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REVIEW ARTICLE

Horticultural oils: possible alternatives to chemical pesticides and insecticides

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Abstract

The farmers and agrochemical industries lack science-based knowledge about sustainable utilization of pesticides and insecticides. The investigation on rising use of chemical pesticides and insecticides has remarkable issue related to environment pollution, soil fertility, and human health; as such, nowadays, many people prefer natural alternatives over synthetic chemicals. Natural products, like horticultural oils, play a significant role for sustainable and safe integrated pest management, providing natural alternatives to chemical pesticides and insecticides. For several decades, both plant- and petroleum-based spray oils have been always used to control various pests, mites, and insects. Currently, these horticultural oils are used as a part of the integrated pest management, which utilizes secure and non-chemical pesticides rather than conventional pesticides. Horticultural oil refers to a complex mixture of hydro-carbons with traces of sulfur- and nitrogen-based compounds, extracted from plants. The key components of horticultural oils include paraffin and olefin. The horticultural oils are considered suitable since they are non-toxic to both plants and animals, are applied easily, have low risk properties, cost-effective, and play significant role in pest control, but show little effects on the beneficial insects. As a result, these attributes make horticultural oils to be considered as secure and effective alternative for chemical insecticides and pesticides for both commercial and domestic agriculture.

Keywords Natural pesticides · Petroleum oils · Herbal · Agrochemicals · Phytotoxicity

Introduction

The plants and plant-based products are receiving considerable attention across the world for their utilization and applications as natural pesticides and insecticides. A wide range of cost-effective, preventive, curative, and safe herbal products are available as natural remedies against various pest and insects. The compounds, oils, and especially horticultural oils extracted from plants and herbs can act as effective larvicides, insect growth inhibitors, and repellents (Suresh et al. 2012; Nile et al. 2018). Horticultural oils refer to complex mixture of hydrocarbons with traces of both nitrogen- and sulfur-based compounds that are applied to control different pests and other insects that cause diseases in plants. They are the most preferred alternative to control insects and pests especially in organic farming since they are non-toxic and have fewer side effects (Agnello 2001). Moreover, horticultural oils are considered both a natural and safe practice to control insects and pests that damage plants. Thus, it is part of the integrated pest management system (IPM). Comparatively, horticultural oils are effective and less harmful towards pest management; thus, they are available as commercial pesticides (Galloway 2011). Another advantage of these oils is their ability to dissipate via evaporation leaving behind minimal residue on the plants, which in turn leaves minimal chemical effects in the ecosystem as well as plant's soil. The affected pests and plants should be thoroughly coated using the horticultural oil, an effective technique in controlling plant pests and diseases. However, these oils cease to have their insecticidal effects once they dry (Galloway 2011). The horticultural oils have been used in both conventional and organic agents for plant protection, fruit production, and to suffocate insects and their eggs by preventing gas exchange, which leads to increased mortality, without resistance development by insect and mites for

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horticultural oils (Alam et al. 2017). Firstly, the application of horticultural oils mainly restricted for the dormant phase of trees, but recent developments, methods of extraction, and processing have made it appropriate for foliar applications (Wins-Purdy et al. 2009). The various refining processes including steam distillation and proper filtration of horticultural oils have demonstrated potential protection against pest and insects, without causing environmental pollution or any adverse effects (Nerio et al. 2010). Most of the chemically synthesized compounds are considered as unsafe agents to control plant pests since they cause environmental pollution, have showed harmful effects to a few living organisms, and cause various chronic diseases in human beings. As a result of these parameters, the excessive usage of chemically synthesized chemicals was ceased or reduced across the world. However, humans continue to look for other practical natural and safe alternatives to control pests as well as insects. Therefore, horticultural oils are continually considered the safest and best available natural agents to control pests damaging crops and plants (Helmy et al. 2012).

The horticultural oils are synthesized using either vegetable oils or petroleum products. They are generated by extracting as well as distilling (i.e., boiling, followed by vapor condensation) vegetable oils or petroleum products. Previously, using horticultural oils was difficult since they damaged the plants, even when applied under perfect conditions (Cranshaw and Baxendale 2005). This was as a result of impurities, especially sulfur and naphthene. In the current times, the process of distillation has greatly enhanced the removal of these impurities and providing safer oils to apply on plants either as insecticides or pesticides. The horticultural oils that control pests by smothering target pests are effective if they are directly applied on the pest and do not provide residual control (Chalker-Scott and Daniels 2015). Also, these oils can be used on various landscape plants to suppress different mites and insects. They are considered desirable since they are safer for humans as well as other non-target organisms (Cranshaw and Baxendale 2005). Although these oils are safer for the animals, they may damage some of the plants; as a result, arborists and landscapers should only apply highly refined oils by knowing the rate to application and the plants' sensitivity to these oils. Based on these factors, horticultural oils are classified depending on these three categories: when and how to apply oils, sensitive landscape plants, as well as insects that are susceptible to oil (Smitley 2008). Amateur and professional horticulturists are usually confused regarding the application of the petroleum oils to control pests on ornamental plants. These oils are referred to as dormant oils, summer oils, or horticultural oils. Both summer oils and horticultural oils are synonymous. In practice, choosing the appropriate oil for mite and insect control on the ornamental plants is simpler than it appears (Glen 2009). The horticultural oils have different synonyms that may be confusing during utilization or application for insect and pest control.

When horticultural oils are used, they also kill susceptible beneficial pests and insects covered by the oils since they are not selective. However, these oils are considered safe for the mammals (i.e., humans), reptiles, and some birds. However, these oils evaporate rapidly, and they have little toxicity when dried. Therefore, these beneficial insects safely reenter the oil-treated areas once the spray residues have dried (http://www.ladybug.uconn.edu/FactSheets/hort-oil_8_660806050.pdf). Regardless of these significant benefits, several potential users never use horticultural oils since they are concerned with phytotoxicity (browning, plant damage, or leaf burning) which may occur. Previously, less purified and heavier dormant oils were used likely to initiate phytotoxic reactions as compared to the current highly refined horticultural oils. Currently, superior horticultural oils are safely used on various kinds of woody ornamentals, berries, various fruits, as well as vegetables. Some horticultural oils may be reapplied since they have less residual effects (http://www.ladybug.uconn.edu/FactSheets/hort-oil_8_660806050.pdf).

Viscosity, density, as well as un-sulfonated residues are three factors that clearly differentiate summer oils from the dormant oils. The effect of horticultural oil sprays on the treated plants depends on these factors. Some of these oils (such as diesel oil, Stoddard solvent) are toxic to the plants onto which they are applied as herbicides (Cloyd et al. 2009). The summer oils cannot be used in full strength to control insects. They are often mixed with water at rates of one to four parts of oils as well as 96 to 99% parts of water depending on the recommendation of the manufacturer for safe use. There are two main types of summer oil formulations, namely concentration emulsions and miscible oils. Miscible oils comprise 95 to 99% oils that produce an emulsion immediately once they get mixed with water. On the other hand, concentration emulsions are about 80% oils together with water and emulsifiers. Agnello (2001) asserts that concentration of emulsions is very thick, and they resemble marshmallow or mayonnaise topping in the appearance. The summers oils are cheap; however, they have less toxicity to the insects and pests compared to most synthetic pesticides. As a result, they are applied in higher rates. Moreover, summer oils have exceptionally good spreading properties. Also, they can be applied at lower concentrations (i.e., 2 to 4 teaspoons/gal) with different synthetic insecticides in order to improve the pesticide treatment coverage (Bogran et al. 2006). Bogran et al. (2006) asserted that the summer oils are easy to mix and safe and have the ability to impart sheen on the treated plants, which made them to be often used by most of the landscapers and homeowners in controlling ornamental plant pests. Furthermore, summer oils are popularly considered as an effective remedy for the armored scale control (such as tea scale and euonymus scale). Some of the commercial names as well as percentages of different summer oils include the following: Spray Oil (98%), Superior Spray Oils (98%, 98.9%), Summer Spray Oil (98%), Volck Oil Sprays (97%), Volck Supreme Oil Sprays (98%), Scalicide (98%), Oil-I-Cide (80%), Unico Spray Oil (98%), Superior Oil (98.75%), and the all-season Hort and Dorm spray oils (Baker 2011). All these names are provided to assist the consumer to recognize the summer oils; however, it never constitutes a recommendation for a certain product. Horticultural oils are considered one of the safest and effective insecticides to apply on various soft bodied insects, like whiteflies, aphids, and scale, which come into direct contact with the oil spray. Resistance should never be anticipated to develop with the oils, and they are likely to be among the least non-target effects (Bogran et al. 2006). The horticultural oils could be utilized as safe and natural alternatives to chemical pesticides and insecticides. Different chemical and physical characteristics of horticultural oils were explained for better understanding to farmers and researchers for use. The types and classes of horticultural oils were explained with the method of applications and nature of oils regarding type of pest control towards the different herbs and crops. Among literatures, the chemical and physical nature of horticultural oils is explained in Table 1 and Fig. 1, respectively. The detailed information of using horticultural oils to improve crop productivity by minimizing cost, phytotoxicity with safe and convenient mode of applications was discussed in the following sections.

Horticultural oils

Horticultural oil refers to a complex mixture of hydrocarbons with traces of sulfur and nitrogen-based compounds, extracted from herbs and plants. The key components of horticultural oil include paraffin and olefin (Fig. 1). Petroleum oils refer to highly refined paraffinic oils industrially manufactured using either vegetable oils or petroleum, and they are used to control pests as well as diseases in plants. Chalker-Scott and Daniels (2015) assert that horticultural oils are a complex hydrocarbon mixture with traces of nitrogen as well as sulfur-based compounds. The commercially available oils are the highly refined petroleum products that have been highly distilled and filtered in order to eliminate compounds that cause harm to plants. These oils have 92 and 99% purity compared to other available oils. After the process of distillation and filtration, these oils are formulated using emulsifier (mixing agent) to blend them with water to apply easily as pest control (Helmy et al. 2012). These plant-based horticultural oils may contain cottonseed, soybean, neem, sesame, or much other plant-based oils. Skelly (2013) asserts that these plant-based horticultural products are not highly refined and may more readily burn the plants on which they are applied (phytotoxicity). Both vegetable oils and petroleum comprise of mixtures of various compounds. For instance, petroleum oils usually consist of two compounds, paraffin and olefin, whose chemical structures were shown earlier. On the other hand, vegetable oils like soybean and canola comprise of mixtures of unsaturated fatty acids or triglycerides. The type and number of compounds in horticultural oil are dependent on how both distillation and extraction were conducted. Also, it depends on the impurities inherent in the horticultural oil (Walsh et al. 2000).

Table 1 Horticultural oils with saturated paraffinic petroleum with specialized specifications

Characters	Specifications
UR, percent (minimum—92)	92–96
Viscosity, seconds, Saybolt (maximum—90)	60–90
Distillation range (°C)	211–242
Gravity (API—American Petroleum Institute)	30–35
Flash point (°C)	173.8

The higher the UR (un-sulfonated residue), the safer is the oil, while the lower the viscosity and distillation range, the lighter is the oil

Chemical nature of horticultural oils

Petroleum spray oils contain four major chemical structures—naphthene, paraffin, aromatics, and olefin (Fig. 1). Aromatic and olefin structures comprise of double-bonded structures making them less stable and highly phytotoxic. Naphthene does not have double bonds, but it can be broken easily and thus more reactive (so more potentially phytotoxic) compared to paraffin. Paraffin has most appropriate structure; it has a better viscosity and less phytotoxic for use. Virtually these oils are a mixture of two or more chemical structures, and for purposes of practical application as petroleum spray oils, they should have about 60% paraffin (Walsh et al. 2000). For in-season (summer) use, the content of paraffin used should be slightly higher. Various improvements in the refinement methods have enhanced the manufacture of petroleum spray oils with higher levels of paraffin. Weidhaas (1988) asserts that most of the horticultural oils are generated from saturated paraffinic petroleum, and they are refined to specifications as shown in Table 1.

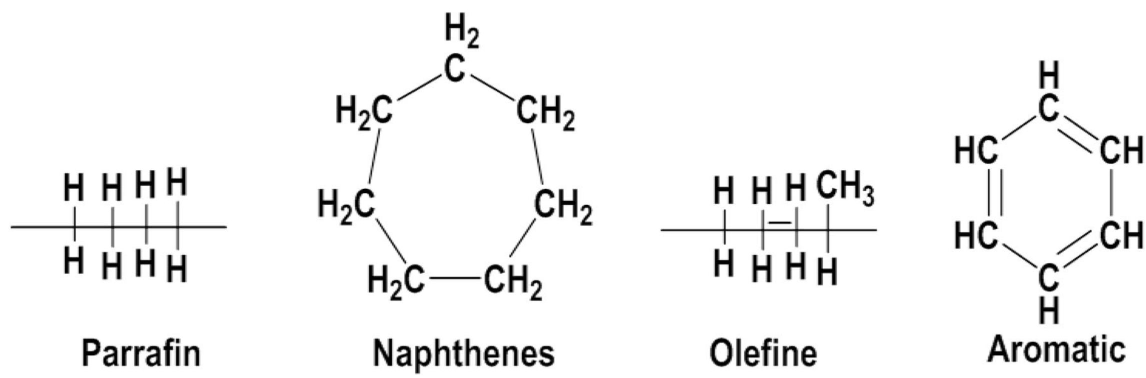

Fig. 1 Petroleum spray oils with four basic chemical structures—paraffin, naphthene, olefin, and aromatic

Primary targets for horticultural oils

Most horticultural oils are considered as more effective pesticides and insecticides against various soft-bodied animals, such as adelgids, aphids, scale insects, spider mites, mealybugs, greenhouse whiteflies, lace bugs, plant bugs, as well as arachnids, including spider mites, on the shade or fruit trees and various ornamental plants, as well as other caterpillars. Also, horticultural oils can be utilized to control diseases, like downy mildew, powdery mildew, leaf spot, and rust (Chen et al. 2009). Horticultural oils can be used both as fungicides and pesticides. Moreover, they minimize the ability of fungi to grow. According to Skelly (2013), viral diseases are significantly reduced by killing the various insects that distribute the viruses. The details about the effects of horticulture oils observed on various insects with probable inhibition of growth and their symptoms are explained in Table 2.

Insects vulnerable to horticultural oils

Most horticultural oils are applied as contact insecticides. Also, they have less residual activity, and these properties are suitable for the beneficial insects. The oil spray works for 24 h on the treated plant. However, horticultural oils are very significant, especially when a safe product is needed or one is attempting to preserve the natural enemies. Horticultural oils which are used during growing season are reported to control various pests (Table 3) (Smitley 2008).

Plants sensitive to the horticultural oils

Several entomologists and labels suggested that there are various plants which are susceptible to the horticultural oils, like maples, especially red and Japanese maple, black walnut and hickories, smoke tree (*Cotinus coggygria*), and plume cedar (*Cryptomeria japonica*). Halcomb and Hale (2012) assert that various plants are sensitive to the horticultural oils, including junipers, redbuds, Douglas firs, spruce, and cedars. According to Miller (1989), black walnut, hickories, beech, maples, Douglas fir, Japanese holly, smoke tree, *Cryptomeria* spp., azaleas, blue spruce, as well as redbugs are also sensitive to horticultural oils (Table 4).

Different classes of mineral oils

a. Horticultural oils: these oils help to control pests on plants
b. Dormant oil: these oils are applied on woody plants especially during the dormant seasons. The term dormant oil refers to less well-defined, heavier weight oils that are not safe for use on various plants once they break dormancy. Nevertheless, there are more refined and lightweight oils currently to replace the older unsafe oils. Currently, dormant oil refers to the effectivity with its application period rather than the oil's characteristic type.
c. Summer oil: These oils also referred to as foliar oils since they are used on the plants when there is foliage. As for dormant oils, this term refers to time of use rather than the oil's properties.
d. Mineral oils: These oils are also called as petroleum-based oils (contrary to vegetable oils). The narrow-range oils: highly refined oils with a narrow distillation range. They are classified under the superior oils. These terms may be applied almost interchangeably. Finally, Spray oil, which is mixed with water and used to spray on plants as a pesticide.
e. Superior oil: This term originated in order to classify summer-use oils that attain certain specifications. Also, these oils have high proportions of the paraffinic hydrocarbons as well as purification which allows them to be applied year-round without phytotoxicity. Due to various technological developments, more refined oils are manufactured that undergo distillation over narrow temperature ranges. Currently, more superior oil is also called narrow-range oil (Helmy et al. 2012).
f. Supreme oil: This term is used to refer to highly refined oils that are distilled at slightly high temperatures as well as wide ranges as compared to narrow-range oils. A number of the supreme oils meet the superior oil's characteristics.

Table 2 Summary of effects of horticulture oils observed in insects with probable effects and actions

Type of HMO	Target crops	Effects	Actions	Insect species	References
Servo agro spray oil	Tea plants (*Camellia sinensis*)	Suffocation by spiracle blockage, cell membrane mating disruption and darkening	Adult mortality and repellent properties	Tea red spider mite, *Oligonychus coffeae*	Roy et al. (2015)
Sunspray ultra-fine	Apple plant (*Malus pumila*)	Ovicidal and residual larvicidal activity	Mortality	European red mite, *Panonychus ulmi*	Agnello (2001)
*n*C-24 and *n*C-27 petroleum spray oils	Maize plants (*Zea mays*)	Oviposition deterring activity	Mortality, egg mortality	*Ostrinia nubilalis*, *O. nubilalis* eggs, and *Trichogramma brassicae*	Al-Dabel et al. (2008)
*n*C-23 HMO	Lemon trees (*Citrus limon*)	Altered leaf metabolism, eliciting kinetic responses	Rejected for oviposition	Citrus leaf miner, *Phyllocnistis citrella*	Liu et al. (2006)
Sunspray, Sun Oil Co., Marcus Hook, PA	Pachysandra (*Pachysandra terminalis*)	Kills scales by smothering them on the leaf surface.	Control of scales	Euonymus scale *Unaspis euonymi*	Sadof and Sclar (2000)
*n*C-23 purespray green horticultural oil	Apple orchards (*Malus domestica*)	Mating disruption	Reduce male mate-finding behavior	*Choristoneura rosaceana* (Harris)	Wins-Purdy et al. (2007)
*n*C-23 Orchex 796	Apple plant (*Malus pumila*)	Deterrence of female oviposition, mating disruption	Suppression of pests	White apple leafhopper, *Typhlocyba pomaria* McAtee, codling moth, *Cydia pomonella*	Fernandez et al. (2005)
*n*C-23 and *n*C-24 petroleum spray oils	Lemon tree (*Citrus limon*)	Reduced oviposition	Suppress leaf miner infestations	Citrus leafminer, *Phyllocnistis citrella* Stainton	Rae et al. (2006)
*n*C24	Tomato plant (*Solanum lycopersicum*)	Suppress oviposition	Prevent development of whitefly infestations	Greenhouse whitefly *Trialeurodes vaporariorum* (Westwood)	Xue et al. (2002)

Mode of action of horticultural oils

Horticultural oils block the insects' spiracles (air holes) preventing gaseous exchange, and this causes them to die due to asphyxiation. Moreover, oils are spread through their respiratory pores blocking the trachea of insects which results to insect death. Horticultural oils are significant sources of insecticides. As an insecticide, they cause chemical interference as well as physical interruption on the insects that kills them. They cause interferences on the insects or pest cell membrane function (Baker 2011). Also, when oil penetration occurs, it causes toxicity to the cells. The mineral oils create a layer on various parts of the plant to eliminate the settlement of the newly hatched insects. They react with the insects' fatty acids and interfere with their normal metabolism. Also, oils interfere with feeding of various leaf-hoppers as well as aphids where oil-covered surfaces occur, which is a significant feature especially in the spread of plant viruses by the aphids (Cranshaw and Baxendale 2005). They make the un-hatched eggs hard making it difficult for them to hatch. Oil sprays only work effectively when exposed against eggs and insects that are covered with the layer of oil. They should be coated long enough in order to suffocate the pests without harming the plants. Heavier oils are more effective in the control of pests; however, they are more likely harmful to the plant. Therefore, one of the most effective ways to achieve better results is by applying lighter oils for both summer and dormant treatments as well as applying higher concentrations during the dormant seasons (Weidhaas 1988).

Type of horticultural oils

There are two major types of horticultural oils, summer oil and dormant oil, irrespective of their similarity; these oils differ in their time of application and degree of refinement. According to Miller (1989), summer oils (lighter weight) are normally used during the plant's active growth stage. At this stage, the plant foliage is often present. On the other hand, Miller (1989) asserts that dormant oils (heavy weight) are normally used during the spring before the bud breaks or during the fall when the leaves drop. Dormant oils are commonly applied to black walnut, maples, beech, redbud, hickories, spruce, Japanese holly, Douglas fir, as well as fall applications to butternut, juniper and ash, and *Cryptomeria*. Summer oils are mainly applied to azaleas, smoke tree, *Savin junipers*, Photinia, blackberry, Amur maple, Japanese holly, as well as raspberries. Smitley (2008) asserts that for these applications, one should ensure the oil spray tank is thoroughly agitated

Table 3 List of insects susceptible to horticultural oils

Good control	Poor control
Boxwood psyllid	Sycamore plant bug
Cottony maple scale crawlers	Imported willow leaf beetle
Euonymus scale crawlers	Birch aphid
Pine needle scale crawlers	Eastern tent caterpillar
Golden oak scale crawlers	Japanese beetle
Honeylocust plant bug	Fletcher scale
European pine sawfly	Apple aphid on crabapples
Sycamore lace bug	Honeylocust spider mite
Elm leaf beetle eggs	
Grape leafhopper larvae	
Codling moth eggs	
Pine tortoise scale crawlers	
Spruce spider mite	
Elm leaf beetle larva	

since oils can easily separate from the water and this may cause problems to the plants due to higher concentration.

Characteristics of horticultural oils

According to Miller (1989), there are three major characteristics to consider when evaluating effective oil to control pests, which are as follows:

Table 4 List of plants sensitive to horticultural oils

Plants	Time of treatment
Maples (Japanese, Silver, Sugar)	Dormant
Hickories	Dormant
Black walnut, Japanese walnut	Dormant
Cryptomeria	Anytime
Smoketree	Summer
Some Azaleas	Summer
Brambles (Rubus)	Summer
Butternut	Summer/dormant
Blue spruce/Koster spruce	Will lose blue color
Alberta spruce	Late summer
Beech	Dormant
Japanese holly	Summer/dormant
Redbud	Dormant
Savin junipers	Summer, spring
Photinia sp.	Summer
Spruce; Norway, White	Dormant
Douglas fir	Dormant

Adapted from: Johnson WT (1985) Horticultural oils. J Environ Hort 3, 188–191

Viscosity

Viscosity refers to the rate of flow (resistance to flow) or the oil's thickness. Viscosity can be measured by passing a substance via special measuring devices in order to record the rate in seconds. The viscosity of most horticultural oils ranges between 60 and 110 s.

Volatility

Volatility, on the other hand, refers to the temperature conditions at which part or fraction of crude oil is fully distilled; the process comprises of driving the vapor or gas from the solid or liquid through heating and then re-condensing the liquid produced. Heavier oils (dormant oils) have lower volatility and are more effective for pest control use. On the other hand, lighter oil (summer oil) is more volatile with lower distillation values (Miller 1989). The oils that have lower distillation values evaporate more rapidly from the plant's surfaces onto which they have been applied than the heavier oils. The insecticide's phytotoxicity and efficacy are directly related to the speed of evaporation.

The un-sulfonated residue rating

Un-sulfonated residue (UR) or purity rating refers to an index of the amount of oil which is free from the unsaturated hydrocarbons. Currently, most of the oils available in the markets have UR indexes ranging between 92 and 99%. When choosing an oil spray, it is significant to consider the volatility and UR index value of the oils as a most crucial characteristic. Miller (1989) asserts to never rely on the oil's viscosity rating because it may change by blending it with different oils during production and refinement.

The nature of horticultural oils

Most of the users do not understand horticultural oils very well. Summer oils and dormant oils are the two main types of horticultural oils used for pest control. When plants are in dormant stage (during winter), then the dormant oils are applied on them. Dormant oils have high heaviness or viscosity. This is very significant since mites and insects have lower respiratory rates during dormant seasons. The heavier is the oil, the slower is the rate with which it spreads and thus covering the pests for a longer time prior to evaporation which enhances its effectiveness. Summer oils (lighter oils) have lower viscosity. Usually, the oils are mixed with an emulsifier in order to make sure the oil mixes evenly with water ensuring uniform spray coverage. The summer oils are often applied mostly during the growing seasons. Pundt (2015) asserts that summer oils are referred by various names including superior oils or ultra-fine oils. Asphaltic and naphthenic oils are highly saturated, aromatic, and applied for fuel oil, motor fuels, as well as solvents, having high toxicity to the plants. Also, paraffinic oils have high saturations and are applied as lubricating oils as well as form base from which a refined horticultural oil is manufactured, which is safer to be applied on the plants (Weidhaas 1988). Cranshaw and Baxendale (2005) assert that horticultural oils refer to paraffinic oils refined particularly for use on the plants in order to control insects. Also, white mineral oils are defined as any of the different tasteless, colorless oils derived from petroleum and used for medicinal or pharmaceutical purposes, like baby oil, laxatives, hand lotions, as well as petroleum jelly (Vaseline), and these oils are fully saturated. Various researchers applying the knowledge of components that improve safety and insecticidal action to the plant tissues came up with oil specifications to apply them on plants when there is foliage. The term "summer oil" came as a result of its application on green plants. These oils can be applied both during the growing and summer seasons. Summer oils and dormant oils entail the time of application, rather than the type of oils. Although some of these oils are meant only for the dormant use. Currently, several horticultural oils can be effectively applied during both growing and dormant seasons of the plants. These oils should be mixed with water before they are applied to plants as an oil spray.

Emulsifiers are very significant, and they are added to oils by producers once it is formulated. An emulsifier is added as an inactive ingredient on a label, rather than being stated separately. Other oil products are referred to as "emulsive oil" or "miscible oil" to demonstrate that they have an emulsifier (Pundt 2015). Finally, the current horticultural oils are manufactured from paraffinic petroleum that is highly saturated as well as refined with various specifications including UR percentage (at least, 92) 92–96; gravity, degrees (API 30–35); viscosity, saybolt, seconds (at least, 90) 60–90; flash point degree, F (for instance, 345 F); distillation ranges, degrees F (412–468). Horticultural oils with higher URs are considered safer. Also, the lower the distillation range and viscosity, the lighter the oils. Based on the Cornell University's recommendations, the UR and distillation range should be at a minimum, 92 and (412–435), respectively (Weidhaas 1988).

Phytotoxicity

Various plants seem to possess inherent variability in terms of sensitivity to the oil sprays. Very little is known regarding plants that are sensitive to oil sprays since there are many types of ornamental plants leaving little studies from which quantitative data can be obtained. Generally, the fresh horticultural oil products are safer to apply on plants. The older cautions on the labels regarding plant damage are not valid. Various factors may significantly affect phytotoxicity of oils on the plants; some of which are well-known based on the fruit tree studies. These factors include high humidity, deficit of moisture in the leaves, high temperature, treatment of young foliage, as well as genetic viability of the plants. Johnson (1985) asserts that little is documented regarding how proper use of oils results to phytotoxicity. It is not recommended to spray oils when the humidity and temperatures are high or during the drought season, as the plants are under stress. If the oils are left in the spray hose to sit and separate, they are likely to cause damage to the plants as a result of high concentrations. Before applying the spray oils, it is recommended to recirculate the spray within the spray tank in order to restore emulsion. Also, it is not recommended to apply oils before, in combination with, or after pesticides. However, improper use of pesticides causes plant damage: incorrect timing, overdosing, oil emulsion breakdown, applying oil together with incompatible materials (such as sulfur compounds), as well as other misuses. Plant damage may involve leaf burn, twig dieback, as well as the death of the new growths. Currently, various indications demonstrate that a variety of plants are sensitive to oils: hickories, maples, as well as dormant sprays (black walnut); smoke tree as well as azaleas (varieties) and summer sprays; as well as *Cryptomeria* (both). Also, other plants exhibiting a tendency towards sensitivity are redbud, beech, Douglas fir, and spruce (dormant); *Photinia* and savin junipers (summer); as well as Japanese holly (both). These oil sprays eliminate bluish blooms from the conifer's needles, particularly blue spruce and many other similar types. Weidhaas (1988) asserts that it may take between one and two years for a new growth to re-generate natural blooms to a tree.

Phytotoxicity as a result of horticultural oil use is likely to occur due to the following factors: when the plant belongs to the variety that is sensitive to oil, when large quantities of oils are applied, having too many oil applications, applying oil regularly, and mixing oil with other incompatible chemicals or applying oils when the conditions are inappropriate. It is recommended to spray summer oils when temperatures range between 4.5 and 29.5 °C and on a day whose relative humidity is moderate. Also, when spraying summer oils, the plant should not be under moisture stress. On the other hand, dormant oils should be applied when temperatures are at least 4.5 °C for a period of 24 h. Various studies have reported that improper application of oils causes plant damage. However, phytotoxicity on the plants is not easy to monitor and does not have adequate qualitative data. In the United States of America, there are various farmers who apply oils on their plants in all seasons as well as under various phonological and temperature/humidity conditions, and they have never reported phytotoxicity issues. For instance, the Monrovia Nurseries found in southern California often applies 1 gal of oil per 100 gal of water as oil sprays in their field-grown plants. In Texas, an arborist applied oil in his entire arboricultural carrier at a ratio of between 2 and 3 gal per 100 gal of water and did not report any plant damage, even when the oils were sprayed at a temperature of 37.8 °C. Also, Dr. Paul Kesley from the University of Delaware in 1960 worked with 70s viscosity oils at the Longwood Gardens in Delaware applying summer oils to 139 species of the woody ornamental plants.

Of these plants, only azalea (*Rhododendron* species) cultivar and smoke tree (*Cotinus coggygria*) show oil injury to the foliage. In the University of Maryland, Dr. John Davidson sprayed 412 oils at between 4 and 60 gal during summer on various woody ornamental plants and reported no toxicity. In the past one and half decades, researchers from New York conducted studies to identify phytotoxic effects experienced as a result of summer treatments. Also, they studied phytotoxic effects reported from plants where basic rules such as moisture-stressed plants, young foliage, and overdose are not considered. There is valid data obtained from the researchers who studied fruit trees to highlight the various conditions that promote phytotoxicity. In the tree fruits, it has been reported that dormant oils cause twig damage to a "Delicious" apple. However, the little data obtained from tree fruits is not enough to fully recommend for the application of oils on woody ornamentals. For researchers, these data offer insights, leads, and some new techniques.

Scientifically controlled experiments should be conducted using the modern horticultural oils under various environmental conditions in order to establish their safety based on the climatic conditions and plant materials. There is need to understand why some plants show sensitivity to horticultural oils. These oils penetrate through the plants' cuticles as well as other membranes. This happens particularly on elongating shoots, young, and newly forming leaves. It is likely to be true non-suberized bark of the twigs. Provided that "defensive chemicals" to horticultural oils have not hardened or formed on the bark surface or leaf, the oil will penetrate through and kill the cells. Also, if the oil clogs the lenticels, it stops respiration, particularly when leaves drop or when the stomata malfunctions and the temperatures remain adequate for metabolic activities, twigs may end up dying (Johnson 1985).

Techniques of applications

Dormant, as well as delayed dormant, applications are done before the bud's break. Also, delayed dormant application can be applied once the buds open at the tips exposing 1/16 to 1/2 in. of green tissue. It is not recommended to apply dormant oils 2 days before or after freeze is predicted or occurs. Quite often, more quantities of dormant oils are applied than the quantity highlighted on the label. On the other hand, summer applications can be used on various woody elements (listed on the label), berries, flowers, and vegetables. Thoroughly mixed oils with water following instructions on the labels ensure a thorough coverage. When using horticultural oils, it is recommended to follow carefully the instructions on the labels. The current improved refinement techniques have produced horticultural oils that have improved safety limits to the plants. Also, the current oils have extended their significance to other seasons unlike the dormant oils. The label instructions will show whether the oils are better for use during the summer or spring. Moreover, if the label indicates that the oils are safe during the dormant season, then it is recommended not to use them until the treated plants experience winter hardening. For optimal results, the dormant application of the horticultural oils should be applied in later winter prior to swelling of buds. This enables the pests affecting the plants to be exposed to winter's adverse effects making them more susceptible to these oils. During winter, it is not advisable to spray oils due to the fluctuating temperatures. If oils are sprayed and the temperature fluctuates suddenly, the plants are most likely to be damaged (Robinson 2011).

There are various spraying concentrations considered suitable depending on distillation rate, viscosity (lightness), as well as intended use of oils. Also, the insect's sensitivity to these oils depends on the insect's groups as well as species. Generally, for dormant oil sprays, the lightest oils are required to be applied at rates ranging between 3 to 4% as well as 2 to 3% for the summer oil sprays. When dealing with pests which are hard to control, then higher rates should be applied. Conversely, when treating with oil-sensitive plants, lower rates less than 1% are highly recommended. The simple rules of the thumb should be applied; using 2% for the summer applications as well as 3% for the dormant treatments, but it should be noted that this may be an oversimplification. The most effective method to utilize is following the instructions on the label explicitly. Most dosage rates for the oils depend on the volumes; therefore, 1% spray represents 1 gal of oil/100 gal of water (i.e., each gallon has 2.66 tablespoons of oil). Generally, it is hard to control armored scales, like obscure, oyster shell, euonymus scales, and calico using dormant oil application as compared to soft scales, like Fletcher, European fruit, lecanium, as well as cottony soft scales. Moreover, the oil's insecticide properties may enhance the control of the armored scales. However, when there are serious infestations, it is advisable to apply oils or labeled insecticides which are recommended at newly hatched (crawler) stages. Weidhaas (1988) asserts that one can determine proper timing through observations or by using GDD (growing degrees days).

Precautions and care in the use and application of horticultural oils

According to Miller (1989), there are various guidelines that should be obeyed to ensure pests are controlled effectively and prevent plant injuries.

a. Do not apply horticultural oils on plants if their tissues are wet or there is a possibility of rain. Spray when the leaves are dry.
b. Never apply spray oils at temperatures above 37.8 °C or below 4.4 °C. However, it is important to note that spray oils can be applied routinely at temperatures more than 37.8 °C in areas with humidity below 50%. If the humidity condition of an area is not considered, there is a likelihood of phytotoxicity occurring above or below these points.
c. Apply the oil sprays based on the label rates. Never over-apply.
d. Avoid drifting spray oils to sensitive plants.
e. If the humidity is anticipated to remain beyond 90% for 36–48 h, do not apply oil spray on the plants
f. Never apply oil spray when buds have fully opened and during shoot elongation.
g. The plant's genetic make-up as well as variability should be taken into consideration.
h. Deciduous plants' dormancy cannot be determined by leaf drop alone. Thus, it is advisable not to spray if there is a likelihood of mistaking dormancy of a plant during fall.
i. Do not apply on transplants or use on tender young shoots.
j. Do not apply treatments using sulfur sprays or sulfur-based products or within two weeks of sulfur spray application since it reacts with horticultural oils forming compounds that damage plants resulting to leaf drop and foliar injury. Some plants are likely to be more sensitive compared to others; nevertheless, the intervals necessary between sulfur spray and oil spray may be longer; often consult the label instructions of fungicide for special precautions.
k. Oil sprays on coleus and wax begonia may cause speckling and pitting of the foliage.
l. Lastly, it is important to be aware to carefully handle various plants which are sensitive to these oil sprays. Read carefully and understand the labels for each plant species as well as varieties. Whenever you doubt the treatment instruction, do not spray! Moreover, when studying several plants, ensure to make notes on plant variety(s) and/or species, weather conditions, as well as application rates.

Advantages of horticultural oils

a. Oils dissipate quickly through evaporation once applied, and very little pesticide residue remains.
b. Horticultural oils are eco-friendly and degradable through evaporation.
c. Horticultural oils are virtually not poisonous to an applicator.
d. When applied correctly, horticultural oils can provide various pest control and mitigation properties without plant injury.
e. Horticultural oils are less harmful to the non-target organisms and highly compatible with the IPM program.
f. Horticultural oils can be mixed together with other synthetic organic insecticides (such as Ethion-oil) (Miller 1989).
g. Horticultural oils are not corrosive to the spray equipment.

Disadvantages of horticultural oils

a. These oils can cause eye irritation or skin cancer to humans.
b. Horticultural oils, if they are applied improperly, may cause phytotoxicity and/or foliage burning. The first injury symptom is the light-yellow foliage. These yellow parts will darken, which may seem to be water-soaked. Also, the leaves may become dark purple and, finally, die. If there is improper application during dormant season, branch dieback and/or terminal are likely to be apparent in subsequent spring (Miller 1989).
c. They can cause injury to sensitive plants.
d. They may harm fish. Some are harmful to bees unless they are sprayed late evening or early in the morning.
e. The blue-colored evergreens may lose their color since oil eliminates the bluish materials from their needles (Skelly 2013).
f. Since oils do not work at once, they dry leaving little residual effect; thus, previous applications do not control new infestations.
g. If oil is sprayed with dormant concentrations once buds break and the leaves have sprouted, the young leaves are more likely to die. Therefore, correct rates should be applied during appropriate times of the year.

The sources of horticultural oils

Horticultural oils are typically refined oils from the petroleum products. Several sulfonated hydrocarbons as well as other impurities are eliminated, making these oils safe and effective on various plant species. Previously, the oils applied as pesticides were under refined and they were only applied during dormant season, thus the term "dormant oils." Also, vegetable oils can be applied as horticultural oils. The effect of horticultural oils depends on their sources. For instance, cotton seeds are considered as best vegetable oil insecticidal, while the soybean oils offer good insecticidal control (Robinson 2011). Skinner (2017) asserts that most petroleum-based oils contain paraffin. These paraffin oils are highly toxic to the mites or insects but safer on the plants as compared to other oil compounds.

Plant-based horticultural oils

Plant-based horticultural oils are available commercially, including vegetable oils, like soybean oil and cottonseed. Also, some may contain significant oils from the herbs as well as spices like mint, thyme, or cinnamon. According to Pundt (2015), oils that are less refined may cause more plant damage (phytotoxicity) as compared to highly refined oils. The various oils are derived from thyme (*Thymus vulgaris* L.), patchouli (*Pogostemon cablin* Blanco), and lemon-scent gum (*Corymbia citriodora* Hook.) used against immature and adult sweet potato whitefly *Bemisia tabaci* (Gennadius) biotype B *Bemisia argentifolii* (Bellows & Perring) (Bahlol et al. 2018). The black pepper (*Piper nigrum*) was used as a biocontrol agent against various pathogens and pests, and the extracted bioactive compounds and oils play a defensive role against pets and insects (Nile et al. 2017). Various plant-based oils were also used as fumigant and antifeedant agents, including anethole, cinnamaldehyde, α-pinene, *Syzygium aromaticum*, star anise (*Illicium verum*), eugenol from cloves, and basil (*Ocimum suave*) against the red flour beetle (*Tribolium castaneum*), maize weevil (*Sitophilus zeamais*), and *Prostephanus truncatus* (Isman 2000). Also, the oils from cumin (*Cuminum cyminum*), oregano (*Origanum syriacum* var. bevanii), anise (*Pimpinella ansium*), and eucalyptus (*Eucalyptus camaldulensis*) are widely used as plant-based oils as fumigants against the cotton aphid (*Aphis gossypii*) and the carmine spider mite (*Tetranychus cinnabarinus*) (Isman 2004).

Essential oils as pesticides

The naturally occurring plant essential oils (EOs) had broad-spectrum effects against various pest insects and plant pathogenic fungi, and some oils have a long tradition of use in the protection of stored food products. EOs are complex mixtures of low molecular weight compounds extracted from plants by steam distillation and various solvent extractions (Benelli et al. 2017). EOs-producing plants are classified and belong to various genera and distributed to around 60 families. Some of the important plant families which include Lamiaceae, Apiaceae, Asteraceae, Alliaceae, Myrtaceae, Poaceae, and Rutaceae are well known for their ability to produce EOs of medicinal, agricultural, and industrial applications (Vigan 2010; Hammer and Carson 2011). Mint (Mentha × piperita, *Mentha spicata*), helichrysum (*Helichrysum italicum*), geranium (*Pelargonium odoratissimum*), yarrow (*Achillea ligustica*), cinnamon (*Cinnamomum verum*), basil (*Ocimum basilicum*), and ginger grass (*Lippia alba*) are widely used commercially available EOs (Benelli et al. 2018). All of the EOs producing plant families are rich in terpenoids, but the plant families like Lamiaceae, Apiaceae, Myrtaceae, Rutaceae, and Piperaceae mainly contain phenylpropanoids (Chami et al. 2004). Terpenoids and phenylpropanoids are the major constituents of EOs, which typically consist of highly complex mixtures of mono- and sesquiterpenoids and biogenetically related phenols and provide characteristic aroma and potential biological properties to plants (Raut and Karuppayil 2014). Some of these EOs are well-known as insect repellents and deterrents (e.g., oil of citronella) and provide characteristics of traditional applications as protectants of stored grains. The relatively high vapor pressures of EO constituents influence both contact and fumigant effects against a wide range of pests (Isman 2004). The EO constituents like eugenol, from cloves, thymol from garden thyme, and cinnamaldehyde from cinnamon are considered as more effective contact and fumigant against a wide range of pests. Some of the EOs also demonstrated to have fumigant action against various plant pests (aphids and spider mites) in greenhouse trials and subterranean termites (*Coptotermes formosansus*) (Isman 2004; Raut and Karuppayil 2014). Several essential oils from plants exhibited pesticidal and insecticidal effects including phytotoxicity towards weeds. These are mainly obtained from *Leptospermum scoparium*, *Hyssopus officinalis*, *Nepeta meyeri*, *Lavandula angustifolia*, *Pinus nigra*, *Majorana hortensis*, *Pimpinella anisum*, *Melissa officinalis*, *Salvia officinalis*, *Origanum vulgare*, *Verbena officinalis*, *Foeniculum vulgare*, *Carum carvi*, *Artemisia scoparia*, and *Citrus aurantiifolia* (De-Almeida et al. 2010; Sharma et al. 2019).

Neem-based oils

Neem (*Azadirachta indica* A. Juss (Meliaceae)) possesses an extensive investigation for its bioactive compounds and oils with numerous biological activities, and it also provides many natural compounds that are widely used as pesticides and applied to protect stored seeds against insects (Boeke et al. 2004). The neem-based products like traditional preparations and formulations have been used extensively to control insect pests attacking agricultural crops. The target phytochemicals were extracted from different parts of neem, but the composition varies considerably due to abiotic and biotic factors from collection of the raw material to extract preparation and product formulation (Gahukar 2014). The azadirachtin extracted from neem was most widely used to produce effective biopesticide that possesses insecticidal properties. The neem seed oil contains triterpenoids, limonoids, and alkaloids, significantly provides various pharmacological properties, and used as natural pesticides and insecticides (Nile et al. 2018; Kamarulzaman et al. 2018). Recently, neem oil extracted from a neem was discovered to possess insecticidal properties and various neem-based insecticides are being developed. Neem refers to natural botanical pesticide that is derived from a neem tree. It comprises of various compounds, but azadirachtin is considered the most active ingredient with insecticidal properties, which helps in minimizing the insect growth, egg laying and growth. Moreover, it plays as an insect repellant. This insecticide is very effective against premature insects. Without azadirachtin, neem seed oils act as protectants against mites and fungi (National Pesticide Information Center 2012). It minimizes fungal infection by eliminating penetration and germination. With or without azadirachtin, neem oils are typically non-toxic to mammals, bees, and birds (provided that it is applied early in the morning or late in the evening when the bees are not active) as well as plants. However, it is slightly toxic to aquatic animals, such as fish. Products from neem can be registered for herbs, vegetables, fruits, as well as woody plants. According to Skelly (2013), one may be required to reapply the horticultural oils at intervals of between 7 and 10 days in order to effectively control pests and insects. Neem oil is mainly composed of oleic (58%), palmitic (14%), and stearic (15%) acids, whereas myristic, arachidic, linoleic, and behenic acids are detectable in very small concentration; the neem oils and azadirachtin, from neem, are known for their pesticidal and insecticidal properties (Pandey et al. 2014). Neem oil studied as less effective against *Leishmania* spp. compared anti-leishmanial effects of neem leaf extracts against *Leishmania donovani* (Dayakar et al. 2015). The neem bioactive called azadirachtin showed promising bioactivity as a potent insecticide in the deterrence of the feeding and oviposition, as a repellent and in the growth inhibition of insects (Morgan 2009).

Conclusions and future prospectus

For several decades, various oils have been applied as natural insecticides and pesticides and they are considered to be safe and effective alternatives for the chemically synthesized insecticides and pesticides. These oils are highly refined paraffinic spray oils that are used to control mites, insects, and pests, insects which attach different edible crops and plants as well as fungal diseases. These horticultural oils are considered both safe and effective, and they comply with the philosophy of IMP (integrated pest management). Irrespective of this, information and utilization concerning oils are still not enough. When used properly, horticultural oils can effectively control pests and insects and be less toxic to the plants unlike chemical-based insecticides. A delayed or dormant application can harm various overwintering pests and insects that often plague plants in late spring, like aphids. Treating plants in early spring or winter can save a lot of time as well as eliminate late plant problems. If summer applications are applied at correct rates, they provide excellent pest and insect control mechanisms with little damage to the environment. These horticultural oils control target pests by smothering them, and they work effectively if they are used directly on the pest with limited residual controls. Moreover, horticultural oils are regarded as the most appropriate "organic pest control." Most of these oils are permitted under the United States National Organic Program.

The application of horticultural oils is considered as a reduced risk technique to control pests using effective and eco-friendly systems. Currently, these oils are directly applied to control mites, scale insects, as well as aphids in some of the crops. More studies should be conducted to enhance efficacy as well as reduce phytotoxicity. The uses of these horticultural oils have been extended to include other insects, like mealybugs, leafhoppers, as well as leaf rollers, more acreage, and other crops. Finally, petroleum spray oils (PSOs) can be combined with synthetic fungicides to minimize or eliminate the buildup of resistance to new fungicides with certain modes of action.

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