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Integrated Weed Management Part V & Fruit Flavor and Color Science

Herbicides and Integrated Weed Management

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INTRODUCTION

It is no surprise that herbicides are heavily relied upon for controlling weeds in conventional systems; and in some respect, that dependence on herbicides discourages producers from embracing the integrated weed management (IWM) concept. Namely, herbicides may prompt producers to adopt a weed control as opposed to weed management approach. Weed control refers to actions used to achieve the immediate elimination of an existing weed population, usually via herbicides for conventional producers. Howbeit, weed management goes beyond trying to control existing problems as similar attention is directed at reducing weed invasion, emergence and reproduction. Thus, while weed control reacts to problems after they occur, weed management emphasizes understanding causes of weed problems with the goal of preventing weeds from becoming problematic in the first place. Further, herbicide applications are often considered the most environmentally unfriendly weed management tool. Still, if responsibly used, herbicides can contribute equitably to a weed management program and should be in every weed management toolbox. Further, herbicide sprays do not have to always blanket an entire field. Herbicides can be sprayed in bands within or between crop rows or spot sprayed to individual weeds. Precision farming technology has advanced in recent years, and several units are being developed that can automatically sense and spot treat individual weeds. In the foreseeable future, herbicide use will continue to be the primary tactic in weed management. However, an IWM approach creates an opportunity to reduce herbicide dependency, integrate it with other management tactics and in some situations, just forgo the use of herbicides. This is the fifth article of a series on IWM. Earlier articles can be access from the March and April Special Editions of Vegetable and Fruit Headline newsletter.

Herbicide resistance and IWM

One fear of herbicide dependency is the creation of herbicide resistant weed populations. An overreliance on herbicides coupled with a poor IWM plan creates conditions conducive for the development of herbicide resistant weeds. A working knowledge of proper herbicide use requires an understanding of terms frequently used in the discipline. Herbicide tolerance and herbicide resistance are terms that are often used interchangeably when defining a weed's ability to survive what should be a lethal dose of herbicide. Herbicide resistance describes the phenomenon of when a weed species was once controlled with a particular type of herbicide, but over time that chemical stops being effective at killing that weed species. This happens when a given population of weeds contains some individuals that possess unique genetics that allow them to survive that herbicide dose. These surviving weeds then reproduce and pass on their genetics to the next generation. If that same herbicide continues to be used on that population, the eventual result is a population dominated by weeds that can survive being sprayed with that type of herbicide. On the other hand, herbicide tolerance is the inherent ability of a weed to survive and reproduce following treatment with a particular herbicide. In this case, there was no natural selection in the weed population, the active ingredient in the herbicide was simply ineffective on that weed species. This may be observed when treating broadleaf weeds with an ACCase inhibiting class of herbicides. This group of herbicides is used primarily on grass species, and naturally, broadleaf plants would be tolerant to this group of herbicides. It is important to distinguish between herbicide resistance and tolerance, if one is to fully understand the different ways weeds survive herbicide treatment. This understanding assists users in choosing the right herbicides for an existing weed problem.

Resistance development is partially dependent upon weed species, efficacy of herbicide being used and the frequency of herbicide applications. Knowledgeable herbicide use can be a great asset in an IWM approach. An example of a situation to avoid is what occurred after the introduction of glyphosate-resistant (Roundup Ready) crops. Many saw this as an opportunity to have glyphosate as the only tool in their weed management portfolio. This eventually led to the rapid development of glyphosate-resistant weeds. Currently there are 512 reported cases of herbicide resistant weeds globally, across 70 different countries. Likewise, there are weed biotypes that are resistant to 167 different herbicides. The sole reliance on herbicides especially a single product to manage weeds is a risky practice that causes serious long-term consequences. To reduce the risk of resistance the following guidelines should be considered: 1) use multiple management practices as part of an IWM plan, and 2) avoid using herbicides with the same mode of action (MOA) in fallow years and in succeeding crops. Herbicide diversification is the key to preventing resistance, since using one system will create resistant weeds.

Herbicide modes of action

To effectively combat the evolution of herbicide resistant weeds, an effective herbicide program should employ multiple MOAs. Further, the selection for herbicide resistant individuals in a population can be exacerbated when there is an over dependency on a single herbicide MOA. The continuous use of the same product or MOA can cause a weed community shift in a field to more dominant and difficult to control weed species. This can occur when new or specific weed species take over a field as the population of others diminish. So, what is herbicide MOA? Simply put, this is the method by which a herbicide controls susceptible plants on a tissue or cellular level. MOA is not to be confused with site of action even though these two terms are often used interchangeably. The site of action explains the specific location within the plant where the active ingredient of the herbicide impacts the plant. However, MOA is the term most commonly used to explain how the herbicide kills the target weed. The proper knowledge of herbicide MOA is an important first step in deciding what herbicide to use for managing weeds. As eluded to earlier, the overuse of one MOA results in a heavy selection pressure on weeds, leading to the evolution of resistant weeds. This can be remedied by using multiple MOAs through tank-mixing herbicides with different MOAs or by rotation of herbicide MOAs in sequential sprays. Research has shown that tank-mixing is more effective than herbicide rotation, with the latter simply delaying the onset of resistant weeds by some years. These are good strategies to put into practice but sadly, they may only delay the evolution of herbicide resistance in weeds. Some weeds have developed resistance to multiple herbicide MOAs and have been given the moniker of "super-weeds". This demonstrates the great plasticity of plants and indicates the importance of adopting an IWM approach. It has been almost 30 years since the last herbicide MOA was introduced to the market. The rapid evolution of herbicide resistance has surpassed MOA discovery, placing an importance on preserving the efficacy of our current herbicide portfolio. This offers the best solution for effectively tackling weeds which are constantly adapting to herbicides.

For easy classification, herbicides are characterized into groups based on how they affect weeds physiologically. For example, 2,4-D is a Group 4 herbicide and all herbicides in this group are growth regulators. Classification of herbicides into groups (**Table 1**) allows for a quick reference of their MOA, making it easier to rotate or mix herbicides with different MOAs. This takes out the guess work when determining an appropriate herbicide program as applying a different herbicide with the same MOA will produce a similar response in a weed. For example, ALS resistance will still be encouraged if you rotate chlorimuron (Classic) with halosulfuron (Permit) regardless of them having different tradenames because both are Group 2 herbicides. Information regarding the group classification of a herbicide is usually included on the label. If questions still arise regarding the group classification of a herbicide, it may prove helpful to get clarification from your local county extension agent.

Herbicide classifications

To ensure the proper efficacy of herbicides, it is imperative that the label's instructions are adhered to. This includes following label recommendations regarding rates, timing, environmental conditions, nozzle types, etc. Herbicides are classified as selective or nonselective and as contact or systemic. Knowledge of these characteristics will help in making an educated decision on the selection of a herbicide. When applying contact herbicides, selection of a nozzle that provides maximum coverage of the leaf surface is important. The rationale is, contact herbicides kill only parts of the plant that they come in contact with. A good example of this is observed when applying paraquat (Group 22) which is often used as a burn-down product, harvest aid desiccant and defoliant. It is a non-selective, fast acting herbicide which disrupts the cell membranes of plants (**Fig. 1a**). In contrast, systemic herbicides can be absorbed by the seeds, roots and shoots before being translocated to other areas of the plant. Typically, symptoms from systemic herbicides develop slower than contact herbicides, however, the former are often more effective at weed control especially on perennial weeds. This is because they move throughout the plant. For example, glyphosate (Group 9) is a systemic herbicide that inhibits amino acid synthesis in plants. This action "chokes" off the food supply to plants and may take up to 10 days for plants to completely die (**Fig. 1b**). Herbicides may also be labelled as PRE or POST. This denotes the timing of the application, either as a pre-emergent at seeding or post-emergent after planting. For example, pendimethalin (Group 3) is a PRE herbicide that inhibits seedling roots, whereas dicamba (Group 4) is a POST applied herbicide that is a plant growth regulator.

Site of Action Group	Mode of Action	Chemical Family	Active Ingredient	Tradename
ACCase Inhibitors				
1	Lipid synthesis inhibitor	cyclohexanedione phenylpyrazoline arloxyphenoxypropionate	sethoxydim pinoxaden quizalofop	Poast Axial XL Assure II
ALS Inhibitors				
2	Amino acid synthesis inhibitor	sulfonylurea imidazolinone triazolopyrimidine	chlorimuron imazethapyr cloransulam-methyl	Classic Pursuit First Rate
Microtubule Inhibitors				
3	Seedling root inhibitor	dinitroanaline	pendimethalin	Prowl
Growth Regulators				
4	Growth regulator	phenoxy-carboxylic acid benzoic acid quinoline carboxylic acid	2,4-D dicamba quinclorac	2,4-D, others Clarity Drive
Photosystem II Inhibitors				
5 6 7	Photosynthesis inhibitor	triazine benzothiadiazinone Urea	atrazine bentazon diuron	AAtrex Basagran Karmex
EPSP Synthase Inhibitor				
9	Amino acid synthesis inhibitor	amino acid analogue	glyphosate	Roundup, others
Glutamine Synthetase Inhibitors				
10	Nitrogen metabolism inhibitor	organophosphorous	glufosinate	Liberty
Diterpene Biosynthesis Inhibitors				
13	Pigment inhibitor	isoxazolidinone	clomazone	Command
PPO Inhibitors				
14	Cell membrane disruptor	N-phenylphthalimide diphenylether pyrimidinedione triazolinone thiadiazole	flumioxazin fomesafen saflufenacil carfentrazone fluthiacet	Valor Reflex, Flexstar Sharpen Aim Cadet
Long Chain Fatty Acid Inhibitor				
15	Seedling shoot inhibitor	chloroacetamine oxyacetamide	s-metolachlor flufenacet	Dual Magnum Define
Photosystem I Electron Diverter				
22	Cell membrane disruptor	bipyridylium	paraquat	Gramoxone
HPPD Inhibitor				
27	Pigment inhibitor	triketone pyrazolone	mesotrione topramezone	Callisto Armezon, Impact

Table 1: Common herbicide classifications by group.

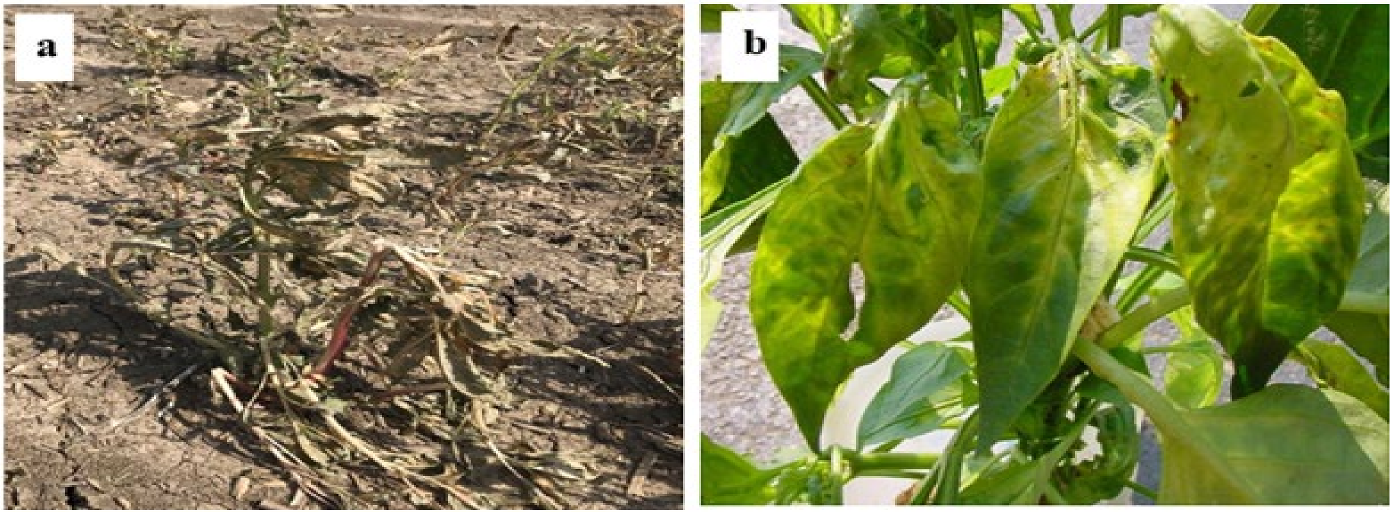

Fig. 1. a) Pigweed leaf necrosis following paraquat treatment. (Photo credit: Jason Bond)
b) Yellowing at the base of young pepper leaves following glyphosate treatment. (Photo credit: P Bachi)

Factors impacting herbicide efficacy

The proper use of herbicides is an important practice in the management of weeds. To achieve this, the factors impacting herbicide efficacy should be fully understood. Many factors influence how effective a herbicide spray will be on a target weed. Hence, their knowledge can aid in the development of an effective IWM plan.

Spray additives - Adjuvants play a key role in herbicide formulation and can enhance its handling and activity. They are either formulated with the herbicide or as an additive that can be incorporated into the spray mixture. Adjuvants are grouped into two broad categories based on their use as either activators or modifiers. Activator adjuvants increase the movement of herbicides into the leaf tissue by enhancing leaf penetration and adhesion. These adjuvants also protect the herbicide from photo degradation and make it rainfast. Modifier adjuvants are used to alter the application characteristics of a spray solution. They can be drift control agents, anti-foaming agents, buffering agents or compatibility agents. Modifiers are usually formulated within the herbicide and are not as well-known as activators that usually have to be purchased separately. The use of adjuvants can increase herbicide efficacy thereby reducing the amount of sprays required.

Water quality – Suspended solids in water (turbidity) can reduce the effectiveness of post-emergence herbicides. Clean spray water, with no organic matter and soil, is best for spray mixes. This is due to some herbicides having a high soil organic carbon sorption coefficient, which causes them to bind to suspended particles in the water, thus rendering them less effective. Herbicides are chemical compounds; therefore, the pH of the spray water has an influence on their chemistry and efficacy. When dealing with weakly acidic herbicides, it is best to use a lower pH (slightly acidic) spray water because it reduces the dissociation of the herbicide. Dissociation occurs when the molecules of the herbicide split into smaller particles when added to water. A plant's uptake of a dissociated herbicide occurs at a lesser rate, thus reducing its efficacy. Generally, a more acidic spray water is best to reduce dissociation, however, there are instances where that isn't the case. For example, the sulfonylurea herbicide family should theoretically benefit from a higher spray water pH due to an increase in their solubility. It is a good practice to know the pH of the spray water used, in doing so, the proper corrective measures can be made, thus reducing any antagonism, and improving herbicide efficacy.

Application timing - The timing of an application is critical with respect to herbicide efficacy. Research has shown that treating weeds early in their growth stage offers the best control. Herbicide efficacy decreases as weeds get larger and become more capable of metabolizing the active ingredients in herbicides. Also, younger plants have less leaf hairs, growing points and defenses making them more vulnerable to sprays. The general rule of thumb is the earlier the application the better, however, the proper timing is important to maximize full weed emergence and limit herbicide applications. Application timing may also refer to the time of day a spray is done. Early morning sprays occur when foliage is covered with dew, preventing the herbicide from "sticking" whereas studies have shown that herbicide performance diminishes late in the day as the sun sets. These responses vary depending on weed species and location, therefore spray timing should be carefully considered to achieve optimum herbicide performance.

PRE herbicides are referred to as residual herbicides because they persist in the soil after application. Timing of a PRE application is important because maximum residual activity is obtained after "activation". Rain or irrigation water facilitates PRE activation by allowing the herbicide to move through the soil and be absorbed by seed radicles of germinating weed seeds. Performing a PRE application before it rains will ensure maximum performance, whereas the same isn't true for POST applications. These require maximum coverage to be most effective, therefore it's best for to them remain on the leaf surface and not be washed off by rain or irrigation water after application.

Tillage - In some instances, the type of tillage system utilized may interfere with the application of a PRE herbicide. For example, the efficacy of a PRE may suffer in minimum-tillage systems due to interception of the herbicide by surface residues. Further, the metabolism of herbicides can be enhanced by the increased microbial activity associated with residues, resulting in reduced efficacy. This may not be true for all PREs, as the herbicide affinity for residue sorption over soil varies depending on its polarity. Tillage methods that significantly disturb the soil are discouraged following a PRE unless they uniformly incorporate the PRE into the immediate soil surface. It is best if residual herbicides remain on the soil surface undisturbed as they await activation by a rain or irrigation event. Knowing the factors that influence herbicide efficacy will help in the selection of the best weed management practices.

Integrating herbicides with mechanical and cultural techniques

Effective weed management takes advanced planning; this requires the use of multiple techniques to address anticipated problems. The development of herbicide resistance can be thwarted with adequate preparation, this involves integrating chemical, mechanical and cultural methods of weed management.

The critical weed free period - Knowledge of the critical weed free period is vital to improving the timing of herbicide applications and using the least amount required to prevent yield loss. The critical weed free period (CWFP) is defined as the period when weeds must be controlled to prevent significant yield loss. This period can vary depending on the crop and weed species. Beyond the CWFP, herbicide sprays will no longer result in a yield increase. Thereby, the CWFP may also be used to reduce weed management cost. After this period passes, available resources should still focus on preventing weeds from going to seed as this may pose problems in the subsequent crop. If non-chemical approaches are available, these may be used to prevent weed seed production.

Banded herbicide application - A successful IWM program uses chemicals synergistically with other management tactics such as physical weed control measures. Research has shown that a banded herbicide application in conjunction with inter-row cultivation can be as effective as using a broadcast herbicide application in managing weeds. In banded applications, total herbicide use may be reduced by 50% depending on the band width. In banded applications, herbicides are sprayed directly over the crop row (**Fig. 2**) and the width of the band depends on the crop and row spacing. Banded herbicide applications have many advantages such as reduced herbicide cost and carryover in the soil. Banded application is often coupled with mechanical cultivation which is effective at keeping between row areas weed free. Banded applications may be applied at planting with a PRE that has good soil residual activity or as a POST that is applied when inter-row weeds are being cultivated. A key to successfully integrating banded herbicide applications with cultivation is to properly adjust the cultivator and choose the correct spray nozzles. A slight overlap between the herbicide band and the cultivator is required to ensure there are no untreated areas. In general, rectangular spray tips that deliver an even flat spray are recommended for banded applications. Standard flat fan tips used often for broadcast applications are not suitable due to their uneven delivery pattern. Herbicide rates for banded applications are the same used for broadcast applications. However, the treated acreage will differ depending on the band width. To this point, if properly applied, banded herbicide applications coupled with cultivation could prove less costly than using broadcast herbicide applications.

Chemical fallow – Fallow is a well-known soil management practice; it promotes soil health, and conserves soil moisture and nutrients. Studies have shown that fallowed lands produce higher yields of subsequent crops and may be a viable option in areas where soil moisture is a limiting factor to crop production. Although this practice provides some benefits, it allows weeds the opportunity to get established. Therefore, to obtain maximum benefits from fallow, weeds must be controlled as they take up soil nutrients and moisture, and produce more seeds. Weed management in a fallow system can be done either chemically or mechanically. Chemical fallow employs the discrete application of herbicides to control weeds, thus ensuring benefits that would have been lost due to weed presence. However, mowing can be a more sustainable approach that prevents herbicide resistance evolution, eliminates herbicide costs, and is compatible with organic production. An effective fallow requires preparation and begins months before harvest. At harvest, crop residues should be well distributed across the field to prevent erosion and moisture losses. Fields should be scouted often to determine weed problems and the appropriate herbicide applications should be made. Selection of the most effective herbicide for the weed types present is imperative. Further, multiple MOAs must be tank-mixed to prevent the selection of resistant weed biotypes. Chemical fallow introduces an additional weed management step resulting in added costs however, it can be an invaluable option in low soil moisture fields.

Herbicides and cover crops – Cover crops can be an important part of an IWM program. They promote soil quality and health by preventing erosion, loosening compacted soil, supplying nutrients to beneficial soil organisms and via other contributions. Cover crops can also be harvested and grazed for feed or forage. Further, cover crops may be used to suppress weeds by competing for resources as a living mulch or blocking stimuli that weed seeds need to germinate by remaining on the soil surface as organic mulch. However, the successful implementation of cover crops into an IWM program depends partially on herbicides used in the prior crop. As previously mentioned, good residual PREs can persist in the soil and prevent the successful establishment of a cover crop. In this situation, herbicide knowledge plays an important role. The herbicide label is a good resource to determine any plant-back or rotational restrictions. Label instructions should be followed to prevent herbicide misuse, protect the subsequent crop from injury and prevent herbicide residues from entering the food chain.

Summary

Herbicides are important IWM tools if used judiciously. However, if improperly used, herbicides can cause unfavorable environmental and ecological consequences including the development of herbicide resistant weeds. Risks attributable to herbicide resistance can be reduced by: **1)** scouting for weeds before and after treatment, **2)** having a proper understanding of how herbicides work, **3)** integrating knowledge of weed biology and ecology in a management plan, **4)** improving herbicide programs (e.g. tank-mixes of POST herbicides with different MOAs) and **5)** adopting a truly IWM program. If producers are willing to accept and subsequently adopt an IWM program, they can achieve large gains in herbicide reduction and consequently reduce risks of herbicide resistance issues in their fields.

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How Do Fruit Get Their Flavor?

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In general, fruit quality is defined by three major attributes: color/appearance, texture, and fruit flavor. Though growers are often paid based on the physical characteristics of their fruit (such as color, size and lack of defects, texture), it is essential that the flavor of the fruit is considered, as this is the main driver for repeated purchases by consumers.

Why is fruit flavor important?

The flavor of the fruit is very closely linked with the consumer's preference and continued consumption of any given fruit variety and should be strongly considered. Meeting consumer expectations for flavor of specific fruit, not only causes consumers to buy more fruit, but it allows growers to increase their profitability. Consumers are willing to pay a higher price for distinctly flavorful varieties that are going to enhance their experience consuming fresh fruit.

There is nothing more disappointing for consumers than finding the perfect apple from the grocery store — a beautiful red color, no bruises, a firm texture — but when taking the first bite, the flavor is boring, flat, and is overall a disappointment. Once a consumer has purchased a fruit with little or poor flavor, they are inclined to not buy those fruit again and/or move on to a different grower or a different fruit all together. Producing fruit with complex and delicious flavor is extremely important to the consumer's enjoyment of their eating experience.

What is fruit flavor?

Flavor is described as the interaction between taste and aroma. Taste relates to the ratios and intensities of non-volatile compounds, specifically sugars and acids. Sugars and acids are detected by five classes of receptors in the tongue – sweet, sour, salty, bitter, and umami (protein taste, represented by glutamate). Volatile compounds, which create the aromas of fruit, are detected by over 650 types of olfactory nerve endings found in the nose.

The sweetness of a fruit is influenced by the quantity and composition of sugars. Higher contents of sugar in the fruit increases the sweetness of the fruit. Additionally, different forms of sugar affect the sweetness of the fruit. In fruit such as apples, peaches and plums, the main sugars present are sorbitol, sucrose, fructose and glucose. Each of these sugars have a different degree of sweetness. Fructose has 1.7 times the sweetness of sucrose, while glucose and sorbitol only have 0.8 and 0.6, respectively. For example, if one apple variety has higher contents of fructose and another variety has higher glucose, the former will taste sweeter.

The acidity of a fruit is influenced by the content and composition of organic acids, and the amount of each type of acid found in each fruit. For example, the dominant acid in apples, peaches, and plums is malic acid.

The balance between the sweetness and acidity of fruit based on the quantity and composition of their sugars and acids is important for developing a complex and interesting taste that will enhance fruit flavor.

Another key component of flavor is aroma. Fruit aroma is influenced by the quantity and composition of volatile compounds. The volatiles that are well-known to affect fruit flavor include esters (fruity aroma), alcohols (fruity or earthy aroma), aldehydes (slightly grassy and bitter aroma), lactones (peach-like aroma), and terpenoids (scented oils aroma). Studies have shown that the flavor intensity of a fruit can be correlated with the quantity and composition of volatiles present. For example, strawberries that presented higher levels of certain key volatiles were perceived as sweeter and highly preferred by consumers, as compared to other strawberry varieties lacking these volatiles.

How is fruit flavor measured?

Fruit flavor can be measured instrumentally as well as through the use of sensory science. Sensory science is a multi-disciplinary field that uses scientific measurements to interpret the human response to the senses of sight, smell, taste, touch, and hearing. This form of science is able to link the product to the person in a direct way.

Instrumentally, sugar content of the fruit is determined by measuring the soluble solid content using a portable refractometer. A refractometer measures how light is bent as it passes through a sample, which is correlated to a specific percentage of sugar in the fruit, and thus is related to fruit sweetness. Titration measures the content of the dominant acid present in the fruit and can also be measured and calculated using portable acidity/pH meters.

Aroma volatiles are challenging to measure with portable instruments. They are quantified by using Gas Chromatography – Mass Spectroscopy (GC-MS), a lab-based technique which helps to separate and identify compounds in their gaseous forms based on their masses.

To correlate these instrumental measurements to consumer perception, two major methods of sensory evaluation are used: consumer testing and descriptive analysis. Consumer testing includes subjective data about the preferences of a large group of untrained tasters (usually more than 100 panelists), while descriptive analysis includes questionnaires for a panel of 8-12 trained tasters who are able to rate specific attributes related to fruit quality.

Portable sugar (refractometer) and acidity meter (left); Gas Chromatography – Mass Spectroscopy (GC-MS) equipment (center); samples for sensory evaluation (right). Photo: Dr. Macarena Farcuh

What factors affect flavor development?

Genetics: A key factor for determining fruit flavor lays in the genetic background of the variety that was chosen. When determining which variety to establish, it is important to choose varieties that were bred for flavor as one of its priorities. Additionally, the choice of rootstock, for fruit such as apples, can influence fruit flavor potential. Studies have shown that particular rootstocks can affect the levels of organic acids and sugar content found in the same variety of apple.

Environmental factors: Environmental factors also play a hugely important role in affecting the flavor of the fruit and strongly interact with the genetic background. Although often times these factors cannot be controlled, they must be taken into account when aiming to improve the flavor of the fruit that are being produced. The major environmental factors affecting fruit flavor development include temperature, relative humidity, and sunlight during the growing season.
A good practice before establishing a new orchard is to conduct small variety trials to evaluate which varieties are capable of developing flavor under the specific environmental conditions. As there is strong interaction between varieties and their growing environment, a variety that is successful in one area may not be as successful in another region.

Preharvest Factors, Orchard Management & Cultural Practices: Fruit flavor can be affected by different orchard management practices, such as planting density, tree structure, irrigation regime, light manipulation, crop load, nutrition, and pest control methods.
Practices that increase the amount of sunlight reaching the fruit, such as pruning or the use of reflective groundcovers, have been shown to increase flavor development as well as color.

Crop load management is another important factor affecting fruit flavor development. In a study done on apples, trees with lower crop loads were found to have fruit with increased flavor development. This was mainly due to higher levels of aroma volatiles and sugars in the apple fruit with lower crop load. Many times, trying to aim for the highest yield will play against flavor development.

Irrigation management can also have an effect on fruit flavor. It is important to maintain balanced irrigation levels in the orchards. Excess irrigation will decrease the overall flavor produced during the fruit growth. Irrigating in intervals to avoid inducing stress on the tree is good practice and will positively impact fruit flavor development.

Concerning nutrition, excessive levels of nitrogen will decrease the "fruity" aromas that are developed in the fruit, while increasing the "green" and "grassy" aromas. Many studies have shown that moderate nitrogen supply for the tree increased fruit flavor, but an excessive amount actually deteriorates fruit flavor.

Fruit Maturity at Harvest: Harvesting practices and the maturity of the fruit at harvest is an often-forgotten key factor in maintaining fruit flavor. Fruit produced for wholesale distribution typically tends to be harvested before fully ripe in order to ensure that the fruit can be transported easily without being damaged. Unfortunately, in this case the fruit's flavor is likely not completely developed. On the other hand, if fruit are harvested over-mature, there is an increase in the "fermented" flavor, which is disliked by consumers. Thus, in the Mid-Atlantic when harvest is delayed waiting for red skin color development in apples, fruit flavor is directly affected. Harvesting over-mature apples is harmful for flavor development, overall fruit quality and fruit storage capacity. This directly impacts profitability.

Harvesting fruit at the correct time is a 'balancing act' between great flavor, overall quality and shelf-life capacity. Favoring one of these factors over others may affect the marketability of the fruit, so it is of key importance to harvest fruit at the correct time.

Postharvest Factors: Once the fruit is harvested, flavor can be maintained or lost, which is why improving postharvest factors is critical to ensure flavor maintenance. These factors are mainly a balance of storage temperature, relative humidity levels, oxygen (O_2) and carbon dioxide (CO_2) balance, and ethylene levels.

The combination of storage temperature and length of storage can cause loss of flavor, and development of physiological disorders that will affect fruit marketability. Storage temperatures vary with each fruit and each variety to ensure the best possible maintenance of flavors. Practices such as fruit conditioning, e.g. storing fruit at 68°F for 24-48 hours or at 50°F for 7 days before cold storage, are used in peaches and 'Honeycrisp' apples, respectively, to avoid development of physiological disorders that will induce flavor loss.

In terms of relative humidity, the target is to achieve ranges between 85-95%. If the humidity levels are too low, the water content of the fruit can decrease which leads to fruit shriveling, weight loss and consequent changes in flavor profiles. In humidity levels over 95%, condensation on the fruit may lead to mold growth.

The balance between O_2 and CO_2 concentration during storage can also directly affect fruit flavor. Storing fruit with a low O_2 supply can cause the fruit to begin undergoing anaerobic respiration which leads to a quick break down in internal sugars, essential to the overall flavor of the fruit. A high level of CO_2 negatively influences the respiration of the fruit in storage, affecting the acidity levels of the fruit. Lower levels of O_2 and high levels of CO_2 can lead to fermentation, which results in the formation of an 'off flavor' which is disliked by consumers. Controlling the atmosphere of apples in storage allows the fruit to maintain their flavor and not develop these unwanted "off-flavors".

Ethylene, a gaseous plant hormone that enhances fruit ripening and can be produced by the fruit itself, plays an important role in fruit flavor development during postharvest. High ethylene levels during storage enhance the development of aroma volatiles, but make fruit become soft and last less in storage. Low ethylene levels during storage, often achieved by using commercial products such as SmartFresh (1-MCP), which blocks the perception of ethylene by the fruit, maintain high fruit firmness, but inhibit production of aroma volatiles. Therefore, maintaining the adequate ethylene levels during storage is a key factor for maintaining fruit flavor.

Summary

As discussed throughout this article, taking the flavor of the fruit into account in every step of the production process is essential. Although it may be complex and difficult to evaluate, fruit flavor is one of the main factors that keeps consumers enjoying eating fresh fruit and pursuing repeated purchases. Therefore, a great fruit flavor development consequently increases the marketability and subsequent profitability of fresh fruit.

Apple Red Skin Coloration: A Grower's Checklist

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Color Importance

Developing strategies on how to improve apple's red skin coloration is a major step towards increasing fruit marketability and profitability. Red skin coloration is highly associated with sales, as vibrantly colored fruits are more appealing to the consumer's eye. In addition, darker fruit coloration is associated with increased nutritional value and antioxidant properties that have many health benefits, including potential cancer prevention. However, in the last few years, reaching the required 50-60% red skin coloration required by retailers, particularly in highly profitable early-season varieties such as Honeycrisp, has been a major challenge in the mid-Atlantic region.

Pigments Involved in Color Development

There are mainly three pigments concentrated in apple's skin that determine its coloration: anthocyanins, carotenoids, and chlorophylls. These pigments are synthesized through multi-step biochemical processes, or from a chain of chemical reactions. These processes are regulated, directly or indirectly, by factors such as genetic background, developmental stage of the fruit, nutritional status, canopy architecture, crop load, but also strongly affected by environmental factors such as temperature and light.

Anthocyanins

Anthocyanins are a set of phenolic compounds which are the main pigments in fruits, generating the characteristic blue, purple, or reddish hues. The content and composition of anthocyanins mainly determine the intensity and quality of red skin coloration in apples. Anthocyanins, as other phenolic compounds, are strongly associated with improved antioxidant activity in fruits and can also improve their nutritional value, hence increasing health benefits for consumers.

Anthocyanins biosynthesis in apple skin is developmentally regulated, taking place during the fruitlet stage as well as during fruit ripening, with the ripening stage being the most important. Furthermore, sugars are a key component of anthocyanins formation, making coloration strongly dependent on apple's sugar contents and composition.

Other Pigments

There are other pigments that contribute to the color of apples, such as carotenoids and chlorophylls. Carotenoids lend a yellow or orange color to fruit, with chlorophylls adding a green hue. Chlorophylls are concentrated in a greater proportion in unripe fruit and decrease as the fruit ripen. More information on apple color from Penn State Extension can be found at https://extension.psu.edu/fruit-color-promoting-red-color-development-in-apple .

Environmental Factors and Apple Red Skin Coloration

The two main environmental factors that affect apple red skin coloration development are temperature and light:

Temperature

The ideal conditions for red color development in apples correspond to bright, clear days with temperatures of around 77ºF (25ºC) and cool nights (59ºF, 15ºC) throughout preharvest (3 weeks before harvest). When exposed to these conditions, trees are not stressed during the day, thus increasing their canopy photosynthesis and decreasing respiration rates at night. Increasing photosynthesis promotes the accumulation of sugars (carbohydrates) and decreasing respiration rates help to decrease the breakdown of sugars. Therefore, under the above temperature conditions more carbohydrates are readily available. This is of crucial importance, as sugars constitute the raw material for the production of anthocyanins.

Anthocyanin biosynthesis is suppressed at warmer temperatures (hot days (>90ºF; >32°C) and warm nights (>68ºF, >20°C)), thus making it difficult to produce apples with sufficient red skin coloration in hot seasons, especially early-harvest varieties such as Honeycrisp.

Light

Light intensity and quality (wavelength) are also crucial factors affecting apple red skin coloration during development and ripening. This is particularly important as all the chain of biochemical reactions involved in the synthesis of anthocyanins are induced by light. Skin color pigments are synthesized as a response to stressors such as sunlight, specifically in the ultraviolet (UV) radiation wavelengths. UV radiation wavelengths are shorter and higher energy than visible light that we see as colors (Figure 1) Therefore, the more that apples are exposed to the sun's rays – specifically UV wavelength – the more color that the fruits will develop on the skin. But this is only to a certain limit, as too much UV radiation can cause fruit sunburn, just like in human skin.

Sub-optimal temperature and light conditions present in the mid-Atlantic at the time that varieties such as Honeycrisp are harvested in recent years have resulted in a poor or marginal red skin coloration development in these varieties. As environmental conditions are difficult to control, the focus must be placed on managing the tree, its physiology, and a uniform light distribution for improving coloration.

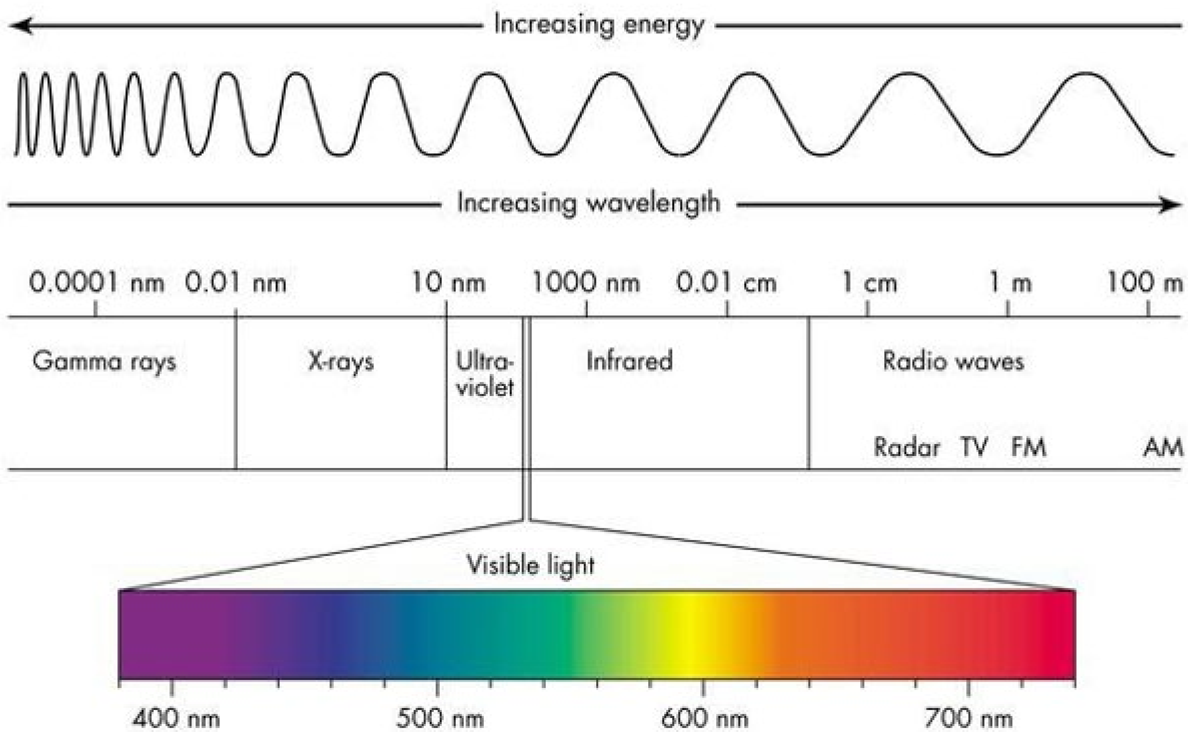

Figure 1. Radiant energy spectrum showing ultraviolet light, which promotes red coloration. Source: Lumenistics, 2012.

Site of Orchard Establishment and Apple Red Skin Coloration

Elevation

The altitude at which fruits are grown can also have an important effect on apple red skin coloration. To maximize fruit color, cooler and higher elevation areas are preferred, allowing for the necessary temperature differential between daytime and nighttime that will increase anthocyanin accumulation and thus development of red skin coloration.

Aspect

Aspect, or the way that the sun hits the earth can also impact the development of red skin coloration. The sun's rays shine more directly on the southern than it does the northern side, therefore south-facing fruits receive much more UV radiation from the sun than a northern facing counterpart.

Soils

The inherent water- and mineral nutrient-holding capacity can affect red color directly, through nitrogen (N) availability (high N delays chlorophyll disappearance), and indirectly by promoting tree vigor and the potential for shading within the canopy.

Cultivars, Strains and Rootstocks and Apple Red Skin Coloration

The maturity date of a cultivar or strain determines the temperature range encountered at fruit maturity. Prolonged warm spells in August and September that have been experienced in recent years can result in insufficient red color of early-ripening cultivars such as Gala and Honeycrisp. Warm harvest weather, combined with ever-stricter color grading standards may result in loss of value, particularly with older, less red strains of these cultivars. Thus, in recent years newer highly colored strains of Gala, such as Gale, Buckeye and Brookfield, have become predominant throughout the industry. Until recently, the supply of Honeycrisp apples lagged behind the demand, which provided some insulation from the need to plant redder strains, but this phase of the Honeycrisp market has ended and strict red color standards are now being enforced. Red strains, such as Firestorm, Royal Red and B42 Honeycrisp should be selected for replacing older selections that can no longer meet color standards (Figure 2).

Figure 2. Two red strains of Honeycrisp (Left and right) with standard strain (center). Photo: J. Schupp

Red strains of apples have received a bad rap owing to the mismanagement and poor eating quality of certain strains of Delicious. There is no evidence of a link between red color and poor taste of redder strains of other cultivars, including Gala and Honeycrisp. Sensory studies of B42 Honeycrisp and a standard strain conducted at Penn State showed that panelists could distinguish no difference between the strains in taste or texture and that they preferred the appearance of B42 over the standard strain.

Red strains may develop marketable red color before reaching the optimal fruit maturity to ensure good eating quality. Growers do need to make sure that the maturity of harvested fruit is appropriate for its intended use and storage period.

Size-controlling rootstocks reduce canopy volume and density, resulting in increased light distribution and improved red fruit color. Tree vigor must be strong enough to develop full productive potential of the orchard, yet result in a calm tree at maturity. Growers should plant the most dwarfing rootstock that can be managed, given the inherent vigor of the soil and cultivar (Figure 3).

Figure 3. Even a dwarf apple tree can have poor fruit color in the lower canopy. Photo: Don Elfving.

Mineral Nutrition and Apple Red Skin Coloration

Balanced mineral nutrition is critical to achieving high marketable yields of attractive red fruit. Although all mineral nutrients are needed to achieve balanced growth and fruit quality, two minerals stand out when focusing on red color—nitrogen and potassium.

Adequate leaf nitrogen is required for high productivity, but excess N is detrimental to red coloration. High N delays chlorophyll disappearance in the peel and results in a dull muddy color. Excess N also promotes vegetative growth, which can result in shading and loss of red color. Cultivars differ in sensitivity to N. Gala color is less sensitive to N, and leaf N levels of 2.1- 2.3% will improve tree vigor and fruit size without being detrimental to color. Conversely, Honeycrisp, Jonagold, and Fuji are sensitive, and leaf N should be managed in the range of 1.8-2.0% to maintain good red color and prevent excessively large fruit.

Low potassium (K) results in poor fruit color. The optimal range for leaf K in apple is 1.5-2.5%, and it should be noted that apple fruit are high in K. This creates a need for active management of this mineral to replace that which is being removed by the crop. Correction of low K can produce a rapid and dramatic improvement in red fruit color, leading some to believe that "more K is better". There is no evidence that excess K can increase red color, but there is ample evidence to show that excess K can make bitter pit worse in Honeycrisp.

Crop Load Management and Apple Red Skin Coloration

An excessive crop causes trees to produce fruit with a poor red skin coloration (Figure 4). The lack of red coloration is due to a shortage of resources, specifically sugars and nutrients reaching each fruit as a result of the increased competition. The lower sugar contents limit the fruit's ability to synthesize anthocyanins, thus preventing red skin coloration development. Excessive crop loads in varieties such as Honeycrisp are particularly harmful as the high depletion of sugars will affect fruit coloration development of the current year's production, and also the juvenile buds that will develop into next year's crop.

Low crop loads, on the other hand, will promote tree vigor and vegetative growth, consequently affecting red skin color development as the few apples that are left on the tree will be shaded and thus will not receive the necessary sunlight required for anthocyanin biosynthesis. This will also limit total crop yield and profitability.

Therefore, crop load management must be targeted towards a balanced orchard. The optimal recommended crop load is around 7-8 fruits per cm^2 TCSA (Trunk Cross-Sectional Area) which will increase red skin coloration and maintain adequate fruit size, while maintaining return bloom for the coming year.

Figure 4. Effect of crop load density on Honeycrisp red coloration. Photo: J. Schupp

Fruit Maturity Management and Apple Red Skin Coloration

Fruit maturity is also a critical factor affecting apple red skin coloration as anthocyanin synthesis is developmentally regulated, occurring mainly during fruit ripening. Therefore, controlling how and when apple fruit ripen will impact red coloration development. Ethylene, which is a gaseous plant hormone controlling ripening, can be regulated with the use of preharvest plant growth regulators, such as Ethephon, ReTain® or Harvista®.

Ethephon (Ethrel®, Bayer Crop Science; Motivate™, Fine Americas; Ethephon 2, Arysta LifeScience North America, LLC), which is an ethylene-releasing chemical, promotes fruit ripening and can help increase red coloration, but if temperatures are above optimal it will only advance maturity without increasing red coloration. Ethephon also accelerates fruit abscission and may negatively impact fruit storability.

ReTain® (active ingredient: Aminoethoxyvinylglycine (AVG), Valent USA) will inhibit ethylene production, delaying fruit ripening as well as color development.

Harvista® (active ingredient: 1-Methylcyclopropene (1-MCP), AgroFresh), will bind to ethylene receptors in the fruit, blocking its perception. This prevents the response to ethylene in the fruit therefore delaying ripening.

ReTain® and Harvista® will allow keeping fruit on the tree for a longer time, preventing fruit drop. If this delay shifts maturity into a cooler weather window, it may help fruit reach optimal coloration. Additionally, these chemistries increase maturity consistency throughout the orchard, which helps managing fruit harvest windows.

Light Management and Apple Red Skin Coloration

Light is one of the critical factors affecting apple red skin coloration. However, undertake canopy light management with caution to avoid excessive exposure of fruit skin. Just like in human skin, the energy of sunlight can increase the potential for sunburn on the sun-exposed surface of apples. The heating effect of sunlight combined with the damaging effects of ultra-violet (UV) radiation are the main causes of sunburn in apples. Therefore, while it is beneficial for red skin coloration to expose the fruit to sunlight, it must be managed with limits.

There are several ways to manage sunlight in the canopy, with pruning, plant growth regulators and use of reflective mulches being the most popular.

Pruning

Pruning is the long-established method of increasing light distribution in the canopy to promote red fruit color and other light-driven processes, such as flowering and fruit set. Conduct annual dormant pruning, making thinning cuts to remove entire limbs at their point of origin. This type of cut slows and limits the amount of regrowth, thus thinning out the branches and creating windows where sunlight can penetrate the canopy. Remove the largest limbs, especially in the top half of the tree to create a cylindrical or cone shaped canopy. Then thin out additional limbs to space them out both radially and vertically. When tree vigor is strong, summer pruning to remove upright shoots and leaves can confer a temporary increase in sunlight. Summer pruning is typically undertaken about two weeks before the start of harvest to provide additional sunlight to promote red coloration.

Root pruning is another technique to reduce canopy vigor and improve red color. Root pruning is done with a tractor-mounted subsoiling blade or coulter wheel mounted offset on a tool bar. Root pruned trees have shorter shoots and smaller leaves, contributing to increased light penetration. To be effective, root pruning is done early in the season just prior to or at the start of growth. Both sides of the row are cut at 16-18 inches from the trunk to remove enough roots to have an effect.

Plant Growth Regulators (PGRs)

PGRs containing the active ingredient prohexadione-calcium (PCa) (Kudos™,Fine Americas; Apogee™, BASF) can be used in combination with pruning to reduce vegetative growth and improve light distribution. PCa reduces shoot elongation, resulting in a more compact canopy with improved exposure to light.

Reflective Mulches

Groundcovers made with reflective material are a preharvest management tool that is used to improve the tree canopy light environment. Reflective groundcovers in apple orchards essentially bounce the light reaching the orchards floor back up into the canopy enhancing the capacity of apple trees to harness sunlight (Figure 5). This increases the amount of light reaching the apple fruit surface and exposes more apples to light within the orchard. This improved light environment is used by the tree to power its production of sugars, increasing fruit size and red skin coloration. The use of reflective mulches can particularly increase light penetration in the inner and lower parts of the canopy, which are areas where generally less light is intercepted.

Figure 5: Deployment of Extenday reflective fabric to a block of Morning Mist ('Fugachee Fuji'). Photo: Thomas Kon.

There are multiple types of reflective groundcovers in the market, such as white reflective fabrics (Extenday; ProLine), white film or metallic films (Mylar). White reflective fabrics can last for up to seven years and can be rotated throughout the orchards; while white and metallic films have lower costs but usually are disposed after one season. When purchasing, make sure that the chosen fabric reflects radiation in the UV range, as this is the wavelength that will promote red coloration. Establishment of these groundcovers is particularly crucial around 3 weeks before anticipated harvest.

Summary

The importance of fruit color cannot be underestimated, as it can increase sales at the marketplace and increase your profits. Not to be forgotten are the nutritional benefits from a deeply colored skin, since a darker color indicates presence of a high concentration of antioxidants. Replace older, less colored orchards with improved red strains when they become available. Since we cannot control temperature, it is important to control other factors of color development. Use leaf and soil analysis to maintain moderate tree vigor, with adequate levels of N and K. Use thinning cuts during dormant pruning to create a narrow canopy and reduce shading from excess branching. It is important to get a significant amount of UV radiation from sunlight in the last few weeks of ripening to get the best color. If standard methods are not working well, consider plant growth regulators to reduce vigor or alter the maturity window, or the installation of reflective mulches to maximize the UV radiation that hits the apples in order to capitalize on what the sun gives us.

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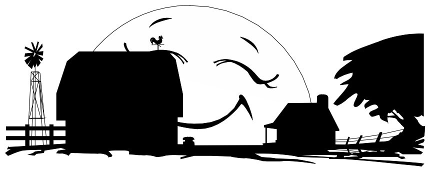

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