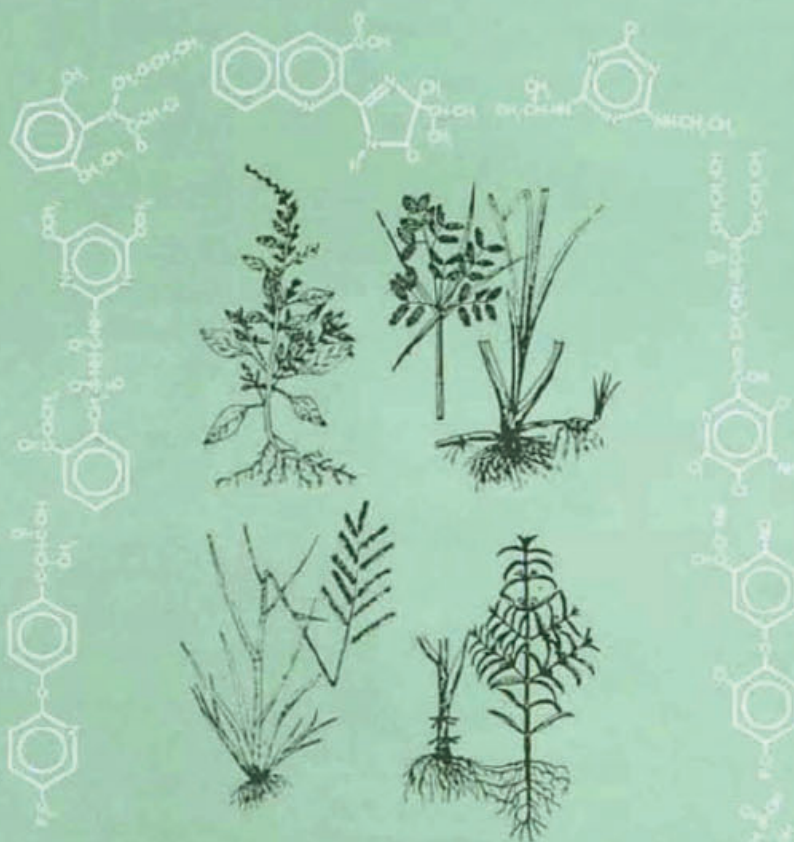


PRINCIPLES OF WEED SCIENCE

Second Edition

V. S. RAO



CRC Press
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Principles of Weed Science

Second Edition

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Dedicated to my loving wife Vallurupalli Nirmala Devi



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Preface

Currently, weed science, like the entire field of agricultural science, is going through a new era of technological change. As a consequence, weed scientists are facing newer challenges, particularly in the light of emergence of weeds resistant to herbicides, shifts in weed flora and concerns about herbicide residues in food, soil, groundwater and atmosphere. This necessitated the need to explore newer avenues of weed management technology involving preventive, cultural, ecophysiological, biological and biotechnological methods. The need to look for alternative strategies does not mean that the herbicide technology, the pivot of current weed management strategies, is expected to be abandoned. On the other hand, it necessitates increasing the levels of sophistication in research on herbicide technology which can be utilized in conjunction with other management practices.

In order for the weed scientist to do this job competently, he/she needs to gain adequate knowledge and training in agronomic, soil, genetical, biological and economic aspects of plant growth, behaviour and production, and utilize them to evolve sound weed management practices.

An effort has been made in the second edition of *PRINCIPLES OF WEED SCIENCE* to present and discuss the various advances made in the field of weed science since the publication of the first edition in 1983. This edition includes an up-to-date information on newer approaches (ecophysiological and biological) in weed management, newer herbicides, bioherbicides, herbicide action mechanisms and transformations in plants, herbicide persistence and behaviour in soil and environment and interaction of herbicides with other agrochemicals. It also contains a chapter on herbicide resistance and genetic engineering. The chapters on the practical aspects of weed science, covered in the first edition, have been retained, but updated and expanded to include the latest developments.

The second edition, like the very popular first edition, has been designed to bring out a comprehensive reference-cum-textbook on the fundamentals and basic principles of weed science. This edition, like the first edition, is expected to serve the students of weed science at undergraduate and graduate (post-graduate) levels as well as teachers, researchers and extension personnel working or interested in weed science in universities, research institutions, governmental and non-governmental organizations, herbicide industry, etc. The subject has been presented in crisp, clear-cut and simple language. As it is impossible to review the entire research done in each of the areas of weed science, I chose to include only the more useful material to bring relevance and objectivity to the subject under discussion. I also chose to exclude some topics because of space constraints.

I accept complete responsibility for choice of information, presentation, interpretation and discussion. The weed management practices suggested for different weeds and in various crop, aquatic and non-crop situations are based on published informa-

tion and experience. I cannot assume responsibility for success or otherwise of a weed management practice at a given place, crop and situation because environmental conditions, weed spectra, cropping methods, experimental techniques, application methods, etc. vary from one place to another. In view of this, the researcher may need to test a particular weed management practice under local conditions before recommending it to the user. Weeds and herbicides have been referred by the names standardized by Weed Science Society of America. If trade names of herbicides have been mentioned, it was only as a matter of convenience to the reader but not as an endorsement of a particular product. I generally followed British orthography while writing this book, except in case of certain words and common names of weeds and herbicides.

During the course of working on this edition, I have drawn heavily on the computer expertise of my beloved son Srinivas R. Vallurupalli and beloved daughter Madhavi Lata Rajavasireddy and I profusely thank them for their help and assistance. I also appreciate the encouragement and support given by my wife Nirmala Devi who ungrudgingly endured the partial loss of my company when I was busy working on the manuscript.

Santa Clara, California
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October 5, 1999

V.S. RAO

Acknowledgement

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Introduction

WEEDS: DEFINITION

Weeds are unwanted and undesirable plants which interfere with the utilization of land and water resources and thus adversely affect human welfare. They can also be referred to as plants out of place. Usually, this means that weeds grow where we either want other plants to grow or where we want no plants at all. In cropland and forests, weeds compete with the beneficial and desired vegetation, reducing the yield and quality of produce. Undesirable vegetation also flourishes in aquatic systems, forestry and non-cropped areas such as industrial sites, roadsides, railway lines, airfields, landscape plantings, water tanks, waterways, etc. Thus, all plants may become weeds in particular situations.

Weeds are an important factor in the management of all land and water resources, but their effective impact is greatest on agriculture. There is no reliable study of world-wide damage due to weeds. However, it is widely known that losses caused by weeds exceed the losses from any category of agricultural pests, such as insects, nematodes, diseases, rodents, etc. Of the total annual loss of agricultural produce from various pests, weeds account for 45%, insects 30%, diseases 20% and other pests 5%.

HARMFUL EFFECTS CAUSED BY WEEDS

Reduction in Crop Yield

Weeds compete with crop plants for nutrients, soil moisture and sunlight. The intensity of weed competition depends upon: a) type of weed species, b) severity of weed infestation, c) duration of weed infestation, d) competing ability of crop plants and e) climatic conditions which affect weed and crop growth.

Reduction in crop yield has a direct correlation with weed competition. Generally, an increase in one kilogram of weed growth corresponds to a reduction in one kilogram of crop growth. Weeds remove plant nutrients more efficiently than crop plants. In a drought situation, they thrive better than crop plants. When left undisturbed, some weeds can grow faster and taller than crop plants and inhibit tillering and branching. They can curtail sunlight and adversely affect photosynthesis and plant productivity.

Depending on the degree of competition, weeds reduce crop yields by 10% to 25%. In other words, if weed competition were completely eliminated from the entire cropland, the world's farm production could be increased by 10% to 25%. At a crop yield loss of 15% in a developing country like India, total weed control in the entire farmland would add US \$5 billion to its economy at the current price level. This figure

would be far greater if the direct and indirect impact of weeds on aquatic systems, forestry and industrial sites are also considered. This loss, if allowed to continue, amounts to a big drain in the nation's economy.

The economic impact of weeds on the US economy equals or exceeds US \$20 billion, with the agricultural sector alone accounting for US \$15 billion [3]. Parker and Fryer [11] estimated that the world was losing annually 11.5% of the total food production. That is, if all the weeds in food crops were controlled, the current world's food production would be higher by 11.5% or 450 million tons. This is too staggering a figure to be ignored by the world leaders and weed scientists.

Crop yield loss from weeds is highest in the tropics. For example, in rice, the mainstay of Asia's economy, proper weed control increases gain yields by 20% to 75%. In extreme weed situations, weed management could triple the yield of rice.

Reduction in Land Value

Heavy infestation of perennial weeds can make the land unsuitable or less suitable for cultivation, resulting in loss of its monetary value. Millions of hectares of cultivable area in the rice-growing regions of Asia have been abandoned or are not being regularly cultivated due to severe infestation of *Cyperus rotundus* (nutgrass or purple nutsedge), *Cynodon dactylon* (bermudagrass), *Imperata cylindrica* (thatchgrass, cogongrass, or alang-alang) and other perennial weeds.

Limited Choice of Crops

Crops differ in their ability to compete with weeds. In many instances the presence of particular weeds in fields limits the choice of crops to be grown. Very heavy weed infestations render some economically important crops, particularly pulses, vegetables, cotton, jute and forage crops unsuitable or less suitable for cultivation.

Loss of Quality

The quality of leafy and other vegetable crops suffers in the presence of weeds. In addition, *Allium canadense* (wild onion), *Avena fatua* (wild oats) and wild rice may impair the quality of onion, wheat and rice produce respectively. The leaves of *Mikania micrantha* may contaminate tea leaves during plucking and reduce the value of tea. Contamination of other noxious weed seeds greatly reduces the value of crop seed and grain and sometimes even renders them unsaleable. The presence of weeds and weed debris in crop grain and other farm products reduces their market value and causes spoilage during storage.

Reduced Human Efficiency

Weeds reduce human efficiency through physical discomfort caused by allergy and poisoning. Weeds such as *Parthenium hysterophorus* (parthenium), *Rhus radicans* (poison ivy) and *Ambrosia* spp. (ragweed) that cause itching, hay fever and other debilitating allergies contribute markedly to chronic human illness and suffering. The presence of spiny and thorny weeds such as *Amaranthus spinosus*, *Argemone mexicana*, *Polygonum perfoliatum*, etc. restricts movement of farm workers in carrying out, efficiently, farm practices such as fertilizer application (top-dressing), insect and disease control measures, harvesting, etc.

Increased Costs of Insect and Disease Control

Weeds serve as alternative hosts to several crop insects, nematodes and pathogens. Insects such as aphids, thrips, weevils and stem flies survive on *Brassica kaber* (wild mustard), *Daucus carota* (wild carrot), *Ambrosia* spp. (ragweed), *Amaranthus retroflexus* (redroot pigweed), etc. Weeds such as *Avena fatua* (wild oats) and some perennial grasses harbour pathogens of black stem rust of wheat. By harbouring these insects and pathogens, their attack on crop plants is increased. This results in increased cost of their control.

Problems Caused by Aquatic Weeds

Aquatic weeds reduce markedly the flow of water in irrigation and drainage canals, channels and streams. Obstruction to water flow raises water levels in canals and streams, resulting in: a) flooding, b) seepage into adjoining areas, c) breaks in canal banks and d) inadequate delivery of irrigation water to farms located at a distance from the main water source. In addition, reduced velocity of flow causes increased siltation and reduced carrying capacity, necessitating more frequent mechanical cleaning. Weeds cause enormous loss of water through transpiration. Aquatic weeds also obstruct weirs, gates and other water-regulating structures. Algae and fragments of plant material clog irrigation equipment. Aquatic weeds form breeding grounds for obnoxious insects like mosquitoes. They reduce recreational values by interfering with fishing, swimming, boating, hunting and navigation on streams and canals. Weeds on watershed areas and floodplains utilize large amounts of water and thereby deny its use for the production of food, feed and fibre. Some of the prominent aquatic weeds include *Eichhornia crassipes*, *Typha angustifolia*, *Hydrilla verticillata*, *Potamogeton* spp., *Salvinia molesta*, *Ipomoea aquatica*, *Nymphaea* spp., etc.

EVOLUTION OF WEED MANAGEMENT

Weeds are no strangers to man. Weeds have been present ever since he started to cultivate crops, around 10,000 B.C. and they were undoubtedly recognized as a problem from the beginning [6]. When man first started to grow crops for food and fibre, he soon learned that yields were much higher when weeds were removed to allow only crop plants to grow. Thus, the concept of weed management is as old as agriculture itself. Later, insects and diseases became of much greater consequence and importance. The universal occurrence of weeds as constant companions of agricultural environment as opposed to the epidemic nature of other pests, delayed recognition of the importance of weed science in crop production. From the beginning of agriculture to the middle of the 20th century, the plough and hoe have been the only widely employed means of weed control. Thus, the man with the hoe became the classical symbol of field agriculture.

As weed infestations began to seriously limit crop production, methods were devised to combat them. Thus came into existence the various manual, mechanical and biological methods and finally the chemical method of weed management. The discovery of many organic herbicides in the past 50 years enabled substantial progress in controlling weeds the world over. The emergence of herbicides has stimulated research in the economic botany of weeds and this eventually led to broader application of the technology to modern weed management.

Hay [6] identified six stages in the evolution of weed control practices, namely: a) 10,000 B.C.—removing weeds by hand, b) 6000 B.C.—the use of primitive hand tools to till the land and destroy weeds, c) 1000 B.C.—animal-powered implements like harrows, d) 1920 A.D.—mechanically-powered implements like cultivators, blades, harrows, finger-weeders, rotary hoes, rod-weeders, etc., e) 1930 A.D.—biological control and f) 1947 A.D.—chemical control, with the commercial development of organic herbicides such as 2,4-D and MCPA.

Thus, through the advances made in weed control since 10,000 B.C. man has succeeded in preventing weed competition and raising crop yield levels to feed and clothe not only himself and his family, but others as well. Holm [7] observed: 'Crop weed control is the most complex, but also the most important dimension of weed control activity, for it is from our immediate efforts here that we may have more food and fibre. Quite unseen and with the dreary stubborn patience of evil, the weeds in crops suck night and day at the soil and moisture to deprive our plants of the vigour and dry matter needed to feed and clothe the world'.

MODERN WEED SCIENCE

Commenting on the discovery of selective action of copper sulphate as a herbicide in 1890, Bolley [2] observed: 'when the farming public has accepted this method of attacking weeds as a regular farm operation, the gains to the country at large will be greater in monetary consideration than that which has been afforded by any single piece of investigation applied to field work in agriculture'. This prophecy came true some 55 years later when 2,4-D was discovered, which revolutionized agriculture so much that food shortages plaguing North America and Europe at the conclusion of World War II disappeared within a few years. Freed [5] observed that without herbicides the world would have been lacking a good many tons of grain and also that the same varieties of wheat under the same climatic conditions yielded 600-900 kg ha⁻¹ more simply due to control of weeds. He further observed that wheat could not be produced in the large acreage in eastern Oregon, USA, which was heavily infested with field bindweed (*Convolvulus arvensis*). Within a year or two of the availability of 2,4-D, this acreage was released for wheat production, something that had not been achieved in almost 15 yr of cultivation using cultural-mechanical practices. Thus, herbicides have made a significant contribution not only to agriculture in the USA and Europe in particular, but also to the world's agriculture in general.

Chandler [4] reported significant increases in the yield of rice through the application of herbicide over the unweeded treatment. The increase due to herbicide treatments was approximately equivalent to two hand weedings. In tea, chemical weed management gave significantly higher yield over manual weed control methods [1]. In Colombia, the use of herbicides improved the yield by 13% in cotton and 24% in rice over what was obtained by manual and mechanical weed control practices and the overall improvement in yields due to herbicides (over manual and mechanical methods) was 19.3% [9]. Matsunaka [10] found that weed control cost in transplanted rice was far higher when hand labour was used instead of herbicides and that tremendous savings could be effected when herbicides supplanted hand labour. These and other numerous reports world over indicate that agriculture is far more profitable when chemical weed management is adopted. Thus, even in developing countries, where the application of modern weed management technology has been slow, the man with the hoe has been replaced by the man with the spray lance.

Herbicides are considered almost synonymous with modern weed science technology as they gave a new direction to the farmer to realize the maximum yield potential of the crop at lower production costs, priorly never possible. At the same time, weed science became an intriguing and a fascinating technology. Weed scientists saw enormous scope for research to unravel the mysteries of their science in the field. Today, 52 years after the commercial development of 2,4-D and MCPA (in 1947), weed scientists have made phenomenal progress in understanding the selective action of over 400 herbicides by studying their absorption and translocation patterns, mechanisms of action in plants, degradative and detoxification mechanisms in plant and soil, interactions with other pesticides and chemicals, etc. All this has helped in making more effective, economical and safe recommendations for control of numerous weeds in different crops, aquatic systems and non-crop areas.

Currently, weed science, like the whole of agricultural science, is going through a new era of technological change. Weed scientists are now facing new challenges, particularly in the light of emergence of weeds resistant to herbicides and concerns and questions about herbicide residues in food, soil, groundwater and atmosphere. These have highlighted the need to evaluate the low-rate concept (LRC), deviate from the path of monoculture systems that rely on herbicides excessively in favour of sustainable agricultural systems incorporating the concepts of integrated weed management and explore the possibility of employing biological, ecological and cultural methods of weed management in addition to the chemical method. There is also a need to study the mid-term and long-term consequences of new weed management practices with respect to the fate of herbicides, soil weed seedbank, weed flora shifts, crop yield and quality, costs of potential control and technical feasibility, and finally the economic returns to the farmer.

Farmers are not the same worldwide. The farmer in a developing country is different from the one in a developed country. Even within a country, the farmers of one region are different from those of other regions. Yet, farmers, irrespective of where they are from, realize that they need to depend on chemical weed management technology as their main defence against weed menace, for the very successful weed control methods the world has ever seen are centred on herbicide use. The farmers need adequate technical support from weed scientists in managing their weeds in the best possible manner. Besides, weed scientists are needed to communicate effectively not only with farmers and the public, but also with politicians, government organizations and environmental groups [13] to project solutions to weed problems.

The field of weed science has now become much broader in scope than it ever was. It has evolved during the past 50 years into a separate and major field of agricultural science. The modern weed scientist is required to gain adequate knowledge in agronomic, soil, genetical, biological, ecological, physiological, biochemical, environmental, toxicological and economic aspects of plant growth, behaviour and production and utilize it to evolve a package of Integrated Weed Management (IWM) strategies comprising chemical, biological, cultural, mechanical and manual methods. IWM is described as the application of these methods of weed management in a mutually supportive manner. The IWM package should be effective enough for long-term maintenance of natural resources and agricultural productivity with minimal adverse environmental impact and adequate economic returns to farmers. In order for the weed scientist to achieve these objectives he may need to interact with specialists of other fields such as entomology, plant pathology, biotechnology and bioengineering and plant breeding. Since weeds dictate most of the crop production practices (e.g. tillage,

herbicides, cultivation, planting date and pattern, etc.), weed scientists could become the leaders of research on collaborative and integrated approaches to agricultural systems [12]. Thus, weed scientists are not only required to be experts in the science and technology of weed management, but also in the art of tilting the crop-weed balance in favour of crops.

Recently, weed scientists have been using computer science to develop computerized and bioeconomic models and database for weed management. These help in a better understanding of: a) crop yield losses due to season-long competition with one or mixed species of weeds, b) future weed infestations from either the present weed population or propagule numbers, c) aggregation and spatial variation of weed populations, d) crop-weed interactions on weed reproduction and e) interaction of microclimate on weed reproduction [12]. These models also focus on herbicide efficacy on a particular weed species or a spectrum of weeds, profitability of weed management practices, predicting weed resistance to herbicides, etc. Developing the computer database will be useful for organizing existing information, helping to identify gaps in the information and identifying processes that can be characterized and then linked to bioeconomic models, which in turn, can be used to develop and refine new hypotheses and assess weed management strategies [12].

The preceding discussion indicates that modern weed science is an amalgamated product of various disciplines of agricultural science and a vital branch of sustainable agriculture. Efforts need to be made by governments and educational institutions to accord greater recognition and importance to weed science and to train more people in this field so farmers' weed problems can be solved with increased efficacy and sophistication.

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Classification and Information on Herbicides, Bioherbicides and Herbicide Safeners

HERBICIDE CLASSIFICATION

Over 400 herbicides have been discovered and developed in the past 55 years. There is almost no weed problem that cannot be solved by herbicides. Today, high-yield agriculture heavily depends on herbicides, as they constitute a vital and integral component of weed management practices. Many of the herbicides widely used in the 1960s and 1970s have been phased out and replaced by the newer and more potent herbicides discovered later. Use of some older herbicides has been considerably restricted, reduced and even eliminated in view of environmental and toxicological problems and the availability of more effective and safer chemicals.

Herbicides (organic) are classified on the basis of: a) method of application, b) chemical affinity and structural similarity, and c) mode of action.

Classification on the basis of method of application divides herbicides into two groups: **soil-applied** and **foliage-applied**. All herbicides applied at preplanting (surface or incorporation) and preemergence (to crop, weeds, or both) are included in the soil-applied group; those applied at postemergence on the plant parts are included in the foliage-applied group.

The most common means of discovering new herbicides is by synthesizing the structural variants of a proven herbicide chemical nucleus or family. Thus, herbicides which originate from one chemical nucleus or family have structural similarities and affinities and this provides the basis for chemical classification.

Classification based on the mode of action takes into account differences in the physiological and biochemical actions of the herbicides. On this basis, they are broadly categorized as **systemic** or **translocated** herbicides and **non-systemic** or **contact** herbicides.

Herbicides may also be divided into **selective** and **nonselective** herbicides. Selective herbicides kill or suppress only certain weeds without significantly injuring an associated crop or other desirable plant species. Usually some weeds are also not injured by selective herbicides. In contrast, nonselective herbicides kill or suppress whatever vegetation (including the crop) is treated. They are used with the intention that none of the plants survive.

In recent years, another classification based on the primary site of action has been gaining wider acceptance. It is becoming more important in view of development of herbicide-resistant weeds. Knowledge on the primary site of action is useful in

planning a herbicide rotation strategy and reducing the potential for selection of resistant weeds. This classification is included in Chapter 7.

The classification considered in this Chapter includes a combination of mode of application, mode of action and chemical affinity (Fig. 5.1).

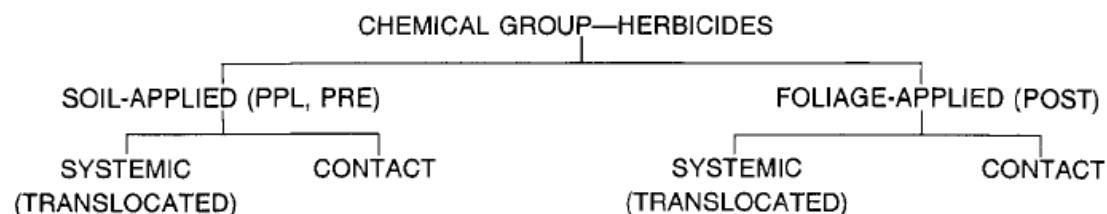


Fig. 5.1. Herbicide classification used in this chapter.

The more commonly used current herbicides belonging to 42 families (groups) are included in this classification (Table 5.1). Herbicides are referred to here by their common names.

Table 5.1. Classification of (organic) herbicides on the basis of chemical affinity, mode of application, and mode of action (herbicides not being widely used or which have been phased out were excluded).

Chemical Family	Soil-Applied Herbicides		Foliage-Applied Herbicides	
	Systemic	Contact	Systemic	Contact
ACETAMIDES	acetochlor, alachlor, dimethenamid metolachlor, napropamide, pronamide, propachlor	—	acetochlor, alachlor, dimethenamid metolachlor, napropamide, propanil	—
ALIPHATICS	—	—	dalapon	acrolein
ARSENICALS	—	—	DSMA, MSMA	cacodylic acid
BENZAMIDES	isoxaben	—	—	—
BENZOICS	dicamba	—	—	—
BENZOTHIA-DIAZOLES	—	—	—	bentazon
BIPYRIDILIUMS	—	—	—	diquat, paraquat
CARBAMATES	—	—	asulam, desmedipham, phenmedipham	—
CINEOLES	cinmethylin	—	—	—
CYCLOHEXANEDIONES	—	—	clethodim, cycloxydim, sethoxydim, tralkoxydim	—
DINITROANILINES	benefin, dinitramine, ethalfluralin, fluchloralin, isopropalin, nitratin, oryzalin, pendimethalin, prodiamine, trifluralin	—	—	—
DIPHENYLETHERS	fluorodifen, oxyfluorfen	nitrofen	acifluorfen, bifenox, fluoroglycofen fomesafen, 'actofen, oxyfluorfen	—

(Contd.)

Table 5.1 (Contd.)

Chemical Family	Soil-Applied Herbicides		Foliage-Applied Herbicides	
	Systemic	Contact	Systemic	Contact
IMIDAZOLID- INONES	buthidazole	—	buthidazole	—
IMIDAZOLIN- ONES	imazapyr, imazaquin, imazethapyr,	—	imazapyr, imazaquin, im- azethapyr, imazamethabenz	—
IMINES	—	—	CGA-248757	—
ISOXAZOLID- INONES	clomazone	—	—	—
NITRILES	—	—	—	bromoxynil, ioxynil
OXADIAZOLES	oxadiazon	—	—	—
OXADIAZOLI- DINES	methazole	—	methazole	—
PHENOLS	—	—	—	dinoseb
PHENOXYALK- ANOIC ACIDS				
Phenoxyacetics	2,4-D	—	2,4-D, MCPA	—
Phenoxybutyrics	2,4-DB	—	2,4-DB, MCPB	—
Aryloxyphenoxy propionics	—	—	dichlorprop, diclofop, fenoxaprop, fluazifop-P, haloxyfop, mecoprop, quizalofop-P	—
N-PHENYLPHT- HALIMIDES	—	—	flumiclorac	—
PHENYLPYRID- AZINES	—	—	pyridate	—
PHENYL TRIA- ZINONES	sulfentrazone	—	sulfentrazone	—
PHTHALAMATES	naptalam	—	naptalam	—
PYRAZOLIUMS	—	—	difenzoquat	—
PYRIDAZINONES	norflurazon, metflurazon, pyrazon	—	—	—
PYRIDINECARBO- XYLIC ACIDS	—	—	clopyralid, picloram, triclopyr	—
PYRIDINES	dithiopyr, thiazopyr	—	—	—
PYRIDINONES	fluridone	—	fluridone	—
PYRIMIDINYLTH- IO BENZOATES	pyrithiobac	—	pyrithiobac	—
QUINOLINE CARB- OXYLIC ACIDS	quinclorac	—	quinclorac	—
SULFONYLUREAS	bensulfuron, chlorimuron, chlorsulfuron, halosulfuron, sulfometuron	—	bensulfuron, chlorimuron, chlorsulfuron, halosulfuron, metsulfuron, nicosulfuron, primisulfuron, prosulfuron, sulfometuron, thifensulfuron, triasulfuron, tribenuron	—
TETRAHYDRO- PYRIMIDINONES	experimental compounds	—	experimental compounds	—
THIOCARBAM- ATES	butylate, diallate, EPTC, molinate, pebulate, thioben- carb, triallate, vernolate	—	—	—

(Contd.)

Table 5.1 (Contd.)

Chemical Family	Soil-Applied Herbicides		Foliage-Applied Herbicides	
	Systemic	Contact	Systemic	Contact
TRIAZINES	ametryn, atrazine, cyanazine, hexazinone, propazine, prometon, prometryn, simazine	—	—	—
TRIAZINONES	metribuzin	—	atrazine, cyanazine, hexazinone, prometon, prometryn	—
TRIAZOLES	—	—	—	—
TRIAZOLOPYR-IMIDINE SULFONANILIDES	flumetsulam	—	amitrole, amitrole-T	—
URACILS	bromacil, terbacil, UCC-C4243	—	—	—
UREAS	diuron, fluometuron, linuron, methabenzthiazuron, metoxuron, isoproturon, monuron, siduron, tebuthiuron	—	UCC-C4243	—
UNCLASSIFIED	bensulide, ethofumesate	—	diuron, fluometuron, linuron, isoproturon, tebuthiuron	—
			ethofumesate, fosamine, glufosinate, glyphosate	—

INFORMATION ON (ORGANIC) HERBICIDES¹

In this part of Chapter 5, only the more prominent and widely used organic herbicides are considered. The herbicides are referred to by their common names. While giving chemical names, the structures of herbicides are also illustrated. For each herbicide, its activity on different weed and crop species, rate and time of application, crops for which it is recommended are described. A short description of plant injury symptoms, characteristic of a herbicide group or herbicide, is given. Wherever possible, the persistence of a herbicide in the soil and method of synthesis are given. When trade names are mentioned in this book, it is only in relation to their first commercial release by the companies which originally discovered, developed and manufactured them. A list of some of the common and trade names of herbicides are given in Appendix I.

Herbicides may be divided into two groups: inorganic herbicides and organic herbicides. The inorganic herbicides include copper sulphate, sodium arsenite, sulphuric acid, ferrous sulphate, copper nitrate, ammonium sulphate, ammonium sulphamate, sodium tetraborate, sodium metaborate, amorphous sodium borate, sodium chlorate, sodium nitrate, ammonium thiocyanate, sodium chloride, etc. These were used between 1896 and 1930s. Although they are no more used as herbicides alone, a few of them are mixed with certain organic herbicides. These inorganic herbicides are not discussed here.

Organic herbicides dominate modern agriculture. Although petroleum oils have been used for several years as contact herbicides, the development of organic compounds for weed control really began with the introduction of 3,5-dinitro-O-cresol (a nitrophenol) in 1932. However, the most significant milestone in the history of organic herbicides occurred with the discovery of 2,4-D as a herbicide in 1944.

While referring to the time of application of herbicides, the following terms are abbreviated thus: **preplanting (PPL)** ; **preplanting surface (PPS)**; **early preplanting surface (E-PPS)**; **preplanting incorporated (PPI)**; **preemergence (PRE)**; **postemergence (POST)**; **early postemergence (E-POST)**; **late postemergence (L-POST)**.

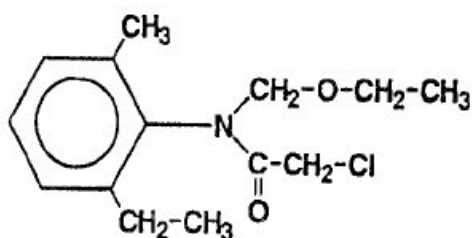
¹Main Source of Information:

Herbicide Handbook 1994. Weed Science Society of America, Champaign, IL, U.S.A., 352 pp.

Acetamides

Acetamides (acetanilides) constitute a prominent and diverse group of herbicides. Most of them are applied PRE, while others have POST activity. When applied PRE, most susceptible grass and broadleaf weeds fail to emerge. The susceptible monocots that do emerge appear twisted and malformed with leaves tightly rolled in the leaf whorl and unable to roll normally. Leaves do not emerge properly from the coleoptile but may do so underground. Broadleaf weed seedlings may have slightly cupped or crinkled leaves and shortened leaf midribs producing a drawstring effect on the leaf tip, especially under cold conditions. Other injury symptoms exhibited are discussed under individual herbicides.

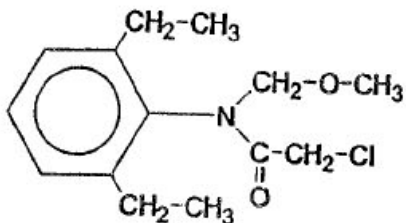
Acetochlor: 2-chloro-*N*-(ethoxymethyl)-*N*-(2-ethyl-6-methylphenyl)acetamide



Acetochlor is applied PPI or PRE at 1.5-3.0 kg ha⁻¹ in soybean and maize. A safener (MON 4600 or dichlormid) is required to preclude herbicide injury to maize. Acetochlor controls most annual grasses, *Cyperus esculentus* (yellow nutsedge) and certain broadleaf weeds. It generally provides 8-12 wk weed control, depending on soil type and weather conditions. Acetochlor residues do not persist long enough

to injure crops the following season. It is used to make packaged herbicide mixtures with atrazine. Synthesis involves ethoxy methylation of the appropriate acetanilide.

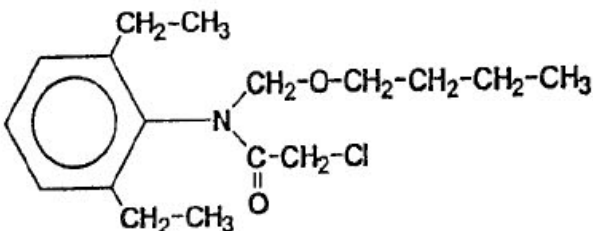
Alachlor: 2-chloro-*N*-(2,6-diethylphenyl)-*N*-(methoxymethyl) acetamide



Alachlor was the first chloroacetamide herbicide; developed in 1966, it was commercialized as LASSO in 1969 by Monsanto. It is applied PPI, PRE, or E-POST at 2-4 kg ha⁻¹ in maize, sorghum, soybean, groundnut, cotton, etc. It can also be applied E-PPI under no-till conditions and PRE in woody ornamentals. Alachlor controls *Cyperus esculentus*, and many annual grasses such as *Echinochloa crus-galli*, *Digitaria*

spp., *Setaria* spp., *Panicum* spp. and *Eleusine indica*, and certain broadleaf weeds including *Galinsoga* spp., *Chenopodium album*, *Portulaca* spp. and *Solanum nigrum*. It generally provides 6-10 wk weed control. Alachlor residues do not persist long enough to injure crops the following season. Its field half-life is 21 d. It is used to make herbicide mixtures with atrazine, glyphosate and trifluralin. The synthesis of alachlor involves methoxy methylation of the appropriate acetanilide.

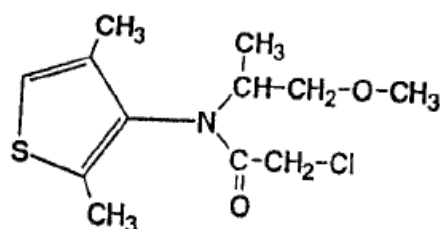
Butachlor: *N*-(butoxymethyl)-2-chloro-*N*-(2,6-diethylphenyl)acetamide



Butachlor, also a chloroacetamide herbicide, was first reported in 1970 and commercialized as MACHTE in 1971 by Monsanto. It is applied in irrigated rice within 2-5 d of transplantation of seedlings. It can be applied 10-15 d after sowing in directly seeded irrigated rice. It is also applied PRE in

rice under assured rainfall conditions. Butachlor is used in several other crops including groundnut, potato, and soybean and other pulses grown under irrigated or assured rainfall conditions. It is very effective against annual grass weeds such as *Echinochloa crus-galli*, *Digitaria sanguinalis*, *Setaria* spp., *Panicum* spp. and certain sedges. Butachlor is the most widely used rice herbicide in the world. The EC (50EC) and granular (5G) formulations are commonly used. The granular formulation is applied in combination with 2, 4-D ethyl ester granular (4G) formulation for a very broad spectrum weed control in irrigated rice. Its field half-life is 13 d. It provides weed control for 4-7 wk and does not injure crops in the following season. Butachlor is synthesized by butoxy methylation of the appropriate acetanilide.

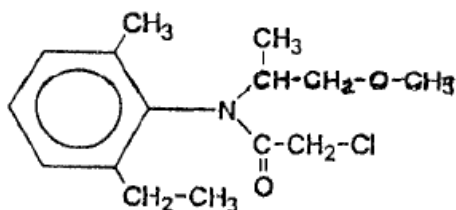
Dimethenamid: 2-chloro-*N*-[(1-methyl-2-methoxy)ethyl]-*N*-(2,4-dimethyl-thien-3-yl)-acetamide



Dimethenamid (SAN 582), a chloroacetamide herbicide, was discovered, synthesized and developed by Sandoz. It was registered as FRONTIER for use in maize in 1993 and soybean in 1994. Susceptible grass and broadleaf weeds fail to emerge. Injury to maize and sorghum can be caused by excessive rates. Affected seedlings show a malformed and twisted appearance. Leaves are tightly rolled in the whorl and may not unroll normally. Injured

soybean seedlings show cupped or crinkled leaves. It has no POST activity on established monocot and dicot seedlings. Dimethenamid is applied E-PPS PPI or PRE at 0.8-1.6 kg ha⁻¹ in maize and soybean to control many annual grasses such as *Setaria* spp., *Echinochloa crus-galli*, *Panicum dichotomiflorum* and *Digitaria* spp. as well as *Cyperus esculentus* and certain annual broadleaf weeds including *Amaranthus retroflexus* and *Solanum nigrum*. It can be used as a mixture with atrazine. Dimethenamid can be applied by conventional spraying in water or liquid fertilizer. It can be impregnated on dry bulk fertilizer. Its field half-life is 20 d. It does not injure other crops planted in the following season. A compatibility agent may be required when dimethenamid is mixed with triazine herbicides.

Metolachlor: 2-chloro-*N*-(2-ethyl-6-methylphenyl)-*N*-(2-methoxy-1-methylethyl)acetamide

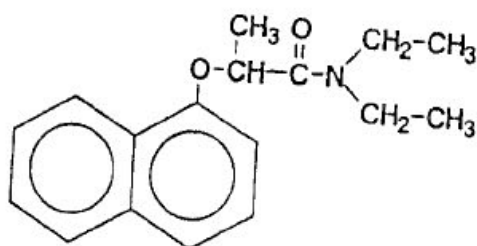


Metolachlor, was synthesized in 1976 by Ciba-Geigy and made available commercially for use in maize in 1977. It can be applied E-PPS, PPI, PRE, or E-POST at 1.5-4.0 kg ha⁻¹ in maize; PRE at 1.0-2.0 kg ha⁻¹ in cotton; PPI, POST-plant incorporated or PRE at 1.5-3.0 kg ha⁻¹ in groundnut; PRE at 1.5-3.0 kg ha⁻¹ in sorghum, safflower and soybean; and PPI, PRE or after hill formation at 1.5-3.0 kg ha⁻¹ in potato. Sequential ap-

plications allow up to 6.0-7.0 kg ha⁻¹. It is also a useful herbicide in nurseries, landscape planting and turfgrass. Metolachlor controls *Cyperus esculentus*, and many annual grass weeds such as *Setaria* spp., *Echinochloa crus-galli*, *Digitaria* spp., *Panicum dichotomiflorum*, *Brachiaria* spp., *Panicum capillare*, etc. It also controls certain broadleaf weed species including *Amaranthus retroflexus*, *Mollugo verticillata* (carpetweed), etc. It can be applied in liquid or dry bulk fertilizer. Metolachlor can be mixed with atrazine, cyanazine, flumetsulam, metribuzin, etc. When applied alone, it provides weed control

for 10-14 wk. Field half-life is 3-5 mon, but residues do not persist long enough to affect crops planted in the following season. The synthesis of metolachlor involves reductive alkylation and subsequent chloracetylation of the alkyl amine.

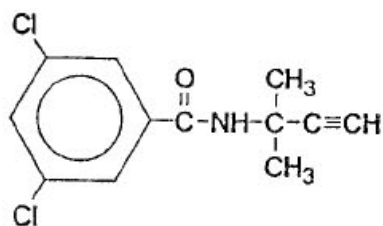
Napropamide: *N,N*-diethyl-2-(1-naphthalenyloxy)propanamide



Napropamide, a substituted amide, is applied PPI or PRE at 1.0-2.0 kg ha⁻¹ in potato, radish, turnip, watermelon, sunflower, safflower, tobacco, groundnut, cabbage, cauliflower, etc. It can also be used PRE (before weed emergence) or E-POST in fruit crops. For best results, it should be incorporated into the soil to a depth of 2-5 cm. Napropamide controls many annual broadleaf and grass weeds including seedling perennial grasses. Seedlings

of susceptible weeds fail to emerge after napropamide application. It primarily inhibits root growth, but may also inhibit shoot growth. Napropamide inhibits sprouting buds of *Cyperus rotundus* (purple nutsedge or nutgrass). Its field half-life is 70 d. When incorporated in loamy sand and loamy soils, its half-life is 8-12 wk. The synthesis of napropamide involves reacting 2-(1-naphthoxy)-propionic acid with diethyl amine under dehydrating conditions.

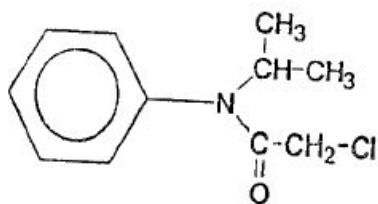
Pronamide: 3,5-dichloro(*N*-1,1-dimethyl-2-propynyl)benzamide



Pronamide is a substituted amide herbicide developed by Rohm and Haas in 1969 (as RH-315 or KERB). It is also known as propyzamide. It can be applied PRE at 1.5-4.0 kg ha⁻¹ in cotton, sunflower, groundnut, fruit crops and vegetables. It has PRE activity against many annual broadleaf and grass weeds including *Echinochloa crus-galli*, *Digitaria sanguinalis*, *Chenopodium album*, *Portulaca oleracea*, etc. It also has POST activity on some annual broadleaf and grass weeds. Its field

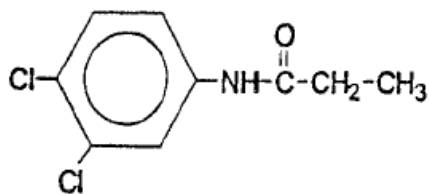
half-life is 60 d. Pronamide does not accumulate from repeated annual applications to the same soil. The synthesis of pronamide involves reaction of 3,5-dichlorobenzyl chloride with 3-amino-3-methylbutyne.

Propachlor: 2-chloro-*N*-(1-methylethyl)-*N*-phenylacetamide



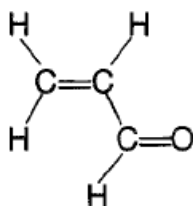
Propachlor, a chloroacetamide herbicide (discovered and developed by Monsanto as RAMROD), is applied PRE at 2.5-6.0 kg ha⁻¹ in maize and at 0.5-5.0 kg ha⁻¹ in sorghum, millets, soybean, legumes, fruit crops and ornamentals. It controls many annual grass weeds such as *Echinochloa crus-galli*, *Setaria* spp., *Panicum dichotomiflorum*, and certain broadleaf weeds such as *Amaranthus retroflexus* and *Mollugo*

verticillata. Propachlor has short persistence, with half-life of 3 d. The half-life is longer in soils high in organic matter. It does not injure rotational crops in the following season. It can be used to make a package mixture with atrazine. Propachlor is synthesized by reacting *N*-isopropyl aniline with chloroacetyl chloride.

Propanil: 2-chloro-*N*-(1-methylethyl)-*N*-phenylacetamide

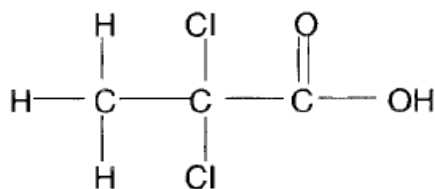
Propanil (an acetamide) was first registered in 1961. It can be applied POST (2- to 4-leaf stage) at 3.0-5.0 kg ha⁻¹ in rice and at 1.0-1.25 kg ha⁻¹ in wheat. It controls several annual broadleaf and grass weeds including *Setaria* spp., *Echinochloa crus-galli*, *Digitaria* spp., *Eleusine indica* and *Amaranthus retroflexus*. Propanil has a field half-life of 1 d. Its residues do

not injure crops planted the following season. It can be used to make mixtures with molinate. Propanil is synthesized by reacting propionic acid and 3,4-dichloroaniline to form *N*-(3,4-dichlorophenyl)propanamide. The residual 3,4-dichloroaniline is reacted with propionic anhydride, followed by vacuum distillation to remove water and residual propionic acid.

Aliphatics**Acrolein: 2-propenal**

Acrolein, also known as acrylaldehyde, was commercially developed as a herbicide during the 1930s. It is an aquatic herbicide (1-15 g L⁻¹⁰⁰, injected below the water surface) on submersed and floating weeds and algae in irrigation canals. It kills weeds by contact action. Emerging weeds are not controlled at recommended rates, but floating weeds such as *Pistia stratiotes*, *Eichhornia crassipes* and *Jussiaea* spp., are controlled when applied at 15 g L⁻¹⁰⁰

concentration for an extended period. As it is hazardous to use, acrolein is applied only by licenced applicators and trained personnel. It is persistent in water for 2-3 d depending on water temperature and pH. One application can keep a canal clean throughout the season. It is toxic to fish and wildlife and must be kept out of lakes, streams and ponds. Its half-life in water is 175 h at pH 5, 120-180 h at pH 7, and 5-40 h at pH 9. Acrolein is synthesized through vapour phase oxidation of propylene with air or oxygen in the presence of a catalyst.

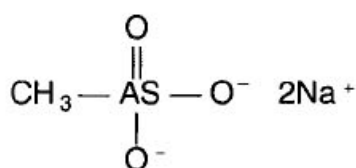
Dalapon: 2,2-dichloropropionic acid

Dalapon, a POST herbicide developed in 1953, is used for selective control of perennial grasses including *Elytrigia repens* and *Imperata cylindrica*. Repeat applications ensure their better control. It is applied in tea, coffee, sugarcane, orchard crops, etc. It is available as sodium salt.

ARSENICALS

Organic arsenical herbicides have been widely used for over 30 yr even though their herbicidal properties were discovered in 1951. As arsenicals are non-degradable in soils, they provide good control of perennial grasses. They have low to medium mobility on sandy soil and are largely immobile on other soils. The affected plants show foliar chlorosis and necrosis. Arsenicals are essentially foliage-applied herbicides, which include cacodylic acid, DSMA and MSMA. The latter two herbicides are considered for discussion here.

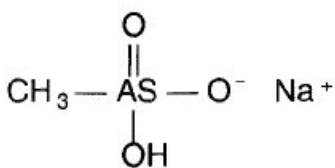
DSMA: Disodium methanearsonate



DSMA is applied POST at 3.5 kg ha⁻¹ in turf, 2.5 kg ha⁻¹ in cotton and 2.5-3.0 kg ha⁻¹ in citrus and non-crop areas. It controls *Digitaria* spp., *Paspalum dilatatum*, *Sorghum halepense*, *Cyperus rotundus*, *Setaria* spp., *Ambrosia artemisiifolia*, *Xanthium strumarium*, *Amaranthus retroflexus*, etc. A surfactant will enhance its foliage activity. Its field

half-life is 180 d. It is strongly adsorbed by soil. DSMA is used to make package mixtures with 2,4-D sodium salt.

MSMA: Monosodium methanearsonate

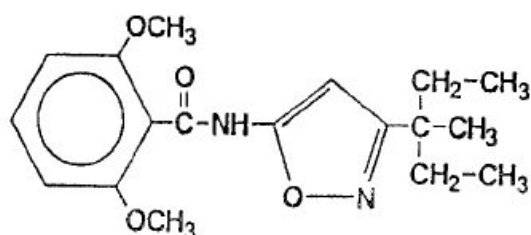


MSMA is foliage-applied at 2.5 kg ha⁻¹ in cotton, turf and non-crop areas. It controls the weed species listed under DSMA, but more effectively. A surfactant enhances its POST activity. It can be used to formulate mixtures with diuron, fluometuron, dicamba, mecoprop, 2,4-D dimethylamine, prometryn and cacodylic acid. MSMA has moderate to long

residual activity in soil, with field half-life of 180 d. It is primarily found in the top 15 cm.

Benzamides

Isoxaben: N-[3-(1-ethyl-1-methylpropyl)-5-isoxazolyl]-2,6-dimethoxybenzamide



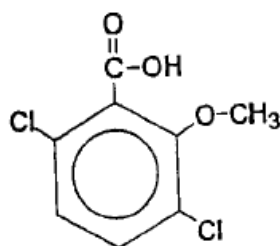
Isoxaben was discovered in 1979 and first reported in 1982. The susceptible weeds fail to emerge following PRE and POST application. Broadleaf weeds show stunting, reduced root growth, root hair distortion and root clubbing symptoms similar to those caused by dinitroaniline herbicides. Foliar application to susceptible broadleaf weeds causes growth inhibition, swelling and

cracking of the stem and petiole within 2 to 3 d. It is applied PPI at 1.5-2.2 kg ha⁻¹ before transplanting tobacco. It controls annual grasses such as *Echinochloa crus-galli*, *Digitaria* spp., *Setaria* spp., *Panicum dichotomiflorum*, etc., and broadleaf weeds including *Chenopodium album*, *Amaranthus retroflexus*, *Mollugo verticillata*, etc. Isoxaben has moderate to long residual activity, with a field half-life of 100 d. When applied at recommended rates, it degrades, however, to non-phytotoxic levels during the following season under warm, moist soil conditions. Isoxaben can be mixed with oryzalin and trifluralin.

Benzoics

The herbicidal properties of benzoics were discovered in 1958 with the invention of dicamba. They show strong plant growth-regulating activity. They are relatively strong acids and thus form salts in vitro as well as in plants and soil. Benzoics show symptoms similar to auxinic herbicides on susceptible species. These include twisting and curling of stems and petioles (epinasty), stem swelling (at nodes) and elongation, and leaf cupping. These symptoms are followed by chlorosis, growth inhibition, wilting and necrosis. Dicamba is a major herbicide among benzoics.

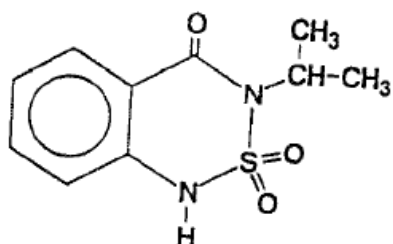
Dicamba: 3,6-dichloro-2-methoxybenzoic acid.



Dicamba can be applied PPS, PRE at 0.5 kg ha^{-1} in maize and POST at 0.25 kg ha^{-1} in maize, sorghum, wheat, turf and non-crop areas. It is available as a water-soluble alkali and applied either as a spray or granules. It controls many annual broadleaf weeds. It can be used to make mixtures with 2,4-D, mecoprop, glyphosate, MCPA, atrazine, etc. Dicamba has a field half-life of less than 14 d. It may be leached out of the zone of activity in soils of humid regions in 3-12 wk.

Benzothiadiazoles

Bentazon: 3-(1-methylethyl)-(1*H*)-2,1,3-benzothiadiazin-4(3*H*)-one,2,2-dioxide



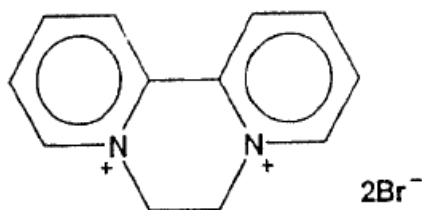
Bentazon, first reported in 1968, is available as a sodium salt formulation (BASAGRAN). It is a POST contact herbicide, used for control of certain 2,4-D-tolerant weeds in cereal crops such as maize, wheat, barley, sorghum, rice and soybean, and also to control *Cyperus* spp. Bentazon is effective against weed species of such families as Amaranthaceae, Caryophyllaceae, Compositae, Convolvulaceae, Cruciferae, Chenopodiaceae, Cyperaceae, Ambrosiaceae, Polygonaceae and Solanaceae. It is se-

lective for rice. Its efficacy is improved by adding non-ionic surfactant, oil adjuvant and ammonium sulphate. The sensitive plants show chlorosis within 3-5 d after application, followed by foliar desiccation and necrosis. Foliar bronzing may occur in tolerant crops. Its field half-life is 20 d. Its residues decline to undetectable levels within 6 wk. Bentazon has little or no residual activity. During synthesis of bentazon, anthranilic acid is reacted with *N*-isopropylamino sulfonyl chloride, followed by ring enclosure with phosgene.

Bipyridiliums

Bipyridiliums, synthesized from pyridine, are related to quaternary ammonium salts, which show phytotoxic properties. Bipyridilium quaternary salts were first evaluated by ICI, UK in 1955 and found to be highly effective, killing plants quickly on contact, since they are rapidly absorbed by the foliage. Even rainfall within 30 min of application has no adverse effect on their activity. Bipyridilium herbicides are available in the form of salts. Diquat and paraquat are the most widely used bipyridilium herbicides.

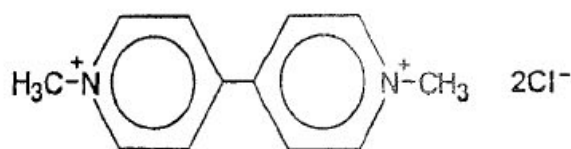
Diquat: 6,7-dihydrodipyrido[1,2- α :2',1'-c]pyrazinediium ion



Diquat, first used as a growth regulator in 1955, is available as diquat dibromide salt. It causes rapid wilting and desiccation of plants within several hours of application in full sunlight. Complete foliar necrosis occurs in 1-3 d. It is applied POST, spray-to-wet, at $0.2-0.4 \text{ kg ha}^{-1}$ to control several aquatic weeds. It can be applied to ponds, lakes, and drainage ditches for control of algae, submersed aquatic weeds such as *Utricularia* spp., *Ceratophyllum*

demersum (coontail) and *Elodea* spp., and floating weeds such as *Centella asiatica*, *Hydrocotyle* spp., *Salvinia* spp., and *Eichhornia crassipes*. Diquat can also be used for tassel control in sugarcane and as a desiccant in cotton, castor, soybean, sorghum, etc. Diquat is strongly bound to clay and hence unavailable to microbes. Its field half-life is 1000 d, but it is not taken up by plants. During synthesis of diquat, 2,2'-bipyridyl is reacted with di-*n*-propyl amine.

Paraquat: 1,1'-dimethyl-4,4'-bipyridinium ion



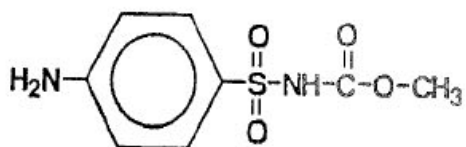
Paraquat, first used as a growth regulator in 1959, is one of the most widely used herbicides in the world. It is available as dichloride and di(methyl sulphate) salt formulations. Of the two, dichloride formulation is more widely used. It causes rapid wilting and desiccation of plants within a few hours of application, with complete necrosis occurring in 1-3 d. It is a POST, non-selective contact broad-spectrum herbicide in crop and non-crop areas. It is applied POST at 0.25-1.0 kg ha⁻¹ to control the existing vegetation at planting in no-till agriculture. It is also widely used in plantation crops such as tea, coffee, rubber, coconut, and in fruit and orchard crops. It can also be used as a post-directed spray in maize, sorghum, sugarcane, pineapple, etc. and as a general spray in non-crop areas. It can be applied as pre-harvest desiccation of potato vines and cotton. It is rapidly and tightly adsorbed by clay particles and becomes completely inactive in soil. Like diquat, paraquat is also biologically unavailable to microbes. Its half-life is 1000 d. Paraquat is synthesized by direct quaternization of 4,4'-bipyridyl with chloromethane under pressure with or without solvent. The iodide salt may be exchanged with the chloride salt or methylsulphate ion by use of ion exchange. Silver methylsulphate gives a quantitative exchange for the halide form.

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Carbamates

Carbamates are the esters of carbanilic acid. They were first discovered in 1945 with the discovery of propham. Carbamates are a diverse group of herbicides, which include alkyl- and aryl-substituted derivatives. The methyl carbamates dichlormate, karbutilate and terbutol, covered in the earlier edition, are deleted now as they are not widely used. Among the phenyl carbamate herbicides only asulam, desmedipham, and phenmedipham are discussed here.

Asulam: methyl[(4-aminophenyl) sulfonyl]carbamate.

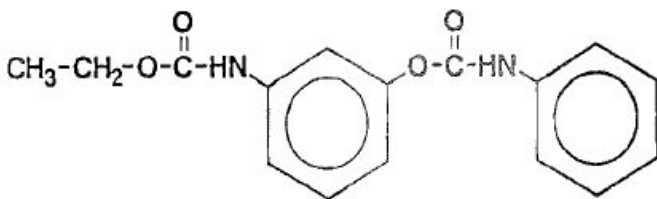


The herbicidal properties of asulam, commercially available as a sodium salt, were first discovered and reported by May and Baker in 1965. The weeds susceptible to asulam show chlorosis in young leaves and plant stunting, followed by necrosis. The growing points are usually killed

within 1-2 wk after treatment, while mature leaves senesce more slowly. Asulam is applied POST at 1.0-3.0 kg ha⁻¹ in sugarcane, plantation and orchard crops, and non-crop areas to control many grass weeds including *Sorghum halepense*, *Digitaria sanguinalis*, *Eleusine indica*, and perennial ferns including *Pteridium aquilinum* (bracken fern). Maximum efficacy is obtained when it is applied to vigorous and actively growing immature weeds. The herbicide is translocated to rhizomes to ensure excellent rapid control.

The bracken fern should be in full frond prior to asulam application. The field half-life of asulam in soil is 7 d.

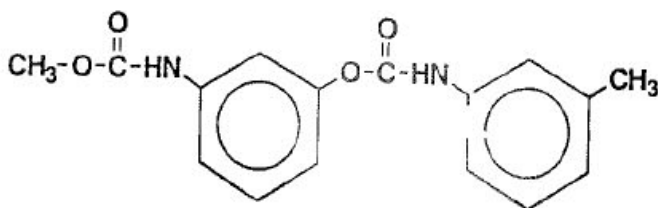
Desmedipham: ethyl{3-[(phenylamino)carbonyl]oxy}phenyl}carbamate



Desmedipham was first reported in 1969 as a POST herbicide (0.8-1.5 kg ha⁻¹) for sugarbeets to control annual broadleaf weeds such as *Sonchus arvensis*, *Solanum nigrum*, *Chenopodium album*, *Ambrosia artemisiifolia* and *Amaranthus retroflexus*. The affected leaves appear water-

soaked within a few days of application, with chlorosis and necrosis following soon thereafter. The field half-life of desmedipham is less than one month in silty loam, sandy loam and silty clay loam soils. Desmedipham is mixed with phenmedipham and ethofumesate.

Phenmedipham: 3-[(methoxycarbonyl)amino]phenyl (3-methylphenyl)carbamate

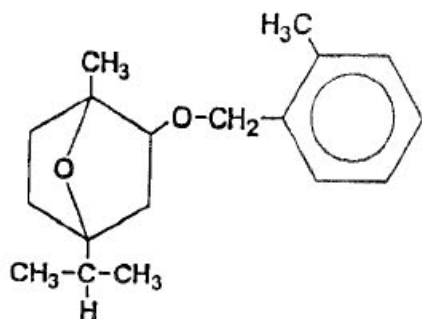


Phenmedipham was first tested in 1966 and reported in 1967 in Europe. The injury symptoms are similar to those shown by desmedipham. It is applied POST at 0.4-0.7 kg ha⁻¹ in sugarbeets and vegetable crops for control of *Setaria* spp., and annual broadleaf weeds includ-

ing *Solanum nigrum*, *Portulaca oleracea*, etc. It is used to make package mixtures with desmedipham and ethofumesate. The field half-life of phenmedipham is 44 d, but it varies with soil temperature and moisture. Soil incorporation slows phenmedipham dissipation.

Cineoles

Cinmethylin: exo-1-methyl-4-(1-methylethyl)-2-[(2-methylphenyl)methoxy]-7-oxabicyclo[2.2.1]heptane



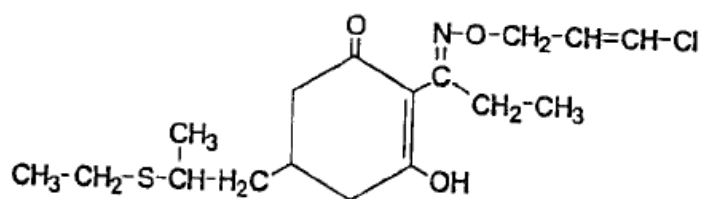
Cinmethylin, a benzyl derivative of the monoterpene 1,4-cineole, was reported in 1985 and later developed by Shell. Although a specific mechanism of action of cinmethylin has not been elucidated, its activity appears to result from the inhibition of mitosis in meristematic regions of susceptible plants. It is a PRE herbicide, effective in transplanted rice at 25-100 g ha⁻¹. It can also be applied PPI or PRE at 0.5-1.5 kg ha⁻¹ in soybean, cotton, groundnut, and certain vegetable and tree crops. It primarily controls annual grasses, but is also effective against

certain annual broadleaf weeds and sedges. Field half-life of cinmethylin is 25-78 d, increasing with organic matter content. Under anaerobic conditions prevalent in rice, its degradation is reduced because of slower microbial degradation.

Cyclohexanediones (Cyclohexenones)

The cyclohexanedione herbicides were first discovered in the 1980s. They are very effective for the control of many annual and perennial grasses. They are most effective when applied POST. Plant growth ceases soon after application, with young and actively growing leaves being affected first. Leaf chlorosis become brown and mushy at and just above the point of attachment to the node. Older leaves often turn purple, orange, or red before becoming necrotic. When applied PRE, the primary root growth is inhibited and leaves fail to emerge from the coleoptile.

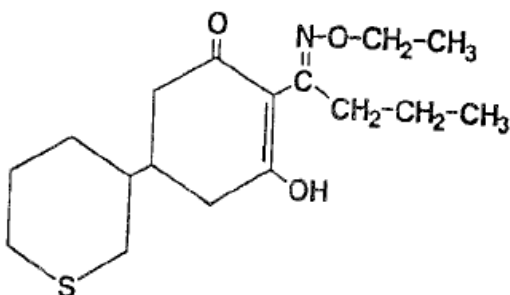
Clethodim: (*E,E*)-($\pm$)-2-[1-[(3-chloro-2-propenyl)oxy]imino]propyl]-5-[2-(ethylthio)propyl]-3-hydroxy-2-cyclohexen-1-one



Clethodim was first reported in 1987 and registered in 1991 as SELECT. It is applied POST at 0.1-0.3 kg ha⁻¹ in cotton and soybean for the control of many annual and perennial grasses. It has no activity against broadleaf weeds and

sedges. It requires an oil adjuvant for maximum activity. Clethodim is non-persistent in soil, with a half-life of 3 d. Its activity is antagonized by bentazon and acifluorfen.

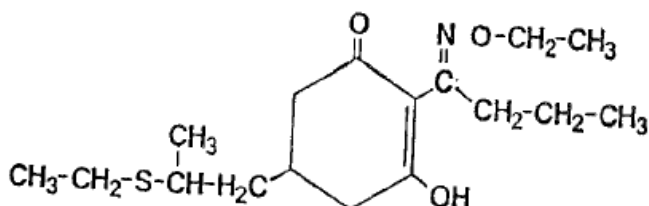
Cycloxadim: 2-[1-(ethoxyimino)butyl]-3-hydroxy-5-(2*H*-tetrahydrothiopyran-3-yl)-2-cyclohexen-1-one



Cycloxadim (formerly BAS 517H) was discovered by BASF and first reported in 1984. It is commercially available as FOCUS and LASER. Cycloxadim is applied POST at 50-400 g ha⁻¹ for control of annual and perennial grasses, with no effect on broadleaf weed species. The emerging grass seedlings are controlled immediately after application. It has a very short residual life, but half-life varies with environmental conditions. Cycloxadim

requires an oil adjuvant or surfactant for maximum efficacy.

Sethoxydim: 2-[1-(ethoxyimino)butyl]-5-[2-(ethylthio)propyl]-3-hydroxy-2-cyclohexen-1-one



Sethoxydim was discovered by Nippon Soda (Japan) and developed by BASF. It was first tested in 1978 as BAS 9052 OH. It is commercially available as POAST. Sethoxydim controls annual and perennial grasses in several broadleaf crops. It can be applied POST at 0.10-0.50 kg ha⁻¹ in al-

falfa, cotton, sunflower, etc. It can also be applied POST at 100-120 g ha⁻¹ for a preplant burndown effect in no-till soybean. At higher rates of 350-550 g ha⁻¹, it can be applied POST in ornamental trees, tree crops and non-crop areas for control of shrubs and hard-to-control weeds. Sethoxydim is rapidly degraded in soil, with an average field half-life of 5 d.

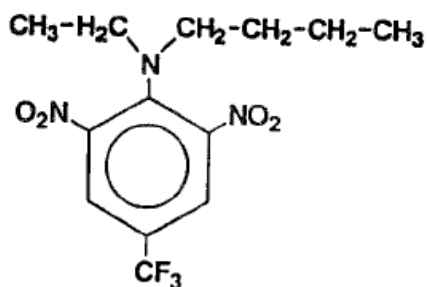
Tralkoxydim: 2-[1-ethoxyimino)propyl-3-hydroxy-5-mesitylcyclohexen-1-one

Tralkoxydim was developed by ICI, UK. Like other cyclohexanedione herbicides, it is very effective in controlling several annual and perennial grasses when used as a POST herbicide. It is applied at 0.1-0.4 kg ha⁻¹ in cotton, soybean and wheat, tea, coffee and other plantation crops, fruit and tree crops, etc. Tralkoxydim is rapidly degraded in soil, with a field half-life of 3-4 d.

Dinitroanilines

Dinitroaniline herbicides were introduced in the 1960s. Trifluralin, the first and most prominent member of this group, was introduced in 1960. The dinitroanilines are orange-yellow coloured compounds with low water solubility. They are volatile and hence need to be incorporated into the soil after application. They are widely used for selective PPI and PRE control of a wide spectrum of grasses and broadleaf weeds. The susceptible weeds fail to emerge, due to inhibition of coleoptile growth or hypocotyl unhooking. Seed germination is not inhibited. Root growth inhibition is a prominent symptom on emerged seedlings and established plants. Roots appear stubby, with tips becoming thickened. The base of grass shoots swell, appearing bulbous, and the hypocotyl may swell in broadleaf weeds. Shoots may be deformed and become brittle. Dinitroaniline herbicides are strongly adsorbed by soil.

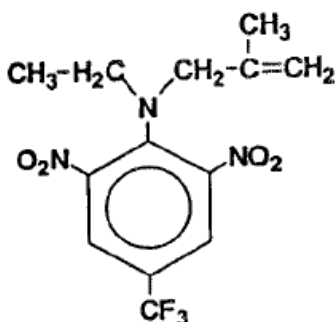
Benefin: *N*-butyl-*N*-ethyl-2,6-dinitro-4-(trifluoromethyl)benzenamine



Benefin was first described as a herbicide in 1965. It is applied PPI at 1.25-1.60 kg ha⁻¹ in groundnut, tobacco, lettuce and turf to control annual grasses such as *Echinochloa crus-galli*, *Brachiaria* spp., *Digitaria* spp., *Panicum dichotomiflorum*, *Setaria* spp. and *Cenchrus* spp., and certain annual broadleaf weeds including *Chenopodium album* and *Amaranthus* spp. It can be applied by conventional spraying or by impregnating on dry bulk fertilizer. Benefin is strongly adsorbed by soil. Its field half-life is 40 d. It controls weeds for a full season. The

crops in rotation are not affected by benefin residues. Benefin can be mixed with oryzalin. Its synthesis involves nitration of 4-(trifluoromethyl)chlorobenzene with fuming nitric acid and sulphuric acids, yielding the 2,6-dinitro derivative, which when treated with *N*-butyl-*N*-ethylamine produces the final product.

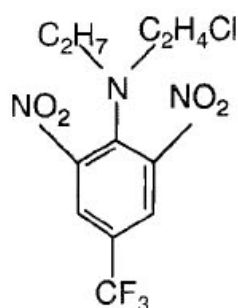
Ethalfuralin: *N*-ethyl-*N*-(2-methyl-2-propenyl)-2,6-dinitro-4-(trifluoromethyl)benzenamine



Ethalfuralin was first described as a herbicide in 1974. It is applied PPI at 0.6-1.2 kg ha⁻¹ in soybean, groundnut, sunflower and vegetables. It can be applied in standing wheat stubble and incorporated next season for the following crop in conservation tillage system. Ethalfuralin primarily controls annual grasses such as *Setaria* spp., *Echinochloa crus-galli*, *Panicum dichotomiflorum*, *Digitaria* spp., etc. and also certain broadleaf weeds such as *Amaranthus retroflexus*, *Kochia scoparia* and *Solanum nigrum*. Its field half-life is 60 d. Ethalfuralin could injure sensitive crops planted even one year after its application. Such carryover prob-

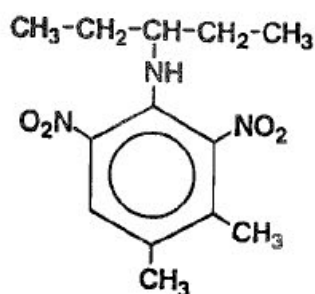
lems can be minimized by deep mouldboard ploughing before planting a sensitive crop.

Fluchloralin: *N*-(2-chloroethyl)-2,6-dinitro-*N*-propyl-4-(trifluoromethyl)aniline



Fluchloralin is a PRE herbicide used in cereal crops particularly wheat and rice, groundnut, pulse crops and many vegetable crops for selective control of many annual broadleaf weeds and grasses. The susceptible weeds are affected during germination or seedling emergence. For better results, soil incorporation is needed.

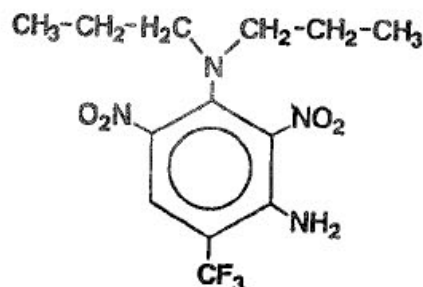
Pendimethalin: *N*-(1-ethylpropyl)-3,4-dimethyl-2,6-dinitrobenzenamine



Pendimethalin was discovered in 1971 by American Cyanamid, first reported in 1974, and registered for cotton, maize, tobacco, sorghum, wheat, peanut, sunflower, rice, sugarcane, etc. It is applied PRE or E-POST at 0.50-2.0 kg ha⁻¹ in the aforesaid crops as also potato, onion, vegetables, fruit crops, etc. It controls primarily annual grass and broadleaf weeds mentioned under ethalfluralin. Besides, it can also control *Sorghum halepense*, *Brachiaria* spp., *Abutilon theophrasti*, etc. It is mixed with imazapyr, imazaquin and oxyfluorfen. Pendimethalin has a field half-life of 44 d, but it varies with soil temperature and

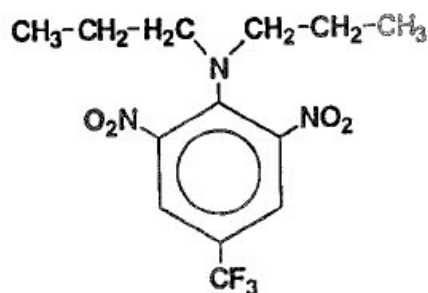
moisture. Soil incorporation slows pendimethalin dissipation.

Prodiamine: 2,4-dinitro-*N*³,*N*³-dipropyl-6-(trifluoromethyl)-1,3-benzenediamine



Prodiamine was developed in 1975. It inhibits root and shoot growth like other dinitroaniline herbicides. It is applied PRE at 0.4-1.7 kg ha⁻¹ in established turf and ornamentals. In addition to the weed species listed under isopropalin, prodiamine can also effectively control *Sorghum halepense*, *Eleusine indica* and *Euphorbia humistrata* (prostrate spurge). The field half-life of prodiamine is 120 d. During the synthesis of prodiamine, 2,4-dichlorobenzotrifluoride is subjected to nitration, dipropylamination and ammoniation.

Trifluralin: 2,6-dinitro-*N,N*-dipropyl-4-(trifluoromethyl)benzenamine



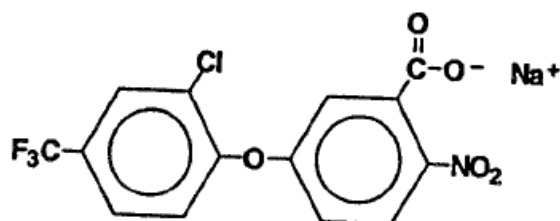
Trifluralin is the most prominent member of dinitroanilines. It was first described as a herbicide in 1960. It was widely used as a soil-applied herbicide in 1964. It was a selective herbicide used in maize, pulse crops, cotton, soybean, safflower, castor, sunflower, vegetable crops, horticultural crops, etc. It is applied PPI at 0.56-1.12 kg ha⁻¹. Soil incorporation within 24 h of application prevents vaporization losses. Trifluralin controls several annual

grasses and certain small seeded broadleaf weeds. In addition to application by conventional spraying system, trifluralin can be impregnated on dry fertilizer or applied in liquid fertilizer through chemigation (application through irrigation water) systems in maize, soybean, wheat and sorghum at $0.84\text{--}2.24\text{ kg ha}^{-1}$. It can be applied POST via chemigation at $0.84\text{--}1.40\text{ kg ha}^{-1}$ in onion, potato, sugarbeets, etc. Trifluralin is mixed with imazaquin, isoxaben, tebuthiuron, benefin, clomazone, metribuzin, triallate and alachlor. Its field half-life is 45 d on moist soils, with $< 10\%$ of the applied trifluralin remaining 1 yr after application. Residues of trifluralin applied at 1.1 kg ha^{-1} may persist long enough to injure certain rotational crops in the following season. Its mobility in the soil is low to negligible due to strong adsorption by soil.

Diphenylethers

Since the introduction of nitrofen in 1964 as a first diphenyl ether herbicide (DPE), 10 more have been developed for use in various crops including wheat, maize, rice, soybean, cotton and groundnut. These herbicides include fluorodifen, bifenox, oxyfluorfen, acifluorfen, acifluorfen methyl, fluoroglycofen, fomesafen, lactofen, nitrofluorfen and chlomethoxyfen. Many of these are applied at PRE, while others can be applied both PRE and POST. They are regarded as contact herbicides, even when applied to the soil, because they are not well translocated in plants. The leaves of susceptible plants become chlorotic and then desiccated and necrotic within 1 or 2 d. The youngest expanded leaves of tolerant crops such as soybean and groundnut also may show chlorosis and necrosis, especially at higher rates. Sublethal rates may produce foliar 'bronzing', usually on expanded leaves. Droplet drift may leave bleached spots or flecks on leaves.

Acifluorfen: 5-[2-chloro-4-(trifluoromethyl)phenoxy]-2-nitrobenzoic acid

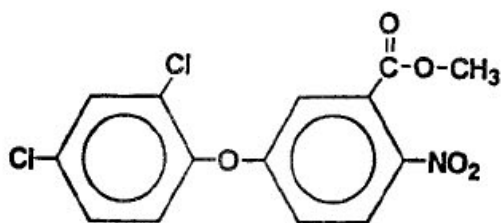


Acifluorfen is available as sodium salt. It is marketed by American Cyanamid (as SCEPTER) and BASF (BLAZER). Acifluorfen can be applied POST at $0.15\text{--}0.40\text{ kg ha}^{-1}$ in groundnut and soybean, and at 0.15 kg ha^{-1} in rice. It controls many annual broadleaf weeds including *Ipomoea* spp. (morningglory), *Solanum nigrum*, *Xanthium strumarium*

(cocklebur), *Ambrosia artemisiifolia*, *Datura stramonium* (jimsonweed), *Sesbania exaltata* (hemp sesbania), *Chenopodium album*, *Amaranthus* spp., *Polygonum* spp., *Brassica kaber*, (wild mustard), etc. and several grasses including *Setaria* spp., *Sorghum halepense*, etc. Addition of surfactants and adjuvants enhances weed control efficacy and crop injury. The half-life of acifluorfen is 14-60 d. Its residues in soil do not affect seedling emergence. Factors which promote microbial activity enhance breakdown. Acifluorfen residues do not persist in the environment. It can be used to make herbicide mixtures with bentazon.

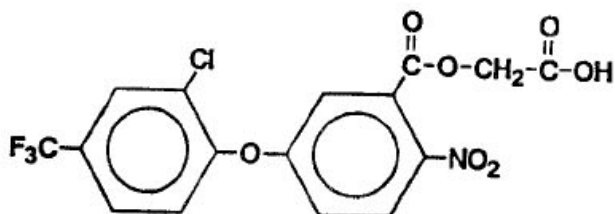
Bifenox: methyl 5-(2,4-dichlorophenoxy)-2-nitrobenzoate

Bifenox was first developed in 1973, and later marketed as MODOWN. It is used POST at $0.5\text{--}1.0\text{ kg ha}^{-1}$ in grain crops, and PRE or E-POST at $1.5\text{--}2.0\text{ kg ha}^{-1}$ in transplanted rice. It is also applied PRE in soybean and sunflower. Bifenox controls many annual broadleaf weeds such as *Kochia scoparia*, *Amaranthus* spp., *Datura stramonium*, *Polygonum*



spp., *Brassica kaber*, *Datura carota*, *Veronica* spp., etc. and grass weeds such as *Echinochloa crus-galli*, and annual sedges. The field half-life of bifenox is 7-14 d. It can control weeds for 6-8 wk, and residues do not injure susceptible crops planted 1 yr after application.

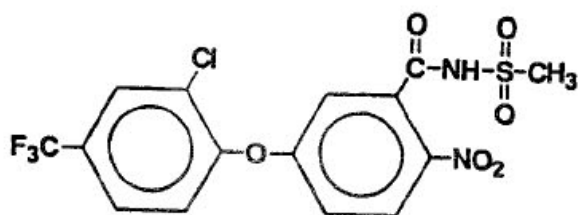
Fluoroglycofen: carboxymethyl 5-[2-chloro-4-(trifluoromethyl)phenoxy]-2-nitrobenzoate



Fluoroglycofen, also known as benzofluorfen, was developed by Rohm and Haas. It is applied as ethyl ester under the trade name COMPETE. It can be applied POST at 15-40 g ha⁻¹ in cereal crops for control of several broadleaf weeds. The half-life of fluoroglycofen is about 1 wk for PRE application and

2-3 wk for POST application. Fluoroglycofen is synthesized by reacting sodium 5-[2-chloro-4-(trifluoromethyl)phenoxy]-2-nitrobenzoate with ethyl monochloroacetate.

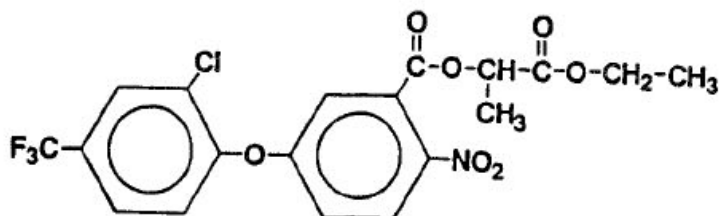
Fomesafen: 5-[2-chloro-4-(trifluoromethyl)phenoxy]-N-(methylsulfonyl)-2-nitrobenzamide



The herbicidal activity of fomesafen was first tested in 1978 by ICI, and developed in 1983. It is available as sodium salt under the trade name REFLEX. Fomesafen is applied POST at 0.25-0.40 kg ha⁻¹ in soybean to control many annual broadleaf weeds including *Ipomoea* spp., *Amaranthus* spp., *Datura stramonium*, *Brassica kaber*,

Solanum nigrum, *Ambrosia artemisiifolia*, etc. Its field half-life is 100 d and residues persist long enough to injure certain susceptible crops such as sugarbeet, sunflower and sorghum for 1 yr after application. It can be used to make a herbicide mixture with fluazifop-P butyl ester. It is synthesized by reacting the appropriate acid chloride with methane sulfonamide.

Lactofen: (±)-2-ethoxy-1-methyl-2-oxoethyl 5-[2-chloro-4-(trifluoromethyl)phenoxy]-2-nitrobenzoate

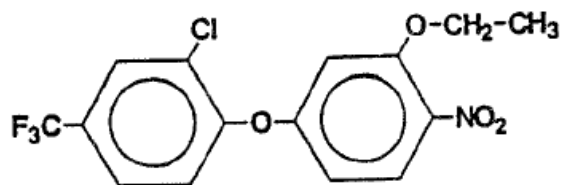


Lactofen is commercially available as COBRA. It can be applied POST at 70-200 kg ha⁻¹ in soybean and as a directed spray in cotton. It controls many annual broadleaf weeds such as *Datura stramonium*, *Brassica kaber*, *Solanum* spp., *Ambrosia* spp.,

Amaranthus spp. and *Xanthium* spp. Oil adjuvants, surfactants and fertilizer adjuvants are often added to enhance control. The half-life of lactofen is 3 d. It usually dissipates

in and around 7 d in moist soils. Residues do not injure rotational crops. As lactofen is compatible with many herbicides, it is used for making several herbicide mixtures.

Oxyfluorfen: 2-chloro-1-(3-ethoxy-4-nitrophenoxy)-4-(trifluoromethyl)benzene



The herbicidal activity of oxyfluorfen was first reported in 1975 and it was registered in 1976 as GOAL. It is applied at 0.25-2.0 kg ha⁻¹ in soybean, groundnut, cassava, leguminous crops, and plantation crops such as tea, rubber and oil palm. It is also a useful herbicide in transplanted rice, vegetables and vineries. As

a POST-directed spray, it is effective in maize, cotton, papaya, soybean, fruit trees and plantation crops. Oxyfluorfen controls many annual broadleaf weeds including *Amaranthus* spp., *Ageratum conyzoides*, *Borreria hispida*, *Commelina benghalensis*, *Portulaca oleracea*, *Chenopodium album*, etc. and annual grasses such as *Digitaria sanguinalis*, *Echinochloa crus-galli*, *Eleusine indica*, *Paspalum conjugatum*, *Axonopus compressus*, etc. It is compatible with pendemethalin and oryzalin. Oxyfluorfen is moderately persistent in soil with a half-life of 35 d. It is immobile in most soils, but slightly mobile in extremely sandy soils. During the synthesis of oxyfluorfen, 3,4-dichlorobenzotrifluoride is reacted with resorcinol. The resultant intermediate is nitrated and then ethoxylated to produce oxyfluorfen.

Imidazolidinones

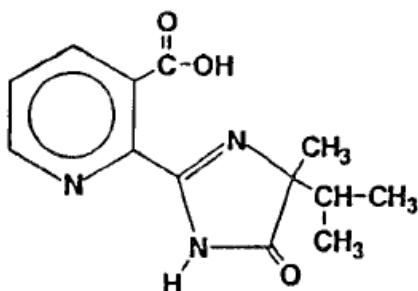
Buthidazole: 3-[5-(1,1-dimethylethyl)-1,3,4-thiadazol-2-yl]-4-hydroxy-1-methyl-2-imidazolidinone

Buthidazole is applied PRE and POST for weed control in maize, wheat, alfalfa and other crops. It is effective against numerous broadleaf weeds and grasses including *Elytrigia repens*, *Teraxacum officinale*, *Echinochloa crus-galli*, *Setaria viridis*, *Abutilon theophrasti*, *Chenopodium album*, *Amaranthus* spp., etc.

Imidazolinones

Imidazolinones are a new group of herbicides discovered by American Cyanamid in the late 1970s and 1980s. Growth inhibition by imidazolinone herbicides begins within a few hours after application and injury symptoms usually appear 1-2 wk later. Meristematic areas become chlorotic, followed by a slow foliar chlorosis and necrosis.

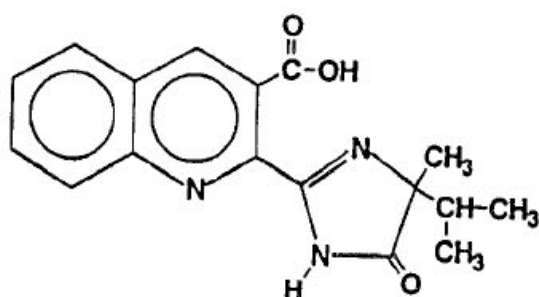
Imazapyr: 2-[4,5-dihydro-4-methyl-4-(1-methylethyl)-5-oxo-1H-imidazol-2-yl]-3-pyridinecarboxylic acid



Imazapyr was discovered in the late 1970s, its herbicidal activity found in 1981, and commercial sales begun in 1984 as ARSENAL. Imazapyr acid is formulated as isopropylamine salt. It is applied PRE and POST at 50-150 g ha⁻¹ in sugarcane and plantation crops and non-crop areas to control several annual and perennial grasses and broadleaf weeds. A non-ionic surfactant improves POST activity. Field half-life ranges from 25 to 142 d depending on soil type and environmental conditions. Weed

control efficacy persists from 3 to 24 mon depending on application rate. It can be mixed with imazaquin, trifluralin, acifluorfen, pendimethalin, etc. During synthesis of imazapyr, 2,3-pyridinecarboxylic acid undergoes dehydration (to form the anhydride), a condensation reaction, and hydrolysis. It is then cyclized (to form the imidazolinone ring) and the end product is precipitated.

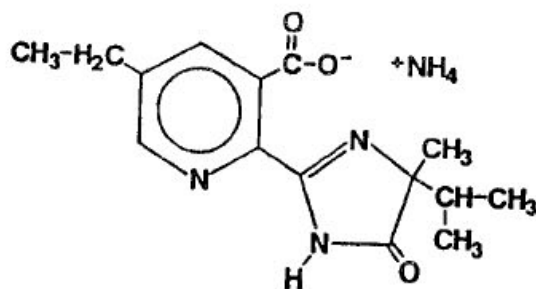
Imazaquin: 2-[4,5-dihydro-4-methyl-4-(1-methylethyl)-5-oxo-1H-imidazol-2-yl]-3-quinolinecarboxylic acid



Imazaquin was discovered in 1980, field tested in 1981 and registered in 1984 (as IMAGE and SCECTER). It was the first imidazolinone herbicide widely used. Imazaquin is commercially available as an ammonium salt. It is applied PRE or POST at 50-70 g ha⁻¹ in soybean, maize, groundnut, pulses, etc. It can be split-applied to soil PPL or PRE (35 g ha⁻¹) and POST (35 g ha⁻¹). It can control a large range of annual broadleaf weeds includ-

ing *Amaranthus* spp., *Xanthium strumarium*, *Datura stramonium*, *Kochia scoparia*, *Chenopodium album*, *Ipomoea* spp., *Solanum nigrum*, *Ambrosia* spp., *Euphorbia* spp., *Anoda cristata* and *Abutilon theophrasti* as also some annual grasses such as *Digitaria* spp., *Setaria* spp., *Echinochloa crus-galli*, *Panicum dichotomiflorum*, *Sorghum halepense*, *Sorghum bicolor* (shattercane), and certain nutsedge species. A non-ionic surfactant, oil adjuvant, or fertilizer adjuvant is required for maximum POST activity. The field half-life is 60-90 d and so planting of rotational crops may need to be delayed. It is compatible with trifluralin, imazethapyr and pendimethalin to make herbicide mixtures. During the synthesis of imazaquin, 2,3-quinoline-dicarboxylic acid undergoes dehydration (to form the anhydride), a condensation reaction, and hydrolysis. It is then cyclized to form the imidazolinone ring, and precipitated to obtain the end product.

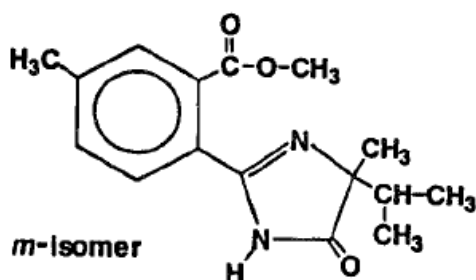
Imazethapyr: 2-[4,5-dihydro-4-methyl-4-(1-methylethyl)-5-oxo-1H-imidazol-2-yl]-5-ethyl-3-pyridinecarboxylic acid



Imazethapyr was discovered in 1981, field tested in 1987-88, and registered (HAMMER, PURSUIT) in 1989. It can be used in soybean, groundnut, peas, edible beans and imidazolinone-tolerant maize. It can be applied POST at 50-70 g ha⁻¹ in soybean, E-PPL and PRE in soybean and imidazolinone-tolerant maize. It can also be used in groundnut and edible legumes. It controls a wide spectrum of annual broadleaf and grass weeds, listed under

imazaquin. Soil persistence is similar to that described for imazaquin. It is compatible with trifluralin, pendimethalin, etc. to formulate commercial mixtures. During imazethapyr synthesis, 5-ethyl-2,3-pyridinedicarboxylic acid undergoes dehydration (to form the anhydride), a condensation reaction, and hydrolysis. It is then cyclized to form the imidazolinone ring and precipitated to obtain the end product.

Imazamethabenz: ($\pm$)-2-[4,5-dihydro-4-methyl-4-(1-methylethyl)-5-oxo-1*H*-imidazol-2-yl]-4-(and 5)-methylbenzoic acid.

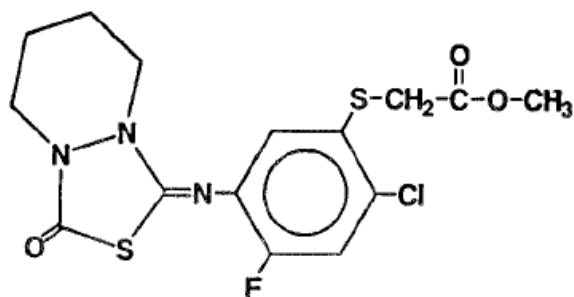


The herbicidal activity of imazamethabenz was first reported in 1982 and registered as AS-SERT by American Cyanamid in 1988. It can be applied POST at 30-50 kg ha⁻¹ in wheat and barley and 20-40 g ha⁻¹ in sunflower. It controls *Avena fatua*, *Brassica kaber*, *Descurainia sophia* (flixweed), *Sisymbrium* spp., *Polygonum convolvulus* (wild buckwheat), *Thlaspi arvense* (field pennycress), *Asperugo procumbens* (catchweed), *Poa* spp., *Galium* spp., etc.

Imazamethabenz can be applied in water or in non-phosphorous liquid fertilizer. Its POST activity can be enhanced by mixing a surfactant or oil adjuvant. Its field half-life is 25-36 d. Planting of susceptible rotational crops may need to be delayed.

Imines

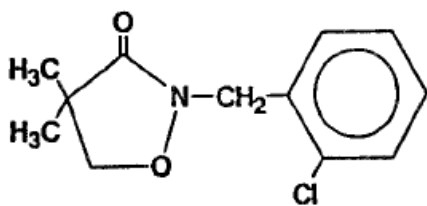
CGA-248757: methyl[[2-chloro-4-fluoro-5-[(tetrahydro-3-oxo-1*H*,3*H*-[1,3,4]thiadiazolo[3,4-*a*]pyridazin-1-ylidene)amino]phenyl]thio]acetate



CGA-248757, (also referred to as KIH-9201), was jointly developed by Kumiai and Ciba-Geigy. It can be applied POST at 3-15 g ha⁻¹ in maize and soybean for control of *Abutilon theophrasti* and certain other broadleaf weeds. Addition of a surfactant or oil adjuvant enhances its efficacy. It has no soil activity. It has a very short persistence in soil, with a half-life of 1-2 d. Synthesis of CGA-248757 involves a multistep process beginning with 2-fluoroaniline.

Isoxazolidinones

Clomazone: 2-[(2-chlorophenyl)methyl]-4,4-dimethyl-3-isoxazolidinone

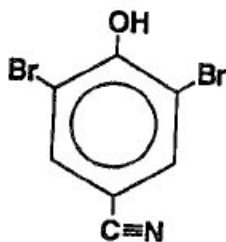


Clomazone was developed in the early 1980s and commercialized by FMC as COMMAND in 1985. Seedlings of susceptible plants emerge from clomazone-applied soil but are bleached white and become necrotic after several days. When applied POST, susceptible species exhibit foliar bleaching in later growth stages. The clomazone vapours from nearby treated areas may also cause foliar bleaching.

It is applied PPI or PRE at 0.56-1.70 kg ha⁻¹ in soybean. It is also used PRE or PPI at 0.56-1.12 kg ha⁻¹ in vegetable crops. Clomazone controls several annual broadleaf and grass weeds including *Abutilon theophrasti*, *Ambrosia artemisiifolia*, *Chenopodium album*, *Echinochloa crus-galli*, *Digitaria* spp., etc. It can be impregnated on dry bulk fertilizer, besides applying by a conventional sprayer. Its field half-life is 24 d but varies with soil type. It is less persistent in sandy loam than in silt loam or clay loam soils.

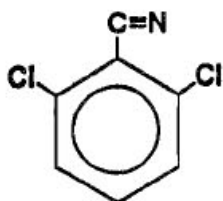
Nitriles

Bromoxynil: 3,5-dibromo-4-hydroxybenzonitrile



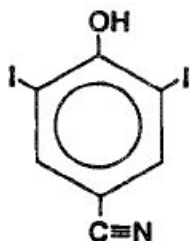
Bromoxynil, a benzonitrile herbicide, was first synthesized in Germany in 1896 and its herbicidal activity reported in 1963. It is applied POST at 0.21-0.56 kg ha⁻¹ for weed control in wheat, barley, oats, rye, triticale, maize, sorghum, etc. It is similar to ioxynil but less active. It is effective against certain broadleaf weeds such as *Chorispora tenella*, *Chenopodium album*, *Solanum spp.*, *Polygonum convolvulus*, *Brassica kaber*, *Kochia scoparia*, *Xanthium strumarium*, *Abutilon theophrasti*, *Capsella bursa-pastoris*, etc. It is also used for weed control on industrial sites, roadsides, railroad shoulders and other non-crop areas. It is applied on weeds at an early growth stage, i.e., 3- to 4-leaf stage. It can be used to make herbicidal mixtures with ioxynil, MCPA, atrazine, etc.

Dichlobenil: 2,6-dichlorobenzonitrile



Dichlobenil was discovered in the mid-1950s and its herbicidal properties were reported in 1960. It is a powerful inhibitor of germination. It is applied to the soil, with or without incorporation, at 4-8 kg ha⁻¹ in fruit and orchard crops, vineries, forest nurseries, etc. Dichlobenil is very effective against *Cyperus rotundus* and other perennial weeds which propagate through underground plant propagules like rhizomes, tubers and stolons. It also kills young seedlings of both monocot and dicot species. Dichlobenil controls many annual and perennial broadleaf and grass weeds such as *Poa annua*, *Digitaria spp.*, *Portulaca oleracea*, *Panicum spp.*, *Daucus carota* (wild carrot), *Taraxacum officinale*, *Cirsium arvense*, *Euphorbia esula*, *Elytrigia repens*, etc. It is mixed with pronamide, diuron, etc. Its field half-life is 60 d. Dichlobenil involves a single-step amoxidation of 2,6-dichlorotoluene to 2,6-dichlorobenzonitrile.

Ioxynil: 4-hydroxy-3,5-diiodobenzonitrile

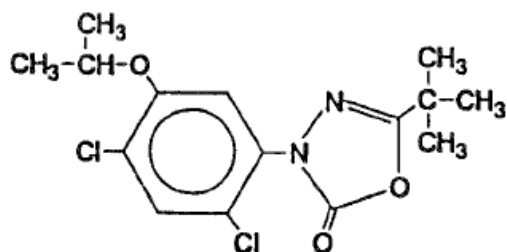


Ioxynil was first synthesized in Germany in 1896 and its herbicidal activity reported in 1963. It is applied POST in wheat, barley and rice. It is available as sodium salt and an oil-soluble amine salt formulation. It is not active through the soil. Treated plants develop blistered necrotic tissues within 24 h of application. This is followed by destruction of leaf tissue. It is normally tank-mixed with bromoxynil (0.2 + 0.2 kg ha⁻¹). Ioxynil controls weeds of Labiatae, Caryophyllaceae, Fumariaceae, Violaceae and Scrophulariaceae families better than bromoxynil. Addition of a surfactant may reduce crop selectivity.

Oxadiazoles

Oxadiazon: 3-[2,4-dichloro-5-(1-methylethoxy)phenyl]-5-(1,1-dimethylethyl)-1,3,4-oxadiazol-2-(3H)-one

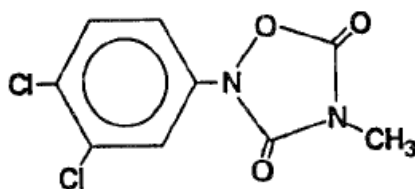
Oxadiazon, first reported in 1969 and introduced by Rhone-Poulenc, is primarily a PRE herbicide (0.50-4.0 kg ha⁻¹), although it shows some POST activity (0.5-2.0 kg ha⁻¹). It is used in rice, cotton, sugarcane, soybean, groundnut, onion, garlic, potato, sunflower, transplanted vegetables, tea, rubber and banana. It is particularly useful to control weeds that grow from bulbs, rhizomes and other deep-rooted plant propagules, including *Cynodon dactylon*, *Lolium perenne*, etc. It is effective against many annual and



broadleaf and grass weeds such as *Oxalis* spp., *Amaranthus* spp., *Richardia scabra*, *Urtica* spp., *Poa annua*, *Digitaria* spp., *Mollugo verticillata*, *Cenchrus incertus*, *Eleusine indica*, *Setaria viridis*, etc. At POST, it is active during the early growth stage of weeds. Oxadiazon has moderate to long persistence, with a field half-life of 60 d.

Oxadiazolidines

Methazole: 2-(3,4-dichlorophenyl)-4-methyl-1,2,4-oxadiazolidine-3,5-dione

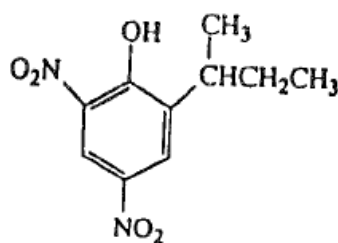


Methazole was synthesized by Sandoz (PROBE) in 1965 and its herbicidal activity reported in 1970. When applied to the foliage, it causes veinal chlorosis followed by general chlorosis and desiccation. It is a PPL, PRE and POST herbicide ($0.5-1.5 \text{ kg ha}^{-1}$), effective against a wide range of weed species, both of annual and perennial types. It is used in cotton, sorghum, maize, wheat, oats, soybean, onion, grapes and several fruit crops. The field half-life of methazole is 14 d. It generally degrades within 30-60 d. The residues do not accumulate in soil and do not injure rotational crops in the following season. It is compatible with most herbicides, including MSMA.

Phenols

Organic chemicals were first used as herbicides in 1932 when 4,6-dinitro-*O*-cresol (2-methyl-4,6-dinitrophenol) was introduced. It was widely used in Europe under the name DNOC and in the USA under the name SINOX. Dinitrophenols are widely used as uncouplers of oxidative phosphorylation. Phenols are generally active by contact action.

Dinoseb: 2-sec-butyl-4,6-dinitrophenol



Dinoseb was first described as a herbicide in 1945. It is the most toxic of substituted dinitrophenols. Its sodium salt is applied POST for selective weed control in potato, beans, peas, orchard crops, plantation crops and vineyards. It is also used as a desiccant in potato and legume crops for seed. The alkanolamine salt (PREMERGE) is applied PRE to kill germinating weeds in the topsoil layer. It can also be used POST. The parent phenol is mixed with a surfactant and used as a general contact herbicide.

Phenoxyalkanoic Acids

Phenoxyalkanoic acids and their derivatives are a major group of organic herbicides because of their selectivity and outstanding ability to be translocated within the plant.

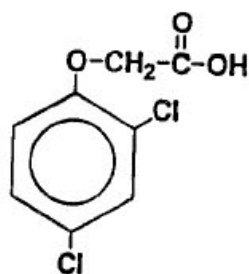
A. PHENOXYACETICS

These include 2,4-D, MCPA and 2,4,5-T. These chlorophenoxy herbicides are of historical importance because of the discovery of 2,4-D in the 1940s and the impetus

given for research on a host of organic herbicides. They have hormonal activity at low rates and bring out growth responses in regions distant from the point of application. At higher rates, they exhibit herbicidal properties. They show a fine degree of selectivity between the susceptible broadleaf weeds and the tolerant grasses, thus facilitating their use in many cereal and grass crops.

The plants susceptible to phenoxyacetics show symptoms typical of other auxin-type herbicides, and include epinastic bending and twisting of stems and petioles, stem swelling and elongation, and leaf curling and cupping. This is followed by chlorosis at the growing points, growth inhibition, wilting and necrosis. The affected plants die slowly, within 2-5 wk. At low concentrations, young leaves may appear puckered and the tips of new leaves may develop into narrow extensions of the midrib.

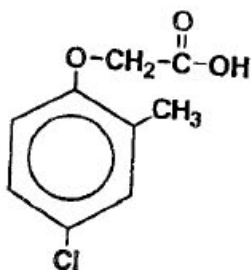
2,4-D: (2,4-dichlorophenoxy)acetic acid



The chemical synthesis of 2,4-D was described in 1941 by Pokorny and its potency as a plant hormone reported in 1942 by Zimmerman and Hitchcock. The herbicidal utility of 2,4-D was reported shortly later by American (E.J. Krause; P.C. Marth and J.W. Mitchell) and British researchers (R.E. Slade, W.G. Templeman and W.A. Serton; T.S. Nutman, H.G. Thornton and J.H. Quaster). It was commercially developed in 1947.

2,4-D is a systemic POST (0.26-2.24 kg ha⁻¹) herbicide used for control of many annual weeds in cereal crops, sugarcane, plantation crops and non-crop areas. Most dicotyledonous crops are sensitive to 2,4-D. It is also effective when applied at PRE (0.26-2.24 kg ha⁻¹) to soil for being absorbed by emerging weed seedlings. It is available in salt and ester formulations. Ester formulations (ethyl ester, butoxyethyl ester, isopropyl ester, isooctyl ester, etc.) are more volatile than salt formulations, which include those of sodium and amine salts. 2,4-D is potentially mobile but rapid degradation in soil and removal from soil by plant uptake minimizes leaching. The persistence of 2,4-D phytotoxicity is 1-4 wk in warm, moist soil. Field half-life is 10 d. It is compatible with most herbicides, making it the most widely used herbicide for making herbicidal mixtures. 2,4-D acid is prepared from 2,4-dichlorophenol and monochloroacetic acid. 2,4-D salts are made by adding the appropriate amine or inorganic hydroxide to the acid. Esters are made by reacting 2,4-D acid with the appropriate alcohols.

MCPA: (4-chloro-2-methylphenoxy)acetic acid

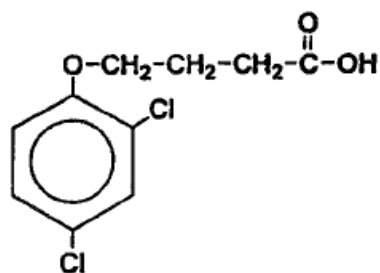


MCPA is an analogue of 2,4-D, used for selective POST (0.25-1.5 kg ha⁻¹) herbicide against broadleaf weeds. It is more selective than 2,4-D at equal rates. It is widely used in cereals, legumes and aquatic areas. It was discovered in 1945. It is available as amines, esters and sodium or potassium salts. The amines and salts are water soluble. MCPA is widely used for making herbicide mixtures with tribenuron, 2,4-D, dicamba, bromoxynil, dichlorprop, etc. It is synthesized by chlorination of *O*-cresol to produce *p*-chloro-*O*-cresol followed by coupling with monochloroacetic acid in an alkane medium.

B. PHENOXYBUTYRICS

2,4-DB: 4(2,4-dichlorophenoxy)butanoic acid

2,4-DB is a POST (0.20-0.45 kg ha⁻¹) herbicide used for selective control of several



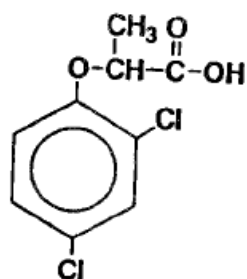
broadleaf weeds in forage legume crops. It can also be applied PRE and PPL ($0.14-0.25 \text{ kg ha}^{-1}$). It is formulated as dimethylamine salt, isooctyl ester and butoxyethyl ester. The visual injury symptoms are similar to those exhibited by 2,4-D and MCPA. A non-ionic surfactant may be needed for maximum efficacy. In addition to application by conventional spraying, 2,4-DB can be applied through sprinkler irrigation systems. Its field half-life is 5 d for the acid, 7 d for the butoxymethyl ester and 10 d for the dimethylamine salt. It can be

mixed with naptalam. 2,4-DB is synthesized by reacting 2,4-dichlorophenol with butyrolactone in the presence of concentrated NaOH.

C. ARYLOXYPHENOXY PROPIONICS

In the 1970s, a number of aryloxyphenoxy propionic (APP) acids and derivatives were synthesized by Hoechst AG. This soon led to the appearance of several heterocyclic oxypropionic acids from different companies. These compounds were found to be highly active selective herbicides giving control of grass weeds mainly in broadleaf crops. The herbicides are generally more toxic towards graminaceous plants, but tolerated by dicotyledonous and some monocotyledonous plants. They are most effective when applied POST.

The POST treatment of susceptible plants by APPs gives similar symptoms of injury. Newly formed leaves and young and actively growing tissues become visibly chlorotic usually within 2-4 d. Progressive necrosis of the meristematic tissue in the nodes and buds develops within 1-3 wk. The oldest leaves show senescent pigment changes. Growth of roots is also strongly inhibited, with damage appearing in the meristematic region of the root tip. Scattered chlorotic mottling may develop on some susceptible species and may resemble the burning effect caused by contact herbicides. With PRE application, the first leaf may emerge, turn purple and die.

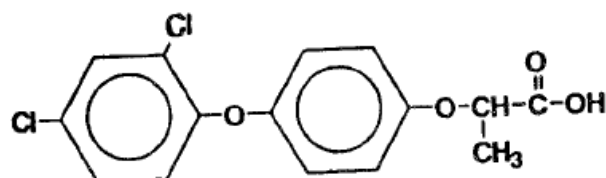


Dichlorprop: 2-(2,4-dichlorophenoxy)propanoic acid

Dichlorprop is commercially formulated as butoxyethyl and isooctyl ester, and dimethylamine salt. It is used mainly for control of general vegetation in non-agricultural areas as a POST, general spray-to-wet as well as directed application ($5-10 \text{ kg ha}^{-1}$). Dichlorprop controls many hardwood brush weeds. It was introduced as a commercial herbicide in 1961. Its average field half-life is 10 d. It is used with mecoprop, MCPA, 2,4-D and other herbicides to make package mixtures. It is synthesized by coupling 2-chloro-propionic acid with 2,4-dinitrophenol in alkaline solution.

A slight molar excess of the phenol and a pH above 9 are needed for good coupling. The acid is obtained by adjusting pH to about 4.9-5.3 and extracting to remove unreacted DCP with toluene. Dichlorprop is then released by adding HCl.

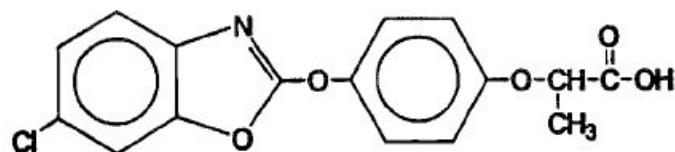
Diclofop: 2-[4-(2,4-dichlorophenoxy)phenoxy]propanoic acid



The herbicide activity of diclofop was reported in 1975. Both diclofop acid and its methyl ester formulation, diclofop methyl ester, are herbicidally active. During metabolism, diclofop methyl is hydrolyzed (demethylated) to diclofop in plants, with the former

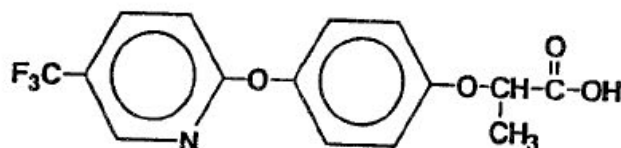
causing leaf membrane damage, and the latter causing inhibition of meristematic activity. Diclofop is applied POST (0.56-1.12 kg ha⁻¹) in wheat and barley to control certain annual grasses such as *Avena fatua*, *Setaria* spp., *Echinochloa crus-galli*, *Lolium* spp., etc. At higher doses, it gives a fairly good control of *Cynodon dactylon*. It may also be applied at PRE (0.75-1.25 kg ha⁻¹). Most broadleaf agronomic and horticultural crops are tolerant to diclofop. The average field half-life of diclofop parent acid is 30 d at pH 7.0.

Fenoxaprop: 2-[4-[(6-chloro-benzoxazolyl)oxy]phenoxy]propanoic acid



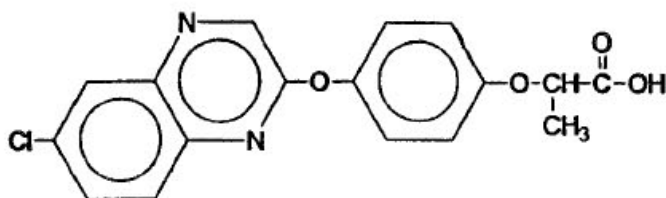
The herbicidal properties were first reported in 1982. It is commercially available as an ethyl ester. It is applied at POST (30-100 g ha⁻¹) in soybean and turf. Fenoxaprop by itself may be phytotoxic to wheat and other crops, but it shows selectivity when applied with 2,4-D, MCPA, thifensulfuron and tribenuron which antagonize its activity. It controls many annual and some perennial grass weeds with no injury to broadleaf weeds. The field half-life of fenoxaprop is 5-14 d depending on soil type.

Fluazifop-P: (R)-2-[4-[[5-(trifluoromethyl)-2-pyridinyl]oxy]phenoxy]propanoic acid



Fluazifop-P, commercially available as butyl ester formulation (FUSILADE), was discovered by Ishihara Sangyo Kaishi, Ltd., Japan, and developed jointly by ICI (now Zeneca) UK. It was first tested for herbicidal activity in 1981. Fluazifop-P is applied POST (50-200 g ha⁻¹) in cotton, soybean, wheat, tea, coffee, tree crops, etc. for control of several annual and perennial grasses including *Echinochloa crus-galli*, *Digitaria* spp., *Bromus tectorum*, *Panicum* spp., *Setaria* spp., *Cynodon dactylon*, *Imperata cylindrica*, *Sorghum bicolor*, *Elytrigia repens*, *Sorghum halepense*, etc. It has no activity against broadleaf weed species. An oil adjuvant or non-ionic surfactant enhances efficacy of fluazifop-P. Its average field half-life is 15 d. Although several methods are used to synthesize fluazifop-P, one method includes reaction of 4-(5-trifluoromethyl-2-pyridyloxy)-phenol with butyl 2-chloropropionate with a base.

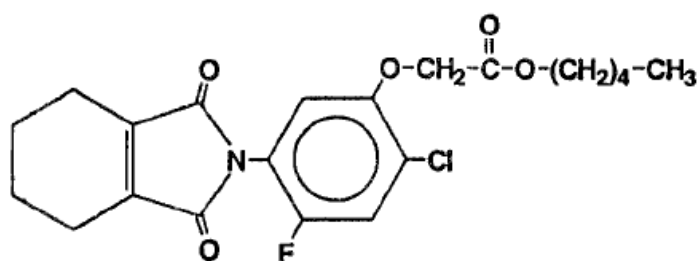
Quizalofop-P: (R)-2-[4-[(6-chloro-2-quinoxalinyloxy]phenoxy]propanoic acid



Quizalofop-P was first registered in the late 1980s in soybean and the early 1990s in cotton. It is commercially available as ethyl ester formulation (ASSURE). It provides POST control of annual and perennial grass weeds in soybean ($35\text{--}80\text{ g ha}^{-1}$) and non-crop areas ($75\text{--}100\text{ g ha}^{-1}$). The grass weeds include *Sorghum halepense*, *Cynodon dactylon*, *Elytrigia repens*, *Muhlenbergia frondosa* (a fern), etc. A non-ionic surfactant or oil adjuvant is required for maximum efficacy. Quizalofop may suppress or control grass weeds germinating after a POST application, but the degree of suppression or control is related to herbicide rate, soil type and environmental conditions. Its field half-life is 60 d.

N-Phenylphthalimides

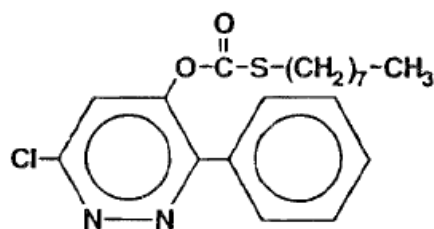
Flumiclorac: [chloro-4-fluoro-5-(1,3,4,5,6,7-hexahydro-1,3-diazo-2*H*-isoindol-2-yl)phenoxy]acetic acid



Flumiclorac was discovered in 1981 by Sumitomo, Japan. It is commercially available as a phenyl ester formulation under its trade names RESOURCE and SUMIVERDE. The susceptible plants exhibit injury symptoms within 1 d under bright sunlight, followed by wilting and bleaching. The leaves then become brown, desiccated and necrotic. It is applied POST at $30\text{--}60\text{ g ha}^{-1}$ in soybean and maize to control *Abutilon theophrasti*, *Chenopodium album*, *Ambrosia artemisiifolia*, *Amaranthus* spp., *Euphorbia maculata*, etc. Flumiclorac is extremely non-persistent with half-lives ranging from 1–6 d, with no rotational crop restrictions. During its synthesis, pentyl 2-chloro-4-fluoro-5-aminophenoxyacetate is treated with 3,4,5,6-tetrahydrophthalic anhydride to obtain the phenyl ester of flumiclorac.

Phenylpyridazines

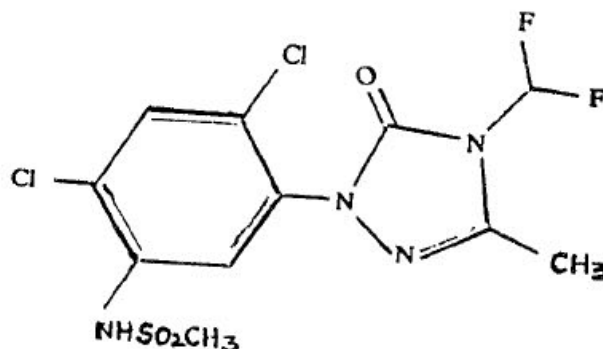
Pyridate: O-(6-chloro-3-phenyl-4-pyridazinyl) S-octyl carbonothioate



Pyridate (TOUGH) was discovered in 1974. It can be applied POST $1.0\text{--}1.5\text{ kg ha}^{-1}$ in groundnut, maize, rice, onion, alfalfa, grassland, rapeseed, orchards, vineyards and some vegetables. The susceptible plants show withering at leaf edges and the effect is complete within 5–10 d. It is non-persistent in soil, with a half-life of 7–21 d. During the synthesis of pyridate, 3-phenyl-pyridazine-6 is chlorinated and then saponified to produce 3-phenyl-4-hydroxy-6-chloropyridazine which is further reacted to produce the final product.

Phenyl Triazinones (Aryl Triazinones)

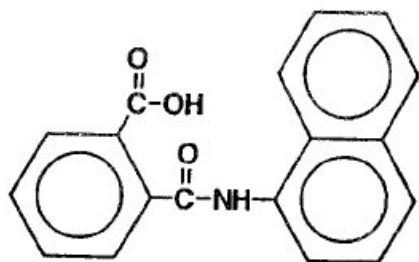
Sulfentrazone: *N*-(2,4-dichloro-5-[4-(difluoromethyl)-4,5-dihydro-3-methyl-5-oxo-1*H*-1,2,4-triazol-1-yl]phenyl)methane sulfonamide



Sulfentrazone (F6285, FMC97285) is a new phenyl triazinone herbicide introduced in 1991, field tested from 1991 to 1997 and registered in 1998 for soybean by the FMC corporation. It can be applied PPI and PRE at 60-90 g ha⁻¹ for control of several broadleaf weeds including *Ipomoea hederacea* (morningglory), *Cassia occidentalis* (coffee senna), *Sida spinosa* (prickly sida), *Cucumis melo* (smell melon), *Acalypha ostryifolia*, etc. Other crops tolerant to sulfentrazone include tobacco, sugarcane and some species of turfgrass. It is also used POST (140 g ha⁻¹) to control a broad spectrum of weeds. Several sensitive weeds may be controlled by foliar application of sulfentrazone at as low as 18 g ha⁻¹. Its POST activity can be enhanced by a surfactant to control several weeds including *Cyperus esculentus*, *Abutilon theophrasti*, etc. at 34-56 g ha⁻¹.

Phthalamates

Naptalam: 2-[1-naphthalenylamino]carbonyl]benzoic acid

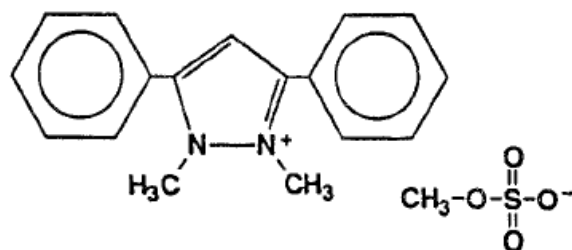


Naptalam was discovered by Uniroyal in 1947 and first registered as a herbicide in 1956. It can be applied PRE or POST at 2.0-4.0 kg ha⁻¹ to control many annual broadleaf weeds such as *Chenopodium album*, *Amaranthus* spp., *Ambrosia artemisiifolia*, *Xanthium strumarium*, *Solanum nigrum*, etc. and certain annual grasses including *Setaria faberi*. Susceptible plants show strong epinasty. Naptalam also produces a strong antigeotropic response, abolishing the normal curvature of roots towards the ground and of shoot towards light. It is used in cucumber, melon, watermelon, groundnut, soybean, etc. Its field half-life is 14 d and the residues do not injure crops planted in the following season.

Pyrazoliums

Difenzoquat: 1,2-dimethyl-3,5-diphenyl-1*H*-pyrazolium

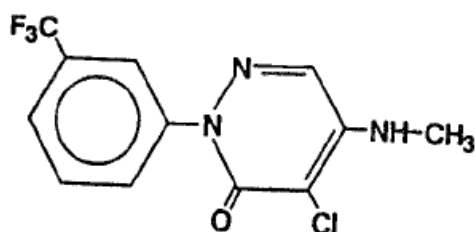
The herbicidal properties of difenzoquat methyl sulphate were first reported in 1973. It is a POST herbicide for wild oats control at 0.7-1.0 kg ha⁻¹. A non-ionic surfactant enhances its efficacy. Plant growth ceases soon after application and injury symptoms appear after 3-7 d. Meristematic regions become chlorotic, leading to necrosis. The field half-life of difenzoquat is < 4 wk.



Pyridazinones

Pyridazinones or fluorinated pyridazinone herbicides were discovered in the 1960s. They are mostly PRE herbicides, which include norflurazon and pyrazon. The susceptible plants show interveinal whitening of leaf and stem tissue. Growth may continue for several days, but seedlings lack green photosynthetic tissue, and eventually turn necrotic and die.

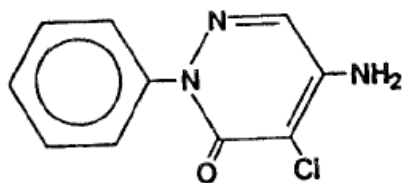
Norflurazon: 4-chloro-5-(methylamino)-2-[3-(trifluoromethyl)phenyl]-3-(2H)-pyridazinone



Norflurazon (SAN 9789H) was first introduced in 1968 by Sandoz. It is a PRE herbicide (2.5-5.0 kg ha⁻¹) used in tree crops, vineries, ornamentals and orchard and plantation crops, besides non-crop areas. It controls many grasses such as *Setaria* spp., *Eleusine indica*, *Panicum dichotomiflorum*, *Digitaria sanguinalis*, *Sorghum halepense*, etc., broadleaf weeds such as *Amaranthus* spp., *Ipomoea* spp., *Portulaca* spp.,

Cirsium arvense, and many sedges including *Cyperus* spp. Norflurazon has moderate to long persistence in soil, with a half-life of 45-180 d. During the synthesis of norflurazon, trifluormethylaniline is acidified, then nitrified, followed by reaction with sulphites, and then by acidification, to form hydrazine hydrochloride, which is then reacted with mucochloric acid. The brown oil is then reacted with monomethylamine, forming a fine suspension. Base is then added and the solvents are distilled. The norflurazon suspension is filtered and washed.

Pyrazon: 5-amino-4-chloro-2-phenyl-3(2H)-pyridazinone

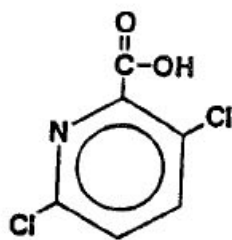


Pyrazon, also known as chloridazon, was the first pyridazinone herbicide to be developed in 1963. It is commercially available as PYRAMIN. It can be applied PRE or early POST at 3-9 kg ha⁻¹ in sugarbeets and onion. Like norflurazon, it controls many annual grass and broadleaf weeds. It provides 4-8 wk weed control, depending on soil moisture and temperature. It is temperature-sensitive, resulting in crop

damage under very unusual temperature extremes. In irrigated regions, it is used with sprinkler and drip irrigation. Better results are obtained with PPI and with furrow irrigation. Pyrazon has short to moderate soil persistence, with a field half-life of 21 d. Pyrazon is synthesized by condensing mucochloric acid with phenyl hydrazine, producing 1-phenyl-4,5-dichloropyridazine-6. It is then reacted with ammonia to produce pyrazon.

Pyridinecarboxylic Acids

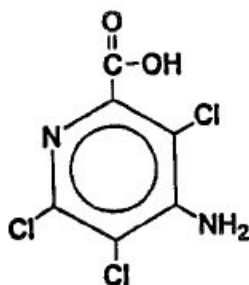
Clpyralid: 3,6-dichloro-2-pyridinecarboxylic acid



Clpyralid was discovered in 1961. It was first marketed in Europe in 1978, while in the US, it was introduced in 1987-89 under the trade names CURTAIL, STINGER and CONFRONT. It is applied POST at 0.1-0.3 kg ha⁻¹ in sugarbeets and maize, and at 0.14-0.56 kg ha⁻¹ in pastures and rangelands. It controls many annual and perennial broadleaf weeds including *Cirsium arvense*, *Polygonum* spp., *Xanthium strumarium*, *Datura stramonium*, *Ambrosia artemisiifolia*, *Iva xanthifolia*, etc. Clpyralid is moderately residual, with an average field half-life of 40 d. Residues may injure certain

crops such as potato, peas, pulses, etc. planted 1 yr after application.

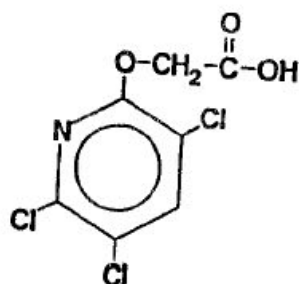
Picloram: 4-amino-3,5,6-trichloro-2-pyridinecarboxylic acid



Picloram was discovered by Dow Chemical (as TORDON) in 1960 and first reported in 1963. It is available as isooctyl ester and triisopropanolamine salt. The symptoms of picloram injury are typical of other auxin-type herbicides. It is applied to the weed foliage at 0.15-1.0 kg ha⁻¹ in forest plantations, non-crop areas, pastures and rangeland. It can be applied on the cut surface (stump, tree injection, or girdle) as treatment for woody species. It controls many annual and perennial broadleaf weeds, vines and woody plants at higher rates. The field half-life of picloram is 90 d. Dissipation is more rapid under warm, humid conditions. It

is compatible with 2,4-D and triclopyr to make pre-mix formulations.

Triclopyr: [(3,5,6-trichloro-2-pyridinyl)oxy]acetic acid



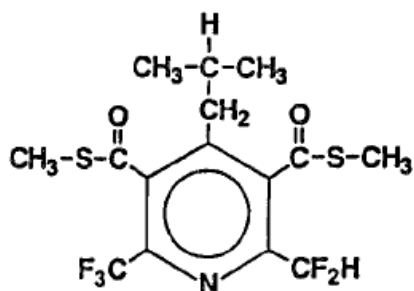
Triclopyr, available as a triethylamine salt and butoxyethyl ester, was introduced by Dow Chemical in 1975 as GARLON. It is applied POST at 1.0-10.0 kg ha⁻¹ in non-crop areas such as industrial sites, forestry, roadsides, rangeland and permanent pastures. At 0.25-0.40 kg ha⁻¹, it can be used in rice. It can be applied to freshly cut tree stumps, and mixed with oil for bark treatment on young trees. Triclopyr can control many annual hard-to-control broadleaf weeds as well as many tree and brush species. A non-ionic surfactant may increase its efficacy. It is moderately persistent in soil, with a half-life of 30 d, ranging from 10 to 146 d depending on soil type, moisture and temperature. It is compatible with several herbicides such as picloram, clpyralid, 2,4-D, etc. to make herbicidal mixtures.

It is compatible with several herbicides such as picloram, clpyralid, 2,4-D, etc. to make herbicidal mixtures.

Pyridines

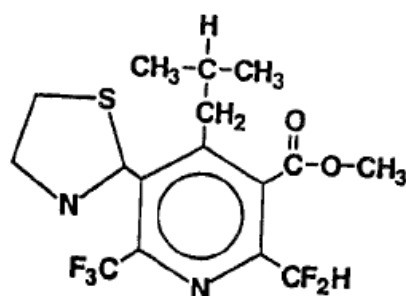
Pyridine herbicides are mostly soil-applied herbicides, with little or no POST activity. These include dithiopyr and thiazopyr, which cause root growth inhibition and swelling in meristematic regions such as root tips. Susceptible plants may show thickened or swollen hypocotyls or internodes. Seed germination is not inhibited.

Dithiopyr: S,S-dimethyl 2-(difluoromethyl)-4-(2-methylpropyl)-6-(trifluoromethyl)-3,5-pyridinedicarbothioate



spp. It has short to moderate soil persistence, with a half-life of 17 d. Metabolites get dissipated almost completely within 1 yr.

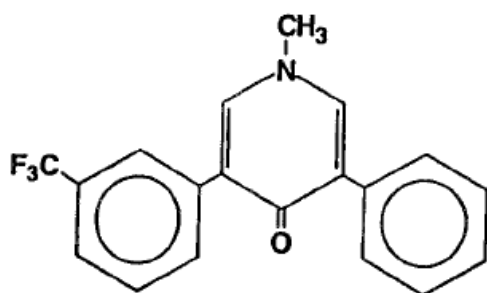
Thiazopyr: methyl 2-(difluoromethyl)-5-(4,5-dihydro-2-thiazolyl)-4-(2-methylpropyl)-6-trifluoromethyl-3-pyridinecarboxylate



depending on temperature, moisture, soil pH and organic matter content. Wheat and sorghum are susceptible to soil residues of thiazopyr.

Pyridinones

Fluridone: 1-methyl-3-phenyl-5-[3-(trifluoromethyl)phenyl]-4(1H)-pyridinone



Myriophyllum spp., *Najas* spp., *Potamogeton* spp., *Hydrilla verticillata*, *Brachiaria mutica*, etc. The affected weeds give white, pink and chlorotic appearance in 7-10 d time, with complete kill requiring more than 30 d. The half-life of fluridone is around 20 d in anaerobic pond water and 90 d in the hydrosol. Fluridone adheres to sediments, but gradually desorbs into the water and then is subject to photodegradation.

Dithiopyr was first introduced (as DIMENSION and STAKEOUT) by Monsanto, but purchased by Rohm and Haas in 1994. It is commercially available in liquid and granular formulations. Dithiopyr is applied PRE at 250-500 g ha⁻¹ or POST at 120-500 g ha⁻¹ in direct-seeded and transplanted rice, established turf, ornamentals, and orchard and other perennial crops. It controls several annual grass and broadleaf weeds such as *Echinochloa crus-galli*, *Digitaria* spp., *Eleusine indica*, *Oxalis* spp., *Euphorbia*

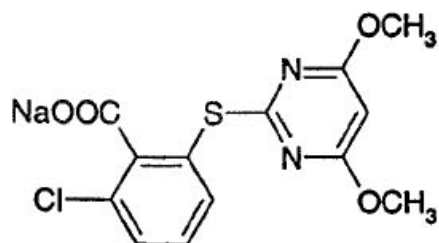
Thiazopyr, like dithiopyr, was first introduced by Monsanto and later purchased by Rohm and Haas in 1994. It is commercially available as VISOR and SPINDLE in EC and granular formulations. Thiazopyr is soil-applied at 0.5-2.0 kg ha⁻¹ in several crops including maize, groundnut, soybean, vineries, sugarcane, sunflower, potato, vegetables, alfalfa, tree crops, and in non-crop areas to control several annual and perennial grasses and broadleaf weeds. Its field half-life is 64 d, with a range of 8 to 150 d,

Fluridone was first described as an aquatic herbicide in 1976. It is applied at 0.06-0.09 mg ai L⁻¹ (ppm ai) in ponds, 0.075-0.15 mg ai L⁻¹ in lakes and reservoirs, or at 2.24 kg ai ha⁻¹ of treated surface in drainage canals, irrigation canals and rivers. Fluridone can be applied on the water surface or subsurface, or as a bottom application just above the hydrosol. It controls most submerged and emerged aquatic weed species including *Utricularia* spp., *Ceratophyllum demersum*, *Elodea* spp.,

Pyrimidinylthio-benzoates (Benzoates)

Pyrimidinylthio-benzoates, also referred to as benzoates, are a new class of herbicides being developed since the early 1990s. Pyrithiobac is the first herbicide in this group.

Pyrithiobac: 2-chloro-6-[(4,6-dimethoxy-2-pyrimidinyl)thio]benzoic acid, sodium salt.

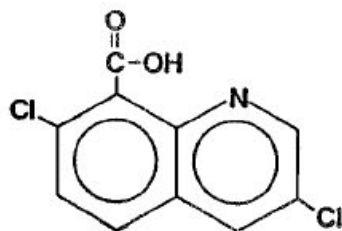


Pyrithiobac (formerly DPX-PE 350 or KIH-8921) was developed by DuPont. It is commercially available as sodium salt. Pyrithiobac-sodium possesses a unique chemistry and is not a member of any existing herbicide family. Pyrithiobac is applied POST at 70 g ha⁻¹ in cotton (1- to 2-leaf stage) for effective control of several broadleaf weeds such as *Xanthium strumarium*, *Ipomoea* spp., *Abutilon theophrasti*, *Sesbania exaltata* (hemp

sesbania), *Salvia reflexa* (lanceleaf sage), *Sida spinosa* (prickly sida), *Amaranthus* spp., etc. When applied at this rate, wheat, soybean and grain sorghum may be rotated with cotton with no crop toxicity to these crops. Cotton is very tolerant of pyrithiobac even at rates as high as 112 g ha⁻¹. It may also be applied PPI or PRE in cotton to control *Cassia occidentalis*, a troublesome broadleaf weed. Higher rates cause injury to cotton. However, caution may need to be exercised, as insecticides (malathion, fenvalerate, methomyl, chlorpyrifos, etc.) applied along with pyrithiobac, as mixtures, are likely to make cotton sensitive to the herbicide. Antagonism occurs when pyrithiobac is applied with graminicides such as quizalofop-P, fluazifop-P, clethodim, or sethoxydim.

Quinolinecarboxylic acids

Quinclorac: 3,7-dichloro-8-quinolinecarboxylic acid



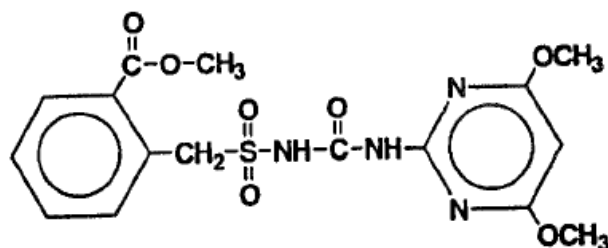
Quinclorac was synthesized and discovered by BASF. It is an auxin-type herbicide, used in direct-seeded and transplanted rice to control important annual grass weeds. It is particularly very effective against *Echinochloa crus-galli*, *Setaria* spp., etc. It is applied PRE, late-PRE, or early-POST to weeds in transplanted rice and direct-seeded rice at 0-25-0.50 kg ha⁻¹. It also controls certain annual and perennial broadleaf weeds including *Convolvulus arvensis*. Its phytotoxicity is characterized by inhibition of shoot growth and chlorosis, and subsequent necrosis of the entire shoot.

Quinclorac is persistent in soil, with residues injuring certain subsequent crops planted 1 yr after application.

Sulfonylureas

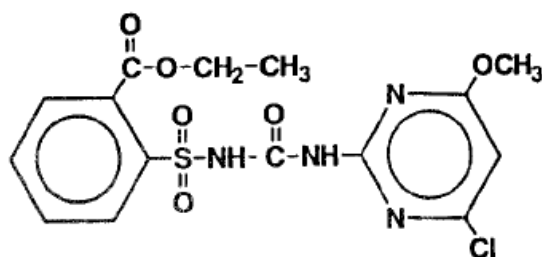
Sulfonylurea herbicides were developed in the 1980s. They show high herbicidal potency at very low rates, making them environmentally safe herbicides. The sulfonylurea group comprises the most widely used herbicides in present-day agriculture. Affected plants show growth inhibition soon after application. Chlorosis appears 3-5 d after application. This is followed by necrosis of the growing point. Plant death occurs within 7-21 d after application. Certain species occasionally remain green, but are stunted and not competitive with the crop.

Bensulfuron: methyl 2-[[[(4,6-dimethoxy-2-pyrimidinyl)amino]carbonyl]amino]sulfonyl]methyl]benzoate



The herbicidal activity of bensulfuron was reported in 1989 and marketed by DuPont shortly later as LONDAX. It can be applied at PRE or POST in irrigated rice at 35-70 g ha⁻¹ or POST in dryland rice at 30-40 g ha⁻¹. It controls many annual grasses (*Echinochloa crus-galli* and *E. Colona*), sedges (*Cyperus rotundus* and other Cyperaceae family weeds) and certain broadleaf weeds such as *Commelina* spp., *Heteranthera limosa* (ducksalad), *Eclipta alba*, *Sphenoclea zeylandica*, *Pontederia cordata*, *Ammania* spp., *Plantago* spp., etc. Bensulfuron has a field half-life of 5-10 d in irrigated rice. It moves no deeper than the top 5-7 cm of soil.

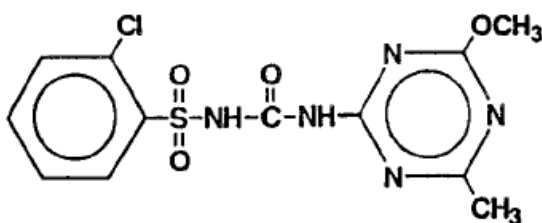
Chlorimuron: ethyl 2-[[[(4-chloro-6-methoxy-2-pyrimidinyl)amino]carbonyl]amino]sulfonyl]benzoate



Chlorimuron was first synthesized and field tested in 1982 and made commercially available in 1986 as CLASSIC. It is applied POST at 8-13 g ha⁻¹, and PRE 30-90 g ha⁻¹ in soybean, groundnut and non-crop areas. It controls many annual broadleaf weeds including *Xanthium strumarium*, *Datura stramonium*, *Ipomoea* spp., *Ambrosia* spp., *Amaranthus* spp., *Polygonum* spp., etc. A non-ionic surfactant

or oil adjuvant is required for maximum foliar activity at POST. Chlorimuron persists longer in high pH soils, with an average field half-life of 40 d. It is used to make herbicidal mixtures with thifensulfuron, metribuzin, linuron, etc.

Chlorsulfuron: 2-chloro-*N*-[[[(4-methoxy-6-methyl-1,3,5-triazine-2-yl)amino]carbonyl]benzenesulfonamide

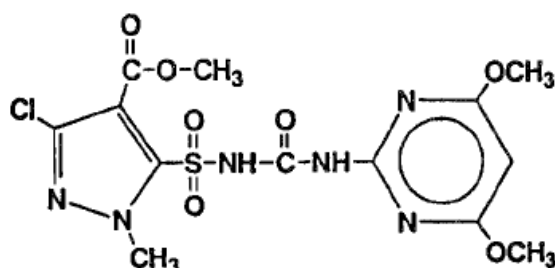


Chlorsulfuron can be applied PRE or POST at 10-20 g ha⁻¹ in wheat. It is used at higher rates in non-crop areas to control many broadleaf weeds including *Kochia scoparia*, *Cirsium arvense*, *Brassica* spp., *Amaranthus* spp., *Chenopodium album*, etc. It is compatible with most broadleaf herbicides and fungicides, and certain organophosphate insecticides. Growth of treated plants is

inhibited within a few hours after application, but injury symptoms appear 1-2 wk later. Meristematic areas gradually become chlorotic and necrotic, followed by a

general foliar chlorosis and necrosis. The field half-life of chlorsulfuron is 40 d, ranging from 4-6 wk. Chlorsulfuron may injure susceptible crops up to 3 or 4 yr after application in high pH soils. It is mixed with metsulfuron to broaden its herbicidal activity.

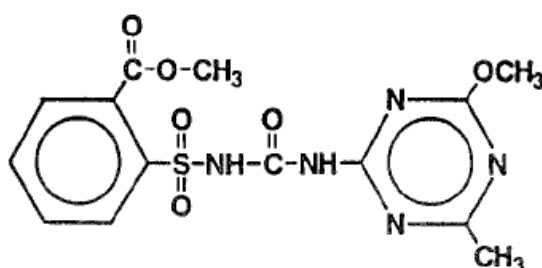
Halosulfuron: methyl 5-[[[(4,6-dimethoxy-2-pyrimidinyl)amino]carbonylamino]sulfonyl]-3-chloro-1-methyl-1-*H*-pyrazole-4-carboxylate



Halosulfuron (MON 1200), introduced in 1991, has been made commercially available by Monsanto. It can be applied early PPS, PPI, or PRE to maize at 70-80 g ha⁻¹ in combination with a safener, Mon 13900. It can also be used as a POST herbicide at 36 g ha⁻¹ in maize, sorghum, sugarcane and turf. It also controls *Abutilon theophrasti*, *Xanthium strumarium* and several other broadleaf weeds, and *Cyperus*

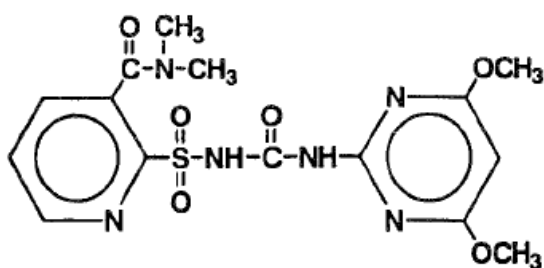
spp. It has short to moderate persistence in soil, with a field half-life of 6-35 d, depending on type of soil, organic matter content and rainfall.

Metsulfuron: methyl 2-[[[(4-methoxy-6-methyl-1,3,5-triazin-2-yl)amino]carbonyl]amino]sulfonyl]benzoate



The herbicidal properties of metsulfuron were first reported in 1983. It was first marketed as ALLY and ESCORT. It is applied POST at 40-60 g ha⁻¹ in wheat for control of broadleaf weeds such as *Kochia scoparia*, *Brassica* spp., *Cirsium arvense*, *Chenopodium album*, etc. It can be used at 40-120 g ha⁻¹ in several pasture grass species. It is moderately persistent in soil with a half-life of 30 d, with a range of 1-6 wk. It is mixed with chlorsulfuron.

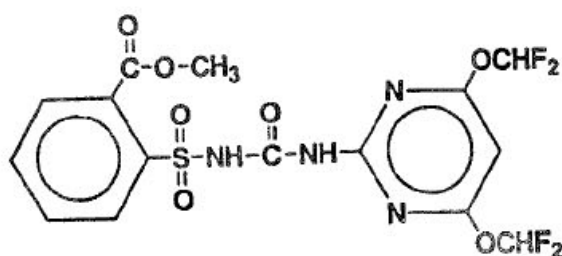
Nicosulfuron: 2-[[[(4,6-dimethoxy-2-pyrimidinyl)amino]carbonyl]amino]sulfonyl]-*N,N*-dimethyl-3-pyridinecarboxamide



Nicosulfuron was first marketed in 1991 as ACCENT. It is applied POST at 35-70 g ha⁻¹ in maize for control of most annual and some perennial grasses, including *Setaria* spp., *Sorghum bicolor* (shattercane), *Eriochloa villosa* (wooly cupgrass), *Panicum miliaceum* (wild proso-millet), *Sorghum halepense* and *Elytrigia repens* as well as certain broadleaf weeds. A surfactant or oil adjuvant is required for maximum efficacy. Its field half-life is 21 d at pH 6.5.

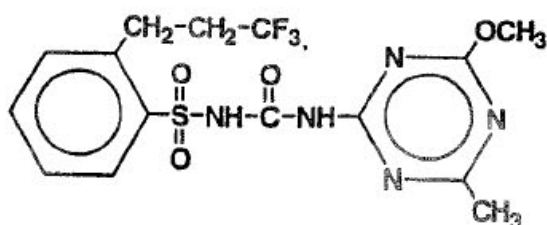
Primisulfuron: methyl 2-[[[[[4,6-bis(difluoromethoxy)2-pyrimidinyl]amino]carbonyl]amino]sulfonyl]benzoate

Primisulfuron was synthesized and discovered by Ciba-Geigy, Basel, Switzerland. It was first field tested in 1983 and became commercially available for use on maize in



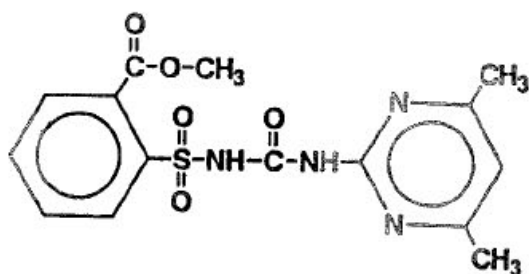
Ambrosia artemisiifolia, *Xanthium strumarium*, *Solanum nigrum*, etc. It is moderately persistent in soils, with an average field life of 30 d. Residues can persist long enough to injure susceptible crops the following year. Its synthesis involves several steps beginning with thiourea and diethylmalonate and culminating with coupling of an aminosulfonyl-benzoic acid with a pyrimidinyl isocyanate.

Prosulfuron: 1-(4-methoxy-6-methyl-triazin-2-yl)-3-[2-(3,3,3-trifluoropropyl)-phenylsulfonyl]-urea



theophrasti, etc. A surfactant or oil adjuvant is required for maximum POST efficacy. It is used to make herbicide mixtures with primisulfuron, bromoxynil, terbutylazine, etc. It is moderately persistent in soil. Its field half-life is 10 d. It is synthesized, multistep, beginning with aniline-2-sulphonic acid and ending in condensation with the appropriate triazine.

Sulfometuron: methyl 2-[[[(4,6-dimethyl-2-pyrimidinyl)amino]carbonyl]amino]sulfonyl]benzoate



reduce selectivity. Its field half-life is 20-28 d at pH 6 to 7.

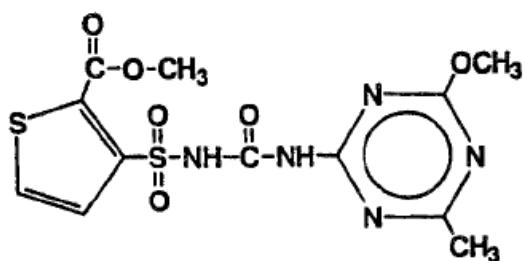
Thifensulfuron: methyl 3-[[[(4-methoxy-6-methyl-1,3,5-triazine-2-yl)amino]carbonyl]amino]sulfonyl]-2-thiophenecarboxylate

The herbicidal activity of thifensulfuron was first reported in 1984 and the herbicide commercially introduced in 1987 by DuPont as HARMONY. It can be applied POST at

1990. Its herbicidal activity was first reported in 1987. Primisulfuron can be applied POST at 20-40 g ha⁻¹ in maize to control certain annual and perennial grass weeds such as *Panicum dichotomiflorum*, *Sorghum bicolor*, *Sorghum halepense* and *Elytrigia repens*, and some annual broadleaf weeds such as *Amaranthus* spp., *Abutilon theophrasti*, *Polygonum* spp.,

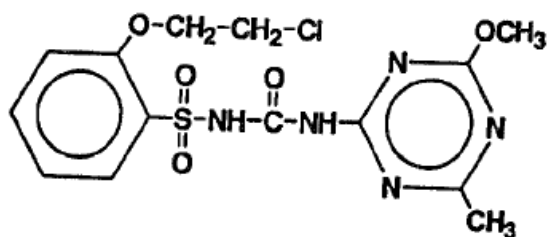
Prosulfuron (CGA-152005) was first field tested in 1988 and registered in the U.S. in 1995. It can be applied POST at 15-40 g ha⁻¹ in maize, sorghum, wheat, barley, sugarcane and certain other graminaceous crops. It controls certain annual broadleaf weeds such as *Xanthium strumarium*, *Kochia scoparia*, *Chenopodium album*, *Amaranthus* spp., *Ambrosia artemisiifolia*, *Abutilon*

Sulfometuron (DPX 5648) can be applied PRE (before weed emergence) or POST at 50-200 g ha⁻¹ in forest areas, roadsides, non-crop areas, etc. to control annual and perennial broadleaf and grass weeds including *Sonchus arvensis*, *Malva* spp., *Rumex crispus*, *Ambrosia tenuifolia*, *Echinochloa crus-galli*, *Setaria* spp., *Aegilops cylindrica*, etc. A non-ionic surfactant improves sulfometuron efficacy but may re-



10-18 g ha⁻¹ in wheat and soybean to control many annual broadleaf weeds such as *Brassica kaber*, *Amaranthus* spp., *Kochia scoparia*, etc. A non-ionic surfactant is used to maximize its efficacy. Its field half-life is 12 d. It is used to make herbicidal mixtures with chlorimuron, tribenuron, fenoxaprop, etc.

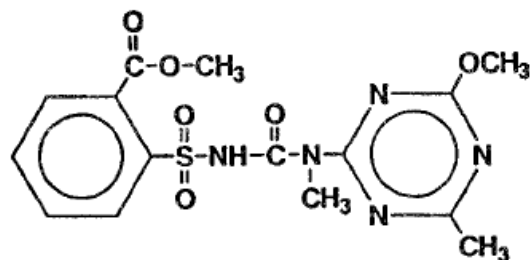
Triasulfuron: 2-(2-chloroethoxy)-N-[[[(4-methoxy-6-methyl-1,3,5-triazin-2-yl)amino]carbonyl]benzene-sulfonamide



Triasulfuron was synthesized by Ciba-Geigy in 1981 and made commercially available for wheat in 1992 as AMBER. It can be applied POST or PRE at 15-30 g ha⁻¹ in wheat for control of many annual broadleaf weeds as *Kochia scoparia*, *Amaranthus* spp., *Ambrosia artemisiifolia*, etc. Triasulfuron is persistent, as its residues can persist long enough to injure certain dicot crops 1-3 yr after application.

It has a multistep synthesis starting with chlorophenol and culminating with the coupling of an amino triazine with a benzene-sulfonyl isocyanate.

Tribenuron: methyl 2-[[[[(4-methoxy-6-methyl-1,3,5-triazin-2-yl)methylamino]carbonyl]amino]sulfonyl]benzoate



Tribenuron was field tested in 1983 and made commercially available by DuPont as CHEYENNE in Spain in 1986 and as EXPRESS in the U.S. in 1989. It can be applied POST at 9-18 g ha⁻¹ in wheat and barley to control many annual broadleaf weeds including *Brassica* spp., *Chenopodium album*, *Lamium amplexicaule*, *Lactuca serriola* and *Kochia scoparia*. It is also used for making commercial mixtures with thifensulfuron, fenoxaprop and MCPA. It has a short residual effect, with an average field half-life of 10 d at pH 6. Rotational crops can be planted 60 d after application.

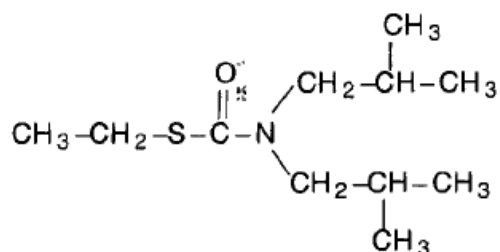
Tetrahydropyrimidinones

Tetrahydropyrimidinones (1,3-diaryl-2-pyrimidinones), also called cyclic ureas, is a new class of photo-bleaching herbicides. Herbicides of this family are yet to be commercialized. Chemically, these herbicides combine several structural elements of well-known chlorotic herbicides including fluometuron, fluridone and norflurazon. Fluridone and fluometuron are the parent structures of tetrahydropyrimidinones (THPs). THPs are expected to be used in rice. They are active on a broad spectrum of monocot and dicot weeds and sedges including *Echinochloa crus-galli*, *Cyperus difformis*, *Scirpus juncoides*, *Monochoria vaginalis*, *Cyperus serotinus*, *Eleocharis acicularis*, *Sagittaria pygmaea*, etc. while not affecting rice.

Thiocarbamates

When one oxygen in the carbonic acid molecule is substituted by sulphur, thiocarbamic acid is formed. Similarly, with two sulphur substitutions dithiocarbamic acids are formed. Thiocarbamate herbicides are toxic to germinating weeds following their soil incorporation before sowing. The susceptible grass and broadleaf weeds fail to emerge. Injury to sensitive crops like maize, when applied without a safener, manifests as malformed and twisted seedlings. Leaves are tightly rolled in the whorl and may not unroll normally. Injured dicot grasses may have cupped or crinkled leaves with a thick, leathery texture. As thiocarbamate herbicides are volatile, they need soil incorporation soon after application.

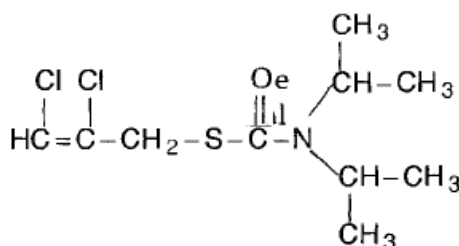
Butylate: S-ethyl bis(2-methylpropyl)carbamothioate



Butylate was first reported in 1962. It is applied PPI at 3.0-6.0 kg ha⁻¹ in maize for control of many annual grasses such as *Setaria* spp., *Echinochloa crus-galli*, *Panicum dichotomiflorum*, *Sorghum halepense*, *Sorghum bicolor*, etc. as well as *Cyperus esculentus* and *Cyperus rotundus*, and a few broadleaf weeds. It must be incorporated into the soil soon after application to prevent volatility losses.

It is lost substantially when applied to wet soils without incorporation, but little loss occurs after application to dry soils. Liquid formulations can be mixed with certain liquid fertilizers, impregnated on dry bulk fertilizers, or applied through irrigation water (chemigation). Its field half-life is 13 d. Butylate provides 4-7 wk of weed control and does not injure the succeeding crops. Butylate can be mixed with atrazine and safener dichlormid. It is synthesized by reacting ethyl chlorothiolformate with diisobutyl amine and a base.

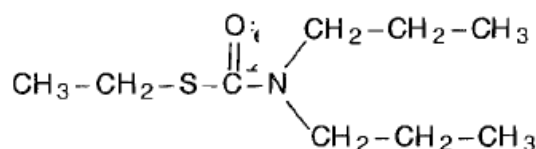
Diallate: S-(2,3-dichloro-2-propenyl)bis(1-methylethyl)carbamothioate



Diallate was developed in the late 1950s and commercialized as AVADEx in 1961. It consists of *cis* and *trans* isomers. It is applied PPI or postplant incorporated (2.0-5.0 kg ha⁻¹) in wheat, maize, soybean, sugarbeets, oilseed crops, ornamentals, root crops and fruit trees. Diallate is very effective against wild oats (*Avena fatua*). It has a field half-life of 30 d. Diallate is synthesized by reacting appropriate polychlorinated

allyl chloride with the appropriate thiol carbamate salt.

EPTC: S-ethyl dipropyl carbamothioate

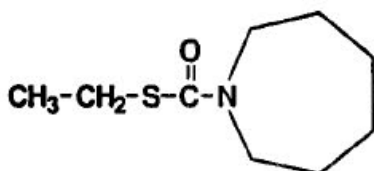


EPTC, the first thiocarbamate herbicide developed in 1957, is very effective against many annual grasses and broadleaf weeds. As it is volatile, it needs to be incorporated into the soil to a depth of 5-10 cm. It is readily lost when the soil surface is wet at

the time of application. It is applied PPI at 2.0-5.0 kg ha⁻¹ in many crops including potato, safflower, vegetables, maize, cotton and orchard crops. It is effective against perennial grasses such as *Elytrigia repens*, *Sorghum halepense*, etc., sedges such as *Cyperus*

spp., and many annual grasses. EPTC has good activity against broadleaf weeds such as *Ipomoea purpurea*, *Solanum villosum*, *Solanum nigrum*, *Chenopodium album*, *Portulaca oleracea*, *Amaranthus* spp., etc. It can be applied through irrigation systems (sprinkler, furrow and drip) and impregnated on dry fertilizers as well as by conventional sprayer. EPTC can be mixed with the microbial inhibitor dietholate and safener dichlormid. It has a field half-life of 6 d and the residues do not injure susceptible crops planted in the following season. It provides weed control for 4-6 wk. EPTC is synthesized by reacting ethyl chlorothiolformate with *di-n*-propyl amine and base.

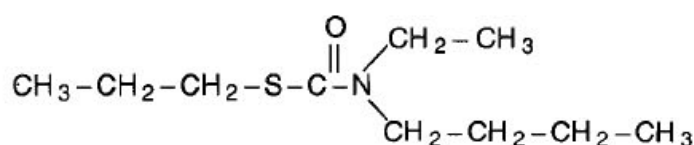
Molinate: S-ethyl hexahydro-1*H*-azepine-1-carbothioate



Molinate is applied at 3.0-5-g ha⁻¹ in irrigated rice after transplantation but before weeds emerge. In dryland rice, it can be applied PPI at 2.0-3.0 kg ha⁻¹. It can also be applied by injecting into irrigation water in direct-seeded irrigated rice. Molinate controls several annual grasses including *Echinochloa crus-galli*, *Leptochloa* spp.,

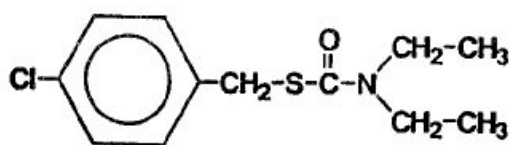
Brachiaria platyphylla, etc. It can be mixed with propanil. Its field half-life is 3 wk and residues do not persist long enough to injure susceptible crops planted 1 yr after application. Molinate, like EPTC, is readily lost from wet soil surface when not incorporated immediately after application.

Pebulate: S-propyl butylethylcarbamothioate



Pebulate was first reported in 1959. It is a selective PPI and PRE herbicide like EPTC used for control of *Cyperus* spp., *Digitaria sanguinalis*, *Setaria* spp., *Echinochloa crus-galli*, *Avena fatua*, and many broadleaf weeds. It is used (3.0-6.0 kg ha⁻¹) in tobacco, sugar beets, and tomato. Pebulate needs overhead or furrow irrigation soon after application to prevent volatility losses. Its field half-life is 2 wk. It is synthesized by reacting *n*-propyl chlorothioformate with *n*-butyl ethyl amine and a base.

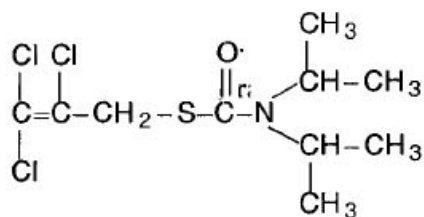
Thiobencarb: S-[(4-chlorophenyl)methyl]diethylcarbamothioate



Thiobencarb, also known as benthicarb, was developed in 1969. It is applied PPI or PRE in rice nurseries at 1.0-1.5 kg ha⁻¹ and PRE in irrigated rice at 1.5-3.0 kg ha⁻¹. It is very selective for rice. It controls many annual

grasses including *Echinochloa crus-galli*, *Echinochloa colonum*, *Leptochloa* spp., *Brachiaria platyphylla*, *Aeschynomene virginica*, *Commelina* spp. and sedges of the Cyperaceae family. The field half-life of thiobencarb is 30-90 d. It can be used to make mixtures with 2,4-D ethyl ester for broad-spectrum weed control in rice.

Triallate: S-(2,3,3-trichloro-2-propenyl) bis(1-methylethyl)carbamothioate



Triallate was commercialized as AVADEx BW in 1962. It is like diallate, except that it has two chlorines on the terminal allyl carbon. It is applied PPI (2.5-5.0 kg ha⁻¹) in wheat, maize, soybean, barley, forage legumes, fruit crops and ornamentals. It is particularly very effective against wild oats. Like diallate, it is active on a wide spectrum of weeds.

Triallate has a field half-life of 82 d. It gives 6-8 wk of weed control. It is mixed with trifluralin and synthesized by reacting polychlorinated allyl chloride with appropriate thiol carbamate salt.

Triazines

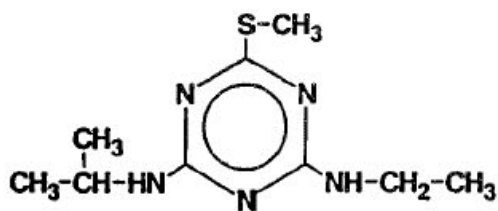
The herbicidal properties of the symmetrical triazines (*s*-triazines) were discovered in 1952 by Geigy Ltd., Basel, Switzerland. Subsequently, numerous triazine derivatives have been synthesized and screened for their herbicidal properties. Triazines became one of the most prominent groups of herbicides to broaden the chemical concept of weed control. They are widely used for selective and non-selective weed control. Their greatest success has been in maize where they are exclusively used for selective weed control. Most of them are soil-applied, while some do exhibit activity through the foliage. Atrazine, simazine, ametryn and prometryn are the triazine compounds that gained major recognition in agricultural and non-agricultural systems.

Various substitutions on the triazine nucleus yield compounds of widely different chemical and biological properties. Accordingly, they exhibit a wide spectrum of selective weed control and biological activities. If the 2-position of the triazine ring is substituted by chlorine, it is termed as **chlorotriazine** (see atrazine structure). If it is substituted by the methoxy group, it is called **methoxytriazine**, and if it is replaced by methylthio (methylmercapto) group (see ametryn structure), it is known as **methylthiotriazine (methylmercaptotriazine)**.

The triazines are usually colourless, non-explosive, non-corrosive and stable compounds, with low mammalian toxicity. The methoxytriazines are prepared by reacting the appropriate chlorotriazine with methanol in the presence of an equivalent base. They are more water soluble and readily absorbed, and have different selectivities than chlorotriazines. The methylthio or methylmercapto triazines are prepared by reacting the appropriate chlorotriazines with methylmercaptan in the presence of sodium hydroxide.

The typical triazine-injury symptoms begin with interveinal chlorosis of leaves and yellowing of their margins. These are followed by further chlorosis and necrosis. Older leaves are more damaged than the new growth. Browning of leaf tips can occur, while root growth is not affected. Triazines do not affect seed germination.

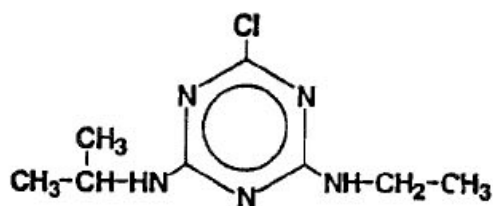
Ametryn: *N*-ethyl-*N'*-(1-methylethyl)-6-(methylthio)-1,3,5-triazine-2,4-diamine



Ametryn is the methylthio analogue of atrazine. It was first released for field evaluation in 1959 and made commercially available in 1964. It is a selective PRE (2.0-8.0 kg ha⁻¹) and POST (0.5-2.0 kg ha⁻¹) herbicide, depending upon the crop, for control of broadleaf and grass weeds in sugarcane, banana, pineapple and citrus. Ametryn has considerable contact activity and hence its POST application must be directed on weeds. It is more soluble than atrazine. The field half-life of ametryn is 60 d. In tropical conditions, it may provide better weed control and its residual life in the soil is expanded to several months. Ametryn is synthesized by successive *N*-alkylation and thioalkylation of cyanuric chloride.

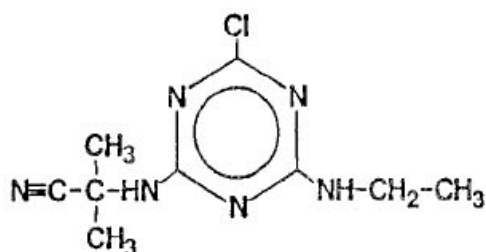
Atrazine: 6-chloro-*N*-ethyl-*N'*-(1-methylethyl)-1,3,5-triazine-2,4-diamine

Atrazine, a prominent triazine herbicide, is currently one of the most widely used



non-selective herbicide in non-crop areas and in minimal or no-tillage programmes in maize and sorghum. Atrazine controls broadleaf weeds including *Amaranthus* spp., *Ipomoea* spp., *Datura stramonium*, *Polygonum convolvulus*, *Ambrosia* spp., *Polygonum* spp., *Abutilon theophrasti*, *Xanthium strumarium*, *Chenopodium album*, etc. and certain annual grasses such as *Echinochloa crus-galli*, *Setaria* spp., *Panicum dichotomiflorum*, etc. When mixed with a non-toxic crop oil or surfactant, it is effective at POST (1.0-2.0 kg ha⁻¹) as well, particularly in maize and sorghum. Many vegetable crops are sensitive to atrazine. It is used to formulate package mixtures with several herbicides including metolachlor, bentazon, simazine, cyanazine, alachlor, propachlor, bromoxynil, dicamba, butylate etc. and a safener dichlormid. Atrazine has a field half-life of 60 d. Its persistence is increased by higher soil pH as well as by cool, dry soil conditions. Most rotational crops can be planted one year after application at selective rates, except under arid and semi-arid climatic conditions. Atrazine is synthesized by successive *N*-alkylation of cyanuric chloride.

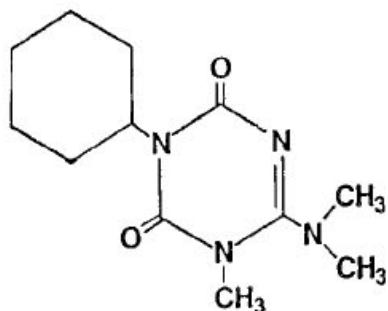
Cyanazine: 2-ethyl-*N'*-(1-methylethyl)-6-(methylthio)-1,3,5-triazine-2,4-diamine



Cyanazine was discovered in 1967 and developed as a herbicide in 1976. It is applied E-PPL, PPI, PRE, E-POST at 1.0-4.0 kg ha⁻¹ in maize, cotton, beans, etc. Cyanazine controls many broadleaf weeds including *Ipomoea* spp., *Portulaca oleracea*, *Ambrosia artemisiifolia*, *Brassica kaber*, *Kochia scoparia*, etc. and several annual grass weeds such as *Setaria* spp., *Digitaria* spp., *Echinochloa crus-galli*, *Panicum capillare*, etc. A surfactant or oil adjuvant may improve its

POST efficacy. It is used to formulate mixtures with atrazine and metolachlor. Cyanazine has a short residual activity, with a field half-life of 14 d. It is synthesized by reacting cyanuric chloride and aminoisobutyronitrile.

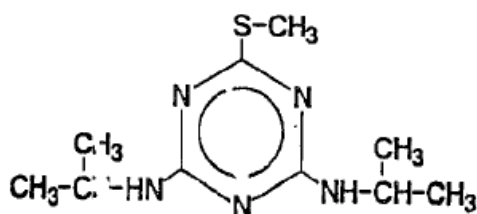
Hexazinone: 3-cyclohexyl-6-(dimethylamino)-1-methyl-1,3,5-triazine-2,4(1*H*,3*H*)-dione



Hexazinone, a PRE (0.62-2.5 kg ha⁻¹) and POST (0.62-1.25 kg ha⁻¹) herbicide introduced for noncrop land weed control in 1975, is used for selective weed control in sugarcane, pineapple and alfalfa. In non-crop areas, including industrial sites, railroad shoulders, storage areas, reforestation sites, etc., it is applied at 2.5-13.5 kg ha⁻¹. It controls many annual and perennial broadleaf and grass weeds, as well as many brush species. Hexazinone is effective against many woody plants and aquatic weeds. A surfactant increases effi-

cacy for foliar applications but may cause undesirable levels of crop injury in some situations. Hexazinone has a moderately long residual activity, with a field half-life of 90 d.

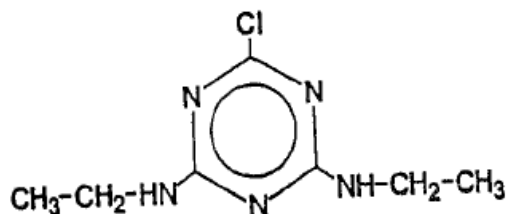
Prometryn: *N,N'*-bis(1-methylethyl)-6-(methylthio)-1,3,5-triazine-2,4-diamine



spp., *Sida spinosa*, *Setaria spp.*, *Eleusine indica*, etc. It is mixed with MSMA. Its field half-life is 60 d. It is synthesized by successive *N*-alkylations of cyanuric acid followed by reaction with mercaptan to attach the thiomethyl group.

Prometryn, the methylthio analogue of propazine, became commercially available in 1964. It is applied PPI, PRE, and directed-POST in cotton at 0.5-3.0 kg ha⁻¹. It is also used in soybean and non-crop areas. As prometryn has considerable contact activity, it should be applied as directed spray at POST. It controls several weeds including *Physalis spp.*, *Chenopodium album*, *Ipomoea spp.*, *Amaranthus*

Simazine: 6-chloro-*N,N'*-diethyl-1,3,5-triazine-2,4-diamine

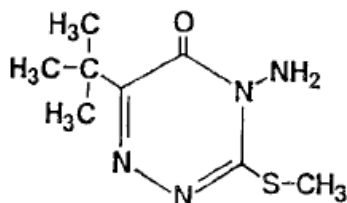


Simazine is one of the first triazine herbicides discovered by Geigy. It was made commercially available in 1958. It is widely used as a selective PRE herbicide (1.0-4.0 kg ha⁻¹) to control many annual broadleaf weeds and some grasses in maize, sugarcane, plantation crops like tea, coffee and rubber and many orchard crops. It is also used as a non-selective herbicide for vegetation control on roadsides, banks of irrigation canals and drainage channels, industrial sites and other non-crop areas. It has little or no POST activity. The field half-lives for simazine are 149 d for a sandy loam soil (OM 1.3%, pH 7.3), 60 d for sandy soil (OM 0.9%, pH 7.8), 55 d for a loam soil with low OM (2.1%) and low pH (5.5), and 186 d for a loam soil containing high OM (6.2%) and high pH (7.9). It is used to make packaged mixtures with metolachlor, prometon, atrazine, etc.

Simazine is one of the first triazine herbicides discovered by Geigy. It was made commercially available in 1958. It is widely used as a selective PRE herbicide (1.0-4.0 kg ha⁻¹) to control many annual broadleaf weeds and some grasses in maize, sugarcane, plantation crops like tea, coffee and rubber and many orchard crops. It is also used as a non-selective

Triazinones

Metribuzin: 4-amino-6-(1,1-dimethylethyl)-3-(methylthio)-1,2,4-triazin-5(4*H*)-one



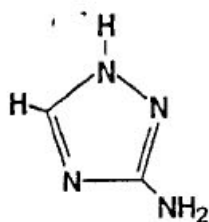
artemisiifolia along with certain annual grasses. It is used to make package mixtures with chlorimuron, trifluralin and metolachlor. Its half-life is 30-60 d. Generally, the residues of metribuzin do not injure susceptible crops planted one year after application. But certain root crops such as onion, potato, and sugarbeets may show susceptibility.

The triazinone herbicide family was first discovered in 1964. Metribuzin was introduced in 1969 and commercially made available by Bayer in 1973. It is applied E-PPS, PPI, PRE, or POST-directed (0.25-0.80 kg ha⁻¹) in sugarcane, maize, soybean, potato, peas, beans, etc. Metribuzin is very active against annual broadleaf weeds such as *Chenopodium album*, *Amaranthus spp.*, *Abutilon theophrasti*, *Datura stramonium*, *Brassica spp.* and *Ambrosia*

Triazoles

Amitrole, Amitrole-T: 1*H*-1,2,4-triazol-3-amine

Amitrole was first reported in 1953 and commercially introduced in 1954 by Union

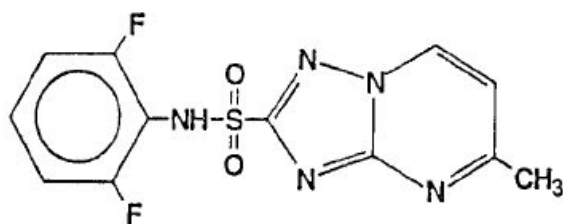


Carbide. The primary symptom of amitrole toxicity is bleaching (albinism) in leaves and shoots, and it is most evident in meristems and developing leaves. Bleached leaves eventually wilt and become necrotic. Amitrole is a POST translocated herbicide, applied spray-to-wet at 2.0-10.0 kg ha⁻¹, in non-crop areas and in locations not used for growing food crops. It controls many annual and perennial grass and broadleaf weeds. Its field half-life is 14 d. Amitrole is synthesized by condensation of formic acid with aminoguanidine.

Amitrole-T is a mixture of amitrole and ammonium thiocyanate. It is more active than amitrole.

Triazolopyrimidine Sulfonanilides

Flumetsulam: *N*-(2,6-difluorophenyl)-5-methyl[1,2,4]triazolo[1,5-*a*]pyrimidine-2-sulfonamide



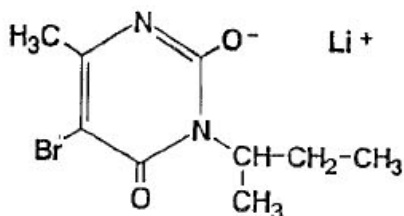
Flumetsulam was discovered in 1984. It is commercially available as BROAD-STRIKE. The weed species most sensitive to flumetsulam are killed before emergence, but some weeds may die after emergence under dry conditions. The emerged sensitive plants exhibit stunting, interveinal chlorosis, veinal discoloration (purpling) and necrosis within

1-3 wk. Flumetsulam is marketed as a package mixture with metolachlor for use in maize and soybean, and with clopyralid for use in maize. It can be applied PRE, PPI, or PPS at 50-75 g ha⁻¹. Flumetsulam controls many annual broadleaf weeds such as *Brassica kaber*, *Amaranthus* spp., *Kochia scoparia*, *Chenopodium album*, *Polygonum* spp., *Solanum nigrum*, *Abutilon theophrasti*, etc, but has little activity against grasses. Flumetsulam is package-mixed with trifluralin or metolachlor to provide control of several annual grasses. Liquid flumetsulam can be impregnated on dry fertilizer. Its field half-life is 1-3 mon. Residues of flumetsulam do not injure soybean, maize, alfalfa, groundnut, potato, rice, sorghum and tobacco planted one year after application.

Uracils

Substituted uracils were first identified as herbicides in 1962. Bromacil and terbacil are the two uracil herbicides presently used in agriculture and non-agricultural areas. The susceptible plants show foliar chlorosis and necrosis, and inhibition of root and shoot growth.

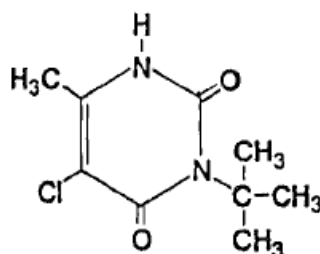
Bromacil: 5-bromo-6-methyl-3-(1-methylpropyl)-2,4-(1*H*,3*H*)pyrimidinedione



Bromacil (lithium salt) can be applied PRE at 5.0-7.0 kg ha⁻¹ in citrus, 1.5-3.0 kg ha⁻¹ in pineapple, and 1.5-5.0 kg ha⁻¹ in non-crop areas. It is good for brush control at higher rates. It controls many annual and perennial grasses, sedges, and broadleaf weeds including *Echinochloa crus-galli*, *Digitaria* spp., *Setaria* spp., *Cynodon dactylon*, *Cyperus* spp., *Sorghum halepense*, *Tribulus terrestris*, *Cenchrus* spp. and

Chenopodium album. At low rates, it is used for selective weed control in orchard crops. Bromacil is used to make herbicide mixtures with diuron, sodium metaborate and sodium chlorate. Its field half-life is 60 d. At higher rates, the phytotoxic residues persist for more than one year.

Terbacil: 5-chloro-3-(1,1-dimethylethyl)-6-methyl-2,4-(1*H*,3*H*)-pyrimidinedione



Terbacil is a PRE (1.0-2.0 kg ha⁻¹) and POST (1.0-1.5 kg ha⁻¹) herbicide for control of many annual and some perennial weeds in sugarcane, established alfalfa, and orchard crops such as apples, peaches and citrus. The weeds include *Stellaria media*, *Lamium amplexicaule*, *Chenopodium album*, *Descurainia* spp., *Lactuca serriola*, *Lolium* spp. and *Echinochloa crus-galli*, with a partial control of *Cyperus* spp. It has medium to long persistence in soil, with a field half-life of 120 d. It needs to be applied just before or during the active growth period of weeds. If dense growth is

present, top growth should be removed. Control of perennial grasses may be improved by cultivation prior to treatment.

UCC-C4243: 2-chloro-5[3,6-dihydro-3-methyl-2,6-dioxo-4-(trifluoromethyl)-1(2*H*)-pyrimidinyl]benzoic acid

UCC-C4243 is an experimental substituted uracil herbicide that controls a wide spectrum of broadleaf and some annual grass weeds when applied to either foliage or soil at 30-140 g ha⁻¹. It is applied in wheat, which tolerates up to 170 g ha⁻¹ when applied to soil. Pea, lentil and barley grown in rotation with wheat are too sensitive to this new herbicide to merit its use. Its herbicide potential is under study. However, it has a potential use as a crop desiccant in potato and cotton. When applied to the foliage, UCC-C4243 causes rapid chlorosis and desiccation.

Ureas

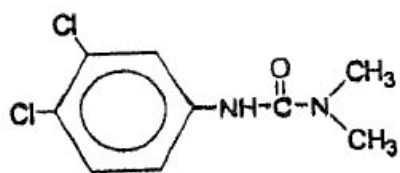
The discovery and development of substituted ureas as herbicides began shortly after World War II. The work led to the discovery of monuron in 1951. Subsequently, several other phenyl substituted ureas including diuron, linuron, fenuron, chloroxuron, fluometuron, chlorbromuron, siduron, tebuthiuron, etc. were developed. Besides, the heterocyclic substituted ureas like noruron and methabenzthiazuron were also discovered and developed. These substituted ureas are used as selective herbicides in agriculture and non-selective herbicides in non-crop areas. These are primarily used at PRE, although some of them show POST activity. At higher rates, they are useful as soil sterilants, particularly in non-crop areas.

The seedlings of susceptible species, following soil application, emerge but become chlorotic within a few days. This is followed by complete necrosis. Foliar application causes interveinal chlorosis of the leaves and yellowing at the leaf margins. The older leaves are more damaged than the new growth.

Of the numerous substituted ureas developed, only the more prominent ones are discussed below.

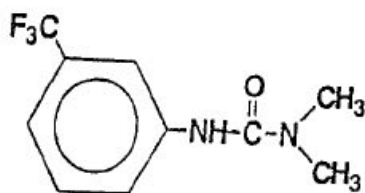
Diuron: *N'*-(3,4-dichlorophenyl)-*N,N*-dimethylurea

Diuron was first reported in 1951. It can be applied PRE at 0.8-2.5 kg ha⁻¹ for controlling emerging grass and broadleaf weed seedlings in tea, cotton, coffee, grapes, pineapple, apples, pears, citrus and other plantation and orchard crops. It can also be



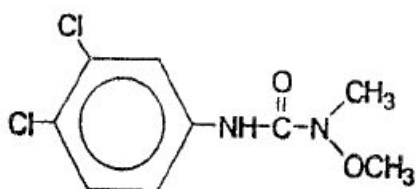
applied as POST-directed spray in maize, sorghum, etc. at 0.2-0.4 kg ha⁻¹. It can be used to formulate POST mixtures with MSMA, paraquat, bromacil, dichlobenil, tebuthiuron, sodium metaborate, sodium chlorate, 2,4-D and imazapyr. Diuron has a field half-life of 90 d. The phytotoxic residues dissipate within a season when applied at lower selective rates. At higher selective rates, residues may persist for more than one year. It is synthesized by reacting 3,4-dichlorophenylisocyanate and dimethylamine.

Fluometuron: *N,N*-dimethyl-*N'*-[3-(trifluoromethyl)phenyl]urea



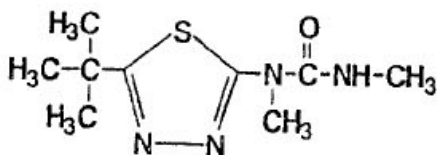
A CH₃ substitution on the meta position of the phenyl ring of urea structure gives fluometuron. As a result, its selectivity is increased. It was first reported in 1964. Fluometuron may be applied PPI, PRE (1.0-1.5 kg ha⁻¹), and E-POST (1.0-2.0 kg ha⁻¹) in cotton, sugarcane, sorghum, citrus and ornamental crops. It controls many broadleaf and grass weeds including *Echinochloa crus-galli*, *Digitaria* spp., *Panicum dichotomiflorum*, *Setaria* spp., *Eleusine indica*, *Brachiaria platyphylla*, *Xanthium strumarium*, *Portulaca* spp., *Ipomea* spp., *Chenopodium album*, *Polygonum* spp., *Cassia obtusifolia* and *Euphorbia esula*. It can be mixed with MSMA. Its field half-life is 85 d. Fluometuron residues often dissipate to non-detectable levels within 4 mon of application. It is synthesized by alkylation of the appropriate aromatic isocyanate.

Linuron: *N'*-(3,4-dichlorophenyl)-*N*-methoxy-*N*-methylurea



Linuron differs from diuron by having a methoxy group in place of one of the methyl substituents. It was first reported in 1962. It can be applied PRE or E-POST-directed (0.30-2.5 kg ha⁻¹) in soybean, cotton, maize, sorghum, wheat, potato and vegetable crops. It controls annual broadleaf weeds including *Brassica* spp., *Amaranthus* spp., *Portulaca oleracea*, *Polygonum convolvulus*, etc. and annual grasses such as *Echinochloa crus-galli* and *Setaria* spp. Foliar application is effective on a wider spectrum of weeds. A non-ionic surfactant increases its weed control efficacy. It can be mixed with chlorimuron. Linuron has a field half-life of 60 d. Its residues do not injure cover crops planted the following season. It is synthesized by reacting 3,4-dichlorophenyl-isocyanate with methoxymethylamine (dimethyl hydroxylamine).

Tebuthiuron: *N*-[5-(1,1-dimethylethyl)-1,3-thiadiazol-2-yl]-*N,N*-dimethylurea

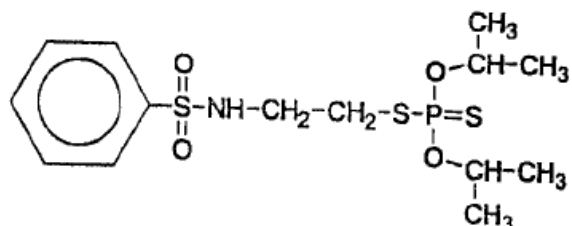


Tebuthiuron was first reported in 1974. It can be applied PRE or POST (0.8-4.0 kg ha⁻¹) in pastures, rangeland and non-crop areas. It controls certain broadleaf weeds and woody brush species at low rates and several broadleaf, grass and brush species at higher rates. Its field half-life is 12-15 mon, and it is considerably greater in low rainfall areas and in muck soils with high organic matter content. It can be mixed with trifluralin and diuron. Tebuthiuron is synthesized by combining pivalic acid and 4-methyl-3-

thiosemicarbazide (MTSC) and then adding a mixture of sulphuric acid and polyphosphoric acid. Towards the end of the reaction, ammonium hydroxide is added to neutralize pH. The lower aqueous layer is removed and isopropylbenzene urea is added to form an intermediate amine. Then 1,3-dimethyl urea is added with HCl. All reactions are conducted under nitrogen. Finally, solvents are removed under vacuum and the resultant crystals are washed in water and dried.

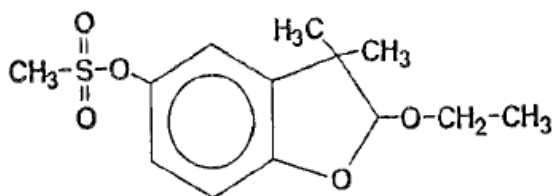
Unclassified Herbicides

Bensulide: *O,O*-bis(1-methylethyl) S-[2[(phenylsulfonyl)amino]ethyl]phosphorodithioate



Bensulide was first reported in 1962 and introduced by Stauffer. It is a PPI and PRE herbicide (5.6-6.7 kg ha⁻¹) used to control annual grass and broadleaf weeds such as *Digitaria sanguinalis*, *Echinochloa crus-galli*, *Eleusine indica*, *Amaranthus* spp., *Chenopodium album*, *Caspella* spp., *Lamium* spp., etc. It is used in vegetable crops such as cucumber, squash, pumpkin, melon, onion, cabbage, carrot, cauliflower and chillies. Bensulide requires rain or irrigation immediately after application for long-term activity in soil. It inhibits root and shoot growth. Its field half-life is 120 d.

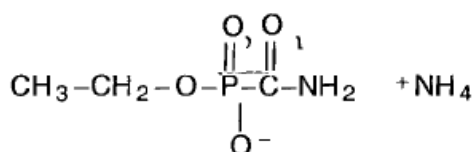
Ethofumesate: (±)-2-ethoxy-2,3-dihydro-3,3-dimethyl-5-benzofuranyl methanesulfonate



The herbicidal properties of ethofumesate were first reported in 1969. It is commercially available as PROGRASS. It can be applied before or after weed emergence at 0.8-2.0 kg ha⁻¹ in sugarbeet. It can also be applied PPI or postplant-incorporated at 2.0-4.0 kg ha⁻¹. Ethofumesate controls several weeds including *Solanum nigrum*,

Stellaria media, *Chenopodium album*, *Kochia scoparia*, *Amaranthus retroflexus*, *Cirsium arvense*, *Polygonum* spp., *Echinochloa crus-galli*, *Digitaria sanguinalis*, *Setaria* spp., *Bromus tectorum*, etc. Its half-life ranges from 5 wk under warm, moist conditions to 14 wk under dry, cold conditions. Ethofumesate can be used to make herbicide mixtures with phenmedipham and desmedipham. Its synthesis involves reaction of the enamine from morpholine and 2-methyl propionaldehyde with *p*-benzoquinone to give 2,3-dihydro-3,3-dimethyl-2-morpholinobenzofuran-5-ol, which is mesylated, and the product converted to ethofumesate.

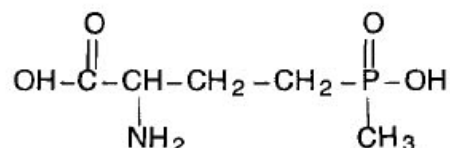
Fosamine: ethyl hydrogen(aminocarbonyl)phosphonate



The herbicidal properties of fosamine were first described in 1974. It is available as ammonium salt under the name KRENITE. In most woody plants, fosamine injury is not apparent before normal leaf senescence in the fall. However, leaf and bud development is

severely inhibited the following spring. Leaves that emerge appear abnormally small and spindly. Other plants such as pines and bindweed may show a response soon after application. On moderately susceptible to resistant species, suppression of terminal growth may occur. Fosamine is used to control brush weeds in non-crop areas. It is applied to the foliage at 10-50 kg ha⁻¹. It can be applied as a spray-to-wet treatment at 1.5-3.5 kg (in 100 L water). An oil adjuvant or surfactant may enhance its POST activity. Its field half-life is 8 d. During the synthesis of fosamine, triethyl phosphate is reacted with methyl chloroformate and ammonia.

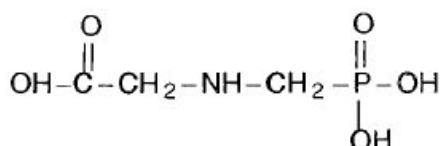
Glufosinate: 2-amino-4-(hydroxymethylphosphinyl)butanoic acid



Glufosinate, a phosphorylated amino acid available as ammonium salt, was first reported as a herbicide in 1981. The injured plants show chlorosis and wilting within 3-5 d after application, followed by necrosis in 1-2 wk. The rate of development of toxicity symptoms is enhanced

by bright sunlight, high humidity and moist soil. Seedlings are not injured before emergence. Glufosinate is applied POST at 0.35-1.5 kg ha⁻¹ in plantation (tea, coffee, etc.) and tree crops and in non-crop areas. As a non-selective herbicide, it controls a broad spectrum of annual and perennial grass weeds such as *Panicum maximum*, *Paspalum conjugatum*, *Axonopus compressus*, *Setaria* spp., *Imperata cylindrica*, *Digitaria sanguinalis*, etc., annual and perennial broadleaf weeds and ferns. Glufosinate has a field half-life of 7 d.

Glyphosate: N-(phosphonomethyl)glycine

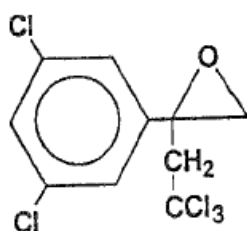


The herbicidal activity of glyphosate was first discovered in 1971 and introduced as an isopropylammonium salt by Monsanto. It is commercially available as ROUNDUP and under several other trade names. The susceptible plants show growth inhibition within 4-7 d of applica-

tion, followed by general foliar chlorosis and necrosis. Chlorosis appears first, more pronouncedly on immature leaves and growing points. Foliage may turn reddish-purple in certain species. Regrowth of treated perennial and woody species often appears deformed with whitish markings or striations.

Glyphosate is a broad spectrum selective POST herbicide used (at 0.5-4.0 kg ha⁻¹) for effective control of rhizomatous and deep-rooted perennial weeds including *Elytrigia repens*, *Imperata cylindrica*, *Cynodon dactylon*, *Paspalum conjugatum*, *Setaria palmifolia*, *Saccharum spontaneum*, *Polygonum chinense*, *Pteridium aquilinum* (fern), *Eleusine indica*, *Sorghum halepense*, *Mikania micrantha*, *Digitaria sanguinalis*, *Echinochloa crus-galli*, *Panicum repens*, *Paspalum dilatatum* and many other species. Greater activity of glyphosate is observed when applied on the foliage during the active growth period. Perennial weeds should have greater leaf area for greater effect. It is extensively used in plantation crops such as tea, coffee, rubber, oil palm, etc., orchard crops, vineyards, pineapple, sugarcane and in non-crop areas such as banks of irrigation canals, drainage ditches, roadsides and industrial and recreational sites. It is also used in minimal tillage cropping systems. Glyphosate has moderate persistence in soil, with a half-life of 47 d. All crops can be planted immediately after application due to strong adsorption by soil. Tank mixing with residual herbicides such as substituted ureas and triazines or with POST herbicides such as paraquat, dalapon, MSMA and phenoxy (or other auxin-type) herbicides may reduce glyphosate efficacy.

Tridiphane: 2-(3,5-dichlorophenyl)-2-(2,2,2-trichloroethyl)oxirane



Tridiphane was discontinued as a herbicide in the late 1980s, but is used as a synergist to enhance the POST efficacy of cyanazine and atrazine, particularly against annual grasses such as *Setaria* spp., *Panicum* spp., *Digitaria* spp., etc. It can be applied POST at 0.5-0.8 kg ha⁻¹ in combination with cyanazine and atrazine in maize. Its field half-life is 28 d under aerobic and 3 d under anaerobic conditions. Tridiphane does not accumulate with repeated annual applications.

INFORMATION ON BIOHERBICIDES²

Currently, three bioherbicide products have been registered for use in certain crops for control of some problem weeds. These are available in commercial formulations. The three bioherbicides BIOMAL[®], COLLEGO[®] and DeVine[®] are discussed as under.

BIOMAL[®]

BIOMAL is a POST mycoherbicide useful for the specific control of *Malva pusilla* (round-leaved mallow) in field crops. The BIOMAL[®] formulation is a wettable powder consisting solely of living spores of *Colletotrichum gloeosporioides* (Penz.) Penz & Sacc. f. sp. *malvae*. It is applied to the actively growing round-leaved mallow plants after the two-leaf stage and preferably before the weeds are 15 cm tall. Although BIOMAL[®] is effective when applied at any stage of weed growth, control occurs at a slower rate in older and the more mature plants. The most effective stage of application is at an early seedling stage. BIOMAL[®] is applied by mixing in water, using any conventional field sprayer at a spray volume of 100-150 L ha⁻¹. The suspension should be agitated constantly during spraying to ensure that the spores stay in uniform suspension. The suspension should be applied within 3 h of preparation. High humidity for approximately for 18-24 h after application ensures successful spore germination and infection. Rainfall during or immediately after application facilitates spore germination. If available, sprinkler irrigation may be used to create more humid conditions after application.

BIOMAL[®]-infected round-leaved mallow plants show typical anthracnose disease symptoms. Lesions will form on the leaves, petioles and stems of infected plants within 2-4 h after application. As the disease progresses, the stems are girdled by lesions, resulting in plant mortality. The commercial BIOMAL[®] formulation does not appear to have adverse toxicological effects on humans and the environment. It is manufactured by Philom Bios, Inc, Saskatoon, Saskatchewan, Canada.

COLLEGO[®]

COLLEGO[®] is a selective POST mycoherbicide used for the control of *Aeschynomene virginica* (L.) B.S.P. (northern jointvetch) in rice and soybean. The living spores of the fungus *Collectotrichum gloeosporioides* (Penz.) & Sacc. f. sp. *aeschynomene* constitute the active ingredient of COLLEGO[®]. It is a two-component product, with component A consisting of a water-soluble spore-rehydrating agent and component B containing a wettable powder formulation of living fungal spores of *C. gloeosporioides* f. sp. *aeschynomene*. COLLEGO[®] should be applied to the emerged northern jointvetch plants that are 20-60 cm tall and have not reached the bloom stage. Rice fields should be flooded before

²Source of Information:

Biological Control of Weeds Handbook (Alan K. Watson, ed.). 1993. Weed Science Society of America, Champaign, Illinois, U.S.A., 202 pp.

application. Soybean fields should be applied just before application. Free moisture or relative humidity above 80% and air temperatures of approximately 26°C for at least 12 h are required for development of the highest degree of infection.

C. gloeosporioides f. sp. *aeschynomene* causes an anthracnose disease by forming lesions on the above-ground parts of northern jointvetch. Lesions occur principally on the stems and once the stems are girdled, plant parts above the girdle collapse and die. Death of plants may not occur for 4-5 wk after the application of COLLEGO®. This product is not known to be hazardous to humans or to the environment. It is manufactured by Ecogen, Inc., Langhorne, Pennsylvania, U.S.A.

DeVine®

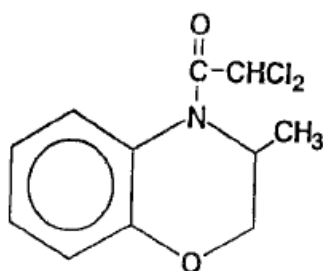
DeVine® is a mycoherbicide used for control of *Morrenia odorata*, strangler or milkweed vine, in citrus plantations. It is a submerged fermentation product containing chlamydospores of the fungus *Phytophthora palmivora* (Butl.) Butl. MWV pathotype. The liquid formulation is available in one pint (U.S. liquid measure, 473.2 ml) containers which must be kept refrigerated (2-8°C) until use. DeVine® may be applied in any type of citrus plantation from May to September after the weed has germinated or is actively growing. It may be applied by using a herbicide boom sprayer, at a spray volume of 124 L ha⁻¹, to achieve uniform coverage of the soil under the tree canopy. The fungus will initiate root infection in milkweed vine plants and kills the vine in 2-10 wk following application, depending on the size and maturity of the vine. The soil surface must be wet at the time of application.

DeVine®-infected milkweed vine shows typical *Phytophthora* rot symptoms. The dying plants are girdled at the soil level and up to an inch above it. The infection progresses until it encompasses all plant roots. Infected plant roots slough the cortex, leaving only the stele when the plant is pulled from the soil. The root rot induces leaf wilt, the leaves wither and eventually fall from the plant. The fungus is not a mammalian pathogen and it presents no imminent hazard to humans upon exposure. DeVine® is manufactured by Chemical and Agricultural Products Division, Abbott Laboratories, Chicago, Illinois, U.S.A.

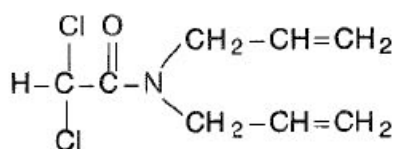
INFORMATION ON HERBICIDE SAFENERS

Herbicide safeners, earlier known as antidotes, protectants or antagonists, protect susceptible crop plants from herbicide injury. They do not have herbicidal properties. They widen the margin of crop selectivity to non-selective herbicides and permit using higher rates of herbicides than normally possible for more effective weed control. Safeners have been in use since the late 1960s and early 1970s with the discovery and development of 1-8-naphthalic anhydride (NA), CDAA and dichlormid. Subsequently several safeners have been developed and their properties and uses are discussed here.

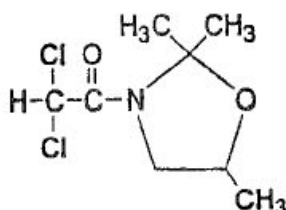
Benoxacor: 4-(dichloroacetyl)-3,4-dihydro-3-methyl-2H-1,4-benzoxazine



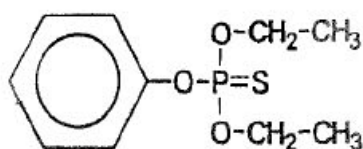
Benoxacor (CGA-154,281), a morpholine safener, was discovered in 1982 by Ciba-Geigy, and premix formulations with metolachlor were tested in 1986. It protects maize from metolachlor injury that may occur during abnormally wet conditions at the time of germination and emergence. It is packaged and applied in a 30:1 ratio of metolachlor and benoxacor. Thus, it can be soil-applied as an E-PPS, PPI, or PRE along with metolachlor. Benoxacor is synthesized by a multistep synthesis, beginning with 2-nitrophenol and a morpholine closing, followed by acetylation.

Dichlormid: 2,2-dichloro-*N,N*-di-2-propenylacetamide

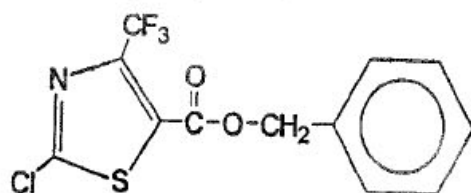
Dichlormid, earlier referred to as R-25788, was discovered in 1970 as an antidote for preventing EPTC injury to maize. It is now widely used to formulate commercial package mixtures with thiocarbamate (butylate and EPTC) and chloroacetamide (acetochlor, alachlor, etc.) herbicides for use in maize. It is also used with atrazine. It is applied at PPI or PRE at 0.14-0.45 kg ha⁻¹ with the herbicide. Dichlormid provides no weed control. It protects maize from injury by acetochlor and butylate. It may also be applied as a soil or seed treatment to protect maize and sorghum from several herbicides.

R-29148: 3-(dichloroacetyl)-2,2,5-trimethyloxazolidine

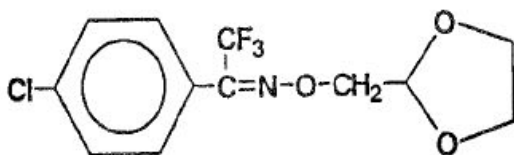
R-29148, like dichlormid, is also used to make premix formulations with EPTC and butylate for use in maize. It is applied at 0.15-0.30 kg ha⁻¹ when used with these herbicides. It was discovered in 1971.

Dietholate: *O,O*-diethyl *O*-phenyl phosphorothioate

Dietholate (R-33865) is a non-phytotoxic microbial inhibitor sold in a commercial package mix with EPTC and butylate for use in maize. By inhibiting soil microbes that degrade EPTC and butylate, dietholate extends the soil residual life of these herbicides, and thereby increases the duration of weed control efficacy. Hence, dietholate is referred to as a herbicide extender. It is applied PPI at 0.75-1.0 kg ha⁻¹. It does not persist in soil.

Flurazole: phenylmethyl-2-chloro-4-(trifluoromethyl)-5-(thiazolecarboxylate)

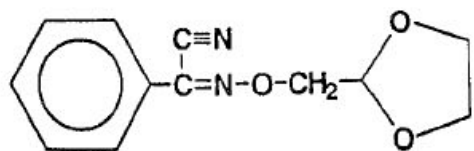
Flurazole (MON-4606) is used as a seed treatment at 1.25-2.50 kg seed on grain sorghum to protect against injury by alachlor and acetochlor. Like other safeners, flurazole has no weed control activity and does not protect weeds from control by herbicides.

Fluxofenim: 1-(4-chlorophenyl)-2,2,2-trifluoro-1-ethanone *O*-(1,3-dioxolan-ylmethyl) oxime.

Fluxofenim (CGA-133,205), an oxime safener, was first tested in 1982 by Ciba-Geigy. It is also used as a seed treatment, like oxabetrinil, to protect sorghum from injury by chloroacetamide (metolachlor) herbicides applied PRE or PPI. It is applied at 0.4 g (ai) per kg of seed and used like oxabetrinil. Fluxofenim is synthesized by a multi-step condensation of trifluorochloroacetophenone with a halogenated dioxolane.

Fluxofenim (CGA-133,205), an oxime safener, was first tested in 1982 by Ciba-Geigy. It is also used as a seed treatment, like oxabetrinil, to protect sorghum from injury by chloroacetamide (metolachlor) herbicides applied PRE or PPI. It is applied at 0.4 g (ai) per kg of seed and used

Oxabetrinil: α [(1,3-dioxolan-2-ylmethoxy)imino]benzeneacetonitrile



Oxabetrinil (CGA-43,089), an oxime group chemical, was first developed in 1982 by Ciba-Geigy. It is used as a safener to protect sorghum from injury by chloroacetamide herbicides (e.g. acetochlor) applied PPI or PRE. It is applied as a seed treatment at 1.25 g (ai) kg⁻¹ of seed, by placing seed in oxabetrinil/water slurry

with a binding agent. Sorghum seed must be dried quickly after treatment to avoid imbibition. Good-germinating hybrids/varieties or seed lots show no loss in germination percentage following oxabetrinil treatment. Weaker-germinating hybrids or varieties or seed lots may germinate at slightly lower percentages. Oxabetrinil is synthesized by coupling benzylcyanide with the appropriate halogenated dioxolane.

Other Safeners: There are many safeners which are in various stages of development, and these are listed below. The exception is NA which was one of the first safeners to be developed.

CGA-185,072; HOE-70,542 (Fenchlorazol-ethyl); Fenchlorim (CGA-123,407); Cyometrinil (CGA-43,089); NA (1-8-naphthalic anhydride); MG-191; OTC; MON 13900.

Herbicide Resistance and Genetic Engineering

RESISTANCE

The intensive and continuous use of herbicides over the last five decades has resulted in the development and evolution of weeds resistant to the normally phytotoxic chemicals. Since the first reports of triazine resistance in the mid-1960s, over 150 weed species have been identified as having developed biotypes resistant to at least one or more herbicide classes. Resistance to at least 15 classes of herbicides have been noted [82, 153]. Moreover, the area of land infested with resistant weeds is increasing rapidly. Reports of evolution of newly resistant biotypes continue to emanate from all over the world, including developing countries, e.g., India [90], where extensive use of herbicides in grain crops began only in the late 1970s. These reports indicate that herbicide resistance problems are accelerating and, consequently, management of weeds is becoming increasingly more difficult and complex.

The phenomenon of herbicide resistance in plants, especially in weeds, is analogous to the evolution of changes that arise in insects and pathogens in response to the continuous use of insecticides and fungicides. Herbicide resistance is the result of selection for traits that allow weed species to survive specific herbicide usage, which would otherwise cause mortality. Herbicide resistance contributes a trait of resistance within the plant species to a herbicide and resistant weeds are those plant species that express the genetic variation required to evolve mechanisms to escape control. Like other crop pests (insects, pathogens, etc.) with reference to pesticides (insecticides, fungicides, etc.), herbicide-resistant weeds are the result of intensive selection pressure in weed populations.

Generally, **resistance** is defined as the ability of a plant species to withstand the phytotoxicity of a chemical. This is the trait normally found in crop plants, as against weeds, thus forming the basis for herbicide selectivity. Crop resistance to a herbicide is often different from the one that exists in the phenomenon of herbicide resistance in weeds.

Herbicide resistance in the context of weeds is defined as a characteristic of the weed species to withstand a herbicide dosage substantially higher than the wild type of the same plant species can withstand. It is the inherent or acquired ability to withstand the dosage of herbicide normally used for satisfactory weed control. Resistant weed populations are unharmed by a concentration of herbicide that completely kills all unselected populations. This herbicide concentration is the one that in field practice produces an effective kill.

Herbicide susceptibility represents the other end of the scale, encompassing natural variability in sensitivity to herbicides within the unselected populations. **Tolerance**, on the other hand, indicates reduced susceptibility (or conversely enhanced resistance) which may sometimes result from selection by herbicides [128]. It is a response rather than 100% survival accompanied by zero reduction in growth at herbicide concentrations, which normally give 100% kill of susceptible biotypes. Tolerance may also be considered the natural or normal variability of response to herbicides that exists within a species and can easily and quickly evolve.

There is no clear distinction between **highly tolerant** and **resistant biotypes**, and low levels of tolerance usually merge into susceptibility. The word **resistance** used in this book encompasses both tolerance and resistance to herbicides in plant species and biotypes.

DEVELOPMENT OF HERBICIDE RESISTANCE

Development of herbicide resistance in weeds is an evolutionary process. There are two pre-requisites for the evolution of herbicide resistance in plant populations: a) the occurrence of heritable variation in genetic composition for herbicide resistance and b) natural selection for increased resistance to herbicides.

In response to repeated treatment with a particular herbicide or class (family) of herbicides, weed populations change in genetic composition such that the frequency of resistance alleles and resistant individuals increase [73]. In this way, weed populations become adapted to the intense selection pressure imposed by herbicides. The evolution of resistance under continuous application of a herbicide may be considered as an example of recurrent selection in which there is a progressive and sometimes rapid shift in average fitness of populations of weeds exposed to a herbicide. This shift in fitness, a genetic trait, is directly related to an increase in frequency of the resistance trait (phenotype) in the population.

The selection pressure for herbicide resistance is contributed by three factors: a) efficiency of the herbicide, b) frequency of herbicide use and c) duration of herbicide effect. Selection intensity in response to herbicide application is a measure of the relative mortality in target weed populations and/or the relative reduction in seed production of survivors; this will be proportional, in some manner, to herbicide dose [100]. The duration of selection is a measure of the period of time over which phytotoxicity is imposed by a herbicide. Both intensity and duration will interact to give seasonal variation in the process of selection, which will in turn depend upon the phenology and growth of a weed species. For example, with preemergence application of a herbicide that inhibits seedling emergence over a time period, the intensity of selection may be much higher on weed seedlings emerging early in the life of a crop than those seedlings emerging later.

The occurrence and speed of evolution of herbicide resistance are determined by several factors. These include:

- a) Number of alleles involved in the expression of functional resistance.
- b) Frequency of resistance alleles in natural (unselected) populations of the weed species.
- c) Mode of inheritance of the resistant alleles.
- d) Reproductive and breeding characters of the weed species.
- e) Longevity of weed seeds in the soil.
- f) Intensity of selection which differentiates resistant biotypes from susceptible ones.
- g) Relative fitness of resistance and susceptible genotypes.

Genetic Variation and Mutation

The mechanisms which interrupt the transport of herbicides to biochemical sites of action, reduce the sensitivity of target sites and detoxify the chemical or enhance repair can potentially confer resistance. The specific biochemical mechanisms include:

- a) sequestration of the herbicide in the apoplast,
- b) modification of cell membrane function and structure,
- c) changes in sensitivity of the key target enzyme,
- d) enhanced production of the herbicide target,
- e) enhanced metabolic breakdown and conjugation of the herbicide and
- f) enhanced degradation of herbicide-generated toxic products.

These mechanisms and consequently the expression of resistance, are controlled by genetic loci. Development of herbicide resistance is dependent on the extent of genetic variation and frequency of occurrence of mutation.

Genetic variation for resistance must be present in a susceptible population for the evolution of herbicide resistance to occur. There are two ways in which resistance traits may arise within a weed population. A major resistant gene, or genes, may be present at low frequency so that selection acts to change a population, which is initially susceptible [100]. Alternately, recurrent selection may occur continuously to achieve a progressive increase in average resistance from generation to generation, with changes in gene frequency at many loci conferring resistance. Thus, herbicide resistance is developed by gene mutations or conferred by pre-existing genes.

In general, gene mutations conferring resistance to a herbicide class are not induced by application of the herbicide, but rather occur spontaneously. Spontaneous mutations at gene loci recur with characteristic frequency such that new mutations are continuously generated in natural populations of weeds. Mutations at some loci, particularly those encoding herbicide site of action, may confer resistance. Typical spontaneous mutation rates in biological organisms are often cited as 1×10^{-5} or 1×10^{-6} gametes per locus per generation [104]. These values are for single, nuclear gene inheritance of resistance related to herbicide resistance evolution. At a rate of mutation to a single, dominant resistant allele of 1×10^{-6} , the probability of occurrence of at least one resistant plant in a 30 ha field with a weed density equal to, or exceeding, five plants m^{-2} is greater than 0.95 for a random mating species [73]. Thus, at least one resistant plant is almost certain to occur in a weed population of this size despite the low rate of mutation to resistance. Factors such as seed inviability and seedling mortality may cause the plant's mortality prior to reproduction [73]. However, should it survive and reproduce and if the corresponding herbicide or herbicide class is applied for several generations, the single resistant plant could give rise to a predominantly resistant population of weeds [73].

If the mutation rates are lower than 1×10^{-6} , i.e., 1×10^{-8} to 1×10^{-10} , the probability of occurrence of a resistant mutant is markedly reduced. It requires densities greater than 50 plants per m^2 for a resistant mutant to occur if the mutation rate is 1×10^{-8} [73]. The positive correlation between the size of a susceptible weed population and probability of occurrence of resistant mutant plants may partly explain why herbicide-resistance has evolved in some species but not in others. The probability of herbicide-resistant plants occurring in a population is greater for weeds with high densities than for those which occur at low densities.

The frequency of mutation may be influenced by environment and dosage of a herbicide. For example, atrazine applied at sublethal doses to certain susceptible genotypes of *Chenopodium album* resulted in a progeny with triazine-resistant

characteristics similar to highly resistant plants [11]. This indicates that herbicide resistance could be induced by low doses of the chemical in certain genotypes.

Most herbicides are extensively screened for efficacy in the field before release for commercial use. Herbicides are not accepted for market without at least 85-90% control of the target weeds. Therefore, it is very likely that resistance traits are present, if undetectable, in weed populations before large-scale selection with herbicides.

Inheritance of Herbicide Resistance

There are two modes of inheritance of herbicide resistance: **nuclear inheritance** and **cytoplasmic inheritance**. Resistance to most classes of herbicides is caused by nuclear inheritance. These include bipyridiliums, benzoics, aryloxyphenoxypropionics, sulfonylureas, substituted ureas, etc. In nuclear inheritance, the resistant alleles are transmitted through pollen and ovules. Adaptive evolution is achieved by the selection of phenotypes encoded by many genes (i.e., polygenes), each with a small additive effect. Generally, herbicide resistance is conferred by major genes present in weeds. In the majority of cases in which the number of genes has been determined, resistance is controlled by a single, major gene [73]. The predominance of major gene inheritance is attributed to the two following factors:

1. The most recently developed herbicides are highly target site-specific and interfere with single enzymes in major metabolic pathways. Mutation of the gene encoding for the enzyme may alter a plant's sensitivity to the herbicide and result in resistance.
2. Repeated application of these herbicides imposes strong selection, often causing 95-99% mortality, against susceptible phenotypes in weed populations.

Adaptation to the herbicide is possible only if resistant genes are present in a population and have a significantly large phenotypic effect to allow the survival of a few individuals in a single generation [102]. With polygenic inheritance, recombination among individuals for many generations is required to bring together a sufficient number of favourable alleles to produce a highly resistant phenotype. Polygenic inheritance of resistance is thus more likely under conditions of weak selection as would occur with sublethal herbicide application [73].

Cytoplasmic inheritance of resistance occurs with triazine herbicides in several weed species. The gene conferring triazine resistance is located in the chloroplast genome [66]. Transmission of the chloroplast resistant gene mostly occurs by pollen, the paternal parent. The mutation that confers maternally inherited triazine resistance involves a single base substitution in the *psbA* chloroplast gene which codes for a Photosystem II membrane protein to which triazine herbicides bind. The expected frequency with which a mutation occurs in the chloroplast genome and gives rise to gamete-transmissible triazine resistance is very low [73]. The probability ranges from 1×10^{-9} to 1×10^{-12} mutations per gene locus [5].

Selection by Herbicides

The evolution of herbicide resistance in weeds is dependent on the intensity of selection imposed by herbicides. Most herbicides are applied at rates that result in the mortality of 90-99% of the susceptible weeds (weed seedlings). If genetic variation for resistance is present due to mutation or gene flow, even at very low frequencies, repeated herbicide application will normally result in a rapid increase in the frequency of resistant individuals until they dominate the population [73]. The selection pressure imposed by a herbicide is a primary factor that determines the rate of enrichment of

herbicide resistance in a weed population. The higher the intensity of selection imposed by a herbicide against susceptible species, the faster the expected rate of evolution and spread of resistance. Several herbicide characteristics and patterns of use result in higher mortality than others do and these impose a more intense selection pressure for the development of resistance. These include a single target site and highly specific mechanism of action, long-term soil residual activity and frequent applications [83].

Seed production is an essential component to assess selection pressure. Effective kill by a herbicide is measured as the percentage reduction in seed yield at the end of the growing season. Values obtained for both resistant and susceptible plants are then used to estimate the selection pressure. The selection pressure of a herbicide is calculated as the ratio of the fraction of resistant plants that survive herbicide application to the corresponding fraction of susceptible plants [52a]. Gressel and Segel [52a] defined the selection pressure of a herbicide on a particular weed species as:

$$\frac{1 - \text{Effective kill of resistant plants}}{1 - \text{Effective kill of susceptible plants}}$$

Measurement of selection intensity exerted by herbicides is done theoretically and phenotypically. Population geneticists measure selection frequency after the action of the selection agent. However, weed scientists measure selection frequency at the phenotype level. Selection coefficients may be variously defined at the gametic (gene) or zygotic (genotypic) level. The coefficient of selection, S , may be defined as the proportionate contribution of a particular genotype to future generations compared with a standard genotype, whose contribution is usually taken to be unity [100].

For a detailed discussion of this subject, the reader may refer to a textbook on population genetics.

Fitness

In the theoretical plant population model constructed to predict herbicide resistance, two sets of biological processes serve as major factors. These are **ecological fitness** and **gene flow**. Knowledge about both factors is necessary to develop effective strategies for management of herbicide-resistant weeds.

An individual plant is a unique genotype with variation at many loci affecting fitness. The fitness of a group of plants having a certain genotype is assessed in relation to the fitness of other genotypes lacking key traits of interest. During breeding of two types of plants in a homogeneous environment allelic changes occur at a single locus, causing genotypic changes. When genotypic response is measured against a constant environment and genetic background, the expression '**genotypic fitness**' is used. It is possible to measure and calculate 'genotypic fitness' in the field and laboratory for a given genotype (homozygote and heterozygote).

Fitness is a measure of survival and ability to produce viable offspring. Under conditions of natural selection, genotypes with greater fitness produce, on the average, more offspring than less fit genotypes. It is measured over the whole life cycle of a plant, encompassing the effects of selection on mortality and seed production of survivors. For an annual species, the seed produced by a genotype per generation constitutes a fitness estimate for a given environment only at one point in the evolutionary time. While determining the fitness of a weed with a persistent seedbank, the rate of loss of seed from the soil needs to be measured. Seed carryover from previous generations plus the seed produced in the current generation contribute to

total seed production. In order to understand the rate of evolution of resistance or management of resistance, measurements of fitness need be conducted only under field conditions with the crop and with and without herbicide application. For vegetatively reproducing weed species, fitness is assessed from the measurement of total biomass or plant parts over a time period appropriate for the species concerned.

Fitness is a dynamic integration of processes that can change with the environment and promote natural selection for more fit genotypes within the resistance phenotype. Fitness is a relative term whereby genotypes are compared among themselves relative to the most successful one. For example, susceptible biotypes produce up to 64% more biomass than their triazine-resistant counterparts under competitive and non-competitive conditions in a selective environment [24, 70, 154]. As many triazine-resistant biotypes are less fit than their susceptible counterpart, it is widely believed that plants resistant to other classes of herbicides also would be less fit than susceptible biotypes.

Certain new genes introduced through mutation to a population can result in a less well-adapted (fit) phenotype than is associated with the original gene if there is no change in the environment [57]. The new genotype would then be displaced by the wild biotype, or increase in frequency to some equilibrium in population. The rate of decrease or increase and the new equilibrium frequency would depend on the relative fitness advantage or disadvantage of the genotype and the rate at which the genotype can acquire compensatory traits by crossing with the wild type. If changes occur in the environment or in the wild-type genotype, then the new genotype may become more frequent in the population within a few generations. In the absence of herbicides, a new herbicide-resistant genotype would become less fit, to a certain degree, than the susceptible genotype and its success will be determined by the rate at which it can acquire compensatory traits. If a herbicide is introduced into the system, the resistant genotype would then immediately become more fit than the susceptible genotype and rapidly account for a greater proportion of the population.

Gene Flow and Spread of Herbicide Resistance

Gene flow has a significant impact on the rate of evolution of herbicide resistance. If a single plant or set of plants survives a herbicide application, the allele for resistance is passed to other plants in the field. Gene flow among plants can occur through: a) pollen dispersal and resultant fertilization and b) seed dispersal.

Rates of gene flow are generally believed to be higher than rates of mutation and hence would result in a higher frequency of plants resistant to a particular herbicide prior to its initial application. Therefore, gene flow and the resultant increase in initial frequency of resistant genes would reduce the time required to reach a specific level of resistance within a field once a herbicide is applied [73].

Gene flow could occur from herbicide-treated fields to adjacent unsprayed areas. Similar flow could also occur from resistant plants within the crop to susceptible plants at the field edge. Devlin and Ellstrand [33] showed that a significant proportion of a population's seed crop can be fathered by plants from outside the population. Such gene flow could lead to a rapid spread of a herbicide resistance gene among weed populations in a particular area.

Pollen movement of resistance alleles within populations occurs in several weed species. For example, outcrossing of resistant pollen to susceptible plants was 1.4% at a distance of 28.9 m in *Kochia scoparia*, resistant to sulfonyleurea herbicide and 1% at > 6.84 m in *Lolium multiflorum*, resistant to diclofop-methyl [99, 143]. Mulugeta et al. [107] recovered *Kochia scoparia* pollen as far as 50 m from its source, indicating that

pollen dispersal could lead to long-distance spread of herbicide-resistant genes. Although pollen dispersal is generally assumed to be the major mechanism of interpopulation gene flow in plants, seed dispersal may play a far greater role in weed populations. In self-fertilizing plants, pollen flow is minimal.

Cross and Multiple Resistance

Cross resistance is an expression of a mechanism that confers on plants the ability to withstand herbicides from different classes [61]. It may be conferred either by a single gene or, as in the case of quantitative inheritance, by two or more genes.

The most common form of cross resistance occurs when a change at the site of action of one herbicide also confers resistance to herbicides from a different class that inhibits the same site of action [61]. For example, weed biotypes resistant to acetolactate synthase (ALS)-inhibiting herbicides (sulfonylureas) become resistant to other ALS-inhibiting herbicides (imidazolinones and triazolopyrimidines). A biotype of resistant *Lolium rigidum* (annual ryegrass) selected with chlorsulfuron, metsulfuron and eight other sulfonylurea herbicides was also selected for resistance to imazapyr and imazethapyr [91, 92]. Similarly a *Kochia scoparia* (kochia) biotype resistant to five sulfonylurea herbicides is also resistant to one imidazolinone herbicide, imazapyr [125]. While being resistant to ALS-inhibitor herbicides, these weed biotypes are not resistant to herbicides with alternate modes of action.

Weed biotypes selected for resistance to aryloxyphenoxypropionic acid herbicides (APPs) which act on acetyl-CoA carboxylase (ACCase) are also less sensitive to cyclohexanedione herbicides (CHDs) and vice versa [119, 146]. There are exceptions for cross resistance in weeds. For example, the R biotype of *Xanthium strumarium* is sensitive to imazaquin and other imidazolinone herbicides, but not to chlorimuron, a sulfonylurea herbicide used in soybean. As this biotype has a significantly different cross resistance pattern, it probably contains a different ALS mutation than the one selected for resistance to sulphonylurea herbicides. This biotype is apparently controlled by herbicides with alternate mode(s) of action.

Multiple resistance in a weed biotype is an expression of more than one mechanism of resistance and hence is endowed with the ability to withstand herbicides from different chemical classes. Multiple resistant plants possess two or more distinct resistance mechanisms. For example, Gill [49] screened 242 populations of herbicide-resistant *Lolium rigidum* in Australia and found that 32% of them were resistant to sulfonylureas and APPs, 12% to sulfonylureas, APPs and CHDs, 6% to APPs and CHDs, 39% only to sulfonylureas and 11% only to APPs. Resistance to many herbicides makes weed biotypes similar to *Lolium rigidum* difficult to manage at the field level.

Target Site Resistance

Target site resistance involves a decrease of the herbicide target site to inhibition by the herbicides. The first target site resistance to ALS-inhibiting herbicides was found in *Kochia scoparia* [132]. Similar decreased ALS sensitivity to ALS-inhibiting herbicides has been reported in several other weed species. In the cases of *Kochia scoparia* [132], *Kochia iberica* and *Lolium perenne* [134], the resistance mechanism was due to an insensitive ALS and not to differential uptake and translocation. Saari et al. [133] reported that all the weeds selected for resistance to one sulfonylurea herbicide are also cross sensitive at the enzyme level to all other sulfonylurea herbicides. Triazolopyrimidine herbicides are also similarly affected by the mutation conferring resistance to the sulfonylureas.

There is also a lower but consistent cross insensitivity to imidazolinone herbicides, especially imazapyr, for weeds selected for sulfonylureas.

The target site resistance also exists in the case of ACCase-inhibiting herbicides. In the case of *Lolium rigidum*, one biotype (WLR 96) developed resistance after 10 yr of exposure to diclofop methyl (an APP herbicide), while the other biotype (SLR 3) developed tolerance after only three consecutive years of exposure to sethoxydim (a CHD herbicide) [69, 146]. Both types exhibit target site cross resistance to the APP and CHD herbicides. However, despite dissimilar periods of exposure, resistance to APPs is higher than resistance to CHDs. Tardif et al. [146] reported that the resistant *L. rigidum* biotypes with resistant ACCase exhibited biotype-specific patterns of resistance both at the whole plant level and in ACCase-assay level, in a manner similar to maize. In all the herbicide-resistant plant ACCases, the inheritance is apparently controlled by single, nuclear-coded, dominant or partially dominant genes [9, 146].

Non-Target Site Cross Resistance

Certain weed biotypes exhibit enhanced rates of herbicide metabolism. In such cases the degree of resistance at the whole plant level, while being sufficient to provide resistance at the recommended rates, is much less than conferred by the target site cross resistance mechanism. Uptake of herbicides and/or its movement to the site of action are the other mechanisms that confer non-target site cross resistance.

Mathews and Powles [97] reported that selection with an ACCase-inhibiting herbicide could lead to a resistant population that displays non-target cross resistance to ALS-inhibiting herbicides without exposure to these herbicides.

Wheat and some biotypes of *L. rigidum* have a similar resistance mechanism. Wheat has a sensitive ALS but can rapidly metabolize some ALS-inhibitors by aryl-hydroxylation, catalyzed by cytochrome P450 (Cyt 450) mono-oxygenases, followed by glycosylation forming non-toxic substances. Similarly, two chlorsulfuron-resistant biotypes of *L. rigidum* which have sensitive ALA, like wheat, can oxidatively metabolize chlorsulfuron more rapidly than the susceptible biotypes, yielding the same metabolites as produced by wheat [22]. The enhanced metabolism of ALS-inhibiting herbicides in *L. rigidum* is catalyzed by Cyt 450 mono-oxygenase. However, chlorsulfuron resistance can be reversed if the herbicide is combined with another chemical.

Similarly, selection with atrazine in conjunction with amitrole, a triazole herbicide, resulted in triazine resistance and cross resistance to a substituted urea herbicide in a *L. rigidum* biotype, WLR 2 [16]. In the case of chlortoluron, a substituted urea, herbicide-resistant plants exhibited an enhanced capacity for *N*-demethylation as an initial metabolic step [17]. An enhanced capacity for *N*-demethylation may explain the broad cross resistance to many substituted ureas which have *N*-alkyl groups in common but differ in phenyl substituents [61].

As another example, two maize inbreds with different sensitivities to thifensulfuron-methyl, more of the absorbed ¹⁴C-herbicide was translocated out of the treated leaf in the susceptible inbred than in the resistant inbred [37]. As the observed differences in translocation were too small to account for the large differences in sensitivity, the greater and more rapid metabolism of thifensulfuron-methyl in the resistant inbred appeared to be the major mechanism conferring resistance [37]. In a similar case, Hall et al. [59] reported that uptake and distribution of foliage-applied ¹⁴C-thifensulfuron-methyl was nearly identical in the resistant commercial mustard (*Brassica juncea*) and the susceptible wild mustard (*Sinapis arvensis* L.). They attributed resistance to more rapid metabolism of the herbicide, yielding two major metabolites, in the commercial mustard than in wild mustard.

These examples indicate that the primary mechanism of non-target cross resistance is metabolic inactivation or target site insensitivity while the differences in uptake and translocation play only a secondary role.

MECHANISMS OF RESISTANCE DEVELOPMENT IN WEEDS

It is important to understand the mechanism of resistance to herbicides in order to develop methods to increase herbicide resistance in crop plants and strategies to overcome development of herbicide resistance in weed species. The crops are resistant because they can detoxify herbicides. The resistance mechanism in weeds is, however, different from that found in crops. The herbicide resistance in weeds can be due to a number of mechanisms: a) modified target site, b) enhanced detoxification (metabolism), c) reduced absorption and/or translocation, d) sequestration or compartmentation and e) repair of the toxic effects of herbicides.

Although the mechanisms of action of various herbicide classes were discussed in Chapter 7, their primary targets of action are briefly mentioned here to bring relevance to the discussion on mechanisms of resistance to various herbicide classes and herbicides. The following presentation pertains only to herbicide classes and herbicides that are known to inhibit major biochemical processes in plants.

Resistance to Photosystem I Inhibitors

Photosystem I (PS I) inhibitors include bipyridilium herbicides (paraquat and diquat) and arsenical herbicides (DSMA and MSMA).

Target Site

Paraquat enters the chloroplast to reach the site of action at PS I. Being a divalent cation, paraquat short-circuits the light-driven photosynthetic electron transport in PS I by accepting electrons that normally flow to ferredoxin. The paraquat radical thus generated reduces oxygen to form superoxide, which is catalyzed by superoxide dismutase yielding a highly toxic hydroxy radical. This toxic form of oxygen, superoxide, causes lipid peroxidation, rapid loss of membrane integrity, photooxidation, desiccation and plant death. Sunlight, which enables photosynthetic electron transport, aids in the toxicity of paraquat.

Weed Resistance

Weed resistance to paraquat was first reported in the late 1970s and early 1980s, after about two decades of use, when resistance was observed in *Conyza bonariensis* (hairy fleabane) from vineyards and citrus plantations in Egypt [47]. Similar resistance was reported in *Erigeron philadelphicus* (Philadelphia fleabane), *Erigeron canadensis* (horseweed), *Hordeum glaucum* (wall barley) and *Poa annua* (annual bluegrass) [75, 127, 153, 156]. The other species which showed resistance to paraquat include *Amaranthus retroflexus* (redroot pigweed), *Parthenium hysterophorus* (ragweed parthenium), *Solanum nigrum* (black nightshade), *Epilobium ciliatum* (willowweed), *Crassocephalum crepidioides*, etc.

The resistant (R) biotypes of these weeds showed evidence of reduced uptake into the leaf and restricted translocation compared to susceptible (S) biotypes. Preston et al. [123] applied paraquat at field doses to the intact plants of R and S biotypes of *Hordeum glaucum* and *H. leporinum* under conditions close to field applications and found reduced paraquat translocation in a basipetal direction. The herbicide moved more rapidly in the S biotypes. Preston et al. [123] reported that there was no difference in gross

translocation of paraquat in the R biotype of *Arctotheca calendula*, but movement to the target site was reduced, probably as a result of reduced penetration of herbicide into the leaf cells. These and other studies suggest that paraquat is rapidly detoxified or removed from the chloroplasts of the R biotype [71, 138].

Although herbicide metabolism is a major selectivity and resistance mechanism in many plant species, metabolism is unlikely to be responsible for resistance to paraquat [68]. The rapid action of paraquat in plants is unlikely to allow metabolic detoxification to non-herbicidal metabolites such as *N*-methyl isonicotinic acid, monopyridone and methylamine found when detoxified by bacteria and fungi. Furthermore, no metabolism of paraquat or diquat has yet been detected for any other higher plants. It has been proposed that resistance to paraquat is possibly due to the detoxification of paraquat-generated toxic oxygen species (superoxide) catalyzed by superoxide dismutase (SOD) and other chloroplast enzymes, ascorbate peroxidase and glutathione reductase. Elevated amounts of these enzymes have been proposed as the mechanism of resistance to paraquat. However, no difference in the amounts of these enzymes has been observed in isolated chloroplasts from R and S biotypes of *Ceratopteris richardii* [19], in crude extracts from R and S biotypes of *Hordeum glaucum* [121], or from separate accessions of R and S biotypes of *Erigeron canadensis* (also referred to as *Conyza canadensis*) [120]. In contrast, other studies showed that a resistant biotype of *Conyza bonariensis* had increased amounts of SOD, ascorbate peroxidase and glutathione reductase [113, 137, 161]. However, increased amounts of these enzymes in themselves will not confer much resistance to paraquat as the reaction-producing superoxide regenerates the paraquat cation (Chapter 7, Fig. 7.5).

Other Photosystem I Inhibiting herbicides

DSMA and MSMA affect chlorophyll synthesis, amino acid content and respiration in sensitive plants. These arsenic herbicides are reduced by PS I to form sulphhydryl groups of enzymes involved in CO₂ fixation and its regulation, thereby inhibiting CO₂ fixation. Uptake, translocation and metabolism are not involved in the mechanism of resistance of the R biotype of *Xanthium strumarium* (common cocklebur) to MSMA [76, 111]. The R biotype is not cross resistant to other herbicides. Inhibition of carbon assimilation is more rapid and of greater magnitude in the S biotype than in the R biotype of *X. strumarium* [112]. MSMA has no direct effect on photosynthetic electron transport. The mechanism of resistance to MSMA and DSMA remains a mystery.

Resistance to Photosystem II Inhibitors

The photosystem II (PS II) inhibitors include triazines and substituted ureas as also herbicide belonging to such structurally diverse groups as nitriles (bromoxynil and ioxynil), carbamates (desmedipham and phenmedipham), dinitroanilines, acetamides (propanil), pyridazinones (pyrazon), benzothiadiazole (bentazon), oxadiazolidines (methazole), phenylpyridazines (pyridate), imidazolidinones (buthidazole), etc. Some of these herbicides/herbicide classes such as nitriles, pyridazinones, dinitroanilines, etc. also have other sites of action.

Herbicide resistance was predicted in the 1950s, even before triazines and ureas were made available for commercial use [62]. That prediction came true in 1968 when the first herbicide-resistant weed, *Senecio vulgaris* (common groundsel) was discovered, as its resistant biotype could no longer be controlled by the PSII inhibitor simazine [131]. In the 30 years since this discovery, there have been reports of scores of weed biotypes exhibiting resistance to PS II-inhibiting herbicides. Of these weeds, dicots,

which are more susceptible to triazines, outnumbered monocots, which are partially resistant. Millions of hectares of cropped land under maize monoculture and receiving triazines repeatedly for several years, particularly in developed countries, are now infested with triazine-resistant weeds.

Target Site

As discussed in Chapter 7, the PS II complex catalyzes the light-dependent oxidation of water with the reduction of plastoquinone (PQ). Light energy absorbed by the light-harvesting chlorophyll (LHC) antenna pigment (or proteins) is transferred to the reaction centre chlorophyll, P680, causing a charge separation. An electron is then passed to pheophytin and then to PQ_A on the D_2 protein (a polypeptide). Plastoquinone can be reduced by two sequential one-electron acceptors. The bound PQ_A transfers two electrons, one at a time, to the second plastoquinone molecule, PQ_B , which is reversibly bound to the $D1$ protein (a polypeptide). Upon transfer of the second electron and the acceptance of two protons from the stroma, fully reduced plastoquinone, plastoquininol (PQH₂), is formed. This molecule leaves the PQ_B site on the $D1$ protein, diffuses across the thylakoid membrane and donates two electrons to the cytochrome *b/f* complex with the release of two protons into the thylakoid lumen. Electrons from the cytochrome *b/f* complex are then transferred to PS I via plastocyanin.

The $D1$ polypeptide, also known as the 32-kDa protein or the PQ_B protein, is encoded by the chloroplast *psbA* gene. In the light, the $D1$ protein undergoes a continuous cycle of degradation and re-synthesis, with a half-life ranging from 30 min to a few hours [1]. Continuous turnover of the $D1$ protein is necessary for electron transport because photoinhibition (photodamage) occurs during the normal operation of the PS II reaction centre [1]. $D1$ protein incurs greater photodamage under conditions that promote photoinhibition (i.e. strong illuminations), thus requiring a faster turnover rate. The photoinhibition is due to formation of radicals or singlet oxygen by redox components associated with the $D1$ protein [1].

The PS II-inhibiting herbicides displace plastoquinone at the PQ_B binding site on the $D1$ protein and thereby block electron flow from PQ_A to PQ_B . [Triazine and urea herbicides act as non-reducible analogues of plastoquinone while nitriles and phenols act as non-reducible analogues of semiquinone anion of plastoquinone]. Binding of the herbicide at the PQ_B niche not only causes photodamage to the $D1$ protein by preventing electron transfer from PQ_A to PQ_B , but also compounds herbicidal activity by preventing replacement (re-synthesis) of the damaged $D1$ protein.

Target Site Modification

LeBaron and McFarland [83] reported that of the 57 weed species (40 dicots and 17 monocots) exhibiting biotypes resistant to PS II inhibitors (primarily triazines), all but a few were resistant due to a modification at the target site. The target site modified in these resistant biotypes was the amino acid residues in the PQ_B -binding niche on the $D1$ protein [45, 148]. This modification reduces the affinity of PS II herbicides at this site so that they can no longer effectively compete for the exchangeable PQ_B .

In all cases of target site resistance, resistance is due to a point mutation in the chloroplast *psbA* gene, resulting in the substitution of glycine for serine 264 [45, 148]. This modification greatly reduces the affinity of atrazine at the PQ_B -binding site, since binding affinity is strongly dependent on H-bonding with the OH-side chain of serine 264. As a result of this modification, there is a 1000-fold reduction affinity at the PQ_B -binding site and greater than 100-fold increase in atrazine resistance at the whole plant level [46]. Triazine-resistant weeds with ser 264-to-glycine mutation exhibit a

modified galactolipid composition, an increase in unsaturation of fatty acids and altered chloroplast structure. The chloroplasts in resistant weeds are similar to 'shade chloroplasts' which develop under low light conditions. In relation to triazine-susceptible chloroplasts, the chloroplasts of triazine-resistant biotypes exhibit increased grana stacking and a reduced chlorophyll a/b ratio.

Aside from reducing the affinity of atrazine at the PQ_B -binding site in a resistant biotype, the **ser 264-to-glycine mutation** of the *psbA* gene also reduces the rate of electron transfer between PQ_A and PQ_B by 3-fold to 10-fold. Modification of amino acid residues in the PQ_B -binding niche on the D1 protein is both herbicide-specific and biotype-specific. The **ser 264-to-glycine mutation** is specific to the R biotypes of *Amaranthus* spp. The R biotypes of other weeds may have a different amino acid residue modification. Each mutation confers varying levels of resistance, each to a different spectrum of herbicides, particularly triazines, uracils and ureas. Biotypes with this mutation exhibit a reduction in CO_2 fixation, quantum yield and seed, and biomass production.

Inheritance of PS II-Inhibitor Resistance

As the D1 protein is a chloroplast gene product, triazine resistance is maternally inherited. Certain weed species exhibit greater than expected incidence of mutation rate of the *psbA* gene, resulting in higher triazine resistance. This is hypothesized as due to the presence of a **plastome mutator**, a nuclear gene, that increases the frequency of chloroplast DNA mutation [5]. The triazine R biotypes of some weed species (e.g., *Chenopodium album*) rapidly develop resistance to other PS II-inhibiting herbicides since the presence of the mutator gene would increase the likelihood of other mutations in the PQ_B -binding pocket [142].

In certain populations of *C. album*, triazine resistance involves a two-step process [11, 28]. It requires the presence of 'R precursor' genotypes that exhibit a high random mutation rate of the *psbA* gene. This precursor genotype mutates in the absence of herbicides to form an 'intermediate biotype' which has the **ser 264-to-glycine mutation** in the *psbA* gene. This intermediate biotype exhibits a high level of atrazine resistance (1000-fold) at the chloroplast level. When treated with other herbicides, e.g., carbamates, ureas, etc. the intermediate biotype produces progeny that are highly resistant to atrazine. This induced expression of a high level of resistance in the intermediate biotype involves an extrachloroplastidic genetic mechanism [11].

The triazine resistance in the R biotypes of *Abutilon theophrasti* is not maternally inherited. It is controlled by a single, partially dominant nuclear gene that is not cytoplasmically inherited [3]. Unlike most triazine R weed biotypes, the resistant *A. theophrasti* biotypes are only 10 times as resistant as susceptible biotypes. Resistance in this weed species is due to enhanced **glutathione S-transferase** activity, which confers enhanced capacity to detoxify atrazine via glutathione conjugation [4].

In the case of *Alopecurus myosuroides*, the inheritance of resistance to chlortoluron and isoproturon is polygenic and under nuclear control. The rapid degradation of these herbicides in the R biotypes is catalyzed by **cytochrome P450 mono-oxygenases**.

Lolium rigidum, a ubiquitous weed widely found in Southern Australia exhibits multiple resistance to several herbicide classes. The R biotype, WLR 2, is cross resistant to several triazines (atrazine, simazine, propazine, cyanazine, prometryn, ametryn, etc.), ureas (chlortoluron, diuron and isoproturon), asymmetrical triazines (metribuzin) and amitrole. The resistance to these herbicides varies from 3- to 9-fold depending on the herbicide. VLR 69, the R biotype of *Lolium perenne* (perennial ryegrass), is not only resistant to triazines, ureas and metribuzin, but also to aryloxyphenoxypropionics

(diclofop, fluazifop and haloxyfop), cyclohexanediones (tralkoxydim), imidazolinones (imazaquin) and sulfonyleureas (chlorsulfuron and triasulfuron) [15]. Both WLR 2 and VLR 69 metabolize simazine and chlortoluron twice as fast as the S biotype [16, 17]. The inheritance of resistance in these R biotypes is a polygenic trait under nuclear control.

A resistant (R) biotype of the dicot weed *Polygonum lapathifolium* (pale smartweed) was 35.5 times more resistant to atrazine than an S biotype [116]. Electron transport in chloroplast thylakoids isolated from the leaves of the R biotype of *Polygonum* was 781 times less sensitive to atrazine than in S biotypes. The atrazine-resistance mechanism in *P. lapathifolium* was due to reduced affinity for atrazine to its target site.

Resistance to Acetolactate Synthase Inhibitors

Acetolactate synthase (ALS) is the first enzyme common to the biosynthesis of the branched-chain amino acids, valine, leucine and isoleucine (vide Chapter 7). Currently, three chemically dissimilar classes of herbicides, sulfonyleureas, imidazolinones and triazolopyrimidines share a common target site, ALS inhibition. These herbicides are commercially used for selective weed control in such diverse crops as wheat, maize, soybean and rice. The list of ALS inhibitors may grow in future as more are discovered.

Resistance in weeds to ALS-inhibiting herbicides was first observed in *Lactuca serriola* (prickly lettuce) in 1987 [91], only five years after the commercial introduction of chlorsulfuron. Later, *Kochia scoparia* (kochia) was identified to have developed resistance to sulfonyleurea and imidazolinone herbicides [125]. Since then, numerous weed species, most of them dicots, have been reported worldwide to have developed resistance to ALS-inhibiting herbicides. These weeds include *Amaranthus retroflexus* (redroot pigweed), *Alopecurus myosuroides* (blackgrass), *Cyperus difformis* (umbrella sedge), *Lolium perenne* (perennial ryegrass), *Lolium rigidum* (rigid ryegrass), *Sagittaria montevidensis* (arrowhead), *Sonchus oleraceus* (annual sowthistle), *Stellaria media* (common chickweed), *Salsola iberica* (Russian thistle), *Xanthium strumarium* (common cocklebur), *Eleusine indica* (goosegrass), etc.

Resistance to ALS-inhibitors evolved relatively quickly—after only four to seven continuous applications of the herbicide in monoculture crop areas and non-crop areas. The long residual activity of many of these herbicides has also contributed to the rapid development of resistance by increasing the effective kill and hence the selection pressure.

Target Site and Its Modification

Resistance to target site involves a reduction in the sensitivity of the herbicide target site to inhibition by the herbicides. The first target site resistance to ALS-inhibiting herbicides was identified in *Kochia scoparia* [132]. In the R biotypes of *K. scoparia* and other weed species, the resistant mechanism identified was an insensitive ALS. The other possibilities such as increased metabolism and differential uptake and translocation have had no role in the resistance mechanism exhibited by the R biotypes.

Saari et al. [132] reported that the insensitive ALS in the R biotypes of *K. scoparia* was due to an altered form of ALS. The R/S ratios of I_{50} values for LAS inhibition ranged from 28 for metsulfuron to 2 for imazethapyr. The chlorsulfuron-resistant isolate demonstrated both intra- and interfamily cross resistance with sulfonyleurea, imidazolinone and triazolopyrimidine sulfonanilide herbicides. They suggested that differences in ALS sensitivity to different classes of herbicides might be due to slightly different binding domains within a common binding site on the protein. Wiersma et al.

[159] found that two protein domains, **Domain A** and **Domain B**, appeared to influence resistance. In Domain A, consisting of 13 amino acids, substitution of serine, glutamine, or alanine for proline residue at amino acid 173 confers resistance to ALS inhibitors. Domain B, with four amino acids, enhanced the level of resistance conferred by mutation in Domain A in tobacco [84]. Wiersma et al. [159] reported that proline residue in Domain A was pivotal for developing resistance to chlorsulfuron.

Seeds from sulfonylurea-resistant *K. scoparia* accessions contained 2-fold higher levels of branched-chain amino acids than seeds from susceptible accessions [36]. Mutations conferring resistance may concomitantly reduce or abolish ALS sensitivity to normal feedback inhibition patterns, resulting in elevated levels of branched-chain amino acids ([36].

Guttieri et al. [56] observed that the Domain A DNA sequence from the chlorsulfuron-R biotype of *Lactuca serriola* (prickly lettuce) differed from that of the S biotype by a single point mutation, which substituted histidine from a proline. The Domain A sequence from a resistant *K. scoparia* biotype also differed from the S biotype by a single point mutation in the same proline codon (**Pro₁₇₃**), substituting threonine from proline. Further work by Guttieri et al. [55] found point mutation in the codon for the proline residue at position 173 in Domain A of the ALS protein in seven of the R biotypes. Among these seven R biotypes, mutation to threonine, serine, arginine, leucine, glutamine and alanine was observed. All the R biotypes were resistant to modified ALS, indicating that at least one non-Domain A mutation site for resistance exists in kochia. Their results indicated the existence of multiple mutations for resistance controlled by multiple resistant alleles.

Resistance to ALS-inhibiting herbicides, usually inherited as a semi-dominant trait, is conferred by single nuclear genes coding for less susceptible ALS. The ALS gene codes for an enzyme of 670 amino acids with a molecular weight of about 73 kDa, an enzyme highly conserved in various organisms, including plants and microbes. Mutant ALS genes contain a single nucleotide change, resulting in a single amino acid substitution for proline, as discussed earlier.

Cross Resistance

All of the weed biotypes resistant to one class of ALS-inhibiting herbicides are also resistant to other classes of ALS-inhibiting herbicides. A biotype of resistant *Lactuca serriola* selected with chlorsulfuron and metsulfuron-methyl is also resistant not only to eight other sulfonylurea herbicides but also to imidazolinone herbicides such as imazapyr and imazethapyr [91]. Similarly, a *Kochia scoparia* biotype is resistant to five sulfonylurea herbicides and one imidazolinone herbicide, imazapyr [125]. The R biotype of *Stellaria media* (common chickweed), selected with and resistant to chlorsulfuron, is also resistant to an ALS-inhibiting triazolopyrimidine herbicide, DE-489. The R biotype of *Datura innoxia* (sacred datura) is resistant to both sulfonylurea and imidazolinone herbicides [135]. The resistant biotype of *Amaranthus rudis* (common waterhemp) which exhibited 130-fold resistance to imazethapyr was found cross resistant to sulfonylureas, chlorimuron and thifensulfuron, both at the whole plant and enzyme levels [87]. These R biotypes, while being resistant to ALS-inhibiting herbicides, are not resistant to herbicides with alternate mode of action.

A notable exception to cross resistance is *Xanthium strumarium* (common cocklebur) resistant to imazaquin. The R biotype is resistant to several imidazolinone herbicides but not to chlorimuron-ethyl, a sulfonylurea herbicide used in soybean. This R biotype, which probably contains a different ALS mutation than those selected with other sulfonylurea herbicides, is controlled by herbicides with alternate modes of action.

The biotypes resistant to one class of herbicides may vary in their magnitudes of resistance to other ALS-inhibiting herbicides. Furthermore, some ALS-inhibiting herbicides may still be very effective in controlling weed biotypes resistant to other ALS-inhibiting herbicides. For example, Kwon and Penner [80] found that the R biotypes of *Kochia scoparia* which showed 22, 18 and 16 times more resistance to primisulfuron, chlorsulfuron and thifensulfuron respectively, exhibited only 1, 2 and 3 times more resistance to imazethapyr, nicosulfuron and flumetsulam (a triazolopyrimidine) than the susceptible biotype. The altered ALS enzyme system of the R biotype has a differential response for the ALS-inhibiting herbicides. A specific alteration in ALS does not confer automatic cross resistance across the different ALS-inhibiting herbicide classes. Given the structural dissimilarities between and within the three ALS-inhibiting classes that share a common ALS binding site, it is likely that individual herbicides have overlapping binding niches [68].

Inheritance of Resistance to ALS-Inhibiting Herbicides

Inheritance of sulfonylurea resistance in weeds has been investigated in *Lactuca serriola* [92], *Kochia scoparia* [108] and *Salsola iberica* [56]. All these weed species are diploid. However, one R biotype of *Salsola iberica* is a polyploid [56]. Sulfonylurea resistance in *K. scoparia* is inherited as a dominant, nuclear trait. However, the resistance of *Lactuca* spp. is controlled by a single gene with incomplete dominance [92]. The best fit for chi-square analysis of the F₂ generation of both the susceptible × resistant *Lactuca serriola*, and *L. sativa* × resistant *L. serriola* crosses was a 1:2:1 ratio, indicating that the trait was controlled by a single nuclear gene with incomplete dominance. Evaluation of F₃ plants grown from seed collected from intermediate and resistant F₂ plants confirmed the F₂ generation findings. Resistant F₃ plants did not segregate, while intermediate F₃ *L. sativa* and *L. serriola* plants segregated 1:2:1 and 3:1 respectively.

In most cases the ALS-inhibiting herbicide resistance trait is controlled by a single nuclear gene with incomplete dominance, which results in survival of both homozygous-resistant and the heterozygous intermediate plants treated with herbicide applied at normal doses. Migration of resistant pollen or seed from fields of non-crop areas infested with ALS-inhibiting-resistant weeds into fields previously infested with susceptible weed population could increase the proportion of resistant plants, even in the absence of selection pressure. The subsequent use of ALS-inhibiting herbicides would accelerate selection of R biotypes. ALS-inhibitor resistance in resistant mutant populations of *L. rigidum* is associated with a modified target site (ALS) [133]. Molecular genetic studies conducted by Saari et al. [133] indicated that a number of mutations at various locations along the DNS sequence encoding for ALS enzyme result in resistance. Murray et al. [109] reported that resistance in both the R populations of *Avena fatua* was encoded at the same gene locus.

Resistance to Acetyl Coenzyme A Carboxylase Inhibitors

Although aryloxyphenoxypropionic (APP) and cyclohexanedione (CHD) herbicides are structurally dissimilar, they exhibit similarities in their activity at the whole plant and physiological/biochemical levels. They share some common structural element(s) responsible for their herbicidal activity. These postemergence herbicides control annual and perennial grass weeds in cereal and dicot crops, with little activity against dicots or non-graminaceous monocots.

APP herbicides are characterized by two aryl groups, one of which is substituted with an isopropyl group on the 1 position. Variation in the second aryl group gives

rise to herbicides with differing biological activity and selectivity. These herbicides are usually formulated as esters of the parent acid (e.g., diclofop-methyl, fenoxaprop-ethyl, fluazifop-butyl, etc.). Once inside the plant, the ester is hydrolyzed to release the parent acid. As APPs are lipophilic, they do not show high phloem mobility. CHD herbicides vary considerably in the substitution at the 2 and 5 positions of the cyclohexane ring.

The synthesis of malonyl-CoA, catalyzed by acetyl-CoA carboxylase (ACCase), is the first step in fatty acid synthesis (vide Chapter 7). Malonyl-CoA is a key intermediate in the synthesis and elongation of fatty acids and for the synthesis of flavonoids. Inhibition of ACCase would deprive the plant of this key intermediate.

Target Site and Its Modification

APPs and CHDs are effective and potent inhibitors of ACCase from susceptible grass species but not from resistant dicot species. Selectivity between grass and dicot species is due to the relative insensitivity of dicot ACCase to these herbicides. Both classes of herbicides are reversible, linear and noncompetitive inhibitors of ACCase [18, 129]. The herbicides interact with an acetyl-CoA binding site, with the release of malonyl-CoA. Both APP and CHD herbicides act at the same site on ACCase.

Resistance to ACCase-inhibiting herbicides in R biotypes is controlled by a single, nuclear, partially dominant gene. The R biotypes possess altered forms of ACCase that are much less sensitive to these herbicides. The R and S biotypes do not differ in herbicide uptake, translocation or metabolism, suggesting that resistance in R biotypes is due solely to resistant ACCase forms.

Electrophysiological evidence suggests the existence of subtle differences in membrane function between the R and S biotypes. Diclofop and haloxyfop appear to interact with specific membrane sites to cause increased permeability to protons. This clearly establishes that resistance to APP herbicides in the R biotypes may be due to unknown structural or functional changes not found in the S biotypes.

It is speculated that APP and CHD herbicides are sequestered or compartmentalized in such a way as to prevent them from entering the plastids [31]. Rapid removal of herbicides from the available pool by such a mechanism (for example, by binding to the cell wall or accumulation in the vacuole) would effectively limit the herbicide concentration in the plastid, allowing lipid synthesis to proceed normally. Besides, the removal of herbicide in R biotypes may allow the membrane potential in these R biotypes to recover to its pretreatment value [31]. Devine et al. [32] found reduced uptake in isolated protoplasts and plasma membrane vesicles from a R *Avena fatua* biotype compared to an S biotype.

Inheritance of Resistance to ACCase-Inhibiting Herbicides

As mentioned earlier, the target enzyme-based resistance to ACCase inhibitors is controlled by a single dominant or partially dominant nuclear gene. This suggests that resistance can be conferred by a number of different point mutations, each of which confers a different pattern of resistance and cross resistance to APP and CHD herbicides.

The R biotype of *Eleusine indica* is resistant even at 100 times the application rate of fluazifop butyl that was lethal to the S biotype [95]. Leach et al. [81] found that the R biotype ACCase was less sensitive to the APP (fluazifop and fenoxaprop) and CHD (clethodim and sethoxydim) herbicides than the S biotype ACCase. They concluded that resistance to ACCase inhibitors in the R biotype of *E. indica* is conferred by a mutant target enzyme with reduced herbicide sensitivity. Besides the R biotype of *E. indica*, the R biotypes of *Setaria viridis*, *Lolium rigidum*, *L. multiflorum* and *Avena sterilis*

also possess altered target enzyme sensitivities to APP and CHD herbicides [54, 93, 94, 146]. However, the R biotype ACCase is not equally resistant to all of the compounds, suggesting that the mutation does not affect the binding of all herbicides equally [81].

While the resistance mechanism in *A. fatua* is controlled by a single, partially dominant nuclear gene [106, 109], the inheritance of resistance in *A. sativa* (cultivated oats) conforms most closely to a two-gene model, with the genes controlling resistance being recessive [151].

Resistance to Auxinic Herbicides

The prominent auxinic herbicides 2,4-D and MCPA, the phenoxy acids, belong to the group of phenoxyalkanoics. These herbicides mimic the action of the natural plant growth substance IAA (indol-3-yl acetic acid), often simply referred to as auxin. Phenoxyalkanoics are a diverse group of herbicides; the following discussion concerns only the auxin-analogue herbicides.

Although auxinic herbicides have been in use for over 50 years, the precise mode of action of these compounds remains unclear. As these herbicides mimic auxins, their phytotoxic effects are believed to be manifested by initiating a plethora of auxin-induced changes, which eventually lead to plant death. The changes include cell elongation, epinasty, hypertrophy (excessive growth), root initiation and ethylene biosynthesis. These morphological and physiological changes are attributed to several biochemical responses, viz. a rapid Ca^{++} influx, activation of plasma membrane ATPase and enhancement in protein and nucleic acid biosynthesis. These biochemical responses are believed to be elicited by a specific receptor, which when it binds auxin or an auxinic herbicide initiates this biochemical cascade. The auxin-binding proteins (ABPs) are known to possess receptor functions. ABPs are located in the plasma membrane and within the cell, primarily associated with the endoplasmic reticulum (ER), but they may also be localized in the nucleus.

Sensitivity or resistance to auxinic herbicides has been correlated with their ABP binding activity and this relationship explains the mechanism of auxinic herbicide resistance in the R biotype of *Sinapis arvensis* (wild mustard) [156].

Target Site

Despite several decades of study, the mechanisms of resistance to phenoxyacetic acid herbicides and hence their target site(s), have not been clearly established. While there is overwhelming evidence that the ABPs possess receptor function, their exact location in relation to the ER is not clear. They are believed to be associated with both the plasmalemma and internal membranes. One possibility for this bilocation is that ABPs are synthesized in the ER, but they are secreted from the ER lumen for subsequent migration to the outer face of the plasma membrane. Another possibility is that two types of ABPs are needed, one type at the plasma membrane, ultimately regulating the H^+ pumping and the other type sensing changes in auxin level within the cell and affecting changes in gene transcription.

Irrespective of where the receptor (ABP) is located, after auxin has become bound, the reception signal is transmitted and amplified to affect the multitude of biochemical events that precede growth stimulation. Amplification of receptor is required due to the relatively small number of available receptors. Phospholipids and Ca^{++} are considered to play a key role in the signal transmission pathway.

It has long been widely known that auxin and auxinic herbicides affect nucleic acid and protein synthesis due to their effect on transcription and translation. Auxin

and auxinic herbicides rapidly and specifically regulate mRNA biosynthesis. An increase in specific mRNA sequences could result from increased transcription rates, or post-transcriptional events such as increased transport of mRNA from the nucleus to the cytoplasm. The available evidence clearly shows that auxin and auxin-analogue herbicides have a direct (not dependent on protein synthesis), selective and rapid effect on nucleic acid biosynthesis and that the primary site of action is at the level of transcription [26]. This becomes the target site for development of plant resistance to auxinic herbicides.

Development of Resistance

Despite extensive and persistent usage of 2,4-D and related herbicides throughout the world for over 50 years, auxinic herbicides are relatively free of resistance problems. Development of resistance has been unequivocally found in only six weed species [68]. There have been reports of differential effects of auxin-type herbicides between biotypes of particular species, but clear evidence of resistance is lacking in most cases [7, 52].

In *Stellaria media*, the R and S biotypes have equal rates of herbicide uptake and translocation [8], with little differences in plasma membrane ATPase activity [27]. But the R biotype exhibited greater rate of metabolism of mecoprop to conjugated metabolites, indicating that increased metabolism (mediated by cytochrome P450 monooxygenases) may be the basis of resistance [8]. However, the resistance in the R biotype of *Sinapis arvensis* to 2,4-D, dicamba and picloram cannot be explained on the basis of differences in rates of herbicide uptake, translocation or metabolism [119]. This suggests that each weed species exhibits a resistance mechanism different from another. Jasieniuk et al. [72] reported that the inheritance of dicamba resistance in this wild mustard biotype was determined by a single, completely dominant nuclear allele. The susceptible biotype of wild mustard produces significantly more ethylene than the resistant biotype following picloram treatment [60]. Although both biotypes possess functional ethylene biosynthesis, increased ethylene in the R biotype is due to differences in pathway regulation. Deshpande and Hall [30] found picloram affecting the ATP-dependent activity of susceptible wild mustard protoplasts to a greater extent than resistant protoplasts. They attributed the differences in ATP-dependent activity to differences in the ability of biotypes to modulate calcium ion channels. Webb and Hall [156] reported that differences between R and S biotypes of wild mustard were due to the differential response of ABPs to auxinic herbicides. Their results also showed that differences in biotype response to auxinic herbicides were due to a link between ABP activity and calcium levels and ATP activity in protoplasts and whole plants. The endogenous levels of calcium were two to three times higher in the R than in the S biotype.

Estelle and Somerville [40] found that a single gene mutation in *Arabidopsis thaliana* resulted in several auxin-resistant lines which display pleiotropic (multiple phenotypic expressions) morphological effects. The isolated mutant lines of *A. thaliana* were 50 and 8 times more resistant to 2,4-D and IAA respectively. The resistance was due to a recessive mutation at the *axrl* locus. The mutant of *A. thaliana* produced bushy and short plants, with small, thin roots and smaller leaves. These authors hypothesized that *axrl* gene (in *A. thaliana*) may encode for a different auxin receptor and resistance may be due to an alteration that has a greater effect on the affinity of this receptor for 2,4-D and IAA. Later, Lincoln et al. [85] reported that all the 20 *axrl* mutants of *A. thaliana*, with at least five different *axrl* alleles, had similar phenotypes and the extent of auxin resistance of each mutant line could be directly correlated with severity of the morphological alterations. The distinct morphological phenotypes of the mutant *A. thaliana* described by them were similar to those described for the R biotype of

Sinapis arvensis [58]. Hall and Romano [58] suggested that in the presence of high levels of calcium and cytokinin, such as those found in the R biotype of *S. arvensis* as a result of mutation, the classic cytokinin responses (such as delayed senescence and morphological alterations) may be involved in the resistance mechanism of the R biotype.

Resistance to Mitotic Inhibitors

The mitotic inhibitors include dinitroaniline herbicides. Dinitroanilines are typically applied preplanting and preemergence and are incorporated to avoid loss through volatilization and photodecomposition. In general, these herbicides remain in the upper layer of soil due to low water solubility and a tendency to bind to organic matter.

Target Site

The most striking symptoms of dinitroaniline injury is a reduction in root length and swelling of seedling roots into a characteristic club shape. In the affected roots, cells undergo prometaphase but not the later stages of mitosis, resulting in a number of cells being arrested at prometaphase. Eventually, a nuclear membrane reforms around the chromosomes, but because of the doubling in chromosome number and the spreading of the chromosomes throughout the cytoplasm, the nucleus takes on a highly lobed morphology. The cells eventually turn isodiametric (square-shaped) in shape, rather than become elongate (rectangular), contributing to the swollen appearance of the root tips.

Dinitroanilines inhibit polymerization of tubulin, a major protein constituent of microtubules, into microtubules. These herbicides are believed to bind to tubulin heterodimers in the cytoplasm and when attached to the growing end of the microtubule, prevent further polymerization of tubulin. By blocking polymerization, the depolymerization process continuously shortens the microtubules until they eventually become undetectable.

Dinitroaniline herbicides are effective against several annual grasses and certain annual dicots. They exhibit poor activity on perennial weeds. Resistance to dinitroanilines may be due to the paucity of detoxification mechanisms in target plants.

Resistance has, however, been reported in *Amaranthus palmeri*, *Eleusine indica*, *Setaria viridis*, *Lolium rigidum*, *Alopecurus myosuroides*, etc. While *E. indica* biotypes exhibited high and moderate resistance, the R biotypes of *S. viridis* [105] and *L. rigidum* [64] showed only moderate resistance. Mitosis in root tips of the highly R biotype of *E. indica* was 1000 to 10000 times more resistant to dinitroanilines than in the S biotype [150]. Mitosis in the R biotype of *S. viridis* was only 2 to 10 times as resistant as in the S biotype [141]. The highly R biotypes of *E. indica* contained higher amounts of tubulin and higher-molecular-weight form of β -tubulin than S biotypes [149, 150]. In the presence of oryzalin, greater polymerization of tubulin takes place in the R biotypes. The resistance trait in the R biotype of *E. indica* is dominant, controlled by several genes (multigenetic effect). Inheritance of resistance in *S. viridis*, however, appears to be under the control of a single, nuclear recessive gene. This indicates that different mechanisms of resistance operate in *E. indica* and *S. viridis*.

Resistance to Inhibitors of Aromatic Compound Biosynthesis

GLYPHOSATE: EPSP synthase (5-enolpyruvylshikimate-3-phosphate synthase) is the penultimate enzyme in the aromatic amino acid biosynthetic (shikimate) pathway. The enzyme catalyzes formation of EPSP and inorganic phosphate from phosphoenolpyruvate (PEP) and shikimate-3-shikimate in an unusual carboxyvinyl

transfer reaction (vide Chapter 7). Glyphosate is a specific competitive inhibitor of EPSP synthase, involved in the shikimate pathway of biosynthesis of aromatic compounds.

Target Site and resistance in Plants

Glyphosate interacts with the EPSP synthase:shikimate-3-phosphate complex and inhibits this reaction, resulting in the build-up of shikimate-3-phosphate. This leads to a deleterious effect on the formation of chorismic acid, a precursor required for the biosynthesis of aromatic compounds. EPSP synthase inhibition is considered to be the primary site of action of glyphosate. Glyphosate binds either entirely or to a large extent to the site outside the site of action. It is trapped on the EPSP synthase enzyme in the presence of EPSP. The carboxyvinyl group of EPSP strongly facilitates the binding of glyphosate to the enzyme. Mutations in this domain confer resistance to glyphosate.

Glyphosate-Resistant Transgenic Plants

Resistance in R biotypes of various plant species such as carrot, tobacco, petunia, chickory, pea, etc. is due to elevated levels of EPSP synthase activity, although the enzyme is still sensitive to glyphosate. Overproduction of EPSP synthase effectively increases the number of molecules that must be inhibited in order to block carbon flow through the shikimate pathway. Enzyme overproduction is due to amplification of the gene(s) encoding EPSP synthase. EPSP synthase activity, gene copy number and glyphosate resistance level correlated positively.

Research on whole plant germplasm screening has demonstrated that variability in glyphosate exists among various plant species [35, 63, 74, 86]. Perennial ryegrass (*Lolium perenne*), soybean and *Convolvulus arvensis* displayed varying degrees of resistance to glyphosate. The resistant lines showed 2- to 3-fold resistance to the herbicide. When *Lotus corniculatus* (bird's-foot trefoil) was subjected to recurrent selection for two cycles, the selected populations showed an increase in resistance levels to glyphosate treatment [14]. Resistance in three clones picked from selected populations correlated positively with elevated EPSP synthase-specific activities.

Although glyphosate has been extensively used worldwide since its commercial production in 1974, there are no confirmed reports of glyphosate-resistant weeds developing in field situations. Although multiple treatments have been applied each year for several years in coffee and banana and in non-agricultural systems, no verified cases of glyphosate resistance have resulted. The lack of control of certain weeds cannot be attributed to the presence of resistant biotypes selected by the herbicide. For example, the low susceptibility of a naturally resistant biotype of *Convolvulus arvensis* (field bindweed) is not due to inherent, physiological, genetic and/or behavioural properties of the plants. The resistant biotype has not evolved due to selection pressure exerted by repeated field applications of glyphosate.

GLUFOSINATE: Phosphinothricin (PPT), also known as glufosinate, is an analogue of glutamine that inhibits the amino acid biosynthetic enzyme glutamine synthetase (GS) of bacteria and plants. Bialaphos is a tripeptide precursor of PPT produced by some strains of *Streptomyces*, in which two alanine residues are linked to the PPT moiety. The active PPT moiety is released intracellularly by peptidase activity. Both PPT (glufosinate) and bialaphos are marketed as broad-spectrum contact herbicides.

Target Site

Glutamine synthetase, the first enzyme involved in the assimilation of ammonia, catalyzes the conversion of glutamate (glutamic acid) to glutamine (vide Chapter 7). Glutamine thus formed serves as an amino donor for a variety of biosynthetic

pathways including amino acid and nucleotide biosynthesis. Glufosinate inhibits GS, resulting in rapid accumulation of ammonia, which leads to death of the plant. GS is the target site for glufosinate resistance. However, no naturally occurring resistance mechanisms are known in plants.

DEVELOPMENT OF HERBICIDE-RESISTANT CROPS

Herbicides are an integral part of modern agriculture because they provide cost-effective increase in agricultural productivity. These have traditionally been discovered by screening novel compounds in a series of tests, including greenhouse and field testing, toxicological testing, etc., spreading over several years. These tests are done to meet various biological, environmental, toxicological and economic criteria, so that the new compounds can compete with the many excellent existing compounds. In the 1950s, about 1 in 2000 screened compounds were commercialized. By the 1970s, the rate had dropped to approximately 1 in 7000 compounds, while in the 1980s hardly 1 in 20,000 compounds emerged from these tests [101]. Thus, the herbicide industry has been finding it increasingly harder and far more expensive to develop new selective herbicides.

Selectivity is a function of the physicochemical properties of a compound and of the biochemical interactions of the compound with the crop and weeds. In developing selective herbicides, the chemical companies resort to a biorational approach in which the pathways of enzymatic degradation of herbicides, specific to the crop, are studied. The herbicidal moiety is then modified by adding a chemical group that will be recognized by those enzymes, thus aiding in the herbicide degradation by the crop. A number of important classes of herbicides such as triazines, sulfonylureas and imidazolinones have been developed by this approach. Another biorational approach is to make current herbicides more effective by adding synergists (safeners or another herbicide) that either prevent their breakdown or prevent detoxification of toxic products in some weeds.

In the past 15 years, biotechnologists in industry and the public sector have been resorting to another approach by making susceptible crops genetically and biochemically amenable to herbicides by conferring resistance. This genetic approach could remove a major factor in determining the choice of herbicides available for use by farmers. It could allow for the wider use of more effective herbicides with broader weed-control spectrums. In addition, compounds that are effective at low application rates have shorter persistence in the soil and also more favourable toxicological properties that might become more generally useful if the constraints of crop selectivity were removed. These possibilities would extend beyond major crops to minor crops that have not yet been benefited from effective herbicides. The introduction of herbicide resistance into crops could give the farmer greater flexibility in choosing crops for rotational or multiple cropping systems. Thus, the combination of chemical approach and genetic approach could provide the farmer a broad range of crop management options for more effective weed control.

Biotechnological Approaches

Herbicide-resistant crops may be developed by using the following biotechnological approaches.

Plant Breeding and Selection

The conventional plant breeding and selection approach is very hard to implement

because of the low numbers of plants involved, low selection pressure and longer regeneration time. Even under high selection pressures, there may be many more susceptible plants that have escaped than plants that are genetically tolerant. If resistance is dominantly inherited on an allele of a single gene, one plant in 10^{-5} to 10^{-7} should be resistant and if it is recessively inherited on a single gene, the frequency is calculated at 10^{-10} to 10^{-14} [51]. For success of this approach, very high seeding rates would be required, many progenies would be needed in the first year and many years of field selection necessitated. Furthermore, there is always the possibility that there will not be a single gene for resistance in the genome and thus the many years of selection wasted [51].

However, Stannard [144] has been successful in obtaining resistance using field screening for chlorsulfuron resistance in alfalfa; he used high rates of chlorsulfuron and applied a very high selection pressure. After sowing 20 million alfalfa seeds in a field pre-incorporated with 16 g ha^{-1} chlorsulfuron, he found 15 putatively resistant plants. Four of these retained resistance after postemergence and laboratory treatments and have been cloned for breeding purposes. None of the resistant plants, however, showed resistance at the level of ALS, the target enzyme.

The plant breeding approach involves crossing, backcrossing and field testing before resistance is transferred into the varieties of choice. It requires two generations per year and at least five years of work before a herbicide-resistant crop variety can be field tested and released. Metribuzin resistance in soybean is inherited by a single dominant gene [39] and was transferred to an important but sensitive soybean variety. Similarly, paraquat tolerance in *Lolium perenne* (perennial ryegrass), polygenically inherited, has been used to breed resistance in perennial ryegrass [41]. The resultant material allows the use of low rates of paraquat in establishing stands of perennial ryegrass in pastures in England.

Many weed species show maternally inherited triazine resistance. Some of these weeds are sufficiently related to crops to allow transfer of the trait into related crop varieties. For example, transferring the trait from *Setaria viridis* (green foxtail) into the crop *Setaria italica* (foxtail millet) was moderately successful. The yields of the resultant crop varieties were considerably lower than the original variety [130]. This loss could be alleviated by further hybridization but so far the resultant hybrids have always yielded less than the reciprocal hybrids whose offspring were triazine-sensitive [12]. The loss of yield is probably due to the low fitness that is usually inherent in the chloroplast genome mutation conferring triazine resistance. The triazines are good candidates for developing crop resistance as they are the least expensive herbicides. However, there is the possibility of evolution of more triazine-resistant weeds if triazine herbicides are used continuously without rotating with non-photosystem II-inhibiting herbicides.

Resistance can be transferred by selection at the whole plant level. Seeds may be mutagenised to isolate resistant genes for genetic engineering, as in the case of *Arabidopsis thaliana*. Another plant in which the whole plant selection approach is used is the fern *Ceratopteris* spp. Selection pressure is applied on the photoautotrophic haploid gametophytes, allowing easier selection of recessive mutants for resistance to herbicides such as paraquat and acifluorfen. Paraquat resistance is monogenically inherited [65]. These mutants can be used, after analysis of fitness, for selecting the resistant genes for genetic engineering. Using similar methods, large numbers of mutation-treated soybean seeds were selected for chlorsulfuron tolerance [136]. However, none of the mutants had target site resistance at the level of ALS.

Tissue culture

Cell cultures have short generation times (doubling in 3-5 d), 10^5 to 10^6 cells ml^{-1} , with each cell theoretically representing a whole plant. This allows the possibility of very uniform treatment with herbicides at high selection pressures. Thus, cell cultures have many advantages over field cultures for selection of resistance. However, many species cannot be regenerated from tissue cultures and only some varieties of some species can be regenerated, although many recalcitrant crop species including maize, wheat and soybean have been regenerated from cell cultures in the recent past.

In tissue culture, selection can be done using non-photosynthetic cells, green tissues and protoplast fusion transfer.

Non-Photosynthetic Cell Culture: Non-photosynthetic cell tissue culture technique is used to select herbicide resistance to herbicides that do not specifically inhibit photosynthesis. Initial selection can be in suspension cultures, large callus species on microcalli derived from plating suspension cultures on a medium and then overlaying the herbicide [103]. The technique involves: a) preparation of cell suspension culture, b) spreading and growing the culture on agar medium containing the herbicide, c) identification and isolation of tolerant callus, d) testing of tolerant isolates for a second passage on herbicide-containing agar medium and e) development of shoots, which finally lead to fully grown plants. The plants are then used for genetic analysis via sexual crosses.

This technique has been used to develop tobacco resistant to picloram [20], paraquat [48] and sulphonylureas [21].

Selection has been achieved with a modicum of success with maize for resistance to imidazolinone herbicides. The resistant maize strains have been transferred to a seed producer for introducing the gene into commercial inbreds for eventual release [2]. Better resistance is achieved when both resistant alleles are present. The resistance is due to a site modification in acetolactate synthase (ALS). The imidazolinone-resistant maize has cross resistance to sulphonylurea herbicides, which act by inhibiting the same enzyme.

Green Tissue Cell Culture: Cell tissue culture technique involving green tissues is used to develop resistance to herbicides that affect photosynthesis. In this method, the seedlings and seeds are mutagenized by irradiation or chemical treatment. The young leaves of the mutagenized plant are then treated with herbicide and allowed to grow. As the leaves show chlorotic appearance, they develop small green islands of cells. These green cells are excised and propagated on a culture medium. The plants that grow from these propagated and regenerated plantlets are tested for herbicide tolerance and then used for genetic analysis via sexual crosses. Using this technique, nuclearly inherited resistance was introduced into tobacco for resistance to the photosynthetic inhibitors bentazon and phenmedipham. Later, tobacco having chloroplast-inherited streptomycin resistance was obtained after using a specific DNA [43]. This technique, using seedlings and isolating 'green islands', is useful in developing resistance to PS II-inhibiting herbicides that interact with the *psbA* gene product.

Protoplast Fusion Transfer: Protoplast fusion transfer technique is used to transfer resistance to a related but non-cross-breeding species. This interspecific protoplast fusion achieves the transfer of genetic material, but the resultant plants are usually infertile. This procedure is useful only when the genes for resistance have unknown products and thus are hard to isolate by molecular biological procedures for genetic engineering. It is also useful when there is no easy way to introduce the known gene(s), as in the case of chloroplast inherited genes.

In the protoplast fusion (hybridization) transfer procedure [157], the protoplasts of triazine-resistant donor are irradiated (X-ray) to cause functional enucleation (inactive nucleus) as the nuclear genome is undesirable in the product. The irradiated protoplasts are then fused with protoplasts of the susceptible crop. The subsequent cell division gives calli and plants with one or the other plastid type. This protocol is the modified technique used to transfer cytoplasmic male sterility. Triazine resistance has been transferred from resistant *Solanum nigrum* to sensitive potato [53, 157] and tobacco using the protoplast fusion procedure.

GENETIC ENGINEERING OF HERBICIDE RESISTANCE IN CROPS

Genetic engineering in crops for herbicide resistance has become a major area of weed research for over a decade. The process of genetic engineering involves isolating the gene from resistant plants or microorganisms (fungi), inserting it into plasmid and then into a vector system, introducing it into plant cultures and regenerating the cultures as a newly resistant crop plant. The main advantage of the genetic engineering approach is that once the gene is successfully engineered into a plasmid vector system, it can be used to transform many different plant species. Besides *Solanaceous* species, which have been used as models, the *Agrobacterium* infection systems (with model marker genes) have been used to successfully transform soybean, cotton, sunflower and maize [51]. Many species have been transformed by incubating protoplasts with plasmid DNA and pushing it through the cell membrane with polyethyleneglycol, or electrophorating it through the membrane with a high voltage pulse or even pelting cells with DNA or microprojectiles [79].

The progress of genetic engineering with respect to development of resistance of major classes of herbicides shall now be discussed.

Engineering for Acetolactate Synthase Resistance

As mentioned earlier in this chapter, the sulfonylurea and imidazolinone herbicides inhibit acetolactate synthase (ALS). In tolerant crops, resistance to ALS inhibitors is based on enhanced capacity for metabolic inactivation rather than differential herbicide uptake, translocation, or altered susceptibility of the ALS target site. Wheat is resistant to chlorsulfuron by way of metabolic inactivation involving aryl hydroxylation followed by conjugation to herbicidally inactive glucose conjugates. Hydroxylation is catalyzed by microsomal cytochrome P450. In susceptible crop species, the same metabolic inactivation can occur but with insufficient activity to confer resistance. Gene transfer and tissue culture technology have been used to produce transgenic plants with less susceptible ALS [110, 114].

Earlier efforts were directed to isolate microbial (yeast and bacteria) genes with a resistant ALS. A single amino acid difference between the resistant and susceptible ALS was found in bacteria. The ALS genes from microbes have been isolated, cloned and sequenced. However, there have been problems transforming plants using the bacterial genes, possibly because of promoters. The bacterial ALS is composed of two different subunits, while plant ALS is localized in the chloroplast. Thus, the generation of herbicide-resistant plants using bacterial ALS genes requires not only an expression of these two protein subunits of the enzyme, but also their translocation into and assembly in plant chloroplasts. For this reason, the isolation and use of plant ALS genes appears to be a more attractive route for engineering sulfonylurea-resistant transgenic crop plants.

Plant species such as *Nicotiana tabacum* and *Arabidopsis thaliana* possess ALS genes. Many crop species carry multiple ALS genes. Efforts have been made to isolate genes carrying ALS mutations from herbicide-resistant plants. In tobacco, the **Hra** and **C₃** lines, which carry mutations at the **SURB** locus and **SURA** locus respectively, were used as sources of mutant ALS genes. Four genes representing all of the ALS loci from these two mutant lines were isolated and sequenced. The **SURB-Hra** gene contained two mutations, which resulted in **proline 196-to-alanine** and **tryptophan 573-to-leucine** substitutions. The **SURA-C₃** gene carried a single mutation that resulted in a **proline 196-to-glutamine** substitution. The double tobacco mutant that carried the proline 196-to-alanine and tryptophan 573-to-leucine substitutions were cross resistant to imidazolinone herbicides.

The tobacco **SURB-Hra** gene was used to transform a number of heterologous species to sulfonylurea herbicide resistance at the cellular and in some cases, whole plant level. These crop species include tomato, lucerne, lettuce, melon, rapeseed and sugarbeet [10]. In some of these species (e.g., tomato), expression of the resistant tobacco ALS gene was efficient while in others (rapeseed) only a low level of resistance was observed.

The **SURB-Hra** gene was introduced into a number of commercial lines of tobacco and the transformed plants showed high levels of resistance in the field. The transformed plants showed no damage at 32 g ha⁻¹, four times that of a typical field application rate. Thus, expression of the **SURB-Hra** gene provides an effective means of producing sulfonylurea herbicide-resistant crops.

As metabolic detoxification is the basis of selectivity of certain crops to sulfonyl ureas, isolation of genes responsible for the detoxification pathways from resistant crops and transferring them to sensitive ones could provide another approach for genetically engineering sulfonylurea resistant crops. This method requires a microbial model. In *Streptomyces griseolus*, chlorimuron ethyl, chlorsulfuron and sulfometuron methyl are metabolized by a three-step process, requiring an NADP-reductase, an iron-sulphur protein and cytochrome P450 enzymes. The genes encoding these proteins could be isolated from this bacterium and introduced into plants by transformation to confer herbicide resistance.

As most of the agronomically important crops are not amenable to transformation, other alternative methods were used to generate resistance to the sulfonylureas and other ALS-inhibiting herbicides. Using the genetic selection of cultured maize cells, imidazolinone-resistant mutants of maize were isolated. Plants exhibiting more than 100-fold increase in resistance to imidazolinones and cross resistance to the sulfonylureas were regenerated from one line. The homozygous progeny showed more than 300-fold increase in resistance to the herbicides. Resistance was inherited in a single dominant nuclear gene. The resistant mutant, which did not show growth or yield reduction, is being developed by Pioneer Hi-Bred International, Inc. [101]. This maize mutant will be the first ALS-targeted herbicide-resistant crop when commercialized.

In another effort, mutagenized soybean seeds were used to obtain herbicide-tolerant soybean mutants. While some of the mutants showed only a 5 to 10-fold increase in tolerance, with little alteration in ALS, others recorded higher levels of tolerance with an altered ALS.

Engineering for Photosystem II Resistance

Such structurally diverse herbicides and classes of herbicides as triazines, ureas, uracils, propanil (acetamide), pyrazon (pyridazinone), desmedipham and phenmedipham (phenylcarbamates) and bromoxynil and ioxynil (benzonitriles)

inhibit electron transport in PS II. Triazine herbicides are metabolized in a naturally resistant crop like maize by several pathways, including 2-hydroxylation, conjugation with glutathione and, to a lesser extent, *N*-hydroxylation of the side chains with subsequent oxidation. Selectivity to substituted urea herbicides is due to limited absorption and translocation, rapid cytochrome P450 mono-oxygenase-catalyzed degradation, or oxidation. Thus, most PS II inhibitors are selective by virtue of degradation by crops.

Triazine-resistant weeds have been used to generate resistant crops. The resistance trait has been transferred by sexual crosses from the weed *Brassica campestris* (bird's-rapeseed) into several related cole crops, leading to release of atrazine-resistant *Canola* (rapeseed) cultivar 'Triton' [13]. Despite a yield penalty of about 20% due to resistant cytoplasm, this R cultivar was planted on about 250,000 acres in 1986 and proved economical in areas where weed densities were high and triazines were used (44). In another case, resistance from the weed *Setaria viridis* (green foxtail) was crossed into the sensitive crop *Setaria italica*. Such interspecific and intergeneric sexual crosses were hampered because only a few resistant weeds are sexually compatible with crop plants. Protoplast fusion has also been used to transfer atrazine resistance between *Solanum* lines but with only limited success.

Even with the availability of a number of resistant genes, genetic engineering of triazine-resistant crop plants via transformation has been difficult. This was because of difficulties in introducing genes into chloroplasts. To bypass this technical problem, transgenic tobacco plants were produced by following nuclear transformation with a mutant *psbA* gene, which encodes for the D1 protein (the PQ_B protein). To accomplish this, a chimeric gene was constructed in which a nuclear promoter and a chloroplast transit peptide-encoding sequence were attached to a mutant *psbA* structural gene. The transgenic plants showed higher tolerance for atrazine.

In other studies, attempts were made to engineer atrazine resistance through the introduction of genes encoding detoxifying enzymes, glutathione-S-transferases (GSTs) from maize resistant to atrazine and alachlor. The transgenic tobacco plants expressed an atrazine-resistant GST enzyme, resulting in increased tolerance to atrazine.

Engineering for ACCase Resistance

Dicot crops and non-graminaceous monocot crops exhibit intrinsic resistance to aryloxyphenoxypropionic (APP) and cyclohexanedione (CHD) herbicides. Dicot crops possess resistant ACCase and many of them are capable of detoxifying APPs and CHDs. Wheat and barley are resistant only to diclofop and tralkoxydim, while most other major graminaceous crops are sensitive to all APPs and CHDs.

In laboratory studies, resistance to APPs and CHDs has been introduced into crops. Resistance to diclofop and sethoxydim was selected in maize tissue cultures exposed to sethoxydim [117, 118]. In one study, resistance was due to increased expression of herbicide-susceptible ACCase, while in the other, resistance in regenerated plants was associated with herbicide-resistant ACCase. The trait of resistance inheritance was controlled by a partially dominant nuclear mutation. A subsequent study [96] suggested that three and possibly five, alleles of the maize ACCase structural gene were present in ACCase mutants which exhibited different levels of herbicide resistance.

Engineering for Auxinic Herbicide Resistance

Many monocot crops are naturally resistant to auxinic herbicides. It is believed that resistance of cereal crops to 2,4-D is due to differences in rates of herbicide translocation,

metabolism and anatomical characteristics. In a resistant crop like wheat, 2,4-D is arylhydroxylated through the catalytic role of cytochrome P450 mono-oxygenases and glucosylated. This was confirmed by recombinant studies.

Soil-borne microbes, in particular *Alcaligenes* spp., contain plasmids that confer ability to degrade auxinic herbicides. A gene encoding for a mono-oxygenase capable of degrading 2,4-D has been identified, cloned and sequenced from a plasmid of *Alcaligenes*. A single, dominant gene from *Alcaligenes* coding for a 2,4-D-degrading mono-oxygenase has been introduced into tobacco, resulting in transgenic plants resistant to high levels of 2,4-D [89]. Commercial cultivars of otherwise susceptible cotton have been transformed with this 2,4-D-resistance gene, producing transgenic plants resistant to 2,4-D [88]. These studies show that increased cytochrome P450-catalyzed metabolism is an important mechanism that can confer crop selectivity to auxinic herbicides.

Engineering for Resistance to Other Herbicides

BROMOXYNIL: Bromoxynil, a benzonitrile herbicide, inhibits photosynthetic electron transport. It is used for dicot weed control in cereal crops. A gene encoding for nitrilase enzyme that detoxifies bromoxynil has been isolated from a strain of soil bacterium *Klebsiella ozaenae*, which uses the herbicide as its sole source of nitrogen. This strain produces a bromoxynil-specific nitrilase protein that degrades the herbicide to 3,5-dibromo 4-hydroxybenzoic acid in a single step. The *bxn* gene that encodes this enzyme was plasmid-borne and it was later cloned. The gene has been placed under the control of plant promoters and has been transferred to tobacco and tomato plants to confer resistance to bromoxynil in these plants.

GLYPHOSATE: In view of the efficacy and desirable environmental and toxicological properties of glyphosate, considerable efforts have been made in the past 10 years to increase the utility of this herbicide by producing resistant crops.

The first report of introduced glyphosate resistance in transgenic plants, using commercial applications of plant biotechnology, was published in 1985 by Comai et al. [23]. A mutant *Salmonella typhimurium* *aroA* gene, encoding a resistant EPSP synthase, was introduced into tobacco cells under the control of octopine synthase or mannopine synthase promoter. The transformed regenerated plants expressed chimeric enzyme levels in the leaves and were two or three times more resistant to glyphosate, although their growth rate was reduced compared to untreated controls. The same gene was also introduced into tomato plants subsequently, with essentially similar results [42].

Glyphosate resistance has also been achieved in crop plants by overproduction of EPSP synthase. A wild petunia cDNA encoding EPSP synthase was linked to the constitutively expressed cauliflower mosaic virus 35S promoter and reintroduced into petunia [78, 139]. The resultant transgenic plants were about 4-fold more resistant to glyphosate, with growth rates lower than those in untreated controls.

The relatively low levels of resistance and poor field performance of transgenic plants, described above, led to efforts to achieve higher levels of resistance. As part of these efforts, the **petunia** gene was subjected to site-specific mutagenesis and a number of mutant enzymes were recovered and tested [77]. Some of these genes overexpressed in transgenic tobacco, enabling the plants to develop 4-fold more resistance to glyphosate, with growth rates and field performance being equal to plants in untreated control. Similar constructions, including recently isolated mutant genes, with very little or no loss of catalytic efficiency, were later introduced into several crop species. These mutant genes, some under the control of meristem-specific promoters, provide high

levels of glyphosate resistance. These efforts may lead to the evolution of glyphosate-resistant soybean, tomato and canola cultivars.

Certain bacteria belonging to genera *Pseudomonas* and *Arthrobacter* are capable of growing on glyphosate as a sole source of carbon. These strains metabolize glyphosate to phosphate, glycine and a one-carbon unit. This is in contrast to soil microbial metabolism of glyphosate being primarily degraded to aminomethylphosphonic acid. The bacterial genes that carry out these metabolic degradations could theoretically be isolated and expressed in plants to produce glyphosate-tolerant plants. No glyphosate-resistant plants have yet been reported in which expression of closed genes enables metabolism of glyphosate to non-toxic products.

GLUFOSINATE: Several approaches have been used to produce plants tolerant to glufosinate, also known as phosphinothricin. In the first one, an alfalfa (lucerne) cell line tolerant to phosphinothricin (PPT), producing elevated levels of GS, was isolated following selection. The amino acid sequences of two internal GS peptides were isolated from this line and used to confirm the identification of an alfalfa cDNA clone. The corresponding genomic DNA clone for alfalfa GS was 4 kb long and contained 11 introns [34]. The encoded protein was 356 amino acids long. In order to produce herbicide-resistant transgenic plants, the alfalfa GS cDNA clone was linked to the cauliflower mosaic promoter and introduced into tobacco plants via transformation. The resultant high level of expression of the alfalfa GS gene in the transgenic tobacco plants conferred a low level of tolerance to PPT [38].

In another approach, a bacterial expression assay system was used. An alfalfa GS cDNA clone was linked to a bacterial promoter and transferred to a strain of *Escherichia coli* devoid of GS activity [29]. Mutations that allowed bacterial growth in the presence of PPT were then selected. A mutant alfalfa GS gene was then transferred to tobacco cells and plants were generated. Although the mutant GS gene protected plants when herbicide was taken up by the roots, it did not protect against foliar application of PPT. This indicated the existence of multiple nuclear GS genes in plants [147]. In pea, one GS gene encodes an isozyme found in nodules, a second encodes a GS enzyme found in chloroplasts and two others encode cytoplasmic forms of GS. This suggests that resistant mutations may need to be introduced into several GS genes to confer whole-plant resistance to PPT.

An alternative approach of introducing resistance into plants via a gene that produces a detoxifying enzyme has been more successful. The gene, designated *bar*, that encodes for PPT-acetyl transferase activity is found in strains of *Streptomyces hygroscopicus* that produce bialaphos, the tripeptide precursor of PPT. This enzyme, PPT-acetyl transferase, converts PPT to a non-phytotoxic acetylated metabolite by transferring the acetyl group from acetylcoenzyme A onto the amino group of PPT. The *bar* gene isolated from *S. hygroscopicus* was placed under the control of the cauliflower mosaic virus 35S promoter and introduced into tobacco, potato and tomato. The genetically engineered crops were thus able to rapidly detoxify PPT (glufosinate). The trait is inherited as a simple dominant allele. The transgenic crops produced in this manner are in various stages of field testing for possible commercialization.

MANAGEMENT OF HERBICIDE RESISTANCE IN WEEDS

Development of herbicide resistance in weeds is a worldwide phenomenon and the number and frequency of resistant biotypes have increased at an alarming pace in recent years. During the past 10 years, herbicide resistance has increased at a rate equivalent to that of insecticide and fungicide resistance. The number of insecticide-

resistant biotypes increased over 500-fold between 1948 and the 1980s [67]. A similar phenomenon has occurred in plant pathogens and microorganisms in developing resistance to fungicides and antibiotics [140]. The rapid spread of resistance to various pesticides is due to many reasons, including the difficulty in predicting the occurrence and spread of resistance and the lack of viable and effective alternatives to pesticides.

Much before weed resistance to triazines was reported in the mid-1960s, Whitehead and Switzer [158] found that control of wild carrot (*Datura carota*) by 2,4-D was diminished after several years of use in Ontario, Canada. Despite frequent reports of weed resistance to triazines, dinitroanilines, bipyridiliums and pyridazinones in the 1970s and early 1980s, only a few weed species were identified as resistant and the area infested by resistant biotypes was only limited. This relatively slow development of resistance to other classes of herbicides coupled with the much lower fitness (of particularly the triazine-resistant biotypes), the ability of herbicide-thinned weed populations to produce high amounts of seed and the large reservoir of susceptible weed seeds in the soil, did not warrant considering herbicide resistance a major problem [128]. However, beginning late 1980s, there has been a rapid and widespread increase in the number of biotypes that developed resistance to a wide range of herbicides, including the ACCase inhibitors (aryloxyphenoxypropionics, cyclohexanediones, etc.), ALS inhibitors (sulfonylureas, imidazolinones and triazolopyrimidines), acetamides, arsenicals, nitriles, carbamates, substituted ureas and uracils [82]. The problem assumed alarming proportions when the R biotypes of *Lolium rigidum* and *Alopecurus myosuroides* exhibited cross resistance to two or more herbicides. Some of these biotypes have the ability to rapidly metabolize a large number of herbicides to non-phytotoxic forms via the same mechanism that allows these compounds to be used successfully in wheat [25, 98]. If this trend continues, the number of effective herbicides for use in crops could be severely reduced. This necessitates development of alternative weed management programmes before resistance becomes a greater problem. Before dealing with weed management strategies, the factors responsible for development of herbicide resistance in weeds need to be examined.

Factors Responsible for Development of Herbicide Resistance

Continuous Use of Herbicides

The continuous use of a herbicide or herbicides sharing the same mode of action as the primary method of weed control is a major factor in the development of herbicide resistance in weeds. LeBaron [82] reported that the time required for weeds to develop resistance ranged from 18 yr (from 1945, the year first introduced, to 1963, the year first reported) for 2,4-D, to 10 yr for atrazine (1958 to 1968) and trifluralin (1963 to 1973) and 5 yr for diclofop (1977 to 1982) and chlorsulfuron (1982 to 1987). Resistance largely depends on the herbicide and its use pattern. If the same herbicide is used in each crop, crop rotation does little to arrest resistance development, as in the case of selection for resistance to ACCase inhibitors (APPs and CHDs). Malik and Singh [90] found that control of *Phalaris minor* in wheat by isoproturon, in continuous use in India since the early 1980s, reduced from 78% to 21% from 1990 to 1993.

Seedbank in the Soil

Development of herbicide resistance development is more rapid whenever weed seed turnover in the soil is rapid. This turnover is characteristic of weed species (e.g., *Kochia scoparia*) and is aided by cultural practices [140]. Changes in tillage practices may result in a more rapid turnover of the seedbank population. Ball [6] found that the

number of seeds in the upper 2.5 cm of soil increased after chisel ploughing compared to mouldboard ploughing. Application of farmyard manure from one field to another is another means of resistance development.

Farming Practices

Ever since the discovery of herbicides, weed scientists and farmers have exploited the efficacy and cost effectiveness of herbicides to maximize crop productivity and economic returns from the land. As a part of their efforts, however, the traditional multicrop systems were discarded in favour of monocrop systems and the normal tillage practices that eliminated persistent weeds more effectively were replaced by no-till or minimal practices, to fit in the existing herbicides and reduce the time needed for weed control. The consequence of this excessive reliance on herbicides is the selection of resistant weed species and biotypes.

Farmer Ignorance

For most farmers, both in developed and developing countries, herbicide resistance is not a high priority issue. Stoller et al. [145] reported that soybean farmers ranked development of strategies for resistant weeds only 7th in 14 categories related to weed management, with the first rank going to development of more economical weed control. This suggested that farmers generally are more concerned with short term economics of weed management than with herbicide resistance management. Most farmers rely on herbicides with the same mode of action and show reluctance to change their weed control programmes.

Strategies to Manage Herbicide Resistance

The selection and evolution of herbicide-resistant weed population, if left unattended, will have serious consequences on farmers' ability to control weeds safely and efficiently. Hence, it is essential for weed scientists to design strategies to manage problems related to herbicide resistance in weeds effectively and economically. These strategies are briefly discussed below.

Containment of Resistant Alleles

Containment of resistant alleles conferring herbicide resistance on weeds is one way of minimizing the spread of herbicide resistance. This strategy requires sound knowledge of the ecology, genetics and biochemistry of weed species undergoing selection. Models of dynamics of resistant and susceptible weed populations serve as a useful tool for understanding the factors that determine rates of evolution of resistance in the field, particularly fitness and gene flow. Screening of unselected weed populations for resistance alleles is valuable in identifying weed species that are likely to become resistant.

Weed scientists and plant geneticists will find it more challenging to understand the genesis of variation in weed populations than in crop plants. For example, in *Avena* spp., there is more genetic diversity in populations found in the habitat of origin than in a population found on agricultural land. This increased diversity may be due to increased niche differentiation driven by higher species diversity in natural plant communities. The species that have evolved resistance to herbicides would naturally be from those with the most genetic diversity. Powles and Matthews [122] reported that there were a number of different resistant mechanisms that contribute to multiple herbicide resistance in *Lolium rigidum* and they attributed the rapid evolution of multiple resistance to general genetic diversity within the species. Guttieri et al. [55] found

that target site resistance of *Kochia scoparia* to ALS inhibitors was due to several different amino acid substitutions, indicating that genetic variation exists within a single mechanism of resistance.

Introduction of Herbicide-Resistant Crops

Introduction of herbicide-resistant crops may help in mitigating the problem of herbicide resistance in weeds. While certain benefits may be realized from using the herbicide-resistant crops, at least initially, resistant-weed problems may be exacerbated when appropriate resistance management is not practiced [68].

Seedbank and its Exhaustion

The simplest option in preventing development of herbicide resistance is to use techniques to reduce weed populations such that the expected weed numbers remain below the economic threshold. A successful adoption of these techniques requires knowledge of seedbank dynamics because the life of the seed propagules in the soil dictates the length of time that weed control measures are needed to be maintained in order to reduce the reservoir of resistant seeds in the seedbank to a low level.

Generally, annual grass weeds such as *Lolium rigidum*, *Lolium multiflorum*, *Lactuca serriola*, *Kochia scoparia*, *Setaria viridis*, etc. have a seedbank life of 3 to 5 yr, with an annual rate of decline of about 50% to 80%. The R and S biotypes of a weed species, as in the case of *K. scoparia* [36], exhibit different germination patterns. The viable population of most of the weed species in the seedbank can be substantially reduced by preventing seed set for 3 to 5 yr.

Methods to reduce the number of viable seeds in the soil and thereby exhaust the seed bank, include:

- a) application of low rates of nonselective herbicides such as paraquat and glyphosate to kill the existing weed growth and prevent the development of fertile seed;
- b) soil disturbance during crop planting to stimulate germination of some weed species; and
- c) adopting chemical or plough fallow method before a crop is planted, so the germinating weed seedlings can be controlled.

Modified Herbicide Usage

The modified herbicide usage approach includes rotation of herbicides with different modes of action and use of combinations of herbicides with different modes of action.

Herbicide Rotation: The logic behind herbicide rotation is that exposure of weeds to different classes of herbicides will decrease the frequency of resistance alleles. This decrease is expected as long as weed species with resistance alleles are less fit than weed species without these alleles. When one herbicide is very useful but prone to resistance problems, it may be useful to rotate it with another herbicide that may be less effective but more reliable. However, before a certain herbicide rotation is recommended, the following factors need to be considered [50]. 1. It is important to understand that rotation of herbicides must involve alternate generations of the weed species. If the same field is treated twice within a single weed generation with two compounds, there is no period during which significant reversion is expected. 2. The cost of resistance is almost always measured in the absence of any herbicide. For a rotation to be successful, it is important for the 'cost' to be expressed when the rotational compound is used. If under the stress of the alternate compound the weed genotypes with resistance to the first compound are as fit as the susceptible genotypes, then the utility of the rotation is compromised. Besides, if there is any cross resistance between the two compounds, a rotation is not generally expected to show the overall resistance

build-up. Gould [50] suggested that from a practical perspective, it may be difficult to implement rotations unless two or more chemicals are of approximately equal cost to the farmers, or farmers are acutely concerned with a resistance problem. In order to provide the farmer a viable and useful rotation programme, it would be necessary for weed scientists to examine, over a period of time, the changes in the frequency of resistance alleles in single fields where rotations are used, so that the empirical basis for judging the rotations can be strengthened.

Herbicide Mixtures: It has been suggested that the use of herbicide mixtures combining herbicides of different modes of action would substantially delay or preclude evolution of resistance to the more vulnerable or at-risk herbicides. This is because weeds resistant to the vulnerable herbicide would be destroyed by the mixing partner, or at least be rendered relatively unfit compared to the wild biotype.

Herbicide mixtures are of two types. In the first type, the **broad spectrum mixture (BSM)**, each member of the mixture affects different weed spectra as in the case of mixtures of grass and broadleaf herbicides (Table 10.1). These BSMs increase weed control benefits but have no influence in delaying evolution of resistance in weeds they do not affect. They might even exacerbate resistance by controlling competing weeds, creating a more open niche for resistant biotypes [160]. This could be true even when the mixing partner has a moderate effect on a species excellently controlled by the vulnerable herbicide. The second type, the **target weed mixtures (TWM)**, both the vulnerable herbicide and the mixing partner, aim at complete kill of the same weed species. In order for the TWM to be effective in preventing resistance, the mixing partner should have the following traits as compared to the vulnerable herbicide: a) control the same spectra of weeds, b) have the same persistence, c) have a different target site, d) be degraded in a different manner and e) preferably exert negative cross resistance [160]. These are elaborated as below.

Table 10.1. Herbicide mixtures and their effects on different weed species.

Type of mixture	Herbicide	Weed Species	
		A	B
Broad Spectrum Mixture (BSM)	Vulnerable herbicide	++	0
	Mixing partner	0	++ (or +)
Target Weed Mixture-I (TWM)	Vulnerable herbicide	++	0
	Mixing partner	++	0
	-II (TWM)	0	++
	Mixing partner	0	++

With respect to control of the same target weed species, the mixing partner should effectively kill or severely weaken the weed most sensitive to the vulnerable herbicide because the target weed is most likely to evolve resistance. It will be of little use if the vulnerable herbicide kills only 95% of the target weed population and the mixing partner kills only 75%, unless the remaining 20% of the population are severely inhibited to incapacitate its reproduction. Otherwise, resistance could quickly evolve in the remaining 20% of the weed population. As seeds of many weed species have many flushes of germination during a cropping season, both components of mixture should have similar persistence to prevent weed germination throughout the cropping season. If the mixing partner has a shorter period of activity than the vulnerable herbicide, then the latter chemical will select for plants resistant only to it after the former has

dissipated. This, however, may be a problem if all seeds of the target weed germinate in a single flush without further germination and if both herbicides outlast the flush with equal efficacy.

In a TWM, the ideal mixing partner should have a target site of action different from that of the vulnerable herbicide. Two Photosystem II inhibitors (triazines and substituted ureas or uracils) or two ALS inhibitors (sulfonylureas and imidazolinones) cannot be considered ideal target weed mixtures for resistance management. Furthermore, the two herbicides should not be degraded in an identical manner. For example, if the vulnerable herbicide is degraded by a glutathione-S-transferase, the mixing partner will then have no chemical site that can be attacked by that enzyme. Possessing a negative cross resistance is a useful attribute for the mixing partner. In this, weeds resistant to the vulnerable herbicide become more susceptible than the wild type to the mixing partner.

Alternative Weed Control Methods

Excessive dependence on herbicides for weed control is the primary reason for the evolution of herbicide resistance in weeds. Integrating herbicide usage with manual, mechanical and biological methods could help reduce the herbicide selection pressure on the weed populations while maintaining crop productivity. This approach would lead to delaying and hence mitigating the herbicide resistance problems.

Implementation of Herbicide Resistance Management Programmes

Successful implementation of programmes related to herbicide resistance management requires an integrated and cooperative approach between research/academic institutions, herbicide industry, government and farmers. Each of these parties has a specific role and responsibility (Fig. 10.1) [140].

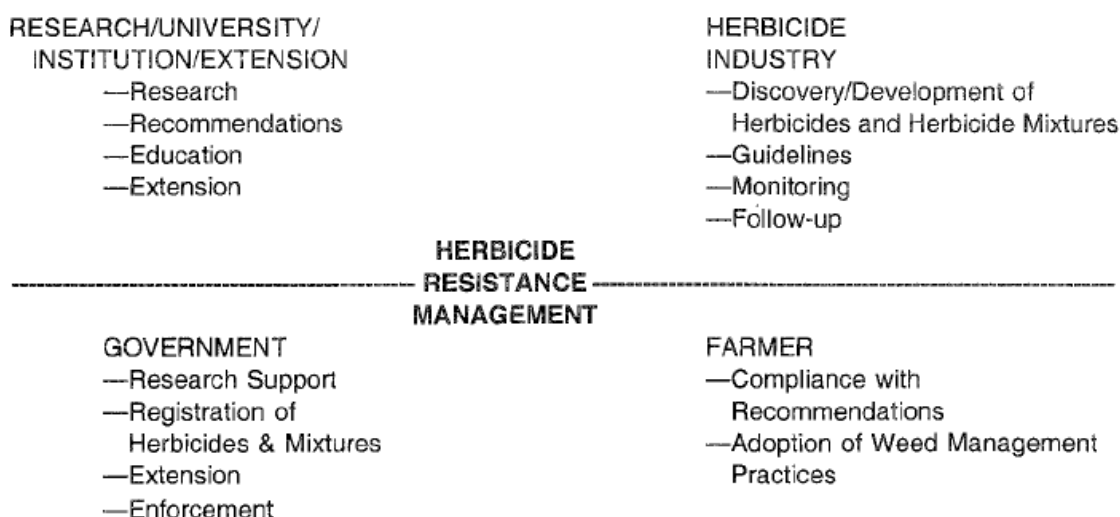


Fig. 10.1. Role of various organizations (research/academic institutions, herbicide industry, government and farmers) in herbicide resistance management

Research/Academic Institutions

Research and academic (universities) institutions, the primary source of information for weed management for farmers, are required to intensify research on herbicide resistance in weeds and develop strategies for effective resistance management

programmes. There is a need to integrate chemical weed control with other methods of weed control, monitor the development and spread of herbicide-resistant biotypes and provide the farmers cost-effective, ecologically sound and resistance-mitigating weed management programmes. They should also develop different models to predict yield losses due to weed pressure and the rate of selection of herbicide-resistant biotypes [52a, 100]. These models are useful in determining which factors are important in selecting for herbicide resistance and in assessing the effectiveness of different management strategies. The models should be thoroughly field-tested.

The extension personnel should be educated and trained in various aspects of weed management and herbicide resistance management so they can form a vital link between the researcher and farmer.

Herbicide Industry

Herbicides will continue to remain as the principal method of effective and economical weed control. Hence, the herbicide industry will continue to be the source of new herbicides and herbicide mixtures. They, however, need to monitor development of resistance to herbicides and take steps to minimize the selection and spread of resistance by developing target weed mixtures consisting of two or more herbicides with different modes of action and those that meet the criteria listed earlier (vide Herbicide Mixtures). The herbicide mixtures should also control an overlapping spectrum of weeds that are high risk for developing resistance. The industry may also need to work with farmers to bring out weed management programmes that do not depend on a single herbicide or mode of action for control. It should also monitor changes in weed spectra and resistance management problems at the field level and develop alternative management programmes. The companies need to educate and train their staff, farmers and herbicide distributors and retailers and certain government agencies on effective herbicide resistance management. They may also work with research personnel of research and academic institutions and government in the implementation of resistance management programmes.

Government

Government agencies, both at the central (federal) and state level and their policies have a great impact on the implementation of effective herbicide resistance management programmes. As herbicide usage has created a multitude of secondary problems (environmental, weed resistance, etc.), several countries began taking steps, in the recent past, to reduce herbicide use, eliminate registration of older herbicides, scale down the number of registered products and shift from dependence on broad-spectrum herbicides to narrow-spectrum herbicides. As a consequence, herbicide resistance problems became more aggravated and widespread than ever.

Government should encourage and support research programmes that offer more options for farmers to tackle herbicide resistance in weeds. Herbicide usage may need to be integrated with other means of weed control. As herbicides will continue to be used extensively and be the vital part of weed management programmes, more herbicides and herbicide mixtures (as premixes) may need to be made available to farmers. Government is required to fund research on integrated weed management (IWM) programmes, incorporating herbicides as one of the management components. It should also educate and train its personnel in various aspects of weed management, particularly in herbicide-resistant management.

Farmer

Currently, herbicide resistance is not a high priority issue for most farmers. Hence, the success or failure of a herbicide resistance management programme depends on the farmer. If farmers do not change weed control practices that lead to weed selection for herbicide resistance or cannot afford to change their programmes because of financial and logistic constraints, then all the efforts of government, research and academic institutions and the herbicide industry will be fruitless [140]. Farmers should be educated in the principles of weed management and development programmes that they can adapt in their farming practices. Reducing reliance on herbicides as the primary means of weed control and moving towards integrated weed management (IWM) programmes will require the cooperation and compliance of farmers. The IWM systems should be flexible enough to allow adjustments to changes in environmental, technological and social factors.

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The Author

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After returning to India in October 1975, Dr. Rao worked as Agronomist (Weed Control) at Tocklai Experimental Station, Tea Research Association, Jorhat, Assam, India for over six years. During this period, he built a strong weed research programme and developed numerous and far-reaching weed management practices for the benefit of tea industry in India. In March 1982, he became Director of Fredrick Institute of Plant Protection and Toxicology, near Madras, India. After leading this pesticide/herbicide contract research laboratory for over three years, Dr. Rao became a professional weed scientist advising national and state governments, herbicide industry and research institutions on matters concerning herbicide technology and its transfer to farmers. During this period (1985-94), Dr. Rao served as Adviser/Consultant to herbicide companies including Mascot Agrochemicals Pvt. Ltd., Bangalore and Hoechst India Ltd., Bombay. He also served as a member of Agronomy Panel of Indian Council of Agricultural Research and Herbicide Panel of Central Insecticides Board, Ministry of Agriculture, New Delhi. Besides, he was also a member of numerous national-level and state-level government committees related to weed management.

After relocating to USA with his family in March 1995, Dr. Rao continued to pursue his interest in his field. Currently, he is a Weed Scientist in a private pesticide laboratory, besides being a Consultant (Weed Science) to certain herbicide companies.

Dr. Rao is an author of over 80 research papers and reports in weed science, plant physiology and agronomy. The first edition of his book 'PRINCIPLES OF WEED SCIENCE', published in 1983, has been a very popular reference-cum-textbook in weed science in India. Dr. Rao has also made a significant contribution to the growth of weed science profession in India. He served as Executive Vice President of Indian Society of Weed Science and Editor-in-Chief of Indian Journal of Weed Science, each for a four-year term, during 1982-90. He is a member of Indian Society of Weed Science for life and Weed Science Society of America for over 25 years. He is presently located at 3575 Lehigh Dr., House # 2, Santa Clara, California 95051, USA.