New York State Integrated Pest Management Program | Cornell Cooperative Extension

Garlic and Garlic Oil Profile

Active Ingredient Eligible for Minimum Risk Pesticide Use

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Label Display Names: Garlic; Garlic oil.

Active Components: Garlic oil, Allicin, Allyl disulfide, Diallyl disulfide, Triallyl disulfide

CAS Registry #: None (garlic);
8000-78-0 (garlic oil)

U.S. EPA PC Code: 128827

CA DPR Chem Code: 2213

Other Names: Allium sativum; Ajo y oleo de ajo (Spanish); Garlic volatile oil; Porrum sativum bulb oil

Other Codes: BRN 1736016; CCRIS 4049; EINECS 209-775-1; FEMA 2042 and 2503; SMILES C(SC=C)C=C; [H]C([H])=C([H])C([H])([H])SC([H])([H])C([H])=C([H])[H]

Summary: Garlic is a food crop with documented therapeutic and pesticidal effects. It has been long-recognized as a bactericide due to the effects of a variety of sulfur-containing compounds with strong biological activity. These same compounds also inhibit fungal growth. Garlic is used as an insecticide with both repellent and biocidal properties. Garlic crop residues have both nematicidal and herbicidal properties. The Select Committee on GRAS Substances (SCOGS 1973) states there is no evidence that garlic or oil of garlic demonstrates a hazard to the public when used at current levels.

Pesticidal Uses: antimicrobial, fungicide, bactericide, virucide; insecticide and acaricide; bird, deer and other vertebrate pest repellent; nematicide; molluscicide; algicide and herbicide.

Formulations and Combinations: Red and black pepper; various other essential and vegetable oils; calcium hydroxide; various emulsifiers; putrescent whole egg solids.

Basic Manufacturers: Christopher Ranch; McCormick & Co.; Elf Aquitaine; Garlic Research Labs.

Safety Overview: Garlic and garlic oil have a nontoxic mode of action for repelling target birds and insects. The EPA stated that registered bird and insect repellent uses of garlic were not likely to cause unreasonable adverse effects in people or the environment (US EPA 1992).

This document profiles an active ingredient currently eligible for exemption from pesticide registration when used in a Minimum Risk Pesticide in accordance with the Federal Insecticide, Fungicide and Rodenticide Act (FIFRA) section 25b. The profile was developed by the New York State Integrated Pest Management Program at Cornell University, for the New York State Department of Environmental Conservation. The authors are solely responsible for its content. The Overview Document contains more information on the scope of the profiles, the purpose of each section, and the methods used to prepare them. Mention of specific uses are for informational purposes only, and are not to be construed as recommendations. Brand name products are referred to for identification purposes only, and are not endorsements.

Background

Garlic is a commonly consumed food ingredient that is derived from a widely cultivated plant, *Allium sativum*. It is a strongly scented culinary herb believed to be native to the high plains of western Central Asia and cultivated throughout the world (Khan and Abourashed 2010). Garlic oil is the product of steam distillation of garlic, and is also edible—though regarded as unpalatable. Fresh garlic needs to be processed before it can be applied as a pesticide. The two most common methods are to prepare dehydrated powders or garlic extracts (US EPA 1992). Dehydration into garlic powder or flakes begins when the garlic is peeled and sliced, then, in most cases, heated to 150°-160°C (~300°-320°F). Water is removed to a 6.5% moisture content, then the garlic is crushed and reduced into particle size by slicing, chopping or mincing (Luh et al. 1975). Constituent extracts of garlic are not eligible as active ingredients for exemption from pesticide registration under 25(b) (Burnett 2017).

The oil is often obtained by steam distillation (Merck 2015). The sulfur-containing constituents diallyl disulfide and diallyl trisulfide are the predominant constituents of the oil, with diallyl disulfide comprising up to 60% of the oil by weight (Khan and Abourashed 2010). Diallyl disulfide is a labile stereoisomer that readily decomposes into two allyl sulfide molecules (Block 2010). Other constituents include ajoene, alliin, allicin, methyl allyl trisulfide, allyl sulfide, as well as terpenes including citral, geraniol, linalool, α – and β-phellandrene (Merck 2015). The source of garlic odor is the result of the enzyme allinase converting alliin to allicin upon cutting or crushing (Block 1985). Because of the intermediate step of enzymatic conversion, biochemists tend not to regard garlic oil as an 'essential' oil in same way as geranium, clove, mint, rosemary, or thyme oils. Instead, allicin and related compounds created by damaging the plant tissue are considered 'secondary metabolites'. Garlic is one of many plants that evolved to create secondary metabolites as defenses to pest and disease damage (Wink 2003).

In 1983, the EPA first registered garlic as a pesticide for use as a bird repellent (US EPA 1992). That formulation also contained red pepper as an active ingredient. The EPA registered an insecticide with garlic as a single ingredient in 1991 (US EPA 1992). At the time of the last registration review, garlic oil was registered as an active ingredient in 11 pesticide products—one technical grade product and 10 end use products (McDavit 2010). There were 30 products registered with the EPA as of May 2017 (US EPA 2017). Garlic is effective in the control of bacteria, fungi, insects, ticks, nematodes, and weeds. Garlic and garlic oil may be applied to aquatic ecosystems both as a mosquito larvicide as well as to suppress undesired algal species.

Chemical and Physical Properties

Fresh garlic is 70% moisture (Palani et al. 2014). The physical and chemical properties for solid garlic are of the dry weight. The chemical and physical properties of garlic oil and garlic extract depend on how it is prepared (Lawson 1996). In particular, the concentration of biologically active secondary metabolites will vary by the method used to process and store the garlic (Brandl et al. 2016). Cloves of garlic (*Allium sativum*) consist of between 0.1 to 0.36% volatile oil (Merck 2015), averaging about 0.2% (Khan and Abourashed 2010). Other constituents include carbohydrates, proteins, amino acids, vitamins, minerals, saponins and enzymes (Merck 2015).

The most common and effective way to apply garlic as a pesticide is to extract the oil—which is the most commonly used form as an insecticide, fungicide, and herbicide. The physical and chemical properties of garlic and garlic oil appear in Table 1.

Table 1

Physical and Chemical Properties of Garlic and Garlic Oil

Property	Characteristic/Value	Source(s)
Molecular Formula:	N/A	
Molecular Weight:	N/A	
Percent Composition:	Garlic: 0.1-0.36%, Protein; Carbohydrates; Vitamins; Minerals. Garlic oil: Diallyl disulfide 60%; Alliin 2.62%; Allicin 0.15-0.66, γ-glutamyl-S-(E,S propenyl) cysteine 0.09-0.68%. Remainder is composed of various non-protein amino acids and lipids.	(Block 2010; Khan and Abourashed 2010)
Physical state at 25°C/1 Atm.	Garlic: Solid (Powder) Garlic oil: Liquid	(McDavit 2010)
Color	Garlic: White to yellowish-white Garlic oil: Clear yellow to red-orange	(Merck 2015)
Odor	Distinct pungent garlic odor	(Merck 2015)
Density/Specific Gravity	Garlic oil: 1.050-1.095	(Merck 2015)
Melting (solidifying) point	Garlic oil: – 59.48°C	(EPI 2012)
Boiling point	Garlic oil: 136.32°C	(EPI 2012)
Solubility	Garlic oil is soluble in most fixed oils, mineral oil; incompletely soluble in alcohol. Insoluble in glycerin, propylene glycol.	(Food Chemicals Codex Committee 2011; Merck 2015)
Vapor pressure	Garlic oil: 10 mm at 20°C	(Matthews 2009)
pH	Garlic oil: 5.5 – 6.0	(McDavit 2010)
Octonol/Water (K_{ow}) coefficient	Garlic oil: 2.61	(EPI 2012)
Viscosity	Garlic oil: η = 9.2 mPa/s ±0.4 (ambient)	(Siddiqui and Ahmad 2013)
Miscibility	Not found	
Flammability	Garlic oil: Highly flammable	(Sigma-Aldrich 2015)
Storage stability	Garlic oil: Stable	(McDavit 2010)
Corrosion characteristics	Garlic oil: Corrosion inhibitor in steel	(Srivastava and Srivastava 1981)
Air half life	Garlic oil: 2.81 hrs	(EPI 2012)
Soil half life	Garlic oil: 720 hrs	(EPI 2012)
Water half life	Garlic oil: 360 hrs	(EPI 2012)
Persistence	Garlic oil: 244 hrs	(EPI 2012)

Human Health Information

The Select Committee on GRAS Substances (SCOGS 1973) stated that, "[t]he long history of the use of garlic in food and acute, chronic and inhalation studies, although limited, reveal no credible adverse biological effects even at concentrations which are of orders of magnitude greater than the levels reported to be currently consumed in man's daily diet. . . There is no evidence in the available information on garlic or oil of garlic that demonstrates a hazard to the public when they are used at levels that are now current or that might reasonably be expected in the future."

Garlic is reported to have numerous health benefits, including as an antibacterial, antifungal and antiviral agent; cholesterol reduction; cardiovascular enhancement; antitumor activity; and antioxidant properties (Khan and Abourashed 2010). As such it is a popular traditional folk remedy in many parts of the world (Merck 2015).

A book that reviewed over 2,000 references about the science and therapeutic application of garlic concludes that the long-term health effects are largely beneficial, but there are some side effects (Koch and Lawson 1996). The review, conducted nearly 20 years ago, noted that the number of papers on the subject was growing exponentially, and searches of the literature since appear to be consistent with that trend. A slightly later review, focused on the anti-oxidant properties of garlic and its constituents, noted that while dietary anti-oxidants are largely beneficial, these biologically active substances also pose health risks—particularly if consumed at levels greater than normal dietary rates (Banerjee et al. 2003). The anti-oxidant properties in garlic may be responsible for the reduction in the efficacy of certain medications, such as anti-viral drugs (Borrelli et al. 2007).

A review of the epidemiological literature found adverse acute human health effects from dietary and occupational exposure include halitosis, dermatitis, ucartia, asthma, coagulation dysfunction, cardiovascular dysfunction, and gastrointestinal dysfunction (Morbidoni et al. 2001; Borrelli et al. 2007). Some of the population has allergic reactions when exposed. Local dermal irritation can develop in the form of a stinging sensation, and people who handle garlic have been known to develop allergic reactions. These are primarily in the form of eczema on the hands and asthma from inhaling garlic powder (Koch and Lawson 1996). Allergies from the consumption of garlic as a food ingredient are more common in members of the population than it is for many other food allergens, but the symptoms tend to be relatively mild, and often dependent on how the garlic is prepared and with what other foods it is served—resulting in cross-sensitivities (Scholl and Jensen-Jarolim 2004).

Unrefrigerated garlic stored in oil can grow *Clostridium botulin* and there have been fatal cases of botulism from people eating improperly prepared and stored garlic (St Louis et al. 1988). Exposure to high doses of garlic can cause severe irritation, particularly to open wounds (Koch and Lawson 1996).

Acute Toxicity

Acute toxicity of garlic and garlic oil was not found. As proxies, the acute toxicity of garlic extracts and the constituent diallyl disulfide appear in Table 2, with the evaluated substance identified.

Table 2

Acute Toxicity of Garlic Extracts and Constituents

Study	Results	Source(s)
Acute oral toxicity	Rat: LD_{50}>30ml/kg (Garlic extract)	(Nakagawa et al. 1984; Koch and Lawson 1996)
Acute dermal toxicity	Rat: LD_{50}>5 g/kg (Diallyl disulfide)	(US EPA OPPTS 2015)
Acute inhalation	Not found	
Acute eye irritation	Rabbit: Moderate eye irritant (Diallyl disulfide)	(US EPA OPPTS 2015)
Acute dermal irritation	Rabbit: Severe skin irritant (Diallyl disulfide)	(US EPA OPPTS 2015)
Skin sensitization	Guinea pig: Contact sensitizer (Diallyl disulfide)	(US EPA OPPTS 2015)

A Japanese study found that a garlic extract used as a proxy for whole garlic was not toxic to rats at the highest dose administered of 30 ml/kg (Nakagawa et al. 1984). None of the rats dermally exposed to the highest dose of the active constituent diallyl disulfide suffered a fatal dose, so the dermal LD_{50} also could not be determined. However, rats in that study exposed to the maximum dose suffered tremors, wobbly gait, circling, head wobble, and apparent paralysis (US EPA OPPTS 2015).

Sub-chronic Toxicity

The sub-chronic toxicity of garlic, garlic oil and extracts appear in Table 3.

Table 3

Sub-chronic Toxicity of Garlic, Garlic Oil and Garlic Extracts

Study	Results	Source(s)
Repeated Dose 28-day Oral Toxicity Study in Rodents	Rats (21 days): Increased lipid peroxidation and decreased antioxidant enzymes (Garlic oil)	(Banerjee et al. 2003)
90-day oral toxicity in rodents	Rats: Decrease in food intake (Garlic extract)	(Sumiyoshi et al. 1984)
90-day oral toxicity in non-rodents	Not found	
90-day dermal toxicity	Not found	
90-day inhalation toxicity	Not found	
Reproduction/development toxicity screening test	Not found	
Combined repeated dose toxicity with reproduction/development toxicity screening test	Not found	
Prenatal developmental toxicity study	Not found	
Reproduction and fertility effects	Rats: Inhibited spermatogenesis at 50 mg/kg (Garlic powder)	(Dixit and Joshi 1982; Banerjee et al. 2003)

As noted above, most long-term feeding studies have primarily been conducted to determine the health benefits of garlic, with few—but notable—side effects. Allicin is strongly hepatotoxic when consumed daily in large doses. Rats fed 100 mg/kg for 15 days had significantly increased lipase and other liver enzymatic activity, as well as lower blood glycogen—both seen as pre-diabetic conditions and symptomatic of liver failure (Augusti and Mathew 1975).

Chronic Toxicity

The chronic toxicity of garlic extract used as a proxy for garlic toxicity appears in Table 4.

Table 4

Chronic Toxicity of Garlic Extract

Study	Results	Source(s)
Chronic toxicity	Ames test: Negative (Aqueous extract)	(Martinez et al. 1999)
Carcinogenicity	Not found	
Combined chronic toxicity & carcinogenicity	Not found	

Garlic and garlic oil are not identified as carcinogens by the International Agency for Research on Cancer (IARC 2014). Garlic and garlic oil are not on the California Proposition 65 list of known carcinogens (Cal-EPA 1997) and do not appear on the Toxics Release Inventory (TRI) Basis of OSHA Carcinogens (US EPA 2015).

Garlic has been the subject of numerous studies that found it has cancer preventive and anti-carcinogenic properties (Koch and Lawson 1996). Garlic oil successfully inhibited papilloma growth on mice treated with a single carcinogenic dose of 7, 12-dimethylbenz[a]-anthracene (DMBA) (Perchellet et al. 1989).

Human Health Incidents

For the period 1992 to 2010, the EPA's registration review of garlic found no reports of human health incidents caused by the use of registered pesticide products where garlic was an active ingredient (McDavit 2010). The National Pesticide Information Center (NPIC) received 32 reports of human health-related incidents involving garlic oil between April 1, 1996 and March 30, 2016 (NPIC 2016). Most of these incidents involved accidental ingestion of animal repellents containing additional active ingredients, primarily putrescent egg solids and dried blood.

Environmental Effects Information

Effects on Non-target Organisms

The effects of garlic and garlic oil are summarized in Table 5.

Table 5

Effects of Garlic, Garlic Oil and Garlic Extract on Non-target Organisms

Study	Results	Source(s)
Avian Oral, Tier I	Not found	
Non-target plant studies	Not found	
Non-target insect studies	Stingless bees: Non-toxic at the highest dose; Honey bees (*Apis mellifera*): Higher mortality than control (Garlic extract)	(Xavier et al. 2010; Xavier et al. 2015)
Aquatic vertebrates	Sea bass: Possible negative hematological and biochemical consequences with diets in excess of 2% garlic (Garlic powder)	(Irkin et al. 2014)
Aquatic invertebrates	Prawns: LC_{50} 700-800 mg/ml (Garlic oil)	(Zhou et al. 2010)

Based on garlic's repellent characteristics, it is considered low risk to birds and mammals (Gwynn 2014), as well as aquatic invertebrates and other non-target organisms (Gwynn 2014).

When tested on honey bee adult workers and larvae (*Apis mellifera*), a garlic extract insecticide product caused a significantly higher mortality rate than the no-treatment control, but showed no significantly different mortality rate than citronella oil, eucalyptus oil, rotenone, or neem oil. However, when garlic extract was compared against the same botanical insecticides, it tested nontoxic to the stingless bee species *Nannotrigona testaceicornis* and *Tetragonisca angustula*—important pollinators in South America (Vania et al. 2010).

Garlic has been studied as a growth promoter, antioxidant, and immune system booster for fish. European Sea bass (*Dicentrarchus labrax*) were fed diets supplemented with garlic powder at 0 (control), 2%, 4%, or 6% levels for a period of 60 days (Irkin et al. 2014). Cholesterol levels were lowered at 2% and 6%. However, red blood cell counts (RBC) and other hematological parameters showed adverse effects at the higher doses of 4% and 6% compared to the control group and 2% dosage group (Irkin et al. 2014).

A formulated 25(b)-exempt insecticide product with the active ingredients garlic extract, cinnamon, clove oil, and rosemary was found to be phytotoxic to the Transvaal daisy (*Gerbera jamesonii*) (Cloyd et al. 2009).

Garlic extract applied in aqueous solution as an algaecide was found to be toxic to two species of prawns: *Litopenneaus vannamei* (LC_{50}=0.07%) and *Pennaeus monodon* (LC_{50}=0.08%) (Zhou et al. 2010). The same study reported garlic extract in aqueous solution to be toxic in higher concentrations to *Plectorhinchus cinctus* (LC_{50}=0.26%) but nontoxic to juvenile fish *Pagrosomus major,* even at the highest dose. Both species of fish became hyperactive during exposure.

Between April 1, 1996 and March 30, 2016, NPIC received 32 reports of animal-related incidents involving garlic oil (NPIC 2016). Most involved dogs eating stored deer repellent that also contained blood and putrescent whole egg solids.

Environmental Fate, Ecological Exposure, and Environmental Expression

Garlic oil is considered readily biodegradable (EPI 2012). Diallyl disulfide, the compound believed to be one of the main mosquito larvicides in garlic oil (Amonkar and Reeves 1970), was found to be 60% degraded in water after 4 hours and 84% degraded after 24 hours (Ramakrishnan et al. 1989).

Environmental Incidents

NPIC received 426 reported incidents involving garlic oil that were not related to animals or human health (NPIC 2016). This, and the total of 489 incidents reported to NPIC, was the second highest of any minimum-risk pesticide active ingredient following putrescent whole egg solids. Miscellaneous inquiries generally involved questions about the product's use, safety, and clean-up after application. 22 incidents were complaints about odor. One hundred and seven of the calls sought product information about Bonide Shotgun Repels-All, a 25(b) pesticide formulation having putrescent whole egg solids and dried blood as active ingredients.

Efficacy

Antimicrobial Activity

Antibacterial activity of garlic was first reported by Louis Pasteur in 1858 (Block 1985; Reuter et al. 1996). Before that, garlic was commonly and effectively used as an antiseptic and disinfectant in traditional medicine. However, the specific antimicrobial agents in garlic were not fully understood for nearly a century. Allicin, first isolated in 1944, was discovered to have antibacterial activity comparable to penicillin (Cavallito and Bailey 1944). Those early experiments showed that allicin prevented the growth of *Staphylococcus aureus, Streptococcus hemolyticus, S. viridans, Bacillus subtilis, B. typhosus, B. enterica, B. typhimurium*, and *Vibrio cholera.*

A review of the literature confirmed these early findings on garlic: its relatively potent antimicrobial activity; an expanded number of human pathogens garlic effectively inhibits; and evidence showing that certain organisms capable of developing antibiotic resistance are significantly less likely to develop resistance to allicin (Ankri and Mirelman 1999). Other reviews of garlic's antimicrobial properties show it to be effective at preventing or inhibiting the growth of a wide range of human pathogens—many of which are food-borne (Reuter et al. 1996; Benkeblia 2004) and include *Salmonella* spp. and *Staphylococcus aureus*. For example, garlic oil created a zone of inhibition for *S. aureus* of 6.3mm at 50 μl/l, which increased to 9.3mm at a concentration of 500 μl/l (Benkeblia 2004). The inhibition zone for *Salmonella enterica* was even greater: 8.3mm at 50 μl/l and 13.1mm at a concentration of 500 μl/l. Garlic inhibits the growth of the bacteria linked to gastric ulcers, *Helicobacter pylori* (Cellini et al. 1996).

Fungicidal Activity

The efficacy of garlic's antifungal properties are supported by a considerable body of research (Koch and Lawson 1996; Block 2010). Most studies are of post-harvest and processing applications. Garlic inhibits the formation of mycotoxin producing fungi (Ankri and Mirelman 1999). Allicin has the properties of a phytoalexin because it is produced as a result of freshly injured garlic plant tissue, consistent with a response to fungal or insect attack (Borlinghaus et al. 2014).

Efficacy can be enhanced when the allicin concentrations are increased. Tomatoes inoculated with late blight (*Phytophthora infestans)* were treated with garlic extract diluted with water to specified allicin levels. A 1:100 dilution, resulting in a concentration of allicin at 55 μg/ml, had less than 50% control of the *Phytophthora*, while a 1:50 dilution with a concentration of 110 μg/ml achieved 100% control (Portz et al. 2008). *Fusarium oxysporum* was inhibited in petri dish studies by a concentration of 500 mg/ml of garlic extract (Tariq and Magee 1990).

Garlic and its active constituent allicin were found to be potent fungistats and fungicides of *Cryptococcus neoformans,* the human pathogen responsible for Cryptococcal meningitis (Davis et al. 1994). Garlic and allicin's antifungal activity may also be indirect, through the stimulation of plant defenses against fungal pathogens. Allicin was observed to increase antioxidants in cucumbers (Hayat et al. 2016).

Insecticidal and Acaricidal Activity

Garlic's insect repellent properties were also long-recognized before the specific mode of action was discovered. Most evidence of efficacy against specific insects prior to 1970 is anecdotal. In the early 1970s, interest in garlic as an insecticide was revived. The first pests targeted were mosquitoes, driven by a public health interest in finding safe and effective replacements for DDT. Many of the efficacy studies pre-date garlic's eligibility as a minimum risk pesticide active ingredient. A number of the studies look at the efficacy of the specific constituents that are not eligible as minimum risk pesticide active ingredients (Burnett 2017). The efficacy data on these substances is included to understand the potential efficacy of garlic.

The insecticidal properties of diallyl disulfide was discovered in 1970 (Amonkar and Reeves 1970). *Culex quinquefasciatus* mosquito larvae exposed to 5ppm of diallyl disulfide, both in garlic oil and in an aqueous extract, experienced 100% mortality (Amonkar and Banerji 1971). Mosquito hatches were observed to be suppressed in unharvestable flooded garlic fields (Crowe 1995). The cultural practices for the garlic were not reported.

As a *Culex pipiens* larvicide, a United Kingdom study showed garlic was more potent and persistent than lemon (*Citrus limon*) peel extracts (Thomas and Callaghan 1999). The 90-hour mortality for 0.16 g/L fresh lemon peel extracts was about 50%, while the 0.16 g/L garlic had a 90-hour mortality of 83% and persisted in its toxicity over 106 hours. Mosquito larvae resistant to organophosphate insecticides in that same study were not found to be significantly less susceptible to garlic than non-resistant mosquitoes, even though the enzymatic activity that detoxifies organophosphate in those strains was thought to detoxify the allyl sulfide compounds as well. Garlic oil is more effective as a *Culex pipiens* larvicide than its constituents, suggesting a synergistic effect of various compounds in addition to diallyl disulfide (Kimbaris et al. 2009).

Garlic extract formulated by preparing a 6% solution of dissolved garlic powder, as well as in an aqueous extract at a solution strength of 1 mg/ml, were both able to completely prevent *Aedes aegypti* eggs from hatching. The structure of the eggs were scanned with an electron microscope, and the eggs treated with the powder were physically damaged, but the eggs treated with the aqueous solution were not, suggesting that it may, in fact, have a chemical mode of action (Jarial 2001).

In one study, garlic oil resulted in less than a 10% mortality rate for adult *Aedes albopictus* and *Culex quinquefasciatus,* suggesting garlic oil is relatively ineffective against adult mosquitoes (Cilek et al. 2011). Garlic inhibited, but failed to completely suppress, oviposition by *Anopheles stephansi* adult females (Dhar et al. 1996). While garlic oil is not biocidal against adult mosquitoes, it does act as a repellent because the organosulfur compounds in garlic elicit avoidance behavior in adult *Aedes aegypti* (Campbell et al. 2011). Although it is generally not fatal in its mode of action, garlic oil can deter adult mosquito feeding. Garlic oil encapsulated in an exempt attractive toxic sugar bait (ATSB) formulation, and applied to riparian vegetation that shelter mosquitoes during the day in the arid lower Jordan Valley of Israel, was able to decrease biting pressure by *Anopheles sergentii* adult mosquitoes by 97% (Revay et al. 2015).

Other dipteran pests are susceptible to garlic as well. The cecidomyiid gall midge (*Camptomyia corticalis*)—a pest of shiitake mushrooms—was the subject of an experiment conducted in South Korea. Midges treated in the third instar had a 100% mortality rate when exposed to commercially available garlic oil at a dose of 1.05 mg/cm^3 for 24 hours (Kim et al. 2012). The 24 hour LC_{50} was estimated to be 0.60 mg/cm^3. Garlic juice was compared with the organophosphate insecticide chlorfenvinphos for lethal effects on the cabbage fly (*Delia radicum*) and the common housefly (*Musca domestica*). Garlic juice at concentrations of 2-5% was effective and sometimes comparable to chlorfenvinphos against the eggs and adults, but not necessarily larvae, of both species (Prowse et al. 2006). The adult LC_{50}s were estimated to be 0.40 for *D. radicum* and 2.19 for *M. domestica.*

In agricultural applications, laboratory screening and field experiments have been conducted to determine the efficacy of garlic, garlic oil, and garlic extract in managing specific pests. Garlic oil is an effective insecticide for controlling some aphids (Greenstock and Larrea 1972). Intercropping garlic as a repellent between host plants is part of an integrated strategy known as ‘push-pull’. Tobacco (*Tobacum nicotiana*) interplanted with garlic had lower green peach aphid (*Myzus persicae*) populations than the tobacco monoculture (Lai et al. 2011).

Wheat (*Triticum aestivum)* grown in monoculture was compared with wheat intercropped with garlic, sprayed with garlic oil, and sprayed with concentrated diallyl disulfide derived from garlic. Populations of English green aphids (*Sitobion avenae*) and various species of lady beetles were then monitored—the number of mummified aphids were indicative of parasitism. The diallyl disulfide-treated wheat had the lowest aphid populations, with garlic oil having aphid populations lower than the control and not significantly different from the intercrop. However, the intercropped system had the highest lady beetles and aphid mummies, with no significant difference between garlic oil and the monoculture control (Zhou et al. 2013). The garlic oil was thought to repel both the beneficial organisms and the pests, while the intercrop repelled only the pests.

A South Korean experiment that compared the efficacy of 92 essential oils for the control of sweetpotato whitefly (*Bemisia tabaci*) found garlic oil to be the most effective, with an LC_{50} of 0.15 mL/cm^3 and 100% mortality at a rate of 2.4 mL/cm^3 (Kim et al. 2011). Cinnamon bark oil, citronella oil, red thyme oil, and white thyme oil also achieved 100% mortality at the same rate, but had higher LC_{50} values indicating they were less toxic.

Not all homopteran insects are susceptible. For example, garlic did not provide adequate control of rosy apple aphid (*Dysaphis plantaginea*) on apple trees in the UK (Cross et al. 2007), and silverleaf whitefly (*Bemisia argentifolii*) survival rates in tomatoes sprayed with garlic were not significantly different from those treated with a water spray control (Liu and Stansly 2000).

Garlic was relatively ineffective in controlling Kelly's citrus thrips (*Pezothrips kellyanus*) in Greek citrus groves when compared with the botanical insecticides azadirachtin and pyrethrins (Vassiliou 2011).

Lepidopteran pests are susceptible to garlic. Early trials that treated the apple ermine moth (*Yponomeuta malinellus*) with garlic achieved over 90% mortality in the field and 98% mortality in the lab (Greenstock and Larrea 1972). The pine processionary (*Thaumetopoea pityocampa*) experienced 88% and 93% mortalities in field and lab, respectively, in the same project. Garlic extract was fatal to common cutworm (*Spodoptera litura*) eggs (Gurusubramanian and Krishna 1996) and larvae (Deb-Kirtaniya et al. 1980). However, use of garlic extract in the field is a challenge, as it does not prevent economic damage of cabbage (*Brassica oleracea* var *Capitata*) by the larvae of diamondback moth (*Plutella xylostella*) and cabbage white butterfly (*Pieris rapae*) (Endersby et al. 1992). Of 17 essential oils, garlic oil was the most lethal to cabbage looper (*Trichoplusa ni*) larvae with an LC_{50} = 3.3 $\mu L\ mL^{-1}$ and LD_{50} = 22.7 μg per insect (Machial et al. 2010). Lemongrass oil had an LC_{50} = 7.2 $\mu L\ mL^{-1}$ and an LD_{50} = 60.5 μg per insect by comparison. The same study found garlic oil to be one of the least effective against the obliquebanded leafroller (*Choristoneura rosaceana*) with only a 22.2% mortality rate at a rate of 5.0 $\mu L\ mL^{-1}$, compared with 97.0% for patchouli oil and 64.0% for thyme oil.

The efficacy of garlic and its derivatives is inconsistent against Coleopteran pests. The Lucerne weevil (*Colaspidema atrum*) had 90% mortality when exposed to garlic extract in the lab and 82% mortality in the field (Greenstock and Larrea 1972). The pea weevil (*Bruchus pisorum*) had an 87% mortality rate in the lab during the same set of experiments. Eight formulated botanical insecticide products—some registered, some 25(b) exempt—were evaluated on the Japanese beetle (*Popillia japonica*), European chafer (*Rhizotrogus majalis*), oriental beetle (*Anomala orientalis*), and northern masked chafer (*Cyclocephala borealis*) (Ranger et al. 2009). Armorex (Soil Technologies), a 25(b)-exempt formulation consisting of 2% garlic, along with sesame oil, clove, rosemary oil, and white pepper, had the lowest LC_{50} and the lowest LD_{50}, making it the most toxic. Veggie Pharm (Pharm Solutions), a 25(b)-exempt formulated product that consisted of 2.5% pure garlic oil, along with soybean oil and peppermint oil, had the highest LC_{50} and the highest LD_{50} of the 8 formulated products, leading the authors to conclude that synergy was an important factor. In a subsequent experiment that looked at the isolated technical grade oils, the same four species were topically exposed to 24 plant derivatives. Garlic oil was one of six oils toxic to all four species, but it was not the most toxic to any of the species (Ranger et al. 2013). Garlic extract resulted in zero mortality for the Colorado potato beetle (*Leptinotarsa decimlineata*) (Greenstock and Larrea 1972).

Seven experimental preparations of garlic were compared to neem (*Azadirachta indica*), *Aloe vera* extract, and turmeric (*Curcuma longa)* in three different experiments that looked at the efficacy of botanical insecticides for control of western corn rootworm (*Diabrotica vergifera vergifera*) (Brandl et al. 2016). Garlic was prepared both as a powder and an oil at different concentrations, both with and without levels of secondary metabolites elevated by processing techniques. The most potent preparation was a thermally degraded garlic powder subsequently frozen at –20°C, with larval reductions of 70-100%. One preparation was not significantly different from turmeric oil in its efficacy of near-total control (Brandl et al. 2016).

Post-harvest use of garlic and garlic derivatives have been studied. One study of wheat treated with garlic and exposed to the red flour beetle and maize weevils found that eggs were the most susceptible. *T. castaneum* eggs were completely killed at a concentration of 4.4 mg/cm^2 (Ho et al. 1996).

A 25(b)-exempt commercial formulation composed of 0.30% garlic extract, 0.30% cinnamon, 0.40% rosemary, and 0.30% clove oil—Dr. Earth Fruit & Vegetable Insect Spray (Dr. Earth)—was relatively ineffective at ready-to-use concentrations against western flower thrips (*Frankliniella occidentalis*) (<20% mortality), sweetpotato whitefly (*Bemisia tabaci*) (<30% mortality), and green peach aphid (*Myzus persicae*) (<20% mortality) (Cloyd et al. 2009).

Garlic is also a potent acaricide. The two-spotted spider mite (*Tetranychus urticae*) has been shown to be susceptible to garlic extract. One study conducted on *T. urticae* in Belgian greenhouses showed an LD_{50} of 7.5 mg/ml, an LD_{90} of 13.5 mg/ml, and decreased fecundity even at lower doses (Attia et al. 2012). Another study confirmed that garlic was more effective at controlling two-spotted spider mites than rosemary oil, jojoba oil or a mixture of soybean and sunflower oil (Ismail et al. 2015). The effective dose in that experiment was temperature dependent. Dr. Earth Fruit & Vegetable Spray, a 25(b) exempt product, was significantly more effective against the two-spotted spider mite (*T. urticae*) than the no-treatment control with a 70-80% mortality, but was the least effective of 10 commercial products compared, including two pesticide products exempt from registration: Bug Assassin and Sharpshooter (Cloyd et al. 2009).

Despite popular belief, internal consumption of garlic has not been consistently shown an effective repellent, regardless of dosage or target organism. One study of tick bites on humans compared subjects having consumed of 1,200 mg/d of garlic in a capsule with a placebo group. The group ingesting garlic received significantly fewer tick bites (Stjernberg and Berglund 2000). However, that study was criticized for its methodology, particularly lack of information about the form of garlic used, the way it was prepared, and calibration of active constituents (Tunon 2001). The treatment group was still bitten by ticks, though not as much, and the researchers did not compare treatments other than garlic, and the effect, though significant, was only slightly better than the placebo (McHugh 2001). A double-blind study, looking at human subjects who consumed garlic and a placebo and subsequently exposed to the mosquito *Aedes aegypti,* found no significant difference between the two groups (Rajan et al. 2005).

Nematicidal Activity

Garlic extract is applied to soil for the control of *Tylenchorhynchus* spp., *Meloidogyne* spp., *Pratylenchus* spp., and other phytophagous nematodes. The garlic extract is considered to act on respiratory enzymes, causing cytotoxic effects, which reduces egg viability and causes death of nematodes at all life stages (Gwynn 2014). Diallyl disulfide and allicin both show potent activity as nematicides.

Mushroom (*Aphelencoides sacchari*) and citrus (*Tylenchulus semipenetrans*) nematodes were exposed to garlic extracts with measured concentrations of diallyl disulfide. Extracts with 0.5% of diallyl disulfide achieved a 100% kill of both species (Nath et al. 1982).

Root-knot nematode (*Meloidogyne incognita*) egg hatches were reduced to zero at concentrations of 10 ppm from a standardized diluted stock solution of 200 ppm of allicin extracted from garlic, while juveniles had 100% mortality when exposed to 5ppm for 72 hours and 12.5ppm for 24 hours (Gupta and Sharmaj 1993). The same study showed that tomato (*Lycopersicon esculentum*) dipped in a solution of 5ppm showed no *M. incognita* damage.

Molluscidal Activity

Gray field slugs (*Agriolimax agrestis*) exposed to garlic extract in the lab showed 82% mortality, while those exposed in the field had 71% mortality (Greenstock and Larrea 1972).

Vertebrate Pest Activity

Garlic is included as an active ingredient in several minimum-risk pesticide formulations. Some formulations, like the Bonide products, Shotgun Repels All and Go Away, contain other eligible minimum-risk pesticide active ingredients such as putrescent whole egg solids, blood meal, white pepper, and cloves. Efficacy data on most of these formulations was not found. Deerbuster's Deer and Insect Repellent (Trident Enterprises) is a minimum-risk pesticide that consists of 10% garlic oil as the active ingredient and 90% soybean oil as the only non-active ingredient. Plant Pro-tec is an EPA registered formulation having 10% garlic oil and 3% capsaicin as the active ingredients, with the remainder of the formulation undisclosed. Both products were tested to protect western red cedar (Thuja plicata) seedlings from black-tail deer (*Odocoileus hemionus*) feeding damage, and neither was effective compared with a no-treatment control (Wagner and Nolte 2001)

Herbicidal, Plant Growth Regulatory, and Algicidal Activity

Comparatively few studies have been performed on the use of garlic and its derivatives as herbicides, though members of the Alliaceae family have properties that make them promising as herbicides. Onion (*Allium cepa*) and garlic have the greatest commercial potential, because they are the first and second most widely grown species of Alliaceae and are therefore relatively inexpensive compared with other allelopathic plants (Sharangi 2011). Onion and garlic crop residues incorporated into soils in the San Joaquin Valley of California inhibited the germination of barnyardgrass (*Echinochloa crus-galli*), common purslane (*Portulaca oleracea*), London rocket (*Sisymbrium irio*) and black nightshade (*Solanum nigrum*), but only when soil temperatures were elevated to 39°C (102°F) by solarization (Mallek et al. 2007). Garlic residues plus solarization showed greater herbistatic properties than onion residues plus solarization, or solarization alone with no allium plant residues.

Garlic has been used for high school biology class demonstrations of allelopathy (Shimabukuro and Haberman 2006). The close wild relative to common garlic, *Allium ursinum* or bear garlic, has been observed to have wide-ranging allelopathic properties (Block 2010).

Conversely, garlic has been observed to have a stimulating effect on the growth of other plants. Decomposed garlic stalks were mixed in soil media in concentrations of 0, 1, 3 and 5 g/l, and the pots were seeded with lettuce (*Lactuca sativa*). At low concentrations, the decomposed garlic stalks stimulated growth, while at the highest concentration, growth was inhibited (Han et al. 2013). Methyl disfulfide extracted from garlic stimulated gladiolus (*Gladiolus x Tubergenii*) corms to break dormancy within 24 hours of treatment (Hosoki et al. 1986).

Garlic also demonstrates efficacy against various invasive algal species. A 0.08% garlic solution was applied to five species of algae responsible for red tide: *Alexandrium tamarense*, *Scrippsiella trochoidea*, *Alexandrium catenella*, *Alexandrium minutum* and *Alexandrium satoanum*. Garlic inhibited *A. tamarense*, *A. satoanum*, *A. catenella* and *S. trochoidea*, but not *A. minutum* (Zhou et al. 2008)

Standards and Regulations

EPA Requirements

Garlic and garlic oil are exempt from the requirement of a tolerance [40 CFR 180].

FDA Requirements

Garlic and its derivatives, including garlic oil, are affirmed Generally Recognized As Safe (GRAS) as a food ingredient, seasoning or flavoring [21 CFR 182.10, 182.20 and 184.1317] by the FDA. The FDA also recognizes garlic's therapeutic effects, approving it as an over-the-counter drug [21 CFR 310.545(a)(8)].

Other Regulatory Requirements

Garlic and garlic oil are allowed by the USDA's National Organic Program (NOP) [7 CFR 205].

Literature Cited

Amonkar, SV, and A Banerji. 1971. "Isolation and Characterization of Larvicidal Principle of Garlic." *Science* 174 (4016): 1343–1344.

Amonkar, SV, and EL Reeves. 1970. "Mosquito Control with Active Principle of Garlic, *Allium sativum*." *Journal of Economic Entomology* 63 (4): 1172-.

Ankri, Serge, and David Mirelman. 1999. "Antimicrobial Properties of Allicin from Garlic." *Microbes and Infection* 1 (2): 125–129.

Attia, Sabrine, Kaouthar Lebdi Grissa, Anne-Catherine Mailleux, Georges Lognay, Stéphanie Heuskin, Saïd Mayoufi, and Thierry Hance. 2012. "Effective Concentrations of Garlic Distillate (*Allium sativum*) for the Control of *Tetranychus urticae* (Tetranychidae)." *Journal of Applied Entomology* 136 (4): 302–312.

Augusti, KT, and PT Mathew. 1975. "Effect of Allicin on Certain Enzymes of Liver after a Short Term Feeding to Normal Rats." *Experientia* 31 (2): 148–149.

Banerjee, S. K., Pulok K. Mukherjee, and S. K. Maulik. 2003. "Garlic as an Antioxidant: The Good, the Bad and the Ugly." *Phytotherapy Research* 17 (2): 97–106. doi:10.1002/ptr.1281.

Benkeblia, N. 2004. "Antimicrobial Activity of Essential Oil Extracts of Various Onions (*Allium cepa*) and Garlic (*Allium sativum*)." *LWT-Food Science and Technology* 37 (2): 263–268.

Block, E. 1985. "The Chemistry of Onions and Garlic." *Scientific American* 252 (3): 114–119.

———. 2010. *Garlic and Other Alliums: The Lore and the Science*. Royal society of Chemistry.

Borlinghaus, Jan, Frank Albrecht, Martin CH Gruhlke, Ifeanyi D Nwachukwu, and Alan J Slusarenko. 2014. "Allicin: Chemistry and Biological Properties." *Molecules* 19 (8): 12591–12618.

Borrelli, Francesca, Raffaele Capasso, and Angelo A. Izzo. 2007. "Garlic (*Allium sativum* L.): Adverse Effects and Drug Interactions in Humans." *Molecular Nutrition and Food Research* 51 (11): 1386–97. doi:10.1002/mnfr.200700072.

Brandl, M. A., M. Schumann, B. W. French, and S. Vidal. 2016. "Screening of Botanical Extracts for Repellence against Western Corn Rootworm Larvae." *Journal of Insect Behavior* 29 (4): 395–414. doi:10.1007/s10905-016-9571-3.

Burnett, Gina. 2017. "Garlic and Garlic Oil," September 7.

Cal-EPA. 1997. "Prioritized Candidate Chemicals under Consideration for Carcinogenicity Evaluation." Sacramento, CA: California Environmental Protection Agency, Office of Environmental Health Hazard Assessment. http://www.oehha.ca.gov/prop65/pdf/batch1.pdf.

Campbell, C., R. Gries, G. Khaskin, and G. Gries. 2011. "Organosulphur Constituents in Garlic Oil Elicit Antennal and Behavioural Responses from the Yellow Fever Mosquito." *Journal of Applied Entomology* 135 (5): 374–81. doi:10.1111/j.1439-0418.2010.01570.x.

Cavallito, Chester J, and John Hays Bailey. 1944. "Allicin, the Antibacterial Principle of Allium Sativum. I. Isolation, Physical Properties and Antibacterial Action." *Journal of the American Chemical Society* 66 (11): 1950–1951.

Cellini, Luigina, Emanuela Campli, Michele Masulli, Soraya Bartolomeo, and Nerino Allocati. 1996. "Inhibition of Helicobacter Pylori by Garlic Extract (*Allium sativum*)." *FEMS Immunology & Medical Microbiology* 13 (4): 273–277.

Cilek, J. E., C. F. Hallmon, and R. Johnson. 2011. "Efficacy of Several Commercially Formulated Essential Oils against Caged Female *Aedes albopictus* and *Culex quinquefasciatus* When Operationally Applied via an Automatic-Timed Insecticide Application System." *Journal of the American Mosquito Control Association* 27 (3): 252–55. doi:10.2987/10-6096.1.

Cloyd, Raymond A., Cindy L. Galle, Stephen R. Keith, Nanette A. Kalscheur, and Kenneth E. Kemp. 2009. "Effect of Commercially Available Plant-Derived Essential Oil Products on Arthropod Pests." *Journal of Economic Entomology* 102 (4): 1567–79.

Cross, J. V., S. Cubison, A. Harris, and R. Harrington. 2007. "Autumn Control of Rosy Apple Aphid, *Dysaphis plantaginea* (Passerini), with Aphicides." *Crop Protection* 26 (8): 1140–49. doi:10.1016/j.cropro.2006.10.007.

Crowe, F. 1995. "Garlic and Mosquitos." *Science* 269 (5232): 1804–5. doi:10.1126/science.269.5232.1804.

Davis, Larry E, Jinkun Shen, and Robert E Royer. 1994. “In Vitro Synergism of Concentrated Allium Sativum Extract and Amphotericin B against *Cryptococcus neoformans*.” *Planta Medica* 60 (6): 546–549.

Deb-Kirtaniya, S, MR Ghosh, N Adityachaudhury, and A Chatterjee. 1980. “Extracts of Garlic as Possible Source of Insecticides.” *Indian Journal of Agricultural Sciences* 50 (6): 507–10.

Dhar, R, H Dawar, S Garg, SF Basir, and GP Talwar. 1996. “Effect of Volatiles from Neem and Other Natural Products on Gonotrophic Cycle and Oviposition of *Anopheles stephens*i and *An-culicifacies* (Diptera: Culicidae).” *JOURNAL OF MEDICAL ENTOMOLOGY* 33 (2): 195–201.

Dixit, VP, and Suresh Joshi. 1982. “Effects of Chronic Administration of Garlic (*Allium sativum* Linn) on Testicular Function.” *Indian Journal of Experimental Biology* 20 (7): 534–536.

Endersby, NM, WC Morgan, BC Stevenson, and CT Waters. 1992. “Alternatives to Regular Insecticide Applications for Control of Lepidopterous Pests of *Brassica oleracea* Var *Capitata*.” *Biological Agriculture & Horticulture* 8 (3): 189–203.

EPI. 2012. “Estimation Programs Interface (EPI) Suite (V4.11).” Washington, DC: US EPA Office of Pesticides and Toxic Substances.

Food Chemicals Codex Committee. 2011. *Food Chemicals Codex*. Rockville, MD: US Pharmacoepial Convention.

Greenstock, DL, and Q Larrea. 1972. “Garlic as an Insecticide.” 2. Braintree, Essex, UK: Henry Doubleday Research Association.

Gupta, R, and NK Sharmaj. 1993. “A Study of the Nematicidal Activity of Allicin—an Active Principle in Garlic, *Allium sativum* L., against Root-Knot Nematode, *Meloidogyne incognita* (Kofoid and White, 1919) Chitwood, 1949.” *International Journal of Pest Management* 39 (4): 390–392.

Gurusubramanian, G, and SS Krishna. 1996. “The Effects of Exposing Eggs of Four Cotton Insect Pests to Volatiles of *Allium sativum* (Liliaceae).” *Bulletin of Entomological Research* 86 (01): 29–31.

Gwynn, Roma L, ed. 2014. *Manual of Biocontrol Agents*. 5th ed. Alton, Hants, UK: British Crop Protection Council.

Han, Xu, ZH Cheng, HW Meng, XL Yang, and I Ahmad. 2013. “Allelopathic Effect of Decomposed Garlic (*Allium sativum* L.) Stalk on Lettuce (*L. sativa* Var. *Crispa* L.).” *Pakistan Journal of Botany* 45: 225–233.

Hayat, Sikandar, Zhihui Cheng, Husain Ahmad, Muhammad Ali, Xuejin Chen, and Mengyi Wang. 2016. “Garlic, from Remedy to Stimulant: Evaluation of Antifungal Potential Reveals Diversity in Phytoalexin Allicin Content among Garlic Cultivars; Allicin Containing Aqueous Garlic Extracts Trigger Antioxidants in Cucumber.” *Frontiers in Plant Science* 7: 1235. doi:10.3389/fpls.2016.01235.

Ho, SH, L Koh, Y Ma, Y Huang, and KY Sim. 1996. “The Oil of Garlic, *Allium sativum* L.(Amaryllidaceae), as a Potential Grain Protectant against *Tribolium castaneum* (Herbst) and *Sitophilus zeamais* Motsch.” *Postharvest Biology and Technology* 9 (1): 41–48.

Hosoki, T, Y Sakai, M Hamada, and K Taketani. 1986. “Breaking Bud Dormancy in Corms and Trees with Sulfide Compounds in Garlic and Horseradish.” *HortScience* 21 (1): 114–116.

IARC. 2014. “Agents Classified by the IARC Monographs.” http://monographs.iarc.fr/ENG/Classification/.

Irkin, Latife Ceyda, Murat Yigit, Sevdan Yilmaz, and Masashi. Maita. 2014. "Toxicological Evaluation of Dietary Garlic (*Allium sativum*) Powder in European Sea Bass Dicentrarchuslabrax Juveniles." *Food and Nutrition Sciences* 5 (Copyright (C) 2015 American Chemical Society (ACS). All Rights Reserved.): 989–96, 8. doi:10.4236/fns.2014.511109.

Ismail, Manal S. M., Maha F. M. Soliman, Ahmed H. Abo-Ghalia, and Mona M. A. Ghallab. 2015. "The Acaricidal Activity of Some Essential and Fixed Oils against the Two-Spotted Spider Mite in Relation to Different Temperatures." *INTERNATIONAL JOURNAL OF PEST MANAGEMENT* 61 (2): 121–25. doi:10.1080/09670874.2015.1018378.

Jarial, MS. 2001. "Toxic Effect of Garlic Extracts on the Eggs of Aedes Aegypti (Diptera : Culicidae): A Scanning Electron Microscopic Study." *JOURNAL OF MEDICAL ENTOMOLOGY* 38 (3): 446–50. doi:10.1603/0022-2585-38.3.446.

Khan, I. A., and Ehab A. Abourashed. 2010. *Leung's Encyclopedia of Common Natural Ingredients Used in Food, Drugs, and Cosmetics /*. 3rd ed. Hoboken, N.J. : John Wiley & Sons,.

Kim, Jun-Ran, Perumalsamy Haribalan, Bong-Ki Son, and Young-Joon Ahn. 2012. "Fumigant Toxicity of Plant Essential Oils Against *Camptomyia corticalis* (Diptera: Cecidomyiidae)." *Journal of Economic Entomology* 105 (4): 1329–34. doi:10.1603/EC12049.

Kim, Soon-Il, Song-Hwa Chae, Hee-Sung Youn, Seong-Hum Yeon, and Young-Joon. Ahn. 2011. "Contact and Fumigant Toxicity of Plant Essential Oils and Efficacy of Spray Formulations Containing the Oils against B – and Q-Biotypes of *Bemisia tabaci*." *Pest Management Science* 67 (Copyright (C) 2015 American Chemical Society (ACS). All Rights Reserved.): 1093–99. doi:10.1002/ps.2152.

Kimbaris, Athanasios C., Elias Kioulos, George Koliopoulos, Moschos G. Polissiou, and Antonios Michaelakis. 2009. "Coactivity of Sulfide Ingredients: A New Perspective of the Larvicidal Activity of Garlic Essential Oil against Mosquitoes." *Pest Management Science* 65 (3): 249–54. doi:10.1002/ps.1678.

Koch, Heinrich P, and Larry D Lawson. 1996. *Garlic: The Science and Therapeutic Application of Allium Sativum L. and Related Species*. Vol. 683181475. Baltimore, MD: Williams & Wilkins.

Lai, Rongquan, Minsheng You, LAP Lotz, and Liette Vasseur. 2011. "Response of Green Peach Aphids and Other Arthropods to Garlic Intercropped with Tobacco." *Agronomy Journal* 103 (3): 856–863.

Lawson, LD. 1996. "The Composition and Chemistry of Garlic Cloves and Processed Garlic." In *Garlic: The Science and Therapeutic Application of Allium sativum L*, edited by HP Koch and LD Lawson, 37–108. Baltimore, MD: Williams and Wilkins.

Liu, Tong-Xian, and Philip A. Stansly. 2000. "Insecticidal Activity of Surfactants and Oils against Silverleaf Whitefly (*Bemisia argentifolii*) Nymphs (Homoptera: Aleyrodidae) on Collards and Tomato." *Pest Management Science* 56 (Copyright (C) 2015 American Chemical Society (ACS). All Rights Reserved.): 861–66. doi:10.1002/1526-4998(200010)56:10<861::AID-PS217>3.0.CO;2-Y.

Luh, BS, LP Somogyi, and JJ Meehan. 1975. "Vegetable Dehydration." In *Commercial Vegetable Processing*, by GS Luh and JG Woodruff, 361–415. Westport, CT: AVI.

Machial, Cristina M., Ikkei Shikano, Michael Smirle, Roderick Bradbury, and Murray B. Isman. 2010. "Evaluation of the Toxicity of 17 Essential Oils against *Choristoneura rosaceana* (Lepidoptera: Tortricidae) and *Trichoplusia ni* (Lepidoptera: Noctuidae).” *Pest Management Science* 66 (Copyright (C) 2015 American Chemical Society (ACS). All Rights Reserved.): 1116–21. doi:10.1002/ps.1988.

Mallek, Susan B, Timothy S Prather, and James J Stapleton. 2007. “Interaction Effects of Allium Spp. Residues, Concentrations and Soil Temperature on Seed Germination of Four Weedy Plant Species.” *Applied Soil Ecology* 37 (3): 233–239.

Martinez, A, Y Ikken, MI Cambero, ML Marin, Ana I Haza, C Casas, and P Morales. 1999. “Mutagenicity and Cytotoxicity of Fruits and Vegetables Evaluated by the Ames Test and 3-(4, 5-Dimethylthiazol-2-Yl)-2, 5-Diphenyltetrazolium Bromide (MTT) Assay/Mutagenicidad Y Citotoxicidad de Frutas Y Vegetales Evaluadas Por El Test de Ames Y El Ensayo Del Bromuro de 3-(4, 5-Dimetiltiazol-2-Il)-2, 5-Difeniltetrazolio (MTT).” *Food Science and Technology International* 5 (5): 431–437.

Matthews, Keith. 2009. “Garlic Oils Final Work Plan.” Registration Review Case EPA-HQ-OPP-2009-0113-0007. Washington, DC: US EPA Office of Pesticides and Toxic Substances. http://www.regulations.gov/#!documentDetail;D=EPA-HQ-OPP-2009-0113-0007.

McDavit, W. Michael. 2010. “Garlic Oil Final Registration Review Decision.” Registration Review Case EPA-HQ-OPP-2009-0113-0011. Washington, DC: US EPA Office of Pesticides and Toxic Substances. http://www.regulations.gov/#!documentDetail;D=EPA-HQ-OPP-2009-0113-0011.

McHugh, CP. 2001. “Garlic as a Tick Repellent.” *Journal of the American Medical Associatio* 285 (1): 41–42.

Merck. 2015. *The Merck Index Online*. Cambridge, UK : Royal Society of Chemistry,.

Morbidoni, Laura, Jennifer Moore Arterburn, Veronica Young, David Mullins, Cynthia Mulrow, and Valerie Lawrence. 2001. “Garlic: Its History and Adverse Effects.” *Journal of Herbal Pharmacotherapy* 1 (1): 63–83.

Nakagawa, S, K Masamoto, H Sumiyoshi, and H Harada. 1984. “[Acute Toxicity Test of Garlic Extract].” *The Journal of Toxicological Sciences* 9 (1): 57–60.

Nath, A, NK Sharma, S Bhardwaj, and CD Thapa. 1982. “Nematicidal Properties of Garlic.” *Nematologica* 28 (2): 253–255.

NPIC. 2016. “NPIC Special Report: 25(b) Incidents.” Corvallis, OR: National Pesticide Informatiom Center.

Palani, S., Nisha Mary Joseph, Yonatan Tegene, and Anish. Zacharia. 2014. “Garlic – a Concise Review.” *International Journal of Pharmacognosy* 1 (Copyright (C) 2015 American Chemical Society (ACS). All Rights Reserved.): 691–95. doi:10.13040/IJPSR.0975-8232.IJP.1(11).691-65.

Perchellet, JP, EM Perchellet, and S Belman. 1989. “Inhibition of DMBA-Induced Mouse Skin Tumorigenesis by Garlic Oil and Inhibition of Two Tumor-Promotion Stages by Garlic and Onion Oils.” *Nutrition and Cancer* 14 (3–4): 183–193.

Portz, Daniela, Eckhard Koch, and Alan J Slusarenko. 2008. “Effects of Garlic (*Allium sativum*) Juice Containing Allicin on *Phytophthora infestans* and Downy Mildew of Cucumber Caused by *Pseudoperonospora cubensis*.” In *The Downy Mildews-Genetics, Molecular Biology and Control*, 197–206. Springer.

Prowse, GM, TS Galloway, and A Foggo. 2006. “Insecticidal Activity of Garlic Juice in Two Dipteran Pests.” *Agricultural and Forest Entomology* 8 (1): 1–6. doi:10.1111/j.1461-9555.2006.00273.x.

Rajan, TV, M Hein, P Porte, and S Wikel. 2005. “A Double-Blinded, Placebo-Controlled Trial of Garlic as a Mosquito Repellent: A Preliminary Study.” *Medical and Veterinary Entomology* 19 (1): 84–89.

Ramakrishnan, V, GJ Chintalwar, and A Banerji. 1989. "Environmental Persistence of Diallyl Disulfide, an Insecticidal Principle of Garlic and Its Metabolism in Mosquito, *Culex pipiens quinquifasciatu*s Say." *Chemosphere* 18 (7): 1525–1529.

Ranger, Christopher M., Michael E. Reding, Jason B. Oliver, James J. Moyseenko, Nadeer Youssef, and Charles R. Krause. 2013. "Acute Toxicity of Plant Essential Oils to Scarab Larvae (Coleoptera: Scarabaeidae) and Their Analysis by Gas Chromatography-Mass Spectrometry." *Journal of Economic Entomology* 106 (1): 159–67. doi:10.1603/EC12319.

Ranger, Christopher M., Michael E. Reding, Jason B. Oliver, James J. Moyseenko, and Nadeer N. Youssef. 2009. "Toxicity of Botanical Formulations to Nursery-Infesting White Grubs (Coleoptera: Scarabaeidae)." *Journal of Economic Entomology* 102 (1): 304–8.

Reuter, Hans D, HP Koch, and LD Lawson. 1996. "Therapeutic Effects and Applications of Garlic and Its Preparations." *Garlic: The Science and Therapeutic Application of Allium sativum L. and Related Species* 1996: 135–212.

Revay, Edita E., Yosef Schlein, Onie Tsabari, Vasiliy Kravchenko, Whitney Qualls, Rui De-Xue, John C. Beier, et al. 2015. "Formulation of Attractive Toxic Sugar Bait (ATSB) with Safe EPA-Exempt Substance Significantly Diminishes the *Anopheles sergentii* Population in a Desert Oasis." *Acta Tropica* 150 (October): 29–34. doi:10.1016/j.actatropica.2015.06.018.

Scholl, I, and E Jensen-Jarolim. 2004. "Allergenic Potency of Spices: Hot, Medium Hot, or Very Hot." *INTERNATIONAL ARCHIVES OF ALLERGY AND IMMUNOLOGY* 135 (3): 247–61. doi:10.1159/000081950.

SCOGS. 1973. "Garlic and Oil of Garlic." Select Committee on GRAS Substances Opinion 17. Washington, DC: FDA SCOGS. http://www.fda.gov/Food/IngredientsPackagingLabeling/GRAS/SCOGS/ucm260417.htm.

Sharangi, AB. 2011. "In Search of Allelopathy from Common Alliaceae Crops for Managing Weeds in Coriander: An Overview." *International Journal of Agricultural Research* 6 (3): 209–217.

Shimabukuro, Mary A, and Vickie Haberman. 2006. "An Aromatic Adventure with Allelopathy: Using Garlic to Study Allelopathy in the Classroom." *The American Biology Teacher* 68 (4): 242–247.

Siddiqui, Nazima, and Adeel Ahmad. 2013. "A Study on Viscosity, Surface Tension and Volume Flow Rate of Some Edible and Medicinal Oils." *International Journal of Science, Environment and Technology* 2 (6): 1318–1326.

Sigma-Aldrich. 2015. "Garlic Oil Safety Data Sheet." MSDS 530316. St Louis, MO: Sigma-Aldrich, Inc. http://www.sigmaaldrich.com/MSDS/.

Srivastava, K, and P Srivastava. 1981. "Studies on Plant Materials as Corrosion Inhibitors." *British Corrosion Journal* 16 (4): 221–223.

St Louis, ME, SH Peck, D Bowering, GB Morgan, J Blatherwick, S Banerjee, GD Kettyls, WA Black, ME Milling, and AH Hauschild. 1988. "Botulism from Chopped Garlic: Delayed Recognition of a Major Outbreak." *Annals of Internal Medicine* 108 (3): 363–68.

Stjernberg, Louise, and Johan Berglund. 2000. "Garlic as an Insect Repellent." *Journal of the American Medical Association* 284 (7): 831.

Sumiyoshi, H, A Kanezawa, K Masamoto, H Harada, S Nakagami, A Yokota, M Nishikawa, and S Nakagawa. 1984. “Chronic Toxicity Test of Garlic Extract in Rats.” *The Journal of Toxicological Sciences* 9 (1): 61–75.

Tariq, V-N, and AC Magee. 1990. “Effect of Volatiles from Garlic Bulb Extract on *Fusarium oxysporum* F. Sp. *Lycopersici*.” *Mycological Research* 94 (5): 617–620.

Thomas, CJ, and A Callaghan. 1999. “The Use of Garlic (Allium Sativa) and Lemon Peel (Citrus Limon) Extracts as *Culex pipiens* Larvicides: Persistence and Interaction with an Organophosphate Resistance Mechanism.” *Chemosphere* 39 (14): 2489–96. doi:10.1016/S0045-6535(99)00161-7.

Tunon, H. 2001. “Garlic as a Tick Repellent.” *Journal of the American Medical Associatio* 285 (1): 41–42.

US EPA. 1992. “Allium Sativum (Garlic) Fact Sheet.” Fact Sheet 738-F-92-015. RED Facts. Washington, DC: US EPA Office of Pesticides and Toxic Substances. http://www.epa.gov/opp00001/chem_search/reg_actions/reregistration/fs_PC-128827_1-Jun-92.pdf.

———. 2015. “Toxics Release Inventory (TRI) Basis of OSHA Carcinogens.” Washington, DC: US EPA. http://www2.epa.gov/sites/production/files/2015-03/documents/osha_carcinogen_basis_march_2015_0.pdf.

———. 2017. “Pesticide Product Labeling System (PPLS).” http://iaspub.epa.gov/apex/pesticides/f?p=PPLS:1.

US EPA OPPTS. 2015. “Chemical Data Access Tool.” Washington, DC: US EPA Office of Pollution Prevention and Toxic Substances. http://java.epa.gov/oppt_chemical_search/.

Vassiliou, V. A. 2011. “Botanical Insecticides in Controlling Kelly’s Citrus Thrips (Thysanoptera: Thripidae) on Organic Grapefruits.” *Journal of Economic Entomology* 104 (6): 1979–85. doi:10.1603/EC11105.

Wagner, Kimberly K, and Dale L Nolte. 2001. “Comparison of Active Ingredients and Delivery Systems in Deer Repellents.” *Wildlife Society Bulletin*, 322–330.

Wink, Michael. 2003. “Evolution of Secondary Metabolites from an Ecological and Molecular Phylogenetic Perspective.” *Phytochemistry* 64 (1): 3–19.

Xavier, Vânia M, Dejair Message, Marcelo C Picanço, Mateus Chediak, Paulo A Santana Júnior, Rodrigo S Ramos, and Júlio C Martins. 2015. “Acute Toxicity and Sublethal Effects of Botanical Insecticides to Honey Bees.” *Journal of Insect Science* 15 (1): 137–43.

Xavier, Vania Maria, Dejair Message, Marcelo Coutinho Picanco, Leandro Bacci, Gerson Adriano Silva, and Jorgiane da Silva Benevenute. 2010. “Impact of Botanical Insecticides on Indigenous Stingless Bees (Hymenoptera: Apidae).” *Sociobiology* 56 (3): 713–725.

Zhou, Hai-bo, Ju-lian Chen, Yong Liu, Frédéric Francis, Eric Haubruge, Claude Bragard, Jing-rui Sun, and Deng-fa Cheng. 2013. “Influence of Garlic Intercropping or Active Emitted Volatiles in Releasers on Aphid and Related Beneficial in Wheat Fields in China.” *Journal of Integrative Agriculture* 12 (3): 467–473.

Zhou, LH, TL Zheng, XH Chen, X Wang, SB Chen, Y Tian, and HS Hong. 2008. “The Inhibitory Effects of Garlic (*Allium sativum*) and Diallyl Trisulfide on *Alexandrium tamarense* and Other Harmful Algal Species.” *Journal of Applied Phycology* 20 (4): 349–358.

Zhou, Lihong, Xuehao Chen, and Tianling Zheng. 2010. “Study on the Ecological Safety of Algacides: A Comprehensive Strategy for Their Screening.” *Journal of Applied Phycology* 22 (6): 803–811.