Spraying May be Effective, But It Surely Is Not Efficient

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Agrochemicals represent a major input cost in modern apple production systems and are applied with axial fan air-assist sprayers. Around full bloom, when plant growth regulators are applied for crop load management, enhancement of fruit shape, or russet reduction, the proportion of spray intercepted by the canopy is typically only 40 percent. Even if spray droplets reach the intended target, penetration of many agrochemicals and foliar nutrients into the plant is low due to the chemical properties of the cuticle. Penetration of the active ingredient in many agrochemicals and nutrient sprays occurs through tiny pores in the cuticle during the droplet drying phase. Minimal additional movement into the plant occurs once the droplet has dried, leaving a dried residue of the active ingredient on the plant surface. Rainfall or dew can initiate additional uptake due to re-wetting of the dried residue, however significant losses can also occur due to wash-off after relatively minor rainfall events. Spray additives such as surfactants, penetrants, or humectants may help (or hinder) uptake by altering droplet spread (contact area), droplet drying time, and how quickly the active ingredient penetrates the cuticle. Estimates of the proportion of active ingredient that actually penetrates the target may be as low as 6 percent at bloom (assuming 40 percent of the total spray volume is intercepted by the canopy, and 15 percent of the active ingredient in a droplet that lands

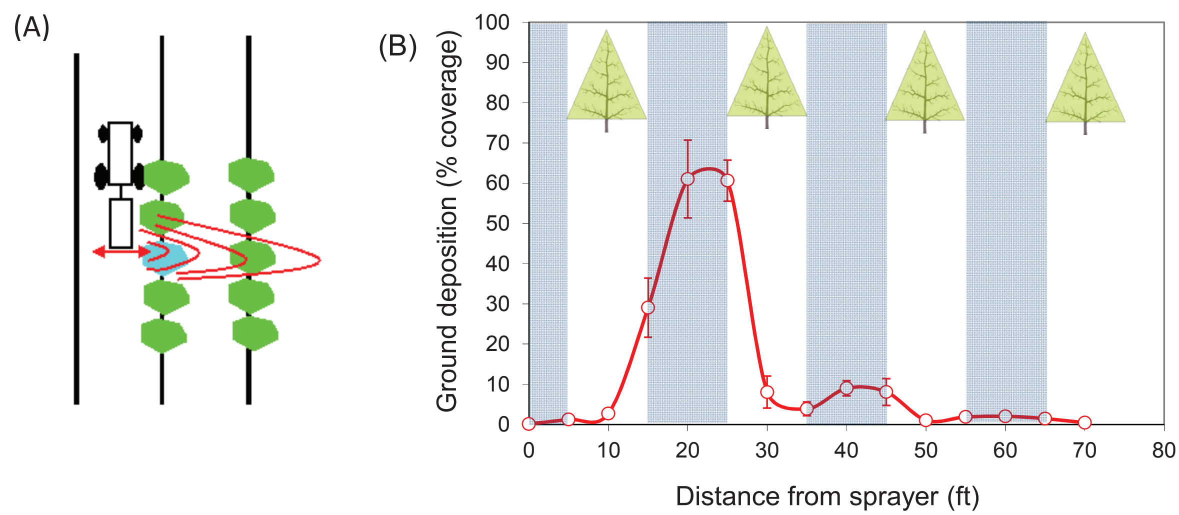

Figure 1. Schematic depicting movement of air carrier and spray droplets from an air assist sprayer in an apple orchard (A). Deposition of spray droplets from an axial fan sprayer onto the ground in a mature 'Pink Lady'/M.7 apple orchard planted in rows 20 feet apart (B). The trees in (B) represent the position of the orchard rows. Shaded columns in (B) represent the row-middles (grass alleyways). Ground deposition was measured as percent coverage on water sensitive cards placed on the ground at 5 feet intervals along a transect perpendicular to the rows. (pressure, 100 psi; ground speed, 2 mph; water rate, 168 gal/acre).

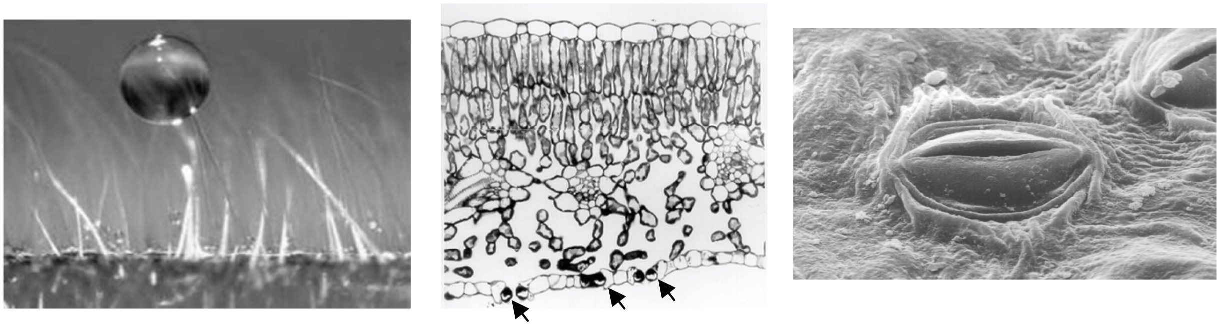

Figure 2. Tiny hairs called trichomes can impede movement of the spray droplet through the cuticle, reducing uptake of dissolved agrochemicals (figure on left: source Xu et al., 2010). Stomata on the underside of the leaf are tiny pores (arrows in middle photograph) that open and close to regulate the loss of water vapor (leaf temperature), carbon dioxide and oxygen. Even when fully open (photograph on right), conventional surfactants permit less than five percent of the total spray dose to infiltrate through the stomata.

on the target will penetrate the cuticle prior to drying), increasing to 12 percent at full canopy development (80 percent interception, 15 percent penetration). How efficient is that?

Interception from Air Blast Sprayers is Low

Axial fan air-assist sprayers are the most common delivery system for agrochemicals (fungicides, insecticides and plant growth regulators) in modern apple orchards. While there is no disputing their effectiveness, air blast sprayers can be a very inefficient system for delivering agrochemicals. Interception of chemical sprays by the canopy of apple trees changes throughout the season; it is lowest in the dormant stage, and increases as the canopy develops. Data from the NYSEAS in Geneva, NY indicate that typical losses from an orchard sprayer include evaporation (4-6 percent), drift (10-15 percent), and spray landing in the row middles (30-50 percent), so that only 29-56 percent of the total spray volume may reach the intended target. In our own research we estimated spray interception values of only 26 percent in a mature ‘Pink Lady’/M.7 orchard just after bloom [1]. Interception values for high density apple orchards in the Netherlands are slightly better, ranging from 20 percent in dormant trees to 70-80 percent at full canopy development [2]. Spray interception in high density orchards was around 40 percent at full bloom, when application of chemical thinners and other growth regulators are frequently made.

One of the shortfalls when considering interception alone as a measure of sprayer efficiency is that it does not account for differences in spray coverage in different parts of the canopy. For example, spray interception may be higher in medium density orchards where the trees are larger and have a dense canopy compared to high density orchards on dwarfing rootstocks. However, in a dense canopy much of the spray is intercepted by the outer leaf layers, and spray coverage on foliage and fruit in the inner zones of the canopy may be reduced to the point where the dose of active ingredient is below that needed to effectively control the pest, pathogen, or plant process of interest. Air provides the carrier for spray droplets, and good dispersal of droplets throughout the canopy is dependent on complete displacement of the air space within the canopy with spray droplets. Complete air displacement is easier to achieve in narrow, low-density canopies typical of high density tall spindle or fruiting wall type orchard systems compared to the wide, dense canopies typically found in medium density orchards.

Alternate-row spraying provides several advantages over spraying every row. While the time between each successive application must be shortened to ensure that adequate coverage of the active ingredient is maintained over time, each spray event is itself much quicker. This helps greatly if you have a lot of ground to cover, or if unfavorable weather limits the amount of time available for spraying. However, not all orchards are suitable for alternate row spraying. Maintenance of an effective concentration of active ingredient across the canopies of all rows is dependent on sufficient movement of pesticide-laden air through the canopy of the row immediately opposite the sprayer, across the adjacent row middle, and into the canopy of trees in the adjacent row. This is likely to occur throughout the entire season in narrow, low density canopies with narrow between-row spacing. In medium density orchards with wide, dense canopies and wide between-row spacing however, alternate-row spraying may only provide adequate spray deposition throughout the canopy until second or third cover. There may be other disadvantages associated with alternate-row spraying. There may be a reduction in spray interception associated with the cost of moving pesticide laden air to the second row from the sprayer – increased ground deposition of spray in the row middles. Furthermore, because the airspeed decreases so dramatically with distance from the sprayer, there will be minimal penetration of spray droplets into the canopy of the second row.

After Interception and Deposition, the Next Obstacle is Getting the Active Ingredient into the Plant

The plant surface is covered by a specialized layer of waxes and cutin/cutan called the cuticle. This forms a barrier between the plant and its environment that protects the plant from desiccation and other environmental stresses. However, the cuticle also forms a barrier to movement of water and most agrochemicals (and foliar nutrients) into the plant. The thickness of the cuticle of an apple increases greatly during the season from around 2 micrometers at bloom to around 15 micrometers at harvest. Movement of water in either direction across this barrier is limited due to the chemical properties of the cuticle.

The underside of apple leaves are covered in small pores, called stomata, through which gases (CO_2/O_2) and water vapor can move. The plant can open and close these pores to regulate water loss and temperature. The density of stomata on the underside of the leaves is high, ranging from 300-400 per square millimeter. It is logical to expect that movement of foliar sprays into the leaves might occur through the stomata. However, because of the small diameter of the stomatal pores (only 2-3 micrometers when open) and the high surface tension of water, spray droplets do not normally penetrate the leaf through stomata. The surface tension of pure water is 72 mN/m, and significant infiltration of liquids through stomata will not occur until the surface tension is lowered to 25 mN/m or less [3]. Conventional surfactants reduce surface tension, but few lower it enough to promote significant stomatal infiltration. With conventional surfactants, stomatal infiltration only accounts for a few percent of the total dose on the leaf [4]. This is probably a good thing, because the last thing you want is to carry an active ingredient like captan into the leaf tissues. Captan residues on the leaf provide protection against fungal pathogens. Captan residues in the leaf on the other hand may cause significant phytotoxicity.

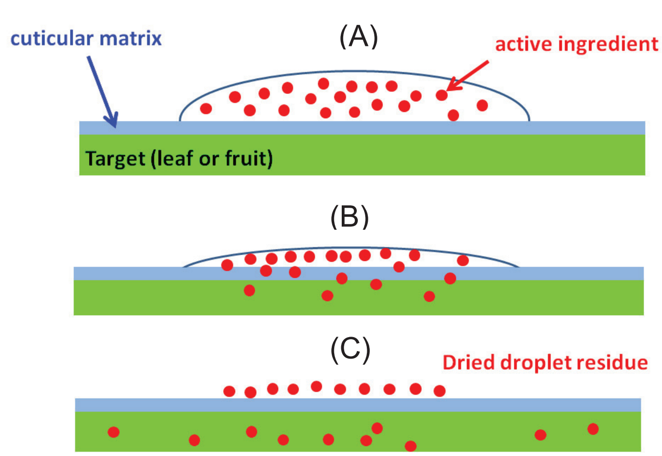

Figure 3. Schematic depicting uptake of active ingredient from a drying spray droplet on the plant surface. Penetration of many active ingredients and nutrients through the plant cuticle is rapid during the drying phase of the droplet, as represented in (A) and (B). Residue on the cuticle after the droplet dries (C). The residue does not penetrate, or penetrates very slowly, unless re-wetting occurs. However, residues may be washed off the plant surface, even after minor rainfall events.

The flowers and young apple fruit are covered by small hairs called trichomes. Trichomes also cover the lower side of the leaves during the entire season. Trichomes act as a barrier to spray droplets, limiting direct contact between the droplet and the cuticle when the surface tension of the liquid is high. Agricultural surfactants reduce the surface tension so that movement of spray droplets to the fruit or leaf surface is impeded by trichomes to a lesser extent.

How Do Agrochemicals Get Into the Plant?

If the cuticle is a barrier to movement of many agricultural chemicals and nutrients dissolved in water droplets into the plant, and infiltration through open stomata is limited, then how do active ingredients get into the plant? Experimental evidence suggests the existence of tiny, water-filled pores in the cuticle with a diameter one-thousand times less than the diameter of open stomata, through which nutrients and the active ingredients in many agrochemical sprays can enter the plant [5]. Recent studies into the movement of ReTain through fruit cuticles [6] indicate that most of the uptake occurs during the droplet drying phase; penetration of ReTain was largely halted once the spray droplet dried, leaving a residue on the cuticle surface which could act as a reservoir for additional uptake upon re-wetting. Only 4 percent of the ReTain in a 10 microliter droplet penetrated the cuticle during the first hour after application, while the droplet was drying. By 120 hours after application of the droplet, the amount of ReTain that penetrated the cuticle increased to only 12.5 percent.

The Wash-off Problem

Rainfall events soon after spraying can greatly reduce the amount of active ingredient present on or in the plant by inducing wash-off. Losses of mancozeb after just 5 mm or 0.2 inches of light (0.5 mm per hour) or torrential (48 mm or 2 inches per hour) rain resulted in losses of 50 percent and 90 percent, respectively [7]. Under dry conditions, the daily loss of captan from apple leaves was around 1 percent, compared to a 50 percent loss after as little as 1 mm of rain following application [8]. Losses of unformulated calcium chloride salt from apple leaves after 1 hour of heavy rainfall (5 mm or 0.2 inches per hour) was greater than 70 percent [9].

Can Spray Adjuvants Help?

Spray adjuvants include surfactants, penetrants and humectants. An excellent review of the effects of adjuvants on activity of plant growth regulators was provided by Bukovac [10]. Surfactants reduce the surface tension of the spray solution, increasing droplet spread on the target, thereby increasing the contact area between the dissolved agrochemical(s) and the pores through which the active ingredient can penetrate the cuticle. Penetrants are specially formulated to increase movement of agrochemicals and nutrients through the waxy plant cuticle. Humectants slow the rate of droplet drying, and can increase penetration by maintaining the active ingredient in solution for longer periods to facilitate increased movement through the pores in the cuticle. Addition of humectants to foliar calcium sprays was found to increase fruit calcium levels and reduce bitter pit of apples in a dry climate, where drying of spray droplets is typically rapid [11]. We tried the same approach in 2013 but found that addition of a humectant (Hum-AC 820, Drexel Chemical Company) to foliar calcium sprays did not affect the incidence of bitter pit at harvest or during storage. However, 2013 was an unusually wet year in the southeast, where we accumulated the average annual rainfall (60 inches) by June 30. The absence of any beneficial effect of a humectant might be due to the excessive rainfall simply washing calcium deposits off the fruit before they could be absorbed. Alternatively, the advantage of humectants might be minimal in humid regions where drying of droplets is much slower compared to arid climates. However, we did find that addition of a penetrant/acidifier (Vader, Loveland Industries) to postharvest calcium drenches resulted in a significant reduction in bitter pit of 'Golden Delicious' during storage compared to drenching without the penetrant. Following on from this research, we are interested in evaluating the effect of this penetrant/acidifier on the efficacy of foliar calcium sprays in future work.

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