. Based on in vivo studies, *Carum copticum* and *F. vulgare* EOs have the potential to control postharvest decay in tomatoes caused by *A. alternata* and *P. digitatum* [31].

E. triquetrum and *S. olusatrum* EOs have potent antifungal and fumigant activity against *Fusarium graminearum* (cereal fusarium) and moderate activity against *Botrytis cinerea* (grey rot on tomatoes, strawberries). *S. olusatrum* EO showed strong antifungal activity against *F. graminearum* and *Zymoseptoria tritici*, which are responsible for the septoria blight [55].

A. graveolens (dill) seeds EO mainly consists of carvone, limonene, α-phellandrene, β-phellandrene and p-cymene and were proved to have antifungal (*Aspergillus niger*, *Aspergillus oryzae*, *A. flavus*, *A. alternata*) and antibacterial (*Escherichia coli*, *P. aeruginosa*, *Bacillus subtilis*, *Staphylococcus aureus*) activities [130].

Food poisoning is the most common cause of illness and death in both developed and developing countries. Most food poisoning diseases are caused by bacterial contamination. Pathogenic and food spoilage bacteria, such as *Salmonella typhi*, *E. coli*, *P. aeruginosa*, *S. aureus*, *Listeria monocytogenes*, and *Bacillus cereus* are the causal agents of foodborne diseases or food spoilage. Plant extracts are a good source of antimicrobial agents that can be used as food preservatives [137,138].

Apiaceae *C. cyminum* was reported to be effective against *S. aureus* [138]. Coriander (*C. sativum*) EO and its major compound linalool showed antibacterial activity against *Campylobacter jejuni* and *Campylobacter coli*, pathogens that cause foodborne diseases [139].

Coriander (*C. sativum*) was also reported to have strong antimicrobial activity against bacteria, *B. subtilis*, followed by *Stenotropomonas maltophilia*, and *Penicillium expansum* (fungi producing mycotoxin). Moreover, the strongest antibiofilm activity of coriander EO was also reported against *S. maltophilia* [140].

Carum nigrum (black caraway) seed EO has antibacterial activity against foodborne bacteria, *B. cereus* and *P. aeruginosa*, and antifungal activity against foodborne fungi, such as *P. purpurogenum*, *Acrophialophora fusispora*, *A. flavus*, and *A. niger* [35].

The antimicrobial activity of *T. ammi* (Ajwain) EO was demonstrated against various food spoilage and foodborne bacteria (*B. cereus*, *S. aureus*, *L. monocytogenes*, *Salmonella typhimurium*, *E. coli*) and fungi (*Penicillium citrinum*, *Penicillium chrysogenum*, *A. flavus*, *A. niger*, *Aspergillus parasiticus*) [70].

Moreover, certain fungi, including *Aspergillus* spp., *Fusarium* spp., and *Alternaria* spp., produce mycotoxins that can be harmful to human health due to hepatotoxic, nephrotoxic, and carcinogenic effects, or even cause death [120]. Mycotoxins are toxic secondary metabolites produced by certain fungal species in various agricultural and other food products, either in the field or during storage. Mycotoxin contamination in crops is potentially harmful to animals and human health. Aflatoxins B1, B2, G1, and G2 are the four major toxins generated in foods, of which the aflatoxin B1, secreted by *A. flavus*, *A. parasiticus* and *Aspergillus nomius*, is the most toxic and has potent teratogenic, mutagenic, hepatotoxic, and immune suppressive activities [141–143].

Apiaceae, *F. vulgare* EO extracted from flowers and roots, significantly inhibited the growth of *A. parasiticus* and the production of aflatoxins B1 and G1 [144]. Carvone and linalool compounds found in *C. carvi* and *C. sativum* seed EOs, respectively, showed an antifungal and aflatoxin-inhibition ability against *A. flavus*. Thus, they can be used as a preservative, particularly in post-harvest processing and the storage of agricultural products that are susceptible to aflatoxin contamination, such as cereals, dried fruits, and spices [143]. EOs of other Apiaceae plants, including *C. cyminum* [145], *C. carvi* [28,146], *C. sativum* [28], and *C. copticum* (*T. ammi*) were also reported to inhibit both growth and/or mycotoxin production. Table 3 summarizes the potential use of Apiaceae extracts as agrochemicals.

Table 3. Potential use of Apiaceae extracts as agrochemicals.

Insects/Weeds/Phytopathogens	Effects	Apiaceae	References
Insecticidal activity to protect crops			
Myzus persicae (Peach-potato aphid)	Agricultural pest	*C. cyminum*, *P. anisum*	[49]
Spodoptera littoralis (Tobacco cutworm/cotton leafworm)	Affects maize, cotton, cereals, potatoes, tobacco, tomato, vegetables, and ornamental plants.	*C. carvi*, *F. vulgare*, *C. cyminum*, *C. caraway*, *C. sativum*, *D. carota*, *P. anisum*, *C. maritimum*, *H. nodiflorum*	[47,49,86]
Spodoptera litura (Tobacco cutworm/cotton leafworm/armyworm)	Agricultural pest, affecting many crops.	*C. maritimum*	[48].
Tetranychus urticae	Affects numerous plants (around 1200 species), including major food crops and ornamental plants.	*A. visnaga*	[125]
Tuta absoluta	Tomato	*C. capticum*	[7]
Insecticidal activity to protect stored products			
Culex quinquefasciatus	Lymphatic filariasis and Zika virus vector	*P. anisum*	[49]

Table 3. *Cont.*

Insects/Weeds/Phytopathogens	Effects	Apiaceae	References
Musca domestica (Common housefly)	Storage pests, Insect vectors	*C. cyminum*, *P. anisum*	[49,130]
Sitophilus oryzae (Rice weevil)	Storage pests	*F. vulgare*, *P. hortense*, *C. sativum*, *P. anisum*, *T. ammi*	[15,43]
Sitophilus zeamais (Maize weevils)	Stored grain pest	*C. carvi*, *A. graveolens*, *C. cyminum*, *P. crispum*	[33,129]
Tribolium castaneum (Red flour beetles)	Storage pests	*F. vulgare*, *P. hortense*, *C. sativum*, *P. anisum*, *C. carvi*, *A. graveolens*	[33,43,130]
Tyrophagus putrescentiae (Mould or cheese mite)	Storage pests, disseminate toxic fungi and induce allergic reactions among workers engaged in agriculture and food industries.	*C. sativum*	[41]
Callosobruchus maculatus (Cowpea weevils) *Tribolium confusum* (Confused flour beetle) *Periplaneta americana* (American cockroach)	Storage pests	*A. graveolens*	[130]
Plodia interpunctella (Indian meal moth) *Sitotroga cerealella* (Grain moth)	Affect stored products, such as grains, flours, feeds, dried nuts, and fruits.	*C. sativum*	[41]
Herbicidal/phytotoxic activity against weeds			
Convolvulus arvensis (Field bindweed)	Common weed over the world	*F. vulgare*	[132].
Echinochloa crus-galli (Barnyard grass, a typical maize weed)	Maize weed	*C. carvi*	[29]
Lepidium sativum (watercress)		*E. triquetrum*, *S. olusatrum*	[55]
Amaranthus retroflexus, *Centaurea salsotitialis*, *Raphanus raphanistrum*, *Rumex nepalensis*, *Sonchus oleraceus*, and *Sinapis arvensis*	Common weeds	*C. carvi*	[131]
Grass weeds, *Phalaris minor* and *Avena ludoviciana*, broad-leaved weeds, *Rumex dentatus* and *Medicago denticulate*	Weeds of wheat (*Triticum aestivum*)	*F. vulgare*	[63]
Antimicrobial activity against phytopathogens			
Alternaria alternata	Phytopathogens; postharvest pathogens in tomato fruits	*C. copticum*, *F. vulgare*, *A. graveolens*, *F. angulate*	[31,57,130]
Penicillium digitatum	Postharvest pathogens in tomato fruits	*C. copticum*, *F. vulgare*	[31]
Pectobacterium atrosepticum	Potato blackleg disease	*E. triquetrum*, *S. olusatrum*	[55]
Pseudomonas cichorii	Soil bacterium causing disease of lettuce, celery, and chrysanthemum		

Table 3. *Cont.*

Insects/Weeds/Phytopathogens	Effects	Apiaceae	References
Bacteria (*Erwinia amylovora*, *Xanthomonas oryzae*, *Pseudomonas syringae*, *Pectobacterium carotovorum*, *Ralstonia solanacearum*, *Bacillus thuringiensis*), and fungi (*Culvularia fallax*, *Macrophomina phaseolina*, *Fusarium oxysporum*, *Cytospora sacchari*, *Colletotrichum tricbellum*)	Phytopathogens	*F. angulate*	[57]
Bacteria; *Agrobacterium radiobacter* pv *tumefaciens*, *Erwinia carotowora*, *Pseudomonas fluorescens*, and *Pseudomonas glycinea*	Phytopathogenic bacteria	*T. anthriscus*, *A. podagraria*, *D. carota*, *H. sphondyilium*, *P. saxifrage*, *P. sativa*, *A. silvestris*, *F. vulgare*	[13]
Fusarium graminearum	Cereal fusarium/wheat head blight fungus	*E. triquetrum*, *S. olusatrum*	[55]
Botrytis cinerea	Grey rot on tomatoes, strawberries		
Zymoseptoria tritici	Septoria blight		
Aspergillus flavus	Food spoilage and foodborne fungi, production of aflatoxins in cereals, dried fruits, and spices	*C. carvi*, *C. sativum*, *T. ammi*, *C. nigrum*, *A. graveolens*	[35,70,130,143]
Aspergillus niger	Food spoilage and foodborne fungus	*A. graveolens*, *C. nigrum*, *T. ammi*	[35,70,130]
Aspergillus oryzae	Foodborne pathogens	*A. graveolens*	[130]
Aspergillus parasiticus	Food spoilage and foodborne fungus, Production of aflatoxins B1 and G1	*F. vulgare*, *T. ammi*	[70,144]
Bacillus cereus	Food spoilage and foodborne pathogenic bacteria	*C. nigrum*, *T. ammi*	[35,70]
Bacillus subtilis	Foodborne pathogenic bacteria	*A. graveolens*, *C. sativum*	[130,140]
Campylobacter jejuni and *Campylobacter coli*	Foodborne pathogens	*C. sativum*	[139]
Escherichia coli	Food spoilage and foodborne bacteria	*T. ammi*, *A. graveolens*	[70,130]
Pseudomonas aeruginosa	Foodborne pathogens	*C. maculatum*, *A. graveolens*, *C. nigrum*	[35,130,136]
Staphylococcus aureus	Food spoilage and foodborne pathogenic bacteria	*C. cyminum*, *A. graveolens*, *T. ammi*	[70,130,138]
Stenotropomonas maltophilia (Bacteria), *Penicillium expansum* (fungi-producing mycotoxin)	Foodborne pathogens	*C. sativum*	[140]
Penicillium purpurogenum, *Acrophialophora fusispora*	Foodborne pathogenic fungi	*C. nigrum*	[35]
Bacteria (*Listeria monocytogenes*, *Salmonella typhimurium*), Fungi (*Penicillium citrinum*, *Penicillium chrysogenum*)	Food spoilage and foodborne bacteria and fungi	*T. ammi*	[70]

5. Future Trends

Although EOs are an excellent alternative for synthetic chemicals, low water solubility, low persistence in the environment, chemical variability, low yield, and easy degradation under heat, humidity, light, and oxygen may limit the application of essential oils as biocides. To overcome these drawbacks, nanotechnologies are modern and eco-friendly approaches that enhance the effectiveness of natural products [48,63,118].

Nanoemulsion is a novel approach that increases the physical stability of active substances, decreases volatility, enhances solubility, and prevents interactions with the environment [48,63]. Nanoemulsions are oil-in-water dispersions with extremely small droplet diameters in the range of 10−100 nm and extended stability [48]. Size reduction to a nanoscale can improve the properties of materials, such as enhanced infusibility, effective release of the active ingredient, rapid interaction, enhanced bioactivity towards the target, and physical stability [63,147]. In agricultural applications, nanoemulsions have significant herbicidal and antimicrobial potential against weeds and pathogens that are resistant to synthetic biocides. This may be attributed to increased chemical stability and solubility, decreased evaporation, and the degradation of active essential oil components [63,148]. Nanotechnology also enhances efficacy and reduces the number of active ingredients currently employed [149].

The germination of *P. minor*, *A. ludoviciana*, *R. dentatus*, and *Medicago denticulate* was completely suppressed by nanoemulsions of *F. vulgare* EO at low concentrations. Further, the storage stability of *F. vulgare* nanoemulsion at ambient temperature was increased [63]. Significant antimicrobial activity of cumin (*C. cyminum*) and fennel (*F. vulgare*) EO nanoemulsions showed antibacterial/anti-biofilm properties against the foodborne pathogens *K. pneumoniae*, *C. violaceum*, and *S. typhimurium* [150]. Repellent activity by aniseed oil against *Rhopalosiphum padi* was also reported [149].

Other than nanotechnology, advanced extraction techniques, chemical synthesis of novel compounds, metabolic engineering, biotechnology, DNA sequencing, and recombinant DNA technologies can also enhance plant product effectiveness and commercial applications [118].

6. Conclusions

In conclusion, plant-based biocides can be a suitable candidate to substitute synthetic chemicals as they are cheap, safe, sustainable, eco-friendly, and biodegradable substances. In this context, secondary metabolites of Apiaceae species are widely used to control most agricultural pests, weeds, pathogenic foodborne, and food spoilage microbes to increase agriculture production and ensure food security. Several studies on various Apiaceae species for their potential biocidal activity proved their potent insecticidal, herbicidal, antibacterial, and antifungal activities. Therefore, Apiaceae-derived secondary metabolites, including EOs, can be used as a natural source in biocontrol products in agriculture, biopesticide, bio-herbicide, bio-fungicide, and antibacterial agents in organic farming and crop protection. However, there are several limitations in the application of secondary metabolites, including EOs, mainly due to their fast degradation and low stability in heat, light, or oxygen. Recently, nanotechnology research has attempted to overcome these limitations of natural products used as biocides.

Author Contributions: Writing—original draft, P.T., N.G., A.G., O.M. and T.M. Writing—review and editing, P.T., A.G., N.G., O.M. and T.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding

Conflicts of Interest: The authors declare no conflict of interest.

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