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Systemic Insecticides and Their Use in Ornamental Plant Systems

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ABSTRACT

Systemic insecticides are compounds that may be applied to plants as a foliar spray or to the soil/ growing medium as a drench or granules. These materials are absorbed by roots or into other tissues and then translocated to plant parts. This may then protect plants from damage associated with phloem-feeding insects such as the Hemipterans including aphids, whiteflies, mealybugs, and soft scales. Factors influencing the activity of systemic insecticides are absorption and translocation, which in turn are affected by plant species, plant age, plant growth rate, environmental conditions, soil/growing medium, and physiological variations of plants. The general advantages of systemic insecticides to ornamental plant systems (greenhouse, nursery, and interiorscape) are that plants are continuously protected for extended periods of time without needing repeat applications; once inside the plant, residues are less susceptible to ultra-violet light degradation or wash-off due to irrigation when applied to soils/growing media; no unsightly residues on plant leaves or stems when applied to the soil/growing medium; plants may be less directly harmful to natural enemies, workers, and consumers; may reduce transmission of plant pathogens; and systemic insecticides may be effective in suppressing insect pests located in areas that are not accessible with spray applications. The disadvantages of using systemic insecticides in ornamental plant systems include potential for secondary pest outbreaks; unintentional direct and indirect effects on beneficial and non-target organisms; potential leaching from potted plants; increased costs of newer systemic insecticides; and drench or granule applications to the soil/growing medium can be labor intensive. Despite the disadvantages, the use of systemic insecticides is a viable option for long-term protection of ornamental plants associated with greenhouses, nurseries, and interiorscapes for pest management.

Keywords: absorption, neonicotinoids, pest management, phloem, translocation, water-solubility, xylem

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INTRODUCTION

Systemic insecticides, according to Bennett (1949), are substances that when applied to a plant are absorbed and translocated into other plant parts through the vascular system thus rendering untreated areas insecticidal or toxic to certain insects (**Fig. 1**). The problems associated with obtaining sufficient plant coverage for control or suppression of particular insect pest populations with contact insecticides may be simplified by the use of systemic insecticides (Jeppson 1953; Reynolds 1954; Rudinsky 1959). It is possible to control or suppress many insect pest populations that spend some or all of their life cycles in inaccessible areas on plants (Ripper *et al.* 1949; Jeppson 1953) with systemic insecticides; a situation that has always presented a challenge when using contact insecticides. Also, plant parts missed during a spray application may be protected (David and Gardiner 1951). Furthermore, new

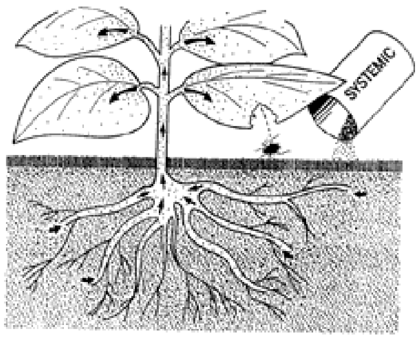

Fig. 1 Diagram showing the application of a systemic insecticide and translocation throughout the plant.

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Review

Fig. 2 Aphids feeding on milkweed (*Asclepias* spp.) plant.

Fig. 3 Sweet potato whitefly B-biotype, *Bemisia tabaci* adults and nymphs feeding on the underside of a poinsettia (*Euphorbia pulcherrima*) leaf.

Fig. 4 Longtailed mealybug, *Pseudococcus longispinus* population feeding on the frond of a fern plant.

growth that develops following application is protected from attack by phloem-feeding insect pests such as aphids (**Fig. 2**), whiteflies (**Fig. 3**), and mealybugs (**Fig. 4**), and xylem-feeding insect pests such as certain leafhopper species and the glassy-winged sharpshooter (*Homalodisca coagulata*) thus reducing the number of spray applications required (Jeppson 1953). The use of systemic insecticides prevents insect populations from building-up and reaching outbreak proportions, and thus avoids the need for frequent spray applications (Reynolds 1954).

The use of systemic insecticides has been studied in both agricultural (Ivy *et al.* 1950; Metcalf and March 1952; Ahmed *et al.* 1954; Castle *et al.* 2005; Byrne and Toscano 2006; Byrne *et al.* 2007) and forestry systems (Rudinsky 1959; Cowles 2010), and now has become a focus of research in the area of ornamental plant production. Although systemic insecticides have been used in ornamental production systems many, if not all, of the "older" systemic insecticides/acaricides are no longer commercially available for use due to voluntary cancellations by manufacturers, and/or issues pertaining to human health and environmental contamination (Risher *et al.* 1987; Moore *et al.* 1998; Hela *et al.* 2005). These systemic insecticides/acaricides include aldicarb, oxamyl, dimethoate, and disulfoton.

This paper will primarily focus on the currently commercially available systemic insecticides for use in ornamental plant systems including greenhouse, nursery, and interiorscape. This paper gleans information from the "older" literature that provided the basic concepts associated with systemic insecticides (some of which are still relevant today), and then as more sophisticated techniques became available, especially with the introduction of the neonicotinoid-based insecticides (discussed below), this made it possible to obtain a better understanding on how systemic insecticides are actually absorbed and translocated in plants and how this is affiliated with mortality of insect pests. This paper is the first to comprehensively collate the "older" and "new" literature in order to gain an appreciation on the function and application of systemic insecticides. Topics to be discussed in this paper include background information on systemic insecticides including the different types of systemic insecticides, the various modes of activity expressed, factors that influence the efficacy of systemic insecticides, the susceptibility of insect and mite pests to systemic insecticides, systemic insecticide categories and types, and the advantages and disadvantages of using systemic insecticides in ornamental plant systems.

HOW SYSTEMIC INSECTICIDES WORK

In greenhouse, nursery, and interiorscape settings, systemic insecticides may be applied to the plant as a foliar spray where the active ingredient directly penetrates plant tissues (e.g., leaves and stems), or to the soil/growing medium. When applied to the soil/growing medium, the material may be drenched as a liquid, distributed into pots in an ebb and flow or subirrigation system, or surface applied as granules. In addition, depending on the specific product, the material may also be incorporated into the soil/growing medium during the mixing process and before planting. From the soil/growing medium, the active ingredient is absorbed by plant roots (David and Gardiner 1951; Rudinsky 1959; Norris 1967), and then translocated (transported) by means of the plant vascular system (David and Gardiner 1951; Rudinsky 1959; Paine *et al*. 2011) to areas throughout the plant such as growing points where certain insect pests feed (Ahmed *et al.* 1954; Reynolds 1954). Systemic insecticides typically move within the vascular tissues, easily through the xylem (water-conducting tissues) (Bennett 1957) but also into the phloem (carbohydrate-conducting tissues), or both depending on physical properties of the active ingredient (Ahmed *et al*. 1954; Norris 1967; Trapp 2003). Once inside the plant, the active ingredient may move back-and-forth, in some cases, from the xylem to the phloem tissues or vice versa via lateral diffusion (Bennett 1957; Rudinsky 1959) although this depends on the rate of uptake and uniformity of distribution (Norris 1967). This type of movement is associated with differences in pH (xylem=5 and phloem=8) (Sur and Stork 2003).

The chemical characteristics of the systemic insecticides may have a profound effect on their movement within plant tissues (Byrne *et al.* 2010). Some systemic insecticides such as imidacloprid are not affected by pH differences and as such can move freely between the xylem and phloem due to biomembrane permeability and diffusion (Sur and Stork 2003). Furthermore, the rate of passive transport in the transpiration stream of the xylem will depend on the rate of water movement through the plant. As such, persistence in plants is influenced by the rate applied, storage within plant tissues, and metabolism and degradation of the active ingredient (Norris 1967). Factors that may influence the rate of passive transport are light intensity, ambient air temperature, relative humidity, plant physiology, soil/growing medium water availability (Reynolds 1954; Norris 1967), and soil/growing medium organic matter content (Byrne *et al*. 2010).

SYSTEMIC INSECTICIDE TYPES AND FACTORS AFFECTING ACTIVITY

Systemic insecticides can be divided into those that remain in plants in the original form and have systemic activity until broken down by the plant, and pro-insecticides, which are eventually converted in the plant into metabolites that are more toxic to insect pests than the original active ingredient (Bennett 1957; Rudinsky 1959; Casida 2010). For example, acephate has minimal or no systemic activity within plants, but is converted into the metabolite methamidaphos, a highly mobile compound with greater activity on insects such as whiteflies than acephate (Bull 1979). Imidacloprid is converted into several metabolites including olefin and 4,5-dihydroxy imidacloprid (Nauen *et al.* 1998; Jeschke *et al.* 2010). These metabolites are typically more water-soluble, and the olefin is more toxic to phloem-feeding insect pests than the original active ingredient (Nauen *et al.* 1998; Rauch and Nauen 2003; Sur and Stork 2003).

The factors associated with activity and efficacy of systemic insecticides when applied to the soil/growing medium as a drench or granules, or spray application are absorption and translocation (Jeppson 1953). Absorption refers to uptake of the active ingredient from the soil/ growing medium by the root system or by plant leaves after a foliar application (Reynolds 1954). Translocation is the movement of the active ingredient throughout the plant, primarily by means of the plant vascular system (Reynolds 1954). Both absorption and translocation, and thus the efficacy of systemic insecticides may be impacted by 1) plant species, 2) plant age, 3) plant growth rate, 4) plant growth stage (e.g., vegetative vs. flowering), 5) environmental conditions (e.g., temperature, relative humidity, and light intensity), 6) soil/ growing medium type and components, 7) soil/growing medium condition (e.g., dry vs. moist), 8) and physiological variations of plants (Ripper *et al.* 1949; Jeppson 1953; Bennett and Thomas 1954; Reynolds 1954; Rudinsky 1959; Byrne *et al.* 2010; Cloyd unpublished data).

Newly expanded younger leaves tend to absorb systemic insecticides more efficiently than mature leaves, both due to easier penetration of these tissues with foliar sprays, and as an effective sink for the active ingredient to be transported through the vascular tissues (Smith *et al.* 1950; Casida *et al.* 1952; Bennett and Thomas 1954; Bennett 1957; Rudinsky 1959). However, translocation from older to younger leaves may only occur if initial basipetal (downward) movement from older foliage is possible (Ripper *et al.* 1950; Rudinsky 1959). Although systemic insecticides are more effective in killing insects on young plants compared to mature plants in which growth is decreased (Ripper *et al.* 1949), certain systemic insecticides (dinotefuran and acephate) may also translocate rapidly through mature trees (Cowles 2010; Byrne unpublished data). Another important factor, in regards to the persistence of systemic insecticides, is detoxification, which involves metabolic breakdown and removal of the toxic active ingredient from the plant (Bennett 1957). This primarily occurs by decomposition of the active ingredient into non-toxic metabolites; however, this may vary depending on plant species (Bennett 1957).

Compounds that move readily in the xylem are more appropriate for soil/growing medium applications as long as they are not too strongly bound by soil or growing medium particles (Reynolds 1957). Placement within growing media can be an effective method to apply systemic insecticides that are bound rather tightly to organic matter. For example, when incorporated into growing media, binding of imidacloprid by organic matter can result in controlled release of the active ingredient to the plant, while simultaneously preventing leaching of the insecticide from the root zone (Cowles 2009). Applications to the soil/growing medium may result in uniform and rapid translocation of the absorbed active ingredient via the xylem, and extended effectiveness as the active ingredient is readily present at a lethal concentration for a longer period of time in the plant (Rudinsky 1959; Byrne *et al.* 2010). Reynolds (1954) noted that systemic insecticides, when absorbed by plant roots, are translocated to "all" plant parts. This may be the case with certain systemic insecticides (Cowles 2010); however, this is not true for others (Metcalf and March 1952), and what is most important is that a lethal concentration of the active ingredient may not be present in areas of the plant where insect pests are feeding.

For foliar applications of systemic insecticides, the plant surface must be sprayed thoroughly because transport from a treated to an untreated area of a plant may be inadequate for effective control or suppression of insect pests (Lickerish 1951; Cloyd 2010). However, at the local level, absorption through the cuticle is not uniform throughout the entire leaf (Bennett 1957). At the whole-plant level, translocation within the plant varies based on the type of systemic insecticide (Reynolds 1954); most systemic insecticides (e.g., organophosphates and neonicotinoids) only exhibit acropetal (upward) movement, and so foliar applications can only target pests located distally from where residues contact the plant.

FACTORS THAT INFLUENCE EFFICACY OF SYSTEMIC INSECTICIDES

Systemic insecticides applied to soil/growing medium are translocated throughout the plant and can provide activity against xylem- and phloem-feeding insects for extended periods of time because they are persistent, although this depends on the particular systemic insecticide. In addition, the active ingredient may take longer to translocate throughout the plant (Cloyd 2010). Therefore, early applications may prevent pests from reaching outbreak proportions and also prevent re-infestations from occurring (Ripper *et al.* 1949).

In contrast, foliar applied systemic insecticides will rapidly kill target insect pests; however, residual activity will be less persistent than soil/growing medium applications (Byrne *et al.* 2010; Cloyd 2010). The persistence of a systemic insecticide depends on the solubility of the material, accessibility of the active ingredient from the soil/ growing medium due to binding, and the ability of the plant to metabolize the active ingredient into a non-toxic compound. Regardless of persistence of the active ingredient in plant tissues, what is most important is that there is a concentration of active ingredient present to kill a high proportion of insect pests, thus reducing the number of individuals in the next generation (Byrne *et al.* 2010). However, the effective concentration may not be present in the plant immediately, and once having reached the effective concentration, there are factors that may determine the length of time that the active ingredient will remain at the effective concentration including dilution due to plant growth, plant metabolism, and leaf age (Leib and Jarrett 2003; Ford and Casida 2008; Byrne *et al.* 2010; Van Timmersen *et al.* 2011).

Foliar surface residue losses may be due to evaporation (dissipation by volatilization), erosion through washing by irrigation or rainfall, and photolysis (loss through degradation via light). Any loss then means that less material is available to enter the leaves (Rudinsky 1959). Moreover, leaf cuticle thickness and leaf surface (trichomes and waxiness) (Bennett and Thomas 1954), leaf age (young vs. old), leaf type (broad vs. narrow), and leaf temperature may hamper penetration through the leaf tissue. Residues may also become entrapped in the cuticular layers and not actually permeate into plant cells (Ripper *et al.* 1949; Bennett and

Thomas 1954). Finally, molecular size and polarity may influence penetration (Collander 1937). For example, highly non-polar compounds may be distributed more rapidly through the plasma membrane than polar compounds (Wedding 1953).

The effectiveness of foliar applications may also be affected by plant type as absorption by the upper and lower leaf surfaces may vary (Bennett and Thomas 1954). For example, in chrysanthemum (*Dendranthema grandiflora*), the lower leaf surface is more absorptive than the upper surface whereas coleus (*Solenostemon scutellarioides*) absorbs equally between the upper and lower leaf surface (Bennett and Thomas 1954).

Systemic insecticides must be water-soluble to some degree (Glynne-Jones and Thomas 1953; Hollingworth and Treacy 2006), which allows the dissolved active ingredient to be absorbed by plant roots when applied to soil/growing medium, and then be translocated throughout the plant (Glynne-Jones and Thomas 1953). Water solubility—expressed as grams per liter (g/L) or parts per million (ppm or mg/L)—determines how rapidly the active ingredient is absorbed by roots and translocated throughout plant parts such as leaves and stems. A highly water-soluble systemic insecticide may kill insect pests quickly but may not provide long-term or sufficient residual activity compared to a less water-soluble systemic insecticide, although higher labeled rates may result in longer persistence. A less water-soluble systemic insecticide may persistent longer, but may not be as efficacious unless the rate is adjusted to compensate for the slower mobility (Byrne *et al.* 2010; Cloyd unpublished data). Systemic insecticides that are highly water-soluble are more prone to leaching, although the solubility/leaching relationship is not universal. Leaching is influenced by watering techniques and growing medium type or composition, which is associated with binding to the active ingredient, thus reducing the leaching potential. Binding to soil/growing medium competes with absorption by plant roots (Gill and Lewis 1971). For example, growing media containing a high percentage of organic matter such as those with >30% bark and/or peat moss tend to bind to the active ingredient of certain systemic insecticides (e.g., imidacloprid and dinotefuran), which may reduce the amount of active ingredient absorbed by plant roots (Norris 1967; Gill and Lewis 1971; Pfluger and Schmuck 1991; Wakita *et al*. 2005), resulting in inadequate suppression of target insect pests. The speed of uptake and leaching may be influenced by root system development and absorption rate of water by the plant (Norris 1967).

Drench, ebb and flow, sub-irrigation, or granular applications of systemic insecticides should be performed, in general, when plants are actively growing and have an extensive, well-established root system in order to enhance the up-take of the active ingredient through the vascular plant tissues (Byrne *et al*. 2010; Cloyd 2010). Applications made during warm, sunny days will also lead to increased movement of the active ingredient through the transpiration stream. In contrast, absorption is inhibited when plants do not have well-established root systems. Additionally, conditions of high humidity and low light may lead to less or slower absorption of systemic insecticide active ingredients by plant roots (Jeppson 1953; Wedding 1953).

Systemic insecticides applied to the soil/growing medium need to be utilized preventatively in order to control or suppress populations of xylem- and phloem-feeding insect and mite pests. Any significant delay in root absorption and accumulation in tissues to insecticidal concentrations (caused by excessive binding of the active ingredient, or insufficient root activity or evapotranspiration) may lead to insect pests' successfully reproducing and causing damage before they ingest a lethal concentration. This concern is especially acute with aphids because once aphids are established and reproducing there may be no way to prevent plant damage (Devonshire *et al.* 1998; Cloyd 2010).

INSECT AND MITE PESTS SUSCEPTIBLE TO SYSTEMIC INSECTICIDES

Most systemic insecticides are translocated through the plant via the transpiration stream, and are active on xylem- and phloem-feeding insect pests with piercing-sucking mouthparts such as aphids, whiteflies, mealybugs, leafhoppers, planthoppers, and soft scales because these insect pests feed exclusively within the xylem vessel elements or phloem sieve tubes (Sur and Stork 2003; Ware and Whitacre 2004; Jeschke and Nauen 2008). As an insect feeds, it withdraws a lethal concentration of the systemic insecticide active ingredient and is subsequently killed. For example, the piercing-sucking mouthpart or proboscis of an aphid is inserted into plant tissues, reaching the conductive cells or sieve tubes through which water and carbohydrates are transported. The aphid then imbibes the active ingredient of the systemic insecticide as it withdraws plant fluids (Cloyd 2010).

Although mites do not feed within the xylem or phloem, they may still be affected by certain systemic pesticides (miticides). Twospotted spider mite (*Tetranychus urticae*), for example, feeds within leaf cells, damaging the spongy mesophyll, palisade parenchyma, and chloroplasts with their stylet-like mouthparts. Destruction of chloroplasts reduces chlorophyll content and the plants' ability to photosynthesize (Lal and Mukharji 1979; Sances *et al.* 1979; Tomczyk and van de Vrie 1982; van der Geest 1985). Spider mites can be targeted with systemics that are able to reach the tissues on which they feed at toxic concentrations. Historically, some systemic organophosphate and carbamate products were highly effective acaricides (e.g., oxydemeton-methyl, aldicarb, and oxamyl) until populations of mites developed resistance to these chemical classes (Smissaert 1964; Voss and Matsumura 1964; Helle and van de Vrie 1974; Helle 1984; Stumpf *et al.* 2001). Neonicotinoids have minimal activity against phytophagous mites, but mites can be targeted with spirotetramat. This active ingredient, which moves both up (xylem) and down (phloem) the plant (Schnorbach *et al.* 2008), has systemic activity against the twospotted spider mite when applied to the soil/growing medium or as a foliar spray (Cloyd, unpublished data).

Western flower thrips (*Frankliniella occidentalis*) also has piercing-sucking mouthparts; however, they do not feed exclusively in the phloem sieve tubes. They instead feed within the mesophyll and epidermal cells of leaf tissues (Mound 1971; Hunter *et al.* 1992; van de Wetering *et al.* 1996). As such, systemic insecticides, in general, when applied to the soil/growing medium are less effective against the western flower thrips (Lindquist 1994; Cloyd and Sadof 1998). However, it has been reported that thrips feeding on plant leaves are suppressed by thiamethoxam when applied to the soil/growing medium (Senn *et al.* 1998). Systemic insecticides typically do not translocate or accumulate in flower parts (petals and sepals) where western flower thrips adults normally feed (Cresswell *et al.* 1994); however, this is contingent on the systemic insecticide and associated water solubility (Cloyd and Sadof 1998) as systemic insecticides with greater water solubility may accumulate in flower parts (Hale and Shorey 1965).

There is some evidence that at least one species of a leaf-feeding thrips imbibes a toxic concentration of systemic insecticides (Bethke, unpublished data), which is uncommon among thrips. Both trunk and drench applications of dinotefuran were effective in controlling *Klambothrips myopori* on *Myoporum laetum*. This thrips species creates a gall-like structure where it is sedentary and survives through several generations. Within this gall, it is protected from insecticide exposure, whereas western flower thrips are more mobile, thus increasing their exposure to frequent insecticide applications resulting in a greater likelihood for resistance developing. As such, *K. myopori* may be more susceptible to systemic insecticides.

Leaf chewing insects tend to be less susceptible to systemic insecticides than Hemipterans, but efficacy is highly

Table 1 Pest control materials (insecticides and miticides) registered for use in commercial greenhouses, nurseries, and/or interiorscapes that may have systemic activity.

Common name (active ingredient)	Trade name[1]	Application type	Chemical class	Mode of action
Acephate	Orthene/Precise	Foliar, Drench, Granule	Organophosphate	Acetylcholine esterase inhibitor
Acetamiprid	TriStar	Foliar	Neonicotinoid	Nicotinic acetylcholine receptor disruptor
Azadirachtin	Azatin/Ornazin[2]	Drench	Botanical	Ecdysone antagonist
Clothianidin	Arena	Foliar, Drench	Neonicotinoid	Nicotinic acetylcholine receptor disruptor
Dinotefuran	Safari	Foliar, Drench, Granule	Neonicotinoid	Nicotinic acetylcholine receptor disruptor
Flonicamid	Aria	Foliar	Trifluoromethylnicotinamide	Selective feeding blocker/block action of potassium channels
Imidacloprid	Marathon/Merit	Foliar, Drench, Granule	Neonicotinoid	Nicotinic acetylcholine receptor disruptor
Pymetrozine	Endeavor	Foliar	Pyridine azomethines	Selective feeding blocker
Spirotetramat	Kontos	Foliar, Drench	Tetramic acid	Lipid biosynthesis inhibitor
Thiamethoxam	Flagship/Meridian	Foliar, Drench	Neonicotinoid	Nicotinic acetylcholine receptor disruptor

[1]Trade names are those found marketed in the USA.
[2]Additional products containing azadirachtin as the active ingredient include Molt-X and Azatrol.

variable. In general, leaf-chewing beetles and sawfly defoliators are sensitive to the neonicotinoids (Jeschke and Nauen 2008), whereas weevils (Reding and Ranger 2011) and externally feeding caterpillars are less affected (Hollingworth and Treacy 2006). Neonicotinoid insecticides may be used to manage Lepidopteran and Dipteran leafminers (Jeschke *et al*. 2010; Hahn *et al.* 2011) mainly because manufacturers have increased the label rates resulting in enhanced activity against leafminers.

SYSTEMIC INSECTICIDE CATEGORIES AND TYPES

Although there are additional types of systemic insecticides used in other crops, the commercially available systemic insecticides in the USA that may be used in greenhouses, nurseries, and/or interiorscapes are associated with chemical classes having five different modes of action (**Table 1**).

The tetramic acid group, represented by spirotetramat (Kontos[TM]; OHP, Inc., Mainland, PA), has been previously described for its activity against mites, but also exhibits some activity against sucking insects. This product and others in its class adversely affect lipid biosynthesis in insects and mites (Hollingworth and Treacy 2006; Yu 2008). In addition, spirotetramat is unique among the systemic products currently available due to its ability to systemically move upwards and/or downwards in plants (Schnorbach *et al.* 2008). The organophosphate acephate, following conversion to methamidaphos within the plant (Bull 1979), translocates upwards in plants, where it then acts by blocking acetylcholinesterase in the insects' central nervous system (Nation 2001).

The neonicotinoid systemic insecticides include acetamiprid, clothianidin, dinotefuran, imidacloprid, and thiamethoxam. All neonicotinoid insecticides have a similar chemical structure and mode of action, which is disruption of nerve signals by binding to the post-synaptic nicotinergic acetylcholine receptors. However, binding affinity varies among these compounds for the nicotinergic acetylcholine receptors, which partly accounts for differences in their insecticidal activity (Nauen *et al.* 2003). They are primarily used against xylem- and phloem-feeding insects such as aphids, whiteflies, mealybugs, leafhoppers, soft scales, and certain leaf-chewing beetles, sawflies, and leafminers; have minimal (if any) direct affect on mites; may be applied, depending on the particular formulation, as a foliar spray, trunk spray, and drench or as granules to the soil/growing medium; have both upward systemic and translaminar (material penetrates leaf tissue and forms a reservoir of active ingredient within the leaf providing residual activity even after leaf residues dissipate) properties; and the active ingredient may be evenly distributed within the entire leaf lamina (Elbert and Overbeck 1990; Abbink 1991; Mizell and Sconyers 1992; Tomizawa and Yamamoto 1993; Maienfisch *et al.* 2001; Tomizawa and Casida 2003; Kaane *et al.* 2005; Hollingworth and Treacy 2006; Jeschke *et al.* 2010). Basal trunk spray or stem applications of these insecticides perform in a manner similar to a soil/growing medium treatment (Cowles 2010).

The neonicotinoid systemic insecticides, as a chemical class, have a similar molecular structure; however, they vary in characteristics that influence movement into plants, including water solubility and two physical estimated properties: p*K*a and log P_{oct} (Briggs *et al.* 1982; Briggs *et al.* 1987; Sur and Stork 2003; Jeschke and Nauen 2008; Cloyd and Bethke 2011). The p*K*a is the acid dissociation constant and indicates the strength of an acid. The larger the p*K*a value the weaker the acid, which influences the ability of the active ingredient to cross membranes. Weak acids, compounds with p*K*a values between 5.0 and 5.5, are highly lipophilic and can cross membranes easily (Sur and Stock 2003). The log P_{oct} refers to the octanol-water partition coefficient and is a measure of lipophilicity, which is the ability of compounds to dissolve in fats, oils, and lipids (Hollingworth and Treacy 2006). Compounds that are lipophilic (log $P_{oct}>4$) are generally not systemic whereas compounds that are considered to be either moderate or intermediate in lipophilicity have a log P_{oct} between 0.5 and 3.5. These compounds move through the xylem to plant shoots. Root absorption is greater when compounds are more lipophilic (Inoue *et al.* 1998; van Leeuwen *et al.* 2005).

The selective feeding blockers, pymetrozine and flonicamid, inhibit the feeding activity of piercing-sucking insects after initial insertion of stylets into plant tissues. Pymetrozine (Endeavor®; Syngenta Crop Protection, Inc., Greensboro, NC), belonging to the pyridine azomethine class, has a unique insecticidal mode of action, probably involving the neurotransmitter serotonin (Kaufmann *et al.* 2004). The trifluoromethylnicotinamide class insecticide, flonicamid (Aria®; FMC Corp., Philadelphia, PA), appears to affect the axonal voltage gated potassium channels (Hollingworth and Treacy 2006; Hayashi *et al.* 2008). These systemic insecticides affect both aphids and whiteflies by inhibiting or disrupting feeding via preventing stylet penetration and interfering with neural regulation of fluid intake in the mouthparts thus resulting in starvation (Flückiger *et al.* 1992; Kayser *et al.* 1994; Harrewijn and Kayser 1997; Kaufmann *et al.* 2004; Hollingsworth and Treacy 2006; Morita *et al.* 2007).

Azadirachtin, a neem-based botanical, is distributed throughout the plants vascular system (Gill and Lewis 1971) when applied to the soil/growing medium and may also have systemic activity against certain insects (Gill and Lewis 1971; Arpaia and van Loon 1993; Thoeming *et al.* 2003). However, this varies depending on the plant species (Larew 1989). The labels of currently available products indicate that azadirachtin has systemic activity against a wide-range of insect pests although initial studies have demonstrated that azadirachtin is not effective against the citrus mealybug, *Planococcus citri* when applied to growing media (Cloyd, unpublished data). Organic matter or organic particles in growing medium bind to azadirachtin,

Table 2 Advantages and disadvantages of using systemic insecticides as either foliar, or drench or granule applications in ornamental plant systems.

Advantages	Disadvantages
Extended persistence[1]	Potential for insecticide resistance due to extended persistence[1]
Less susceptible to photo-degradation[1]	Lead to secondary pest outbreaks
Minimal unsightly residues[1]	Leaching from potted plants[1]
Less susceptible to "wash-off" by irrigation or rainfall[1]	Newer insecticide products are expensive
Less directly harmful to beneficial insects and mites[1]	Unintentional direct and/or direct effects on non-target organisms
Greater worker and consumer safety[1]	Labor intensive when applied as a drench or granules to the growing medium[1]
Higher probability of affecting inaccessible insect pests	
Less potential for phytotoxicity, especially flowers[1]	
Reduce transmission of plant pathogens by insect vectors	
Multi-generational regulation of insect pests[1]	
Reduced contact with residues and lower mammalian toxicity[1]	

[1]For soil/growing medium applications only.

thus inhibiting translocation of the active ingredient and reducing efficacy (Meisner *et al.* 1986). There is minimal systemic activity when azadirachtin is applied to foliage (Larew 1989). Azadirachtin has a multitude of biochemical targets and may primarily be an insect growth regulator, repellent or anti-feedant rather than an acute toxicant (Gill and Lewis 1971).

ADVANTAGES AND DISADVANTAGES OF SYSTEMIC INSECTICIDES

Producers associated with ornamental plant systems including greenhouses, nurseries, and interiorscapes deal with an array of insect pests that must be suppressed in order to maintain the aesthetic quality of plants (Bethke and Cloyd 2010). However, in some cases, foliar applications may provide inadequate suppression due to poor coverage or resistance, or they may be prohibited in interiorscape settings due to public traffic. Consequently, the use of systemic insecticides in ornamental plant systems may provide a variety of benefits (**Table 2**).

Plants treated with systemic insecticides may be continuously protected (especially new growth) for extended periods of time (Reynolds 1954; Byrne *et al.* 2010); potentially throughout the growing season. As such, repeat applications are not required thus reducing costs associated with foliar applications, although this may depend on the plant type and cultivar (Jeppson 1953; Rudinsky 1959; Byrne *et al.* 2010). In addition, systemic insecticides are more likely to affect inaccessible or difficult to contact insect pests such as mealybugs that are typically located in tightly-enclosed areas on plants (Ripper *et al.* 1949; Jeppson 1953). An indirect advantage of systemic insecticides, in this case the neonicotinoids imidacloprid and clothianidin, is their ability (or their metabolites) to activate salicylate-associated plant defenses against plant pathogens, which can help protect plants from disease and abiotic stressors (Thielert 2006; Ford *et al.* 2010).

When applied to the soil/growing medium, systemic insecticides are less susceptible to ultra-violet light degradation and are less likely to lose effectiveness due to rain or overhead irrigation. In addition, there are no unsightly residues on plant leaves or stems, which make plants less harmful to workers, consumers, and natural enemies compared to plants having received spray applications of contact insecticides (Cloyd 2010). Because residues are internal to the plant, systemic insecticides, in general, are less harmful to natural enemies (Jeppson 1953; Rudinsky 1959; Bellows *et al.* 1988; Mizell and Sconyers 1992; Stapel *et al.* 2000). However, based on a review of the scientific literature by Cloyd and Bethke (2011), this is not necessarily the case with neonicotinoids, as under certain circumstances systemic insecticides may be both directly and indirectly harmful to natural enemies.

Since spray applications of some insecticides have been shown to affect the physiological processes of plants such as photosynthesis (Ferree 1979) and production of secondary metabolites (Parrott *et al.* 1983) an additional benefit of applying systemic insecticides to the soil/growing medium is that there is less potential for phytotoxicity, which includes damage to flowers and bracts, as long as the proper rates are applied (Norris 1967).

There is evidence now suggesting that systemic insecticides, which are quick-acting, may reduce insect vector transmission of plant pathogens. For example, virus transmission in potatoes (potato virus Y), *Xylella fastidiosa* transmission by glassy-winged sharpshooters, and citrus greening disease are reduced due to effective (lethal) concentrations of the neonicotinoids or pymetrozine present in plant tissues (Bethke *et al.* 2000; Gatineau *et al.* 2010; Margaritopoulos *et al.* 2010). In addition, there may be potential in reducing disease transmission of podyviruses by aphids, tospoviruses by thrips and tobamoviruses by whiteflies in ornamental plant systems (Stansly *et al.* 1998; Mowry 2005; Castle *et al.* 2009; Coutts *et al.* 2010; Cherry and Mila 2011). However, it should be noted that inhibition of disease transmission depends on the persistence of the active ingredient within the plant tissues (Margaritopoulos *et al.* 2010). Another benefit of systemic insecticides involves limiting honeydew production, thus indirectly eliminating the role of ants in 'farming' hemipterans, which has long been recognized as a means of managing phloem-feeding insect pests such as aphids (Nagro 2011).

Despite the many benefits of systemic insecticides as presented above there are disadvantages associated with the use of systemic insecticides. For example, extended exposure of an insect population to persistent systemic insecticide residues in plant tissues is equivalent to continuous use of the same mode of action, which enhances the possibility of resistance developing (McCord *et al.* 2002; Margaritopoulos *et al.* 2007; Yu 2008). An important consideration when using 'newer' systemic insecticides is that they have been developed under more stringent regulations, which has resulted in greater development costs. As such, they are substantially more expensive than the traditional broad-spectrum insecticides. In addition, drench applications to soil/growing medium is labor intensive, hence increasing the cost of using systemic insecticides. However, the benefits associated with this type of application far outweigh the initial economic costs, and less expensive incorporation methods are available such as pre-plant incorporation while mixing growing media and the use of ebb and flood or subirrigation systems (van Iersel *et al*. 2000, 2001).

Another potential disadvantage of using systemic insecticides in potted plant production is that the active ingredient can leach from pots during irrigation or excessive rainfall. This may be a concern as regulators are becoming increasingly aware of selected toxicants and their movement in nursery production systems. This may also result in direct and/or indirect impact on non-target organisms including earthworms (Capowiez *et al.* 2005; Capowiez and Bérard 2006; Faheem and Farhanullah Khan 2010). Finally, there is evidence that the use of certain neonicotinoid systemic insecticides may cause secondary pest outbreaks of twospotted spider mite (*Tetranychus urticae*) populations (James and Price 2002). A summary of the advantages and disadvantages of using systemic insecticides is presented in **Table 2**.

SUMMARY

Ornamental plant systems including greenhouses, nurseries, and interiorscapes are primarily valued for aesthetic quality. Many insect pests of ornamental plant systems are difficult to manage with foliar applications of contact insecticides. The use of systemic insecticides, which are mobile in the plant vascular tissues, is a viable management option with many advantages. Systemic insecticides are generally most effective against hemipteran insects that feed on the vascular tissues of plants including aphids, whiteflies, leafhoppers, and mealybugs. However, some systemic insecticides are active on mites, leaf-chewing beetles, leafminers, and thrips. In all cases, efficacy depends on the intrinsic toxicity of the insecticide to the pest, application rates and method of application, and pest feeding behavior. Systemic insecticides are associated with different chemical classes (organophosphate, neonicotionoids, pyridine azomethine, trifluoromethyl-nicotinamide, tetramic acid, and botanical) each with a distinct mode of action. Within each category, there are differences in physical characteristics such as water solubility and binding coefficients that may impact each systemic insecticide's mobility and persistence. Systemic insecticides that are highly water soluble are rapidly taken up by roots and translocated throughout plants whereas those that are bound by soil/growing medium take longer to become available but may be more persistent in plant tissues. Transport of systemic insecticides within plants is influenced by a variety of factors including plant species, plant age and growth rate, environmental conditions (e.g., temperature, relative humidity, and light intensity), soil/growing medium type and components, and physiological variations of plants. When used appropriately, systemic insecticides may provide a variety of advantages including long-term protection from certain insect pests without having to rely on routine spray applications; thus reducing labor costs. They are less susceptible to ultraviolet light degradation once inside plants, and present less exposure to workers, consumers, and natural enemies. All these factors may result in a reduction in costs associated with dealing with insect (and mite) pests. However, it is important to emphasize proper insecticide stewardship in order to reduce the risk to natural enemies and to avoid resistance development in pest populations to these valuable insecticides.

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