Herbicide Mode of Action

K-STATE Research and Extension

Department of Agronomy C715 Herbicide

Herbicides inhibit or interrupt normal plant growth and development. Herbicides provide cost-effective weed control while minimizing soil disturbance; however, improper herbicide use may result in crop injury, poor weed control, selection of herbicide-resistant weeds, environmental contamination, or health risks.

Publications such as the K-State Research and Extension Report of Progress, *Chemical Weed Control for Field Crops, Pastures, Rangeland, and Noncropland* provide information on available herbicide options and application guidelines; but the best source of information for herbicide use is the product label. Always apply herbicides according to label directions. The herbicide label is a legal document and an applicator is responsible for following all label directions.

Herbicides kill plants in different ways, but all herbicides must meet several requirements to be effective. A herbicide must come in contact with the target weed, be absorbed by the weed, move to the site of action in the weed, and sufficiently accumulate at the site of action. Weed control is unsatisfactory if these requirements are not met. Understanding how herbicides work provides insight into how to use the chemicals and helps diagnose causes of poor weed control or crop injury.

The way in which a herbicide kills weeds is called its **mode of action**. Herbicide mode of action is generally a term that describes the plant process (e.g., photosynthesis) or enzyme (e.g., ALS) that is disrupted by the herbicide. Herbicide **site of action** refers to the specific biochemical or biophysical process in the plant that the herbicide disrupts to interfere with plant growth and development processes. This means that one mode of action may be associated with multiple sites of action. The term "herbicide mode of action" is sometimes used interchangeably with "herbicide site of action" or "herbicide mechanism of action." Within a mode of action, herbicides may also be grouped by their chemical structures. Herbicides that share similar structures are said to be in the same **chemical family**.

Definitions

Chemical family: A group of herbicides that share common chemical components.

Mode of action: The overall way in which a herbicide interferes with essential plant processes.

Site of action: The specific enzyme or binding site affected by a herbicide. Also called a target site.

Plant characteristics affecting weed control

Growth Habit

The general shape in which a plant grows is called its growth habit and affects how much herbicide spray reaches the leaf surface to be absorbed. Plants with upright growth, such as grasses, tend to be more difficult to wet than broadleaf plants. Grass leaves present a small, vertical target, resulting in a good chance the spray droplet will roll off the leaves on contact. Broadleaf plants may be easier to wet because they present a larger, more horizontal target (Figure 1). Some weed species, like velvetleaf, change leaf orientation based on time of day, with their leaves folding down and becoming more vertical at night, which results in less herbicide interception and reduced control.

Leaf waxiness and pubescence (hairiness) also affect spray retention. Waxy leaf surfaces repel water-based spray solutions, allowing spray droplets to run off more easily than on less waxy leaves. Sparse leaf pubescence or hairs may help retain spray droplets, but dense pubescence can hold spray droplets above the leaf surface and reduce spray contact with the leaf (Figure 2).

Plant Maturity

Annual plants are usually more susceptible to herbicides when they are small than when they are mature. As they mature, plants develop thicker wax layers on leaf surfaces, reducing herbicide absorption. In addition, it is harder to achieve thorough spray coverage of a large,

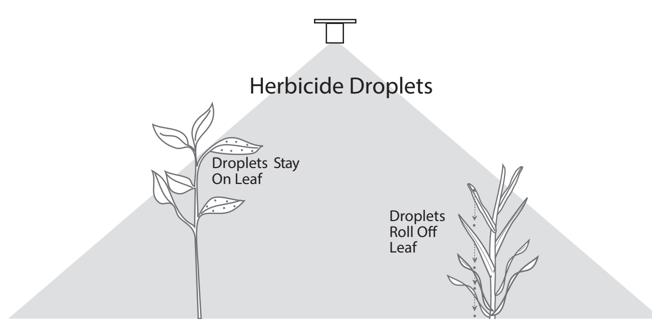


Figure 1. *Spray droplet retention on grass and broadleaf leaves due to leaf orientation.*

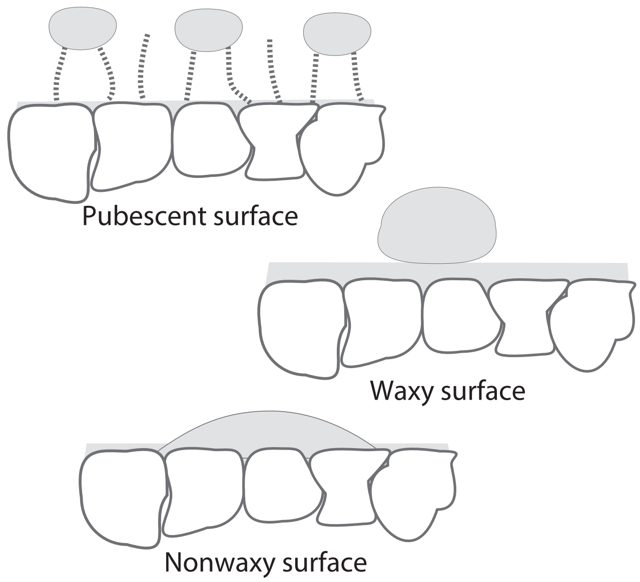


Figure 2. *Spray droplet spread on a leaf surface as influenced by leaf pubescence and waxiness.*

Definitions

Cross resistance: Occurs when a weed population becomes resistant to two or more herbicides as a result of a single resistance mechanism.

Herbicide resistance: The inherited ability of a plant to survive and reproduce following exposure to a dose of herbicide that would normally be lethal.

Herbicide tolerance: The inherent ability of a species to survive and reproduce after herbicide treatment. This implies that there was no selection or genetic manipulation to make the plant tolerant; it is naturally tolerant.

Metabolic resistance: Resistance that occurs as a result of changes in herbicide metabolism in the plant. Also called nontarget-site resistance.

Multiple resistance: Occurs when a weed population becomes resistant to two or more herbicides with different modes of action.

Selection pressure: An external factor that determines which individuals in a population survive.

dense plant, making it more difficult to kill all growing points on large plants compared to small plants.

Seedlings of perennial plants respond like annuals and are much easier to control than established perennial weeds. Once established, perennial weeds tend to be more susceptible to herbicides applied during the early flowering stage of growth or to actively growing plants in the fall. This is likely because application at these times results in the greatest translocation of the herbicide throughout the plant.

Herbicide Metabolism

Metabolism is one of the most important ways a plant can escape the toxic effects of a herbicide. Selectivity of many herbicides is based on differing rates of metabolism. Table 1 illustrates differential metabolism and tolerance of imazaquin (Scepter) among soybeans, velvetleaf, and common cocklebur. Herbicide-tolerant plants often metabolize, or break down, the chemical to nonactive compounds before it can build up to toxic levels at the site of action. Susceptible plants are unable to detoxify herbicides.

Herbicide metabolism can be reduced in certain environmental conditions, such as cold weather. Reduced metabolism of a herbicide in tolerant crops may result in crop injury. Herbicide metabolism can also be affected when applied with certain insecticides, such as organophosphates, resulting in crop injury. Enhanced herbicide metabolism within a plant species could be a potential mechanism of **herbicide resistance**.

Site of Action

The site of action targeted by herbicides varies by plant species. The sites of action discussed in this publication are listed in Table 2. Differences in the target site can result in herbicide selectivity, as in the case of grass-controlling herbicides such as clethodim (Select). Similarly, selection of plants with an altered site of action can result in herbicide resistance. An altered site of action refers to genetically different biotypes that have a structurally altered site of action that prevents herbicide binding and activity. An altered site of action can be visualized using the lock-and-key concept illustrated in Figure 3. Altered site of action has been

Table 1. *Scepter selectivity due to differential metabolism in different plant species (Shaner and Robson, 1985, Weed Science 33:469–471).*

Plant species	Scepter remaining in plants after 3 days	Scepter half-life in plants (days)	Plant response
Common cocklebur	99%	30	Very Susceptible
Soybean	38%	3	Tolerant
Velvetleaf	89%	12	Susceptible

Table 2. *Various modes and sites of action.*

Mode of Action	Group	Page	Site of Action
Lipid Synthesis Inhibitors	1	7	ACCase Inhibitors (acetyl CoA carboxylase)
Amino Acid Synthesis Inhibitors	2	8	ALS Inhibitors (acetolactate synthase)
	9	10	EPSP Synthase Inhibitor (5-enolpyruvyl-shikimate-3-phosphate)
Growth Regulators (Synthetic auxins)	4	11	Various sites
	19	11	Auxin Transport
Photosynthesis Inhibitors	5	13	Photosystem II Inhibitors (serine 264 binders)
	6	14	Photosystem II Inhibitors (histidine 215 binders)
Nitrogen Metabolism	10	15	Glutamine Synthesis Inhibitor
Pigment Inhibitors	12	15	PDS Inhibitor (phytoene desaturase synthesis)
	13	15	DOXP Synthesis Inhibitors (1-deoxy-D-xyulose 5-phosphate)
	27	15	HPPD Inhibitors (hydroxyphenylpyruvate dioxygenase)
Cell Membrane Disrupters	14	16	PPO Inhibitors (protoporphyrinogen oxidase)
	22	16	Photosystem I Electron Diverters
Seedling Root Growth Inhibitors	3	18	Microtubule Inhibitors
Seedling Shoot Growth Inhibitors	15	18	Very Long-chain Fatty Acid Inhibitors

the basis for many herbicide-resistant weed problems and usually results in a high degree of resistance. Kochia resistance to atrazine or chlorsulfuron (Glean) is an example of herbicide resistance due to an altered site of action. Weeds that are resistant to a specific herbicide due to an altered site of action often are also resistant to other herbicides with the same site of action. This is called **cross resistance**.

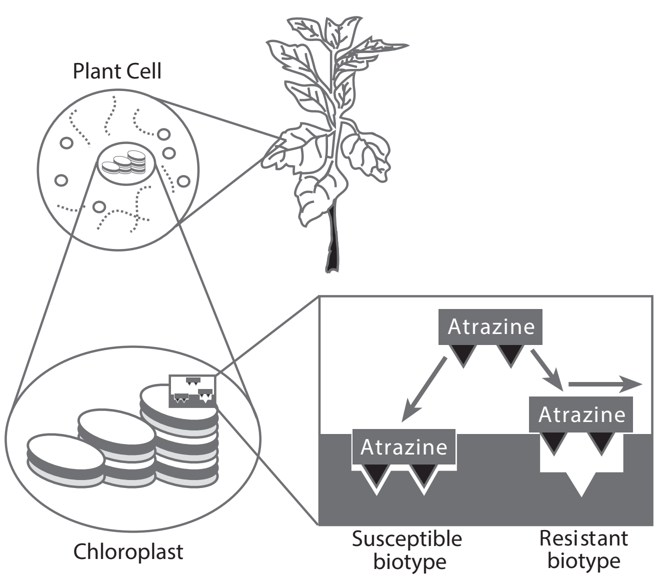


Figure 3. *Site exclusion type of herbicide resistance. Atrazine is ineffective on resistant biotype because a conformational change in the chloroplast prevents it from binding at the site of action (adapted from Gunsolus et al. 2002).*

Herbicide Resistance

Herbicide resistance is defined by the Weed Science Society of America (WSSA) as "the inherited ability of a plant to survive and reproduce following exposure to a dose of herbicide normally lethal. In a plant, resistance may be naturally occurring or induced by such techniques as genetic engineering or selection of variants produced by tissue culture or mutagenesis." Plant species that are not controlled by a herbicide before any **selection pressure** or genetic manipulation would be considered naturally **herbicide tolerant**, but not herbicide resistant.

Herbicide-resistant weed populations are generally selected from the native population in field situations through repeated treatment over time with a given herbicide or herbicides having the same site of action. A small percentage of the original weed population is genetically different and contains the resistant trait. Selection pressure is the repeated use of the herbicide or herbicides with the same site of action, resulting in the removal of susceptible biotypes, while resistant biotypes increase until the weed population is no longer controlled by that group of herbicides. Therefore, one of the most effective methods to prevent or slow the development of herbicide resistance is to mix and rotate herbicide modes of action in each field.

Herbicide resistance may be based on differential absorption, translocation, metabolism, an altered site of action, sequestration of the herbicides, or over-expression of the target protein. Herbicide resistance can result from a single gene mutation or from a combination of multiple gene changes. Single gene mutation resistance generally confers a relatively high level of resistance and population shifts can occur in just a few years. Multigene resistance may begin as a lower-level resistance that gradually increases over time. One category of multigene resistance is called **metabolic resistance,** which means resistant plants are able to detoxify the herbicide. Metabolic resistance can result in a high degree of resistance, for example metabolic atrazine resistance in Palmer amaranth and waterhemp. Often, metabolic resistance is associated with cross resistance to herbicides with multiple sites of action.

A weed biotype may be resistant to more than one herbicide as a result of multiple changes in the plant. This is called **multiple resistance**. For example, a biotype of common waterhemp found in northeast Kansas is resistant to ALS-inhibiting herbicides (imazethapyr), Photosystem II inhibiting herbicides (atrazine), and PPO-inhibiting herbicides (acifluorfen, lactofen, fomesafen).

Environment factors affecting weed control

Precipitation and temperature influence herbicide efficacy by affecting plant growth. Plants are generally most susceptible to postemergence herbicides when actively growing, and environmental conditions that slow growth can reduce herbicide effectiveness. Crop injury from a herbicide, however, can increase during poor growing conditions because of slower metabolism and detoxification of the herbicide. Thus, if crop tolerance is based on the ability of the crop to rapidly metabolize the herbicide, the potential for crop injury increases and weed control decreases if a herbicide is applied when plants are not actively growing. For this reason, most herbicide labels caution against application during extreme environmental conditions.

Temperature affects the activity of soil-applied herbicides primarily because of its influence on the rate of seed germination, emergence, and growth. Young seedlings tend to be more susceptible to soil-applied herbicides under cool conditions because plant emergence is delayed and metabolism is slowed. On the other hand, extremely high temperatures sometimes increase crop injury simply by placing the plant under multiple stresses. Periods of low precipitation and/or extreme cold or hot temperatures also can reduce the degradation rate of soil-active herbicides, leading to greater risk of crop injury.

Lack of precipitation can result in reduced control of drought-stressed weeds due to a thicker leaf cuticle and reduced rate of plant growth. The activity of soil-applied herbicides is also affected by lack of precipitation, which is essential to move surface-applied herbicides into the soil where they must be to control weeds.

Soil Conditions and Characteristics

Soil conditions, such as texture, organic matter, and moisture, affect how much of a soil-active herbicide is adsorbed to soil particles and how much is available for plant roots to take up. Herbicides can become adsorbed to soil particles largely due to interactions with clay and organic matter. Herbicide **adsorption** is greater in fine-textured soils with high organic matter content than in coarse-textured soils low in organic matter. Thus, a lower proportion of applied herbicide is available for plant uptake in the fine-textured soils, so a higher herbicide application rate is required to provide the same level of weed control as in a coarse-textured soil. At the same time, the chance of crop injury is greater on coarse-textured soils low in organic matter because a higher proportion of the applied herbicide is available for plant uptake. Select appropriate application rates based on herbicide label directions for your soil texture and organic matter content.

Soil moisture is important because it influences the amount of herbicide that can be dissolved in the soil solution. After application, herbicide molecules adhere to soil particles and organic matter. While adsorbed, herbicide molecules are unavailable for **absorption** by plants. Water molecules compete with herbicide molecules for adsorption sites on soil particles and organic matter; therefore, herbicide adsorption is greatest under dry soil conditions, and least in moist soils. Weed control by soil-active herbicides is generally best with moist soil conditions because more herbicide is in the soil solution or gaseous phase and available for plant uptake. Some herbicides, such as isoxaflutole (Balance Flexx) may be 'reactivated' by precipitation that allows additional herbicide molecules to leave the soil surface and return to the soil solution.

Soil pH influences the availability and persistence of certain herbicides in the soil. Soil pH can alter the ionic nature of the herbicide molecule, which influences adsorption, solubility, and rate of herbicide breakdown. Triazine herbicides such as atrazine and metribuzin and some of the sulfonylurea herbicides such as chlorimuron

Definitions

Adsorption: The attraction of a substance to the surface of soil particles. Conversely, **absorption** is the movement of a substance into another object, such as a soil particle or plant root.

Enhanced degradation: Dissipation of soil-active herbicides that occurs more rapidly in soils following continued application of certain herbicides.

(Classic), prosulfuron (Peak), sulfosulfuron (Maverick), and triasulfuron (Amber) are more active and more persistent in high pH soils (> 7.0) than in low pH soils. A few herbicides such as flumetsulam (Python) and imazaquin (Scepter) may be somewhat more persistent in low pH soils, but that response is less common and generally less dramatic than for the opposite reaction.

In addition to herbicide resistance management, avoiding **enhanced degradation** is another reason to avoid using the same herbicide in a field during consecutive years. Repeated use of a particular herbicide on the same field results in a buildup of microbes that break down the herbicides, decreasing their residual life and period of weed control. This phenomenon is known as enhanced degradation or soil conditioning. Some herbicides, such as atrazine, 2,4-D, or EPTC are particularly prone to enhanced degradation. Enhanced degradation can also occur across multiple herbicides with similar chemical characteristics.

Application variables affecting weed control

Herbicide application techniques, including spray volume and spray pressure influence the amount of herbicide that reaches the target weed. In general, greater volumes result in better coverage of leaf surfaces, which is especially important for contact herbicides such as paraquat (Gramoxone). Spray pressure is inversely related to the size of spray droplets. In other words, higher spray pressure results in smaller droplets, which may increase coverage. Smaller droplets, however, are also more likely to drift from the spray target and cause injury to sensitive vegetation. When this occurs, it is called herbicide **particle drift**. Some herbicides, such as 2,4-D and dicamba are also prone to **vapor drift**. Vapor drift is the movement of the herbicide as a gas. It increases as air temperature increases and may occur for several hours or even days after application with movement farther from the application site than that occurring with particle drift.

Temperature inversions also can affect off-target movement. During a temperature inversion, a layer of cool air becomes trapped at the soil surface. This layer of cool air can capture fine droplets. The droplets can move away from the target area with very slight winds and be deposited in another location. Temperature **inversions** are most likely to form between dusk and dawn. The Kansas Mesonet provides a real-time map of temperature inversions across the state at *www.mesonet.ksu.edu/agriculture/inversion*.

Spray Adjuvants

Many types of spray adjuvants are available that have different functions, including drift reduction and increased absorption through the leaf. Adjuvants, such as drift reduction agents, that change properties of the spray mixture are called **utility adjuvants**, whereas adjuvants that improve herbicide activity are called **activator adjuvants**. **Surfactants** are a type of activator adjuvant that improve spray retention and absorption by plant foliage by reducing the surface tension of the spray solution, allowing the spray droplet to spread more evenly over the leaf surface (Figure 4). Herbicide absorption may be further enhanced by adjuvant interaction with the waxy cuticle on the leaf surface, allowing more of the water-based spray solution to enter the plant. Crop oil concentrates and methylated seed oils are examples of adjuvants that are used for this purpose.

To optimize product performance, follow label guidelines for the proper type and rate of adjuvant. Spray adjuvants can increase weed control, but potentially can reduce selectivity by increasing the spray retention and herbicide absorption by the crop more than by the weed. Spray adjuvants should be used only as recommended on the herbicide label.

Definitions

Activator adjuvant: Substance added to a spray solution to improve herbicide activity.

Inversion: A layer of cool air trapped near the soil surface, generally occurring between dusk and dawn.

Off-target movement: Occurs any time a herbicide reaches a site other than the intended target. The most common types of off-target movement are particle drift and vapor drift; but herbicides can also move off target when soil solution or soil particles leave the application site.

Particle drift: Occurs when herbicide droplets do not reach their intended target after leaving the application equipment.

Surfactant: A type of activator adjuvant that reduces the surface tension of spray droplets to improve spreading, wetting, dispersion, or emulsion.

Utility adjuvant: Substances added to a spray solution to improve application quality.

Vapor drift: Occurs when the herbicide evaporates (volatilizes) after reaching the intended target but before it is absorbed by the plant.

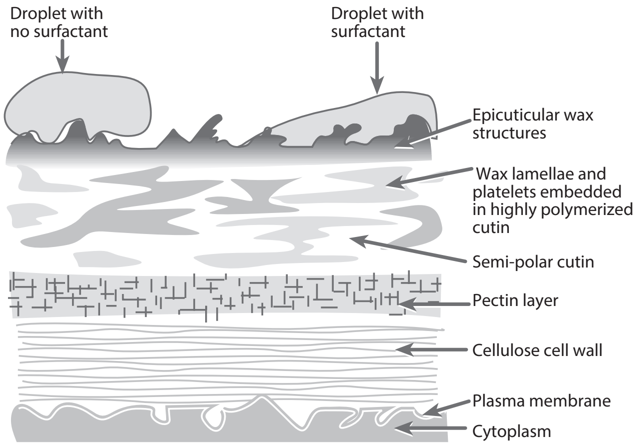


Figure 4. *Leaf surface composition and the influence of surfactants on droplet spread over the leaf surface (adapted from Hull, Davis, and Stolzenberg).*

Categorizing herbicides

Herbicide Selectivity

The potential for a herbicide to kill certain plants without injuring others is called selectivity. **Nonselective herbicides** kill or suppress the growth of most plant species. Their use is limited to situations where control of all plant species is desired, or the herbicide is directed on the target weed and away from desirable plants. Glyphosate, glufosinate (Liberty), and paraquat (Gramoxone) are considered nonselective herbicides; however, glyphosate and glufosinate are used as a selective herbicide in glyphosate- and glufosinate-resistant crops.

Most herbicides used in crop production are selective. Herbicide selectivity is relative and depends on several factors, including plant biology, environment, herbicide application rate, application timing, and application technique. Even a tolerant plant species may be susceptible to a herbicide if the application rate is high enough. Herbicide selectivity may be based on herbicide placement, differential spray retention, absorption, translocation, metabolism, or an insensitive site of action.

Definitions

Contact herbicide: Herbicide that is not translocated throughout the plant and generally kills the tissues they contact, making spray coverage important for effectiveness.

Nonselective herbicide: Herbicide that is toxic to all plant species.

Systemic herbicide: Herbicide that moves throughout the plant, either with sugars or water.

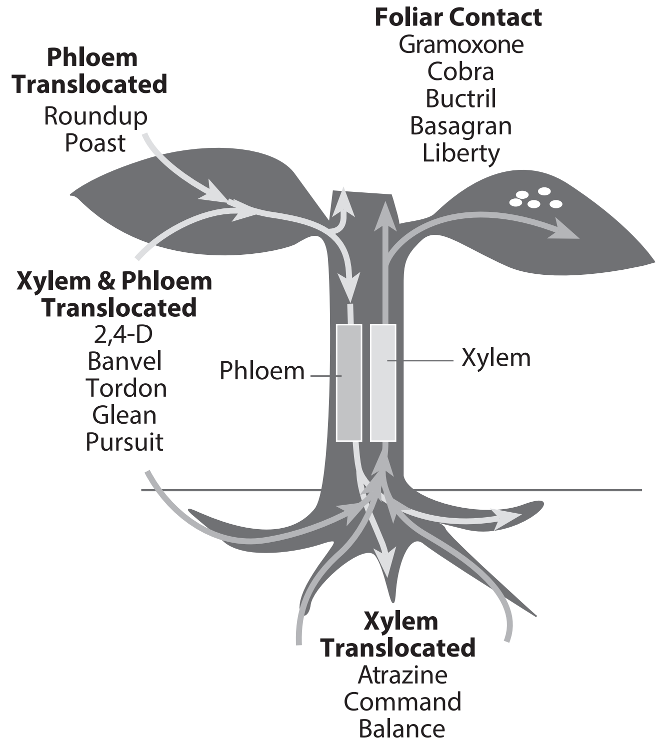


Figure 5. *Herbicide translocation in plants. Brand names are used for example only, similar products may be available under different names.*

Herbicide Translocation

Contact herbicides do not move throughout treated plants. Examples include paraquat, glufosinate (Liberty), and acifluorfen (Ultra Blazer). Thorough spray coverage of a plant is essential with foliar-applied contact herbicides because contact herbicides only damage the plant parts that the spray solution contacts. Underground portions of plants are unaffected and can initiate new growth, therefore, contact herbicides generally are ineffective for long-term perennial weed control. Contact herbicides often are more effective on broadleaves than on grasses. The growing point of young grasses is in the crown region of the plant, which is at or below the soil surface, and thus, difficult to contact with spray. In contrast, the growing point on young broadleaf plants, which is near the top of the plant, is exposed to the spray treatment. Thus, paraquat may not kill all the growing points of a tillered grass plant, and regrowth can occur. In addition, larger broadleaf plants may have regrowth because of sprouting from multiple axillary buds that were not in contact with the herbicide.

Systemic herbicides can be translocated to other parts of the plant either in the xylem or the phloem (Figure 5). Xylem is nonliving tissue through which water and nutrients move from the roots to the shoots and leaves of plants. Translocation in the xylem is only upward and outward in plants from the roots to the leaves and leaf margins. Phloem is a living system in which materials can move both upward and downward. Phloem transports the food that is produced in the leaves to the roots and to areas of new growth.

Herbicides can be translocated in the xylem, the phloem, or both. Translocation depends on the chemical characteristics and the plant species. Herbicides translocated only in the xylem are most effective as soil-applied or early postemergence treatments because translocation occurs only upward. Atrazine is a good example of a herbicide that is translocated only in the xylem. Phloem translocated herbicides that move downward and disrupt root and rhizome growth, as well as top growth, provide the best perennial weed control. Glyphosate, picloram (Tordon), and 2,4-D are examples of systemic herbicides that will translocate in the phloem and provide good control of certain perennial weeds. Reduced herbicide translocation within a plant species could be the basis for herbicide resistance, but probably would result in only a marginal decrease in plant susceptibility.

Herbicide Placement

Placement influences herbicide effectiveness and selectivity, especially for soil-applied herbicides. Most small weed seeds germinate and emerge from the top ½ inch of soil. Soil-active herbicides near the soil surface will be most available for absorption by shallow-germinating weed seeds; however, larger seeded weeds that emerge from deeper in the soil may not be controlled well by a preemergence herbicide unless it is incorporated or moved deep enough into the soil by water movement. Selectivity may be achieved by seeding the crop below the herbicide-treated zone, especially if the herbicide is root absorbed and relatively immobile in the soil.

Mechanically incorporated herbicides tend to provide more consistent weed control than surface-applied herbicides because the herbicide is in place, and adequate moisture usually is present in the soil to activate the chemical. Incorporation too deep into the soil, however, may dilute the herbicide, resulting in poor weed control. Improperly adjusted equipment or incorporation when soils are too wet may result in poor weed control.

Herbicide placement can also be used for selectivity of postemergent herbicide applications. For example, carfentrazone (Aim) can be applied post-directed in corn and cotton, but care must be taken to prevent herbicide contact with growing points of desirable plants.

Herbicide Site of Action

Herbicides work at various sites in plants. Herbicides generally interfere with a process essential for normal plant growth and development. Herbicides can be classified by site of action based on how they work and the injury symptoms they cause. WSSA has developed a numbered classification system that groups herbicides based on the site of action. This is a fluid system, and updates are made to the groupings as new information is discovered. The listings in this document reflect what is represented on herbicide labels at the time of publication (2021).

Knowledge of herbicide sites of action allows proper selection and rotation of herbicides to reduce the risk of developing herbicide-resistant weeds. It is important to note that many herbicide formulations are premixes of multiple herbicides. The herbicides, as well as their WSSA group number are listed on the product label. Classification of individual herbicides by mode of action, site of action, WSSA group number (in parenthesis), and chemical family are described in the following sections. An example of a formulation commercially available at the most recent update of this publication is listed for each product. These examples are not an endorsement of any product, nor does the omission of a product imply criticism. Key points related to herbicide use are also included, but readers should remember to read and follow all label instructions.

Lipid Synthesis Inhibitors

Group 1: ACCase Inhibitors (acetyl CoA carboxylase)

Chemical family	*Example herbicides (trade name)*
Aryloxyphenoxy-propionate	fluazifop (Fusilade DX) quizalofop (Assure II)
Cyclohexanedione	clethodim (Select) sethoxydim (Poast Plus)
Phenylpyrazolin	pinoxaden (Axial XL)

Acetyl-CoA carboxylase (ACCase)-inhibiting herbicides are used primarily for control of emerged grasses in broadleaf crops. They have little or no broadleaf activity. These herbicides are absorbed through the foliage and translocated in the phloem to the meristematic regions. The postemergence grass-control herbicides halt meristematic activity by inhibiting the ACCase enzyme that is involved in the synthesis of fatty acids. Fatty acids are essential components of cell membranes, and without them, new cells cannot be produced.

Injury symptoms caused by the ACCase inhibitors are not evident until several days after treatment, although the plants cease to grow soon after herbicide application. Fully developed leaves of treated grass plants may still look healthy for several days after treatment, but new leaves in the whorl of the plant will pull out easily, exposing decayed tissue at the base of the leaves (Photo 1). The plants will gradually turn purple, brown, and die, but older leaves may stay green for a long time.

Photo 1. *ACCase inhibitors such as Select, Poast, Fusion, and Assure are systemic herbicides that interfere with the production of new cells at the base of grass leaves. Consequently, about 1 week after treatment the new leaves can be pulled out of the whorl and the leaf tissue at the base of the leaves appears rotten.*

Photo 2. *Sublethal doses of ACCase inhibitor herbicides can cause a chlorotic band across the leaves of grasses as they emerge from the whorl of the plant.*

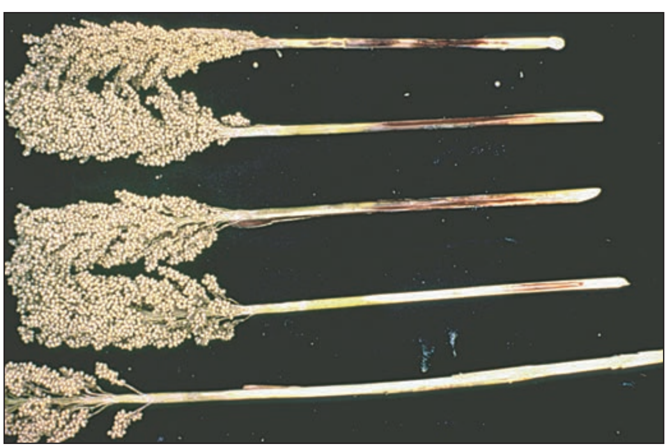


Photo 3. *Drift of ACCase inhibitors to susceptible grass crops such as grain sorghum, can partially damage and weaken the stem without completely destroying the tissue, as shown on these sorghum stems.*

Drift of sublethal rates of lipid synthesis inhibitors to susceptible grasses can cause a chlorotic band across the leaves in the whorl, damage the stems, or kill the main shoots, depending on the dosage and stage of growth of the plant (Photos 2 and 3).

Environmental and use considerations. ACCase-inhibiting herbicides are foliar applied, are short-lived in the soil, have a low water solubility, and are used at relatively low rates. Thus, they have a low leaching potential and do not pose a serious threat to the environment. Application of the postemergence grass herbicides tank-mixed with a broadleaf herbicide often results in reduced grass control, a response called antagonism. Antagonism can be overcome by applying the herbicides separately, several days apart, or by increasing the rate of the grass control herbicide in a tank mix. More than a dozen weeds in the United States have been identified with resistance to ACCase-inhibiting herbicides, although none have been officially reported in Kansas.

Amino Acid Synthesis Inhibitors

Group 2: ALS Inhibitors (acetolactate synthase)

Chemical family	*Example herbicides (trade name)*
Imidazolinone	imazamox (Beyond) imazapic (Plateau) imazapyr (Arsenal) imazaquin (Scepter) imazethapyr (Pursuit)
Pyrimindinyl-thiobenzoic acid	pyrithiobac (Staple)
Sulfonylamino-carbonyl-triazolinone	flucarbazone (Everest) propoxycarbazone (Olympus) thiencarbazone (component of Autumn Super)
Sulfonylurea	chlorimuron (Classic) chlorsulfuron (Glean) halosulfuron (Permit) iodosulfuron (Autumn) mesosulfuron (Osprey) metsulfuron (Ally) nicosulfuron (Accent) primisulfuron (Beacon) prosulfuron (Peak) rimsulfuron (Resolve) sulfometuron (Oust) sulfosulfuron (Maverick) thifensulfuron (Harmony) triasulfuron (Amber) tribenuron (Express)
Triazolo-pyrimidine	cloransulam (FirstRate) florasulam (component of Orion) flumetsulam (Python) pyroxsulam (PowerFlex HL)

Photo 4. *ALS-inhibiting herbicide injury generally appears as chlorosis and general stunting of the growing point, followed by gradual death of the plants. The tansy mustard in this wheat was treated with Glean.*

The ALS-inhibiting herbicides have a broad spectrum of selectivity and are used at low rates as soil-applied or postemergence treatments in a variety of crops. These herbicides inhibit the activity of the enzyme ALS, which is involved in the synthesis of the branched-chain amino acids (leucine, isoleucine, and valine). Amino acids are essential building blocks of proteins and are required for plant metabolism to function properly. ALS-inhibiting herbicides are readily absorbed by both roots and foliage, and they are translocated in both the xylem and phloem to the site of action at the growing points. Selectivity is based on differential metabolism and/or an altered site of action. Varieties of corn, soybean, wheat, grain sorghum, canola, and sunflower resistant to specific ALS-inhibiting herbicides are commercially available.

Injury symptoms caused by ALS-inhibiting herbicides are not apparent until several days after treatment, although susceptible plants stop growing almost immediately. Affected plants can exhibit stunting, interveinal chlorosis (Photos 4, 5, and 6), chlorotic banding on grass leaves (Photo 7), red leaf venation (Photo 8), purpling, root pruning (Photo 9), and gradual death.

Environmental and use considerations. These herbicides have exceptionally low mammalian toxicity and have minimal environmental concerns because of the low use rates. Herbicide drift and spray contamination, however, are a concern because susceptible crops are very sensitive to these chemicals. Many of the ALS-inhibiting herbicides can carry over in the soil and injure subsequent crops. Carryover of the sulfonylurea herbicides is much greater in high pH soils than low pH soils (Photo 10), while carryover of the imidazolinone and sulfonamide herbicides tends to be more likely in soils with low pH. The widespread development of ALS-resistant weed populations has decreased the utility of

Photos 5 and 6. *Some ALS-inhibiting herbicides can carry over and damage the following crop. These soybeans were damaged by Peak carryover, resulting in yellow, stunted plants (top). Planting ALS-resistant or tolerant crops can help alleviate the potential for carryover, as with the STS soybeans (sulfonylurea tolerant) planted in the background of this picture (bottom).*

Photo 7. *ALS-inhibiting herbicides, such as Basis, Resolve, Spirit, Accent, and Beacon, can sometimes cause a chlorotic band, crinkled leaves, and bending of new corn leaves coming out of the whorl, especially with cold conditions following application or when applied in conjunction with certain insecticides.*

Photo 8. *ALS-inhibiting herbicides sometimes cause a purple or red venation of leaves as evident on the underside of this soybean leaf that was treated with Classic herbicide.*

Photo 9. *ALS-inhibiting herbicide carryover can cause a proliferation of secondary roots or "bottle brushing" on susceptible crops. The roots do not function normally and shoots may be stunted and show nutrient deficiency symptoms.*

Photo 10. *ALS-inhibiting herbicide injury is sometimes confounded by iron deficiencies on high pH soils resulting in interveinal chlorosis, as evident on this grain sorghum that was treated preemergence with Peak herbicide.*

this class of herbicides over time. Populations of kochia, Palmer amaranth, waterhemp, marestail, common sunflower, shattercane, common cocklebur, Russian thistle, cheat, Japanese brome, henbit, bushy wallflower, and flixweed resistant to ALS-inhibiting herbicides have all been confirmed in Kansas.

Group 9: EPSP Synthase Inhibitor (5-enolpyruvyl-shikimate-3-phosphate)	
Chemical family	*Example herbicides (trade name)*
Organo-phosphorus	glyphosate (Roundup)

Glyphosate is readily absorbed through plant foliage and translocated in the phloem to the growing points. This herbicide inhibits the EPSPS enzyme, which is involved in the synthesis of the aromatic amino acids (tyrosine, tryptophan, and phenylalanine), which are important for cell wall production. Glyphosate is a nonselective postemergence herbicide that is inactive in the soil because of adsorption. Glyphosate-resistant crops with an alternative EPSP enzyme were the first widely adopted crops developed through genetic engineering.

Injury symptoms are not apparent until 3 to 5 days after treatment and include stunting, foliage discoloration, and slow plant death (Photo 11). Grasses exposed to a sublethal dose of ESPSP inhibitors may exhibit a chlorotic band across the leaves in the whorl of the plant. Glyphosate drift to wheat at the heading stage of growth can result in white heads and stems above the flag leaf, while the rest of the plant remains green. Some tillers may turn white while others remain green due to minor differences in developmental stage at the time of exposure (Photo 12).

Photo 11. *Glyphosate is a systemic herbicide that affects the growing points and causes a gradual discoloration and death of plants. The glyphosate drift to sorghum plants in this picture is causing different degrees of injury, including chlorotic banding of the leaves in the whorl on the center plant and purple and brown plants on either side.*

Glyphosate application can negatively impact glyphosate-resistant crops. For example, application to corn after labeled growth stages or heights causes deformed ears (Photo 13). In soybeans, applications of high rates of glyphosate may be associated with 'yellow flash' of new leaves (Photo 14), especially if plants are stressed at the time of application.

Environmental and use considerations. The EPSPS-inhibitors have exceptionally low mammalian toxicity and have minimal pollution concerns because of high adsorption to soil colloids. Herbicide drift and spray contamination are a concern because of the sensitivity of susceptible crops to these chemicals. Glyphosate resistance has been confirmed in at least 17 weed species in the United States. Several weed species have developed resistance to glyphosate in Kansas, including Palmer amaranth, marestail, waterhemp, giant and common ragweed, and kochia. Glyphosate resistance in weeds appears to be due to an altered EPSPS gene or duplication of EPSPS gene resulting in the overproduction of the EPSPS protein and weeds may have varying degrees of resistance.

Photo 12. *Glyphosate drift to wheat plants at the heading stage of growth can result in white heads and stems above the flag leaf, while the rest of the plant remains green. Wheat heads of some tillers may turn white while others remain green depending on the stage of development at exposure.*

Growth Regulators

Group 4: Synthetic Auxins

Chemical family	*Example herbicide (trade name)*
Arylpicolonate	halauxifen (Elevore)
Benzoic acid	dicamba (Clarity, Distinct, Engenia)
Carboxylic acid	aminopyralid (Milestone) clopyralid (Stinger) fluroxypyr (Starane Ultra) picloram (Tordon) quinclorac (Facet) triclopyr (Remedy)
Phenoxy	2,4-D (Enlist One, Weedmaster) 2,4-DB (Butyrac 200) MCPA

Group 19: Auxin Transport Inhibitors

Chemical family	*Example herbicide (trade name)*
Semicarbazone	Diflufenzopyr (component of Status)

Photo 13. *Glyphosate applied to Roundup Ready corn hybrids later than label specifications, may result in malformation of ears and poor seed set.*

Photo 14. *Late applications of glyphosate on glyphosate resistant-soybeans can result in chlorosis or yellow flashing of the new growth.*

Growth-regulator herbicides consist of the synthetic auxin and auxin transport inhibitor compounds, which are used primarily for controlling broadleaf weeds in grass crops and pastures and include some of the more effective chemicals for perennial broadleaf weed and brush control. Most growth regulator herbicides are readily absorbed through both roots and foliage and are translocated in both the xylem and phloem. Translocation of foliar-applied treatments, however, is more restricted in grasses than in susceptible broadleaves.

Herbicides such as dicamba, triclopyr, and 2,4-D are called growth regulators or auxin herbicides because they mimic the natural plant growth hormone auxin, and thus, upset the natural hormone balance in plants. Growth hormones regulate cell elongation, protein synthesis, and cell division. The killing action of growth-regulating chemicals is not caused by any single factor, but rather by the disruption of several growth processes in susceptible plants.

Injury symptoms on susceptible plants treated with growth regulator herbicides include growth and reproduction abnormalities, especially on new growth. Broadleaf species exhibit stem and petiole twisting (epinasty); leaf malformations, such as parallel venation, crinkling, leaf strapping, and cupping (Photos 15 and 16); stem callus formation; and stunted root growth. Grass plants exhibit rolled leaves often called onion leafing (Photo 17), fused brace roots (Photo 18), leaning stems (Photo 19), and stalk brittleness (Photo 20). Growth regulator herbicides may affect reproduction, resulting in sterile or multiple florets (Photos 21 and 22) and nonviable seed production.

Photos 15 and 16. *Growth regulator herbicides often cause abnormal leaf growth and development, such as the cupping symptom on soybean leaves from dicamba injury (top) and the puckering and parallel venation in the soybeans from 2,4-D (bottom).*

Auxin transport inhibitors such as diflufenzopyr inhibit the movement of auxinic compounds out of cells. Consequently, when combined with a synthetic auxin herbicide such as dicamba, the dicamba can move into the cells, but cannot move back out of the cell. This maintains a greater concentration of the auxinic herbicide within the cell. Diflufenzopyr has minor herbicide activity when applied alone but enhances the activity of auxinic herbicides.

Environmental and use considerations. The phenoxies are relatively short-lived in the environment and have limited pollution potential. Picloram is water soluble and persistent in the soil; consequently, it has a high leaching potential and should not be used on coarse-textured soils with a shallow water table, where groundwater contamination is most likely to occur.

Growth regulator herbicides can cause serious drift injury to susceptible plants (i.e. cucumbers, cotton, grapes, soybeans, sunflowers, and tomatoes) by both physical

Photo 17. *Grasses treated with growth regulator herbicides sometimes exhibit leaf rolling or "onion-leafing" similar in appearance to drought stress. Injury can be exaggerated by tank mixes with other herbicides or the addition of adjuvants.*

Photo 18. *Growth regulator herbicides can interfere with normal root growth as exhibited by the brace roots on this corn plant that was treated with 2,4-D.*

Photos 19 and 20. *Growth regulator herbicides such as 2,4-D and dicamba can cause the stems of grasses to lean over and become weakened after application (top), after which the stems may exhibit "goosenecking" as plants try to grow upright (bottom). May also cause complete stem breakage, called "green snap," from which plants do not recover.*

Photo 21. *Misapplied growth regulator herbicides can cause sterility, twisted awns, and head trapping in small grains, as pictured on the right.*

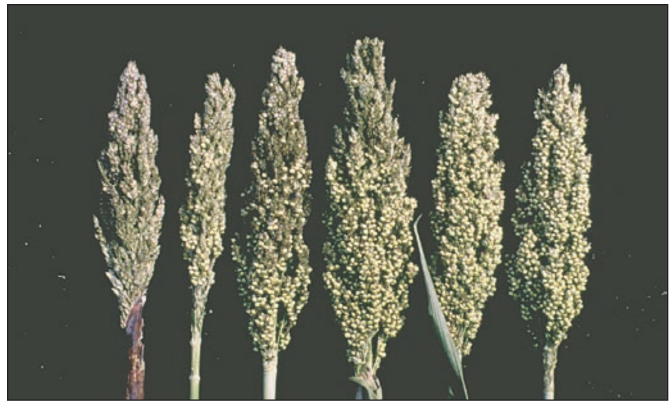


Photo 22. *Late applications of plant growth regulator herbicides such as dicamba and 2,4-D can interfere with pollination and seed production, sometimes called headblasting in sorghum. Cold night temperatures during pollination can also cause poor grain fill.*

spray drift and vapor drift. Phenoxy herbicides may be formulated as esters or amines. Esters are more volatile and are more susceptible to vapor drift. Amine formulations are less volatile and therefore less susceptible to vapor drift. Although they are less volatile, amine formulations such as Clarity, Distinct, Status, Engenia, and XtendiMax are subject to vapor drift. Engenia, and XtendiMax formulations are reduced-volatility formulations that were developed for, and are the only formulations labeled for use in, dicamba-resistant (Xtend) cotton and soybeans. Similarly, 2,4-D resistant (Enlist) corn, cotton and soybeans can be treated with the choline formulation of 2,4-D (Enlist One, Enlist Duo).

Several species with resistance to growth regulator herbicides have been identified in the United States. In Kansas, populations of kochia and Palmer amaranth have been confirmed resistant to postemergence applications in recent years.

Photosynthetic Inhibitors

Group 5: Photosystem II Inhibitors (Serine 264 binders)

Chemical family	*Example herbicide (trade name)*
Triazine	ametryn (Evik) atrazine (Aatrex) prometon (Pramitol) simazine (Princep)
Triazinone	hexazinone (Velpar) metribuzin (Sencor)
Uracil	terbacil (Sinbar) bromacil (Hyvar)
Urea	diuron (Diurex) linuron (Lorox) tebuthiuron (Spike)

Photosystem II, Site C (Group 6)	
Chemical family	*Example herbicide (trade name)*
Benzothiadiazole	bentazon (Basagran)
Nitrile	bromoxynil (Moxy)

Photosynthetic inhibitor herbicides control many broadleaf and some grass weeds. These herbicides work by disrupting photosynthesis, but there are three different binding sites. The triazines, triazinones, uracils, and phenylureas are soil-applied or early postemergence herbicides in crops and noncropland sites. These herbicides are absorbed by both shoots and roots but are translocated only in the xylem. Bentazon and bromoxynil are used primarily as early postemergence treatments. They are contact herbicides that are not translocated in the plant. Thorough spray coverage of the foliage is essential for good weed control with these herbicides.

These herbicides block photosynthesis, the food production process in plants. Plants are not affected by the herbicide until after they are exposed to light and begin photosynthesis. Even though photosynthesis is inhibited, susceptible plants do not die simply from starvation. Herbicide injury symptoms appear too quickly and are not typical of starvation. Instead, susceptible plants treated with a photosynthetic inhibitor die from a buildup of highly reactive molecules that destroy cell membranes.

The selective action of triazine herbicides is primarily determined by differential metabolism. Plant species such as corn and sorghum possess the enzyme glutathione-S-transferase and can metabolize atrazine into nontoxic substances. Crop and weed selectivity to urea herbicides, such as Linuron, is due primarily to herbicide placement rather than metabolism or differential physiological tolerance of plant species.

Injury symptoms from soil-applied treatments will not appear until after photosynthesis begins; however, plants may not fully emerge above the soil surface for photosynthesis to begin. Filtered sunlight near the soil surface may begin photosynthesis, so the plants do not fully emerge before being controlled by the herbicide. Susceptible broadleaf plants exhibit interveinal chlorosis and necrosis beginning around the leaf margins and progressing toward the center of the leaves (Photo 23). Susceptible grasses will become chlorotic and necrotic beginning at the leaf tips and progressing toward the base of the leaves (Photo 24). Injury symptoms from foliar applications will appear as leaf burn as cell membranes are destroyed. Leaf burn symptoms generally occur most rapidly with hot, humid conditions.

Photos 23 and 24 . *Photosynthetic inhibitors can cause chlorosis and necrosis around the margins of the oldest leaves of susceptible plants. Atrazine can carry over and cause damage to susceptible crops. Carryover injury is most likely on high pH soils or in areas with higher application rates such as turn row overlaps. Affected plants will emerge, followed by leaf yellowing and dieback beginning at the tips.*

Environmental and use considerations. Bentazon and bromoxynil are foliar-applied and relatively short-lived in the environment. They do not pose a serious environmental threat. The other photosynthetic inhibitor herbicides are primarily soil-applied and have longer persistence in the soil. These herbicides may contaminate surface water in regions with fine-textured soils and contaminate groundwater in regions with coarse-textured soils and shallow water tables. Resistance to photosynthesis-inhibiting herbicides has been reported for many weed species in the United States; but two-thirds of those cases have been reported for Group 5 herbicides. In Kansas, atrazine resistance has been reported for kochia, waterhemp, and Palmer amaranth.

Nitrogen Metabolism Inhibitors

Group 10: Glutamine Synthetase Inhibitors	
Chemical family	*Example herbicide (trade name)*
Phosphorylated amino acid	glufosinate (Liberty)

Glufosinate is a broad-spectrum postemergence herbicide that has no soil activity. Liberty inhibits the activity of the glutamine synthetase enzyme that is necessary for the plant to convert ammonia into other nitrogen compounds. Consequently, ammonia accumulates and glutamine levels decrease. Plant damage occurs due to ammonia toxicity and deficiency of amino acids required for other metabolic processes. Liberty has limited translocation, so thorough spray coverage of small weeds generally provides the best performance. Glufosinate-resistant (Liberty Link) crops with an alternative glutamine synthetase enzyme have been developed. Injury symptoms appear as foliar burn within several hours following application. Large weeds often initiate regrowth from axillary buds.

Environmental and use considerations. Liberty has low mammalian toxicity and minimal pollution concerns because of high adsorption to soil colloids. Perennial ryegrass is the only species for which glufosinate resistance has been confirmed in the United States (Oregon and California).

Pigment Inhibitors

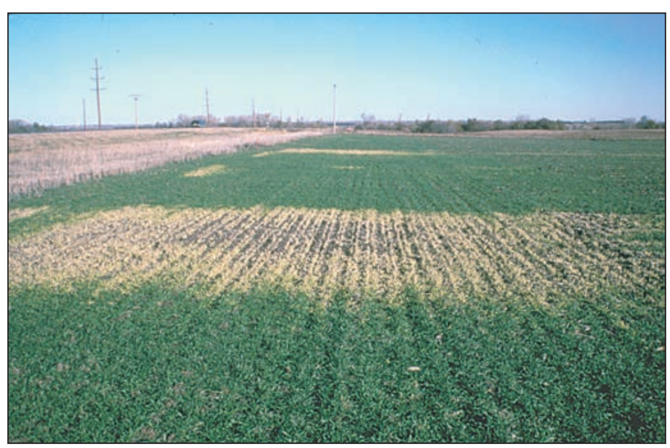
Groups 12: PDS Inhibitor (phytoene desaturase synthesis)	
Chemical family	*Example herbicide (trade name)*
Pyridazinone	norflurazone (Solicam)

Group 13: DOXP Synthesis Inhibitor (1-deoxy-D-xylulose 5-phosphate)	
Chemical family	*Example herbicide (trade name)*
Isoxazolidinone	clomazone (Command)

Group 27: HPPD Inhibitors (Hydroxyphenylpyruvate dioxygenase)	
Chemical family	*Example herbicide (trade name)*
Isoxazole	isoxaflutole (Balance Flexx)
Pyrazole	pyrasulfotole (component of Huskie)
Pyrazolone	tolpyralate (Shieldex) topramezone (Armezon)
Triketone	mesotrione (Callisto) tembotrione (Laudis) bicyclopyrone (component of Acuron)

The pigment-inhibiting herbicides interfere with pigment production and protection of chlorophyll. Ultimately, chlorophyll production is inhibited, and plant foliage turns white and appears bleached. Although injury symptoms are similar with these herbicides, the specific site of action is different. Injury symptoms from the pigment inhibitor herbicides are expressed as white to translucent foliage (Photos 25, 26, 27, 28, 29, and 30). But, similar to the photosynthesis-inhibiting herbicides, plants ultimately die from a buildup of highly reactive molecules that destroy cell membranes. Corn is tolerant to commonly used herbicides, like mesotrione (Callisto) and isoxaflutole (Balance Flexx), due to rapid metabolism. Isoxaflutole-resistant soybean varieties are available.

Environmental and use considerations. Drift to nontarget plants causes foliage to turn white. Isoxaflutole is quickly converted to a fairly soluble and persistent herbicidally active metabolite in the soil; therefore, use is restricted on coarse-textured soils with a shallow water table. Resistance to pigment-inhibiting herbicides has been identified in the United States. Palmer amaranth is the only species that has been confirmed to be resistant to HPPD-inhibiting herbicides in Kansas.



Photos 25 and 26. *Pigment inhibitor herbicides cause a bleaching symptom when the chlorophyll in the leaves is destroyed (top). Command herbicide can carry over and damage small grains, especially in areas with higher application rates (bottom).*

Photo 27. *Species susceptible to pigment inhibitors will have white or bleached foliage following emergence, as shown by this crabgrass emerging from soil treated with Balance herbicide.*

Photo 28. *Corn injury from Balance can result following cool, wet conditions on low organic matter, high pH soils.*

Photo 29. *Typical HPPD-inhibitor injury symptoms resulting from a misapplication of Callisto + methylated seed oil to emerged corn. Callisto should not be applied with methylated seed oil.*

Photo 30. *Sorghum injury from preemergence-applied Lumax or Lexar can result from excess rainfall following herbicide application and before sorghum emergence or when applied on sandy soil types. Do not use Lumax on sorghum planted in sandy soils.*

Cell Membrane Disrupters

Group 14: PPO Inhibitors (protoporphyrinogen oxidase)

Chemical family	*Example herbicide (trade name)*
Aryl triazinone	carfentrazone (Aim) fluthiacet (Cadet) sulfentrazone (Authority)
Diphenylether	aciflourfen (Ultra Blazer) fomesafen (Reflex) lactofen (Cobra) pyraflufen (Vida)
N-Phenyl-phthalimide	flumiclorac (Resource) flumioxazin (Valor)
Pyrimidinedione	saflufenacil (Sharpen)

Group 22: Photosystem I Electron Diverters

Chemical family	*Example herbicide (trade name)*
Bipyridilium	paraquat (Gramoxone) diquat (Reglone)

The cell-membrane disrupters are primarily light-activated contact herbicides. Paraquat and diquat are relatively nonselective chemicals used to control all existing vegetation and as preharvest desiccants. The PPO-inhibitor herbicides provide selective broadleaf weed control in various crops. These herbicides quickly form highly reactive compounds in the plants that rupture cell membranes, causing the fluids to leak out. Thorough spray coverage is essential for good postemergence weed control. Because they are not translocated to the roots, these herbicides are ineffective for long-term perennial weed control.

Injury symptoms can occur within 1 to 2 hours after application, appearing first as water-soaked foliage, which is followed by necrosis (browning) of the tissue

Photo 31. *Cell membrane disruptors cause foliar burn type symptoms, as exhibited by this soybean leaf treated with Cobra herbicide.*

Photo 32. *Aim and Resource herbicides frequently cause foliar burn on corn, especially when conditions are hot and humid following application.*

Photo 33. *Sorghum injury from a late application of Aim + NIS is frequently observed when conditions are hot and humid or a light dew is present at application.*

Photo 34. *Paraquat drift will cause necrotic burn spots wherever the spray droplets come in contact with plant foliage, as with this wheat that was next to a treated field.*

Photo 35. *Preemergence sulfentrazone treatments may cause a mottled chlorosis of foliage, especially with wet conditions on coarse-textured soils having high pH and low organic matter, as with these sunflowers treated with Spartan.*

wherever the spray contacts the foliage (Photos 31, 32, and 33). Symptoms appear most quickly with bright, sunny conditions at application. Drift injury appears as speckling on leaf tissue (Photo 34). Injury from soil applications or residues appears as a mottled chlorosis and necrosis (Photo 35).

Environmental and use considerations. The bipryidiliums are irreversibly adsorbed upon contact with the soil and have no soil activity. They are persistent in the soil, however, and could potentially move with the soil particles. Bipyridiliums are respiratory inhibitors and can be a significant risk to humans if inhaled or ingested. Precautions should be taken to prevent unnecessary access or exposure to these products. In the United States, resistance to PPO-inhibiting herbicides and bipyridiliums has been reported, including a population of common waterhemp in northeast Kansas with resistance to PPO-inhibiting herbicides. No instances of resistance to bipyridilium herbicides have been documented in Kansas, however, there are populations of paraquat-resistant horseweed (marestail) and grass species in the United States.

Seedling Root Growth Inhibitors

Group 3: Microtubule Inhibitors

Chemical family	*Example herbicide (trade name)*
Dinitroaniline	ethalfluralin (Sonalan) pendimethalin (Prowl H2O) trifluralin (Treflan) benefin (Balan)

Dinitroaniline herbicides are generally applied preemergence to control annual grasses and some broadleaf weeds in many crops. Trifluralin, ethalfluralin, and benefin need to be incorporated to avoid photodecomposition and volatility losses. Pendimethalin is less volatile than the other dinitroaniline herbicides and can be applied preemergence, but it generally provides better weed control when soil incorporated. The dinitroaniline herbicides are absorbed by both roots and shoots of emerging seedlings, but these herbicides are not readily translocated. The primary site of absorption and action on grass species is the germinating shoot. These herbicides are mitotic disrupters that inhibit cell division; thus, the meristematic regions, such as the growing points of stems and roots, are most affected. Selectivity may be based on metabolism, as well as herbicide placement and type of emergence of the grass species.

Injury symptoms on grass species include short, swollen coleoptiles (the emerging shoot). Injured broadleaf plants often have swollen hypocotyls (the stem below the cotyledons). Preemergence application of pendimethalin sometimes causes callus formation and brittle stems near the soil surface, which may break over during the growing season (Photo 36 and 37). Both grasses and broadleaves may have short, stubby secondary roots (Photo 38). Consequently, affected plants may be stunted and exhibit nutrient deficiency or drought symptoms because of the poorly developed root system.

Environmental and use considerations. The dinitroanilines are characterized by low solubility in water and high adsorption to soils; thus, they are not readily leached or moved in water. Resistance to microtubule-inhibiting herbicides have been reported in the United States, but none have been reported in Kansas.

Seedling Shoot Growth Inhibitors

Group 15: Very Long Chain Fatty Acid (VLCFA) Inhibitors

Chemical family	*Example herbicide (trade name)*
Acetamide	*S*-metolachlor (Dual Magnum) acetochlor (Harness) dimethenamid-P (Outlook)
Oxyacetamide	flufenacet (Define)
Pyrazole	pyroxasulfone (Zidua)
Thiocarbamate	EPTC (Eptam) triallate (Far-Go)

VLCFA herbicides are used preemergence or with shallow soil incorporation to control annual grasses and some small-seeded broadleaf weeds in a variety of crops. The VLCFAs affect susceptible weeds before emergence, but do not inhibit seed germination or control emerged plants. The primary site of absorption and action of these herbicides on broadleaf species is the roots, while the primary site of absorption and action on grass species is the shoot. The VLCFAs are not readily translocated in the plant, so herbicide placement and availability are important. In addition, thiocarbamate herbicides are volatile and need to be incorporated immediately after application to avoid excessive vapor loss. Less vapor loss occurs when thiocarbamate herbicides are applied to dry soils than when applied to moist soils. The thiocarbamates are absorbed from the soil solution or vapor phase through both roots and emerging shoots but are translocated only in the xylem.

Seedling shoot growth inhibitors target enzymes that are needed for the production of some fatty acids, which are needed for seedling growth. Dual Magnum, Degree Xtra, FulTime NXT, Warrant, and Outlook may be used in sorghum if the seed is treated with Concep seed protectant. The seed protectant increases sorghum tolerance to the acetamide herbicides by increasing metabolism of the herbicide to inactive compounds. Dual II Magnum contains a safener that increases soybean tolerance to the herbicide.

Injury symptoms on grass species include failure of the shoot to emerge from the coleoptile or whorl of the plant, giving the plant a buggy-whip appearance (Photo 39). Susceptible grass seedlings often fail to emerge from the soil. Injury symptoms on broadleaf plants include enlarged cotyledons; general stunting and a drawstring effect around the margins of the true leaves (Photo 40); restricted growth of the true leaves; and a dark-green color, a symptom sometimes referred to as bud seal. The roots become short, thick, brittle, and club shaped.

Photo 36. *Preemergence pendimethalin can cause callus formation and brittle stems on soybeans, resulting in breakage and lodging.*

Photo 37. *Slow or delayed emergence in Prowl-treated fields can cause callus formation and brittleness on sunflower stalks*

Environmental and use considerations. The thiocarbamates are characterized by low solubility in water and high adsorption to soils; thus, they are not readily leached or moved in water. The VLCFAs are more soluble and less adsorptive, but less persistent in the soil. No cases of resistance to seedling shoot growth inhibitors have been reported in Kansas; however, S-metolachlor-resistant pigweeds have been reported in Illinois and Arkansas.

Nonherbicide stresses

Occasionally, physiological crop responses to diseases, insects, or nutrient deficiencies may be mistaken for herbicide injury (Photo 41). Gather information about agronomic practices and herbicide application history before determining the cause of crop responses.

Photo 38. *DNA herbicides like Treflan and Prowl can cause poor root development and short, stubby roots, especially if misapplied.*

Photo 39. *VLCFA herbicides can cause emergence problems and distorted shoots of grasses, such as this unsafened sorghum that was treated with Dual. Only Concep-treated sorghum seed should be planted if VLCFA herbicides will be used.*

Photo 40. *VLCFA herbicides sometimes cause minor stunting and distorted leaves such as the heart-shaped leaf on this soybean plant, which resulted from acetochlor injury following cold, wet weather during emergence.*

Photo 41. *This picture shows symptoms from a disease, downy mildew, which can often be mistaken for Lumax and Lexar injury.*

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