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Herbicides Applications: Problems and Considerations

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1. Introduction

Methods of weed control are many and varied including prevention, mechanical, cultural, physical, biological and chemical (Qasem, 1992), each may be used alone or all are usually integrated for any successful weed control program (Qasem, 2003; Singh et al., 2006). However, weed control is jointly used with other farm operations for efficient crop production. Herbicides are chemicals inhibit or kill weeds, do not harm crops if properly handled and selectively used. They are organic or inorganic (contain no carbon) chemicals (California Weed Conference, 1985) and can be easily designated from botanical or microherbicides (Rice, 1983, Mo & He, 2005). Although the use of herbicides for weed control create public concern and receives much criticisms nowadays at which most naturalists and environments oppose their use and other pesticides, recommend alternative weed control methods or natural eco-friendly chemicals, but synthetic herbicides remained widely used, considered for weed control and intensively applied in developed and many developing countries. Herbicides however, represent 44% of the world's pesticide markets while out of which 57% is for the USA (Kiely et al., 2004). In developing countries, chemical weed control is not widely practiced because of relatively cheap labor, high chemicals prices and lack of technical extension and experience in herbicides application which leads in most cases to the misuse of these chemicals and crop injury (Su, 2006), failure of selective herbicides and weed control operation, soil and air pollution and limitation in crop rotation options. Different factors are occasionally involved in herbicides failure under field conditions which most due to human mistakes lead to improper application technique (Ross & Lembi, 1999). In addition, lack of correct diagnosis of the weed problem, selection of incorrect herbicide and prevalence of unsuitable weather conditions for chemical weed control are all reasons behind failure of the herbicide in controlling existing weeds (Gwynne & Murray, 1985). In this chapter, proper handling, precautions and some considerations in herbicides application in the field are considered and discussed as factors contribute in the success of chemical weed control; enable farmers to effectively control weeds in crop fields with low cost and more economical, less hazardous and low environmental pollutions.

2. Important

The chapter deals with problems and considerations in herbicides applications mainly facing farmers in the field. Factors affecting herbicides application and performance under

field conditions including herbicidal, plant and environmental factors are discussed. Technical problems that lead to improper application and failure of the herbicide are covered. Aspects related to sprayer calibration, herbicide labels, methods of application and requirements, surfactants, chemical drift, formulations, selectivity, mixtures, development of herbicide resistance, herbicides stability and effectiveness in the field, integration of chemical control with other methods of weed control are all dealt with. The chapter also covered the interaction between weeds and crop plants and the responses of both to herbicides and environmental conditions. Impact of the interaction between the three components on the success of chemical weed control operation, crop production and clean environment was discussed. Measures aimed to reduce crop injuries, herbicide persistence, development of weed tolerance/resistance, weed races and crop relatives, and shift in weed population are suggested. Therefore the chapter addressed the proper handling and application of herbicides as an effective weed control technology and their proper application in the field.

3. Information

3.1 Considerations

3.1.1 Weed factors

3.1.1.1 Weed identification

Diagnosis of the weed species found in the field is the first step toward any successful weed control program. Generally, weeds are narrow- or broad-leaved, annuals, biennials or perennials. Biennial weeds are few in number, most are prolific seed producers and many are ruderals (Grime, 1986); annuals reproduce from seeds, mostly short-lived terminate their life cycles before crop mature and can be easily controlled by other weed control methods or with contact herbicides (Qasem, 2003). Weeds, however, are different in their competitive abilities that determine the extent of yield loss and other negative effects of weeds on crop plants, the need for control and time required (Zimdahl, 1980). They are also widely differing in their physiology, biology and biochemistry. Yield losses although are different from one weed to another since differ in requirements and growth habits but competition is greatly influenced by weed density (Ziomedahl, 1980). Therefore, considering the critical density at which the weed must be controlled is important if to avoid any significant yield loss (Qasem, 2009). Although weed growth in certain important cash crops, is not allowed at any density eventhough for a short period. However, as a general rule weeds of similar requirements and growth habit to crop plants are known to be more competitive and cause greater yield loss and higher damage to crop plants than weeds of dissimilar requirements or morphology (Ross & Lembi, 1999).

3.1.1.2 Weed morphology and herbicide application

It is generally approved that narrow- leaved weeds intercept and retain less amount of spray solution on their vegetative parts than broad-leaved weeds , growing points or shoot apexes in many species of these are encased (e.g. cereals) by coleoptiles and thus protected against spray solution or herbicide droplets. In contrast, shoot apexes of broad-leaved weeds are directly exposed to herbicide solution; have horizontally extended leaves and thus better exposed to herbicide and subsequently intercept and retain higher amounts of spray solution.

Early weed (< 10 cm in height) control is always recommended. Weeds at early growth stage are small, short, their competition effect not started yet or minimum and thus weed management by herbicides is quite possible at the recommended or even lower rates of herbicide application beside they require low volume of spray solution for thorough coverage with contact herbicides. Annual weeds and to some extent biennials may be easily controlled using contact herbicides since reproduce by seeds, while creeping perennials are generally difficult to control by such chemicals since vegetatively reproduce from the below or sometimes above ground organs, and thus need translocated herbicides while repeat application may be mostly necessary. However, full coverage of the weed vegetative parts with contact herbicide solution is essential since only plant parts that became in contact with spray solution are affected while others are not, these may remain photosynthesizing, recover from herbicide injuries, then weed resume growth and successfully complete its life cycle.

However, morphological differences between the two groups may not be always the base since depend on ecology at which these weeds are growing (Grime, 1986; Holt, 2006). Broad-leaved weeds may have hairy, leathery small leaves with a low number of stomata on the upper surface or have some morphological modification under certain conditions (e.g. in arid and semi-arid regions) which may challenge chemical control at normal rates. The opposite is also true at which narrow-leaved weeds could be easily controlled at the recommended or lower rates of herbicides when found in moist, fertile soils or humid regions. Weeds under such conditions may lack or have a very thin waxy layer on leaf surface, absence of hairs with a high number of stomata projected on the upper surface and high physiological activity in general. It is well established that weeds are more susceptible to herbicides at early than at late growth stages which may be largely due to morphological and/or physiological sensitivity to herbicides.

Annual weed control should be carried out from after emergence to the full vegetative or pre-flowering stage. Weed control at this period prevents seed production and competition effect of tall growing weeds. However, this could be easily achieved using contact general herbicides such as glufosinate-ammonium, paraquat, bromoxynil, oxyfluorfen and others.

Perennial weed control using herbicides must be timed at three main important and critical growth stages of weeds, these are as follows:

1. Before establishment, at which weed seedlings can be easily controlled by a nonselective contact herbicide, but sometimes repeat application may be necessary.
2. After establishment, at which weeds are treated with translocated herbicides at full vegetative/pre-flowering growth stage, during which most of the reserved food in regenerative organs is directed toward the above ground parts for flowering and thus stored food left in the below-ground organs at this time is at low ebb. Although the symplast translocation of herbicides from shoots to the below ground parts with photosynthate materials is opposing the upward movement of stored food at this stage which may be more rapid and occurs at a higher rates. Killing or harming the above ground vegetative parts could result in a serious damage to weeds or even their death because of deficient food in perennating organs.
3. At late growth stage, at which perennial weeds may be effectively controlled by translocated herbicides late in the growing season and before plants lose their green color. At this stage the herbicide easily translocates with carbohydrates to the below ground parts and accumulates where carbohydrates are finally stored. Herbicide movement from the above to the below ground parts normally occurs and possible re-vegetation of treated weeds is slim.

Sometimes translocated herbicide may be followed with a contact herbicide after a while. This complementary treatment may be effective in controlling difficult perennial weeds by allowing translocated herbicides reaching the below ground parts and then prevention of any supply of photosynthate materials using foliage contact applied herbicide.

Chemical weed control however, is generally not recommended at late growth stages because of the following:

1. Weed competition effects on crop plants and thus on yield is irreversible at late growth stages.
2. Weed physiology (absorption, translocation and metabolism) is low, leaf surface may be heavily covered by wax and hairs and thus herbicide treatment may not be effective in most cases.
3. Weed morphology and anatomy is well differentiated and mostly do not facilitate herbicide penetration through thick cuticle layer on leaf surface and hard tissues on other foliage parts. Movement of the herbicide within plant tissues is becoming more difficult due to deposition of cutin, wax, cellulose and other byproducts or secondary metabolites in cell sap and on tissues themselves.
4. Weed vegetative mass may be thick enough, mostly not possible to fully cover with spray solution and/or needs a high volume of spray solution, and therefore possible recovery from herbicide treatment is high.
5. Spray retention is lower on mature than young plants since cuticle and thus waxy layer on leaves in the latter are not complete.
6. In most cases weeds reached seeding stage or finished their life cycle, therefore, any disturbance may help their seed dissemination, and herbicide application may not be effective in preventing weed seed production or maturation.
7. Herbicide possible residue in crop materials (mainly straw and grains) at harvest is high and the same is the run-off herbicide solution into the soil.
8. Cost of weed control may much exceeds the return yield value, considering that more crop plants are destroyed or crushed by labors and spray machines.

Soil applied herbicides should be used at a certain time when weed seeds are readily germinating and most sensitive to herbicides. At pre-germination stage, seeds may easily absorb herbicide with soil water; imbibed seeds take up an amount of the herbicide solution enough to kill the embryo. Therefore application of herbicides to control dormant weed seeds or during drought conditions should be avoided since of low or no response of the physiologically inactive weed seeds. It is suggested that these herbicides may be applied after seed bed preparation and before sowing or planting and may be followed by irrigation or rain that activate both the herbicide molecules (Friesen & Dew, 1966), and seed absorption, imbibition and germination. It is usually recommended that soil applied herbicides should be selected according to the type of weed to be treated, cultivated crop and soil type, while most of these chemicals are susceptible to soil microorganisms. However, when shallow-root annual weeds present in a perennial deep rooted crop it becomes important to select a soil surface active, none-leachable herbicide and the opposite is true for deep-rooted weeds in shallow-rooted perennial crops. The adsorptive relationship between the herbicide and treated soil, the size, diversity and activity of soil microbes' population, soil organic matter content, pH, and soil type are all factors determining the rate of herbicide application and its degradation. While leachability of the herbicide through the soil is determined by the adsorptive relationship between herbicide molecules and soil colloids and the amount of water passing through the soil.

3.1.1.3 Weed height and vegetative mass

Large growing weeds require higher volume of spray solution especially from contact herbicides. In this case weed control may become more expensive, time and labor consuming. Tall growing weeds could escape chemical control because of location of their growing points and shoot apices which are not possibly hit by herbicide droplets since placed at a higher level above sprayer boom that is usually fixed at a standard regular height in tractor-mounted, pull-type and self-propelled sprayers. Uniform spray is also difficult to achieve having tall and large growing weeds.

3.1.2 Crop factors

3.1.2.1 Crop species / varieties

Crop species are different in their sensitivity and responses to herbicides. Differences have been also reported between different crop cultivars in response to the same or different herbicides (Duwayri & Saghir, 1983; Felix et al., 2007; Abit et al., 2009; Kong et al., 2009 & Jin et al., 2010) hence differ in morphology, physiology, growth habit and phenology. In addition, cultivars are different in germination, emergence, growth development and duration, physiological and biochemical responses (Grime, 1986). All greatly affect herbicides performance in plants, their effectiveness and thus herbicides physiological, physical and biochemical degradation.

3.1.2.2 Crop growth and herbicide tolerance

As early mentioned, tolerance of crop plants to herbicides determines herbicide selectivity and its safe uses. Crop plants similar to weeds in that are more susceptible to herbicides early in the growth at which crop injury is commonly observed. Anatomy, morphology, succulence and physiology of crop seedlings are all factors determine the extent of herbicide effectiveness and crop injuries. It is generally approved that crop plants grown from seeds are more susceptible to herbicides than those from transplants and therefore, herbicides sensitive crops are recommended to be grown from seedlings instead of seeds when soil applied herbicides are used. Foliage applied herbicides are well effective against weeds at early (1-5 leaf) growth stages while crop seedlings at this stage may also show some injury symptoms which could recover from otherwise a more selective and safe herbicide must be used. This depends on time and rate of herbicide application (Friesen, 1967; Friesen et al., 1968; Carter et al., 2007) and prevailing environmental conditions (Coupland, 1987). Selectivity of the herbicide is highly dependent on crop internal factors as well as climatic conditions that activate/ inactivate herbicide molecules. For example, it is well established that crop plants have certain period/s in the life cycles during which physiological activity is low and thus absorption and translocation of herbicide may become very limited. Conversion of the herbicide from a toxic to a non- or less toxic form or the opposite is also affected and varied at different growth stages. Active growing weeds are required for effective chemical control. For example, application of Diclofop-methyl, Barban, Diallate, Triallate, Difezoquat, Bromoxynil in cereals, and many others are usually recommended at early growth of weeds and before reaching 5-leaf stage (Virginia Polytechnic Institute and State University, 1999a & b; Mu et al., 2007). The same is also true with other herbicides in vegetable crops such as oxadiazon (Fig. 1) and oxyfluorfen for weed control in onions



Fig. 1. Selective control of *Ammi majus* L. in onion with post-planting treatment of oxadiazon. Treated onion rows (left) and untreated rows (right).

(Qasem, 2005). On the other hand, 2,4-D and MCPA are best applied at full tillering stage of cereal (wheat and barley) crops and when crop plants are at resting stage and exhibit low physiological activities. Weeds at the same time are physiologically active; their cell division and cell elongation rates are high and thus accumulate lethal doses from these herbicides in embryonic tissues (Fig. 2). Differences in selectivity between legume crops and their associated broad-leaved weeds to 2,4-DB depends mainly on the ability of these to accumulate and convert large amounts from this herbicide to 2,4-D (more toxic) and the rapid conversion process. Weeds accumulate and convert larger amount within a relatively short period and thus affected more rapidly than crop plants that escape injuries because of



Fig. 2. Selective control of broad-leaved weeds by 2, 4-D in wheat field.

slow conversion process and the non-lethal level accumulated in their tissues. Therefore, herbicide application is a skill that allows farmers take an advantage from morphological, physiological or biochemical differences between weeds and crop plants in response to herbicides and thus may be considered as an opportunistic operation should be implemented on time and when conditions permit.

3.1.2.3 Crop morphology

Crops are different from above ground morphology; some are narrow-leaved while others are broad-leaved. The same as for weeds leaf arrangements on the stem and their display are also different for different crop species, in addition to differences in morphology size and heights. All affect herbicide spray retention on crops vegetative parts, herbicide selectivity and safe use on these crops. Narrow-leaved crops with somehow vertically arranged and less displayed leaves receive less volume of foliage-applied spray solution and the opposite is true for broad-leaved crops. In addition, the deposited waxy layer on leaves of different crop species or varieties is widely different which in turn affects the amount of herbicide intercept and retained on leaves and subsequently their absorption rates. Crucifers and onions are examples on crops of wax covered leaves and thus their wettability with herbicide solution may not be possible without surfactants and the run-off into the soil surface is quite high. Crop species are different in location of their growing points, amounts of embryonic tissues, presence or absence of cambium, physiological and biochemical activities, depth of their root systems, root distribution, surface area, capacity and efficiency in taking up herbicides molecules from soil solution. All these factors could affect herbicide sensitivity or tolerance of crop plants. However, differences were detected on families, species and cultivars levels in response to herbicides and therefore any selective herbicide on a specific crop cultivar may confer injury to other cultivars (Felix et al., 2007; Abit et al., 2009; Kong et al., 2009; Jin et al., 2010). However, production of cuticular wax tends to be reduced under warm humid conditions which may result in a higher retention of spray solution on crop leaves and more injury under such conditions.

3.1.3 Herbicide factors

3.1.3.1 Herbicide status and type

Herbicides are chemicals negatively affect weeds normal growth, they quickly act and may be applied to a specific area or where other methods of weed control are not possible, or may be integrated with other weed control methods. However, chemical weed control has many advantages among which is the use of pre-emergence herbicides which provides control of strong competing weeds during crop establishment and thus help get a weed control job that otherwise cannot be done.

Herbicides are classified based on different factors among which is the selectivity. Based on that, herbicides kill or inhibit weeds and don't harm crop plants beyond point of economic recovery. The nonselective herbicides referred to those chemicals kill all plants when applied at enough rates and mainly used where no vegetation is required. Selectivity however, depends on rate and formulation of the herbicide applied, time of and method of application, environmental conditions and stage of weeds and crop plants. Herbicides are also categorized based on their method of action to contact which only kill plant parts that became in contact with and most are effective against annual weeds, but if used on perennials another applications may be necessary. On the other hand, systemic

(translocated) herbicides are those absorbed by leaves, shoots or roots, transport from the site of application to where toxic action take place. These are useful against established perennials and unlike contact herbicides uniform coverage is less important. These chemicals kill slowly (toxicity symptoms may take weeks and up to a year to be developed for certain herbicides such as amitrole) while contact herbicides are rapidly acting. Herbicides are also classified based on method of application to soil-applied absorbed by roots of large plants mainly affect seed germination, germinated seeds or small seedlings and thus used to eliminate weeds before emerge and can selectively eliminate germinating weeds in established crops. These may or not be foliage active.

Foliage applied herbicides are contact or translocated and may or not be soil active. If translocated, they move passively through the symplast system with photosynthate materials.

Considering time of application, herbicides are either preplanting applied at which crop should resist herbicide treatment and herbicide must be short-lived; pre-emergence used after crop is planted (vegetative parts) or sown (seeds) but before emergence and crop tolerance is necessary; post-emergence applied after crop emerged, may be soil or foliage applied but crop resistance is essential. If soil applied, they kill newly germinated seedlings while foliage applied herbicides kill emerged weeds. Persistence of soil-applied herbicide may be required since offer a long period of weed control and may be through out the whole growing season or until harvest. However, herbicide carry-over problem should be taken into account using such chemicals (Schnoor, 1992).

3.1.3.2 Time of application

Time of herbicides application is important in determining the effectiveness and length of weed control duration (Carter et al., 2007; James et al., 2007). Herbicides are applied at preplanting in crops grown from seedlings such as of most vegetables; pre-sowing in case of seed-sown grain field crops and some vegetables such as many cucurbits; and as post-emergence. The first two groups are soil applied, control germinated seeds or weed seedlings either by a contact or systemic action, prevent weed seed germination or seedlings growth and thus prevent early weed competition and protect crops from planting or sowing date until a good canopy is developed. This period in crop life cycle is most vulnerable to weed competition and crop recovery may not be possible if weeds escape control during this period. In all cases crop tolerance and herbicide selectivity are essential factors.

3.1.3.3 Herbicide formulations

Herbicides formulations are many including water soluble (WS, S, SL) liquids require wetting agents, water soluble powders (SP) need stirring or agitation in preparation, water emulsions (E, EC) require some agitation and held together by an emulsifier, wettable powders (W, WP) need continuous agitation and most used on soil, water dispersal liquids (WDL, L, F), water dispersed granules (WDG, DF), granules (G) need water to leach them down into the soil, and pellets usually used in spot treatments (Foy & Pritchard, 1996). Herbicide formulation affect selectivity and thus crop growth. The most used herbicide formulations are aqueous and granules. For each formulation there are certain equipments to apply, these are sprayers or spreaders, respectively. However, both forms should be uniformly applied with the second most commonly used in horticultural crops and is least selective. It is well known that forms such as powders (dust), granules, ester forms are less stable than others while water soluble forms are more stable than emulsions.

3.1.3.4 Labels and technical pamphlets

Herbicide label and technical bulletin must be carefully read prior to herbicide application. Label shows herbicide trade and common names and carry important information on herbicide selectivity, formulation, active ingredient, volume of spray solution or carrier required per unit area, method of application, time of herbicide application, rate of application, post-application treatments, persistence (carry-over) (Felix et al., 2007), weed species affected, and crops in which the herbicide is recommended, weed control spectrum and tolerant weeds, volatility and conditions under which the herbicide is selectively used and any possible crop injures and precautions. All these information are of high value for the farmer and must be consulted and strictly followed if a successful weed control operation is the ultimate farmers' goal. Considering all of these would help in achieving effective chemical weed control with no hazards or environmental pollution.

3.1.3.5 Herbicide resistance and selection pressure

One of the causes of herbicide tolerance/resistance in weeds is the continuous application of the same herbicide or herbicides of the same mechanism of action year after another in the same field (Caseley et al., 1991; Duke, 1996). This practice imbalances weed population at which certain group of weeds (broad or narrow-leaved) is affected while the other is not harmed (Fig. 3). This is usually resulted from use of selective rather than general herbicides. However, within the affected weed group sensitive species are the first harmed and disappear later. The less affected species may include some individuals within populations that withstand the rate of herbicide applied or may be partially affected but could recover late in the season and set seeds. Continuous use of the same herbicide impose a selection pressure that force some individuals within the weed population to physiologically, morphologically and may be biochemically distinct and adapt themselves to tolerate the rate of herbicide used (Powles & Holtum, 1994; Pline et al., 2003; Qasem, 2003). This will lead later to development of individuals within the same weed population that resists chemical



Fig. 3. Weed population shift to narrow-leaved weeds (Mainly bulbous barley, *Hordeum bulbosum* L.) resulted from continuous application of broad-leaf killers in olive orchard.

treatments (e.g. *Senecio vulgaris*, *Chenopodium album* and *Amaranthus retroflexus* to triazines). At present, the total number of resistant weeds may exceed 668 species of more than 346 biotypes (<http://www.weedscience.org/summary/MOASummary.asp>). However, continuous application of the same herbicide or group of herbicide with the same mechanism of action may lead to the following problems:

1. Imbalance natural weed population
2. Cause shift in weed population toward perennation.
3. Encourage dominance and existence of certain weed species
4. Promote development of weed tolerance followed by weed resistance
5. Lead to development of weed races or crop- relative weeds that become irresponsive to agricultural practices employed and dominate cultivated fields.

However, these problems can be avoided by the following measures:

1. Rotation of chemical control method with other methods of weed control
2. Rotation of the herbicide with other herbicides of different mechanism of action.
3. Adoption of crop rotation system which is usually accompanied with herbicide rotation and thus leads to brake down the build up of dominant weed population.
4. Alternate selective chemical control treatment with fallow years during which general (nonselective) herbicides may be used to control all weed species in the field including resistant species.

3.1.3.6 Sprayers and calibration

The main and serious problem with herbicides application or uses is the people apply these chemicals. Wrong application is commonly resulted from failure in sprayer calibration.

Sprayer calibration aims at uniform herbicide spray distribution and coverage of treated weeds/surface that means the receipt of the same amount of spray solution per each unit area of treated surface. Sprayer calibration is the first step to be carried out before herbicide application. Herbicide application in the field should be properly carried out since failure of uniform distribution of any herbicide may result ineffective weed control or crop injures and thus herbicide residues (Badowski et al., 2008). Therefore, sprayer calibration is mainly conducted to determine the volume of the carrier (mostly water) required to dissolve in the amount of the herbicide calculated (based on recommended rate) and required for specific area. In other words, it aimed to determine exactly the volume of water required to hold/dissolve the amount of the formulated herbicide specified to cover a measured area infested by weeds. It is also required to know how much of the herbicide is applied per treated area (Kansas State University, 2010). Failure to calibrate the sprayer can injure crop, cause pollution, and waste time and money. Therefore, calibration should be carried out regularly and nozzles must be cleaned at each spray time and before herbicide application. Therefore, several factors must be considered which influence this operation, these are as follows:

1. Solution/ tank pressure. It is well known that pressure inside sprayer tank may range between 15 to 50 pounds per square inch (psi) and application rates can vary from less than 15 to more than 250 gallons per hectare. The higher the pressure imposed on spray solution the more fine are the spray droplets and the higher is their liability to drift. The volume of spray solution ejected from the nozzle is linearly correlated with the pressure imposed on spray solution and the greater is the nozzle discharge. In addition, the higher pressure the wider is the spray swath and the larger the area covered per unit time. Therefore, pressure must be calibrated and adjusted to be the same as that used in calibration and must be kept constant (labor carried sprayers) through out the whole time of herbicide application. Any

deviation from a constant pressure may result failure in obtaining uniform coverage of the weeds vegetative parts or differences in coverage of the treated soil surface when pre-emergence herbicides are used.

2. Sprayer ground speed. The volume of spray solution applied is affected by sprayer speed. The higher the speed the larger is the area covered by herbicide solution and the lower is the volume used per unit time and *vice versa*. Doubling the ground speed (mph) of the sprayer reduces the gallons of spray applied by one-half. Sprayer speed should be determined through calibration directly in the field to be sprayed. However, this could be affected by weed species, weed size, height, population thickness and soil structure and topography. Small and short grown weeds may be easily controlled using small spray volume. In contrast, large and tall growing weeds require more coverage by herbicide solution, thus large volume of spray solution is applied at low sprayer speed. This however, is in link with herbicide method of action whether is a contact or translocated herbicide. Application of the former requires slow movement, low speed and full coverage of the treated surface. However, both pressure and nozzle size are factors controlling the delivered spray volume.

3. Sprayer boom height. Nozzle height has obvious effect on the area covered by herbicide solution. The higher the boom height the wider is the spray swath and the larger is the area covered with spray solution of different nozzles mounted on the sprayer boom. Changing boom height from above the soil level during spray operation may easily result in a non-uniform coverage leads to overlapping between spray swath of different nozzles fixed on the boom and thus crop may be injured or killed since received a double dose of the herbicide solution which could be easily observed in the field. When nozzles are placed at low height from the soil level possible gaps left uncovered by the herbicide solution are mostly resulted and thus weeds in these gaps may continue growing in regularly spaced strips in the field (Fig. 4). In both situations lack of uniform coverage by the herbicide solution could result in equally spaced strips of growing weeds or killed crop plants under



Fig. 4. Wild mustard (*Sinapis arvensis* L.) grown in strips after escaped from control by 2, 4-D in wheat due to low boom height level.

low and high levels of sprayer boom height, respectively. Therefore, one of the objectives of calibration is to exactly determine the optimum boom height that provides uniform coverage (a single coverage treatment) of the sprayed surface or treated weeds with herbicide solution.

4. Nozzle type and discharge of spray solution

Nozzle type determines the spray discharge, the uniformity of spray application and spray pattern, the coverage of sprayed surface of a target plant and the drift rate. It is generally agreed that the same type of nozzles must be used on the sprayer and these should be carefully checked for correct number and against tip damage or orifice clogging. All should be mounted and directed similarly on the sprayer boom. However, nozzle type is different between different nozzles but generally two main types are commonly employed. These are cone type and flat fan type nozzles. In the first, orifice is rounded gives a cone type spray while the orifice opening in the second is straight flattened. Each type includes hollow or solid spray patterns. Cone type is used to produce a coarse spray for aerial and other low drift purposes and is more commonly used for woody shrub or tree control but its use in field crops is limited or rare. Turbo flat-fan, venture flat fans and drift reduction pre-orifice flat-fans are commonly employed in crop protection products. For herbicide application, the flat fan type of a straight orifice opening is usually used since gives a flat spray swath in a straight line (sheet of spray) which could thoroughly cover all weeds within the spray swath limits. Each nozzle type could carry a number (mostly not found in knapsack sprayers or other compressed manual operated sprayers) fixed on the nozzle tip that represents spray angle and spray discharge. The higher the spray angle the larger the area covered and the delivered spray volume. Nozzle discharge is measured as gallon per minute. The higher the number the higher is the nozzle discharge. Spray angle and solution discharge are in link with type of the herbicide used and the volume of spray solution and influenced by tank pressure and nozzle size. It is advised that low spray solution volume is better used for systemic herbicide application while high volume is more relevant to thorough coverage of weed vegetation using contact herbicide solution. All thus depend on the nozzle type and could be determined from the type of weeds found in the field. Annual weeds may require contact herbicide, full coverage treatment, high volume of spray solution and subsequently higher spray angle and solution discharge. The opposite is true for perennial weeds and systemic herbicides at which may be absorbed and translocated through the whole plant system once an amount of the spray solution is absorbed from any part of the plant. In summary, nozzles are different in specifications, spray angle and discharge, orifice or tip type and size, materials which are made from, all these determine with the density of the spray liquid the spray volume applied, the type of the herbicide used, and the type of weeds to be treated by each nozzle type.

4. Problems

Like any weed control method, chemical weed control has advantages and disadvantages. Among problems encountered are the following:

1. Herbicides may cause shift in weed population (Owen et al., 2008) because of continuous use of certain chemical, chemicals of the same mechanism of action or family create selection pressure and development of weed races.
2. Imbalance weeds population mainly when selective herbicides are used. Broad-leaf killers imbalance weed population toward dominance of narrow-leaved weeds and the opposite

is true for narrow-leaved killers and broad-leaved proportions. Therefore, both types of herbicide groups should be occasionally complimented or alternated in the field.

3. Herbicide residues in plant materials. Herbicides are absorbed by crop plants as well as by weeds. Certain herbicides are completely metabolized while others are not (Hatzios & Penner, 1982; Pline et al., 2003). The second group mostly is not recommended on food or feed plants. Examples are paraquat that not permitted on food crops, and dinoseb-acetate, another contact herbicide used in alfalfa fields. Because toxicity is extended on harvested alfalfa plants therefore is always advised that first harvest should not be fed to the cattle but rather burned and people should stay away from the smoke of burned plant materials. Residues of herbicides in plant materials are most commonly found when herbicides were applied late in weed and crop growth.
4. Herbicide carry- over problem and limitation in crop rotation options. This problem may be easily observed with some long persistent herbicides. Some examples are urea and sufonyl-urea herbicides. Planting of non cereal crops in soil treated with these chemicals may result in serious crop injuries. Cucurbits and some legumes are good examples on sensitive crops to herbicides. Injury effect on the same crops may be also observed after metribuzin and many other soil applied herbicides.
5. Herbicide leaching to ground water. Pollution of ground water is possible when leachable herbicides are used (Smith et al., 1984; Vizantinopoulos & Lolos, 1994). Leachability may be high with salt formulated herbicides used or in treated sandy soils under heavy irrigation or rain.
6. Herbicide chemical drift and crop injuries. This is an important problem encountered with certain herbicides and usually take place as spray-drift occurs when small droplets of spray liquid are carried away from target plants by wind currents, vapour-drift resulted from application of high volatile chemicals enhanced by high temperature or wind currents, and the blow-off which is associated with light soils and resulted from movement of tiny particles of soil treated by herbicide.
7. Herbicide persistence in environment. This may be in relation to half life of the herbicide and its rate of degradation in the environment. Certain herbicides have long half-life and persist in the environment for along period of time that limits agricultural land uses. These however, may be traced in the soil, air, surrounding environment, ground water and even agricultural products and may become a serious threat to public health. Therefore, these chemicals should be avoided, highly restricted and only applied in absence of other alternatives and when are extremely needed.
8. Herbicide storage and handling. Herbicides and pesticides in general should be properly handled and safely stored since are toxic to humans and other living organisms. Stores should be properly located, designed specifically and locked to prevent contamination, pollution and protect chemicals from any degradation and loss in activity before use. Loss in any form must be prevented. Therefore, temperature, humidity, and aeration must be strictly controlled to prevent any loss in chemicals activities. Chemicals however, should be stored in their original containers, kept away and separately stored from other stored agricultural materials and preferably used within a short period where possible.

Empty glass, metal, or plastic made containers should be thoroughly washed with water that to be added to the spray solution in the sprayer tank. Containers must be punctured, destroyed and then deeply buried (deeper than 1m) in the soil or disposed in a sanitary licensed area. Herbicides containers made from cartoon or paper bags

- should not be burned in a residential area or where smoke of these may become in contact with animals or cause air pollution and toxicity.
9. Herbicide and toxicity to mammals. It should be clearly declared that all pesticides are toxic to humans and mammals in general but toxicity is different between these chemicals. Herbicides are the least toxic among all agricultural pesticides. This however, may be determined by considering the LD₅₀ or LC₅₀. Among herbicides with relatively low LD₅₀ are paraquat, diaquat, dinoseb, diclofop-methyl and some others. It should be known that toxicity may occur through absorption, smoking, inhalation, swallow through contaminated hands, food and drink. Certain highly toxic chemicals should be avoided unless no alternatives are available.
 10. Herbicide resistant weeds. This is a serious problem that could totally cause shift in weed population from susceptible to resistant. The main cause of this is the high selection pressure imposed by use of only a single herbicide or herbicides having the same mode or mechanism of action for a relatively long period. Farmers should keep watching changes occur in weed population in response to chemicals used and take measures when observe scattered individuals of certain weed species start tolerating the herbicide normal rate of application. This is the first sign on development of herbicide resistance in that species.
 11. Crop injury. This may be due to direct or indirect exposure of crop plants to herbicide molecules. Herbicide treated crop may show signs of herbicide injuries that may or may not recover from. This is mostly related to herbicide rate of application, form used, surfactant added, time of application relative to crop physiological or morphological stages or prevailing climatic conditions at spray time. Indirect injury may result from sprayer tank contamination through herbicide traces left unwashed and used to apply insecticides or fungicides using the same sprayer (Fig. 5), drift of volatile herbicides applied in the nearby fields, leached herbicides to ground water, running water used to irrigate sensitive crops or from carry-over problem of certain previously applied herbicides.



Fig. 5. Toxicity symptoms on Jute (*Chorchorus olitorius* L.) resulted from 2,4-D traces left in the sprayer tank used for insecticide application. Plants showed abnormal growth (malformed leaves, twisting and yellowing).

12. Herbicide application and technicality required. This is an important factor determines the success or failure of weed control operation. Some of the problems detected including herbicide application without sprayer calibration but rather addition of a measured/unmeasured amount of the selected herbicide to the tank (unmarked) filled by unmeasured volume of water, spray weeds thoroughly, heavily and deeply covered by dew droplets which may dilute the spray solution, failure to thorough mixing of herbicide solution, failure of continuous stirring or agitating spray solution (suspensions) during spray time, failure to maintain a fixed pressure or a constant ground speed during spraying (in case of knapsack or shoulders-hilled sprayers) this resulted in uneven spray distribution, partial coverage of sprayed surface or low volume of spray solution received per unit area, failure in maintaining straight forward travel in manual operated sprayers with no overlapping or area left uncovered by the spray solution.
13. Cost of chemical weed control and precautions required. In absence of any studies on the economic use of herbicides compared with other methods of weed control, chemical weed control may be thought by farmers as an expensive tool, needs a lot of preparations and accuracy, unsafe to crop plants if not properly and carefully considered, cause soil and environmental pollutions if not well designed and carefully selected, and doesn't give complete solution to all weeds present in the field and thus other methods of weed control should be also incorporated.
14. Herbicides toxicity and public concern. With the present trend toward public concern from synthetic chemicals and tendency in crop cultivation and food production through an organic farming system, use of agrochemicals in general including herbicides became much restricted. People world over preferred, chemical untreated and naturally produced crops despite high prices and payments for this staff of organic food.
15. Human failure to properly apply the herbicide on time, conducting sprayer calibration, after herbicide application operations and uniform distribution and application.

5. General rules, recommendations and concluding remarks

Before start considering chemical weed control method think carefully in the following:

1. Look first for weed control options other than herbicides.
2. There is no best weed control method but rather integrated methods of weed management.
3. Consider the economic return value from weed control using herbicides.
4. Weed control in general, and using herbicides in particular may be of no value after certain period of weed/crop competition since crop recovery may not possible and more expensive without crop yield return.
5. Weeds as well as crops are different in their competitive abilities and these are different from region to another within the same country.
6. Critical period of weed control is different for the same crop and weed species from area to another.
7. Always search for an eco-friendly herbicide suit weed control in the specified crop, cheap, with low rate, short life and non residual, environmentally compatible and safe for mammals and biological system in general.
8. Identify weed species and predicted weed population in the field, determine if the critical density of weeds is reached, therefore weed population prediction is important

- before start any weed control program. Weed population under critical density may doesn't need immediate control.
9. Always look for differences between crop plants and weeds in growth, requirements, development and responses, benefit from these to favor crop plants over weeds. Therefore, field managements may be of high value for crop plants the same as the use of herbicide.
 10. Weed control aimed at keeping weed population below the level cause economic crop injury. Eradication of weeds commonly found in the area may not be possible or economically unfeasible. Therefore, weed control should be implemented when weed density in the field is becoming critical. Sometimes it is strongly advised to use a spot treatment rather than an overall spraying of the herbicide when weeds are found growing in patches or forming scattered colonies in the field.
 11. Chose registered herbicide recommended for use in the grown crop.
 12. Obtain the herbicide from local chemical agent with full detailed information on its uses and supplement of technical bulletin.
 13. Be sure that the purchased herbicide is a new valid (not or nearly expired) product; handle carefully its storage until being used.
 14. Think always that both crop plants and weeds take up herbicide and the differences in susceptibility between both may be marginal and easily affected by plant, herbicide and environmental factors. These marginal differences determine herbicide selectivity.
 15. Weeds grown under harsh environmental conditions (drought, high temperature, salinity, highly disturbed habitats) have different morphological modifications and are more difficult to control by herbicides compared with those grown under favorable growth conditions.
 16. Early weed control is always recommended and for each crop there is a critical period of weed control at which weeds must be removed to avoid any significant yield loss. Weeds competed with crop plants before or after this period cause no significant effect on crop yield providing weeds are controlled during this period. This however, is greatly influenced by crop species and cultivars, weed species and density, and agricultural practices followed. At the critical period chemical weed control may not the best method of weed control considering crop growth stage and status, crop physiology and possible injury or weather conditions that may lead to more toxic herbicide even though the recommended rate is used.
 17. Determine the best time for herbicide application and chose conditions favored crops over weeds. Consider environment, herbicide and plant factors before herbicide application. Plant morphology, physiology, anatomy and biochemical activities are important factors in determining the ultimate effect of herbicide on crop and weed plants.
 18. Be sure that there are certain periods in crop and weed growth cycle at which herbicide by any is tolerated/resisted or these are more susceptible. Look always for the differences in weed and crop plants tolerance to herbicides treatment.
 19. Before preparing herbicide solution, carefully consult the technical bulletin provided by the manufacturer with herbicide, read carefully all information in herbicide label and consider all factors affect herbicide performance in the field and weed control operation.
 20. Sprayer inspection, preparation and calibration must be considered. Sprayer check out, tank or nozzle leakage, pump working order, type of nozzles and fixation on spray

- boom, nozzle clogging, nozzle spacing and direction, boom height, tank pressure, ground speed of the sprayer and spray volume, all should be considered and optimized.
21. Conduct sprayer calibration directly in the field to be treated by the herbicide. Always keep in mind that spray volume is affected by sprayer ground speed, pressure, boom height and nozzle type, weed growth and population thickness.
 22. Calibration of the sprayer mainly aims to determine the volume of water needed to carry in the amount of herbicide required for weed control in a specific area. It is conducted always at fixed pre-determined ground speed, pressure, boom height, same nozzle type and at suitable climatic conditions.
 23. Once the volume of water needed to dissolve or carry with the amount of herbicide required per intended area for spray is determined start preparations for herbicide application. Prepare the special dress/apron designed for spray operation.
 24. Calculate the amount of herbicide required for that specific area based on the recommended rate of herbicide application by the manufacturer, don't exceed the specified rate or go lower than that because in both cases wrong results may be obtained. In the first the crop may be killed/injured while in the second failure of weed control. In both cases the required amount of herbicide per unit area is not received on the sprayed surface.
 25. Herbicide selectivity is not an absolute value or character of a herbicide rather than resulted from the interaction between plant, herbicide and environmental factors.
 26. Herbicide mixtures must be compatible, beneficial and used mainly to widen the weed control spectrum. However, these may be already available and prepared in advance by the manufacturer or used as tank mixtures at spray time.
 27. Weed population is either active or passive, each of which needs certain herbicides determined based on their method of application. Passive weed populations is controlled using soil applied herbicides while active weed population may be treated by foliage or soil applied herbicides. Both weed populations must be considered in any weed control program.
 28. Before herbicide application, consider crop grown and tolerance, crop rotation followed, herbicide cost, duration of weed control required and herbicide persistence in the environment. Don't exceed or lower the recommended rate of the herbicide unless based on experimental results obtained under local conditions and no residues or pollution are left in the environment.
 29. Avoid the use of growth regulator herbicides (such as phenoxy or benzoic herbicides) during flowering time of field crops (e.g. tomato) or fruit trees (e.g. citrus). This may result in flower abortion in most cases.
 30. Chemical weed control may cause shift in weed population toward perennation therefore this practice must be changed by time, rotated or integrated with other weed control methods to maintain weed population balance.
 31. Selective herbicides may imbalance weed population thus herbicide mixtures of broad-leaf and narrow leaf killers are recommended or may be alternately applied.
 32. Wettable-powder formulated herbicides may need continuous agitation of spray solution through out the whole spray operation to prevent settling at tank bottom, separation and precipitation. Liquid herbicides may need emulsifying agent when dissolved in water especially for emulsifiable concentrate (EC) formulated herbicides
 33. Use surfactants when necessary especially wetting, spreading, sticking and drift control agents.

34. Certain materials may act as surfactants by modifying leaf surface and increase herbicide wettability to leaf surface or penetration through increasing compatibility between herbicide and waxy leaf layer on leaf surface, these include ammonium sulfate, urea, soap, washing or cleaning powders, liquid detergents and acidic plant extracts.
35. Different soil types require different rates of application from the same herbicide based on their mechanical and structural analysis.
36. Herbicide susceptible weeds may become tolerant at certain period after emergence or when reaching certain morphological stage since resulted from changes in weed physiology and/ or biochemistry.
37. Herbicide rotation is essential to keep weed population under control; any deviation from this system may result in weed population shift, development of weed races, crop-relative weeds and herbicide resistance.
38. High volatile herbicides should not be applied during hot weather conditions, since chemical drift in vapor form or crop injury is highly possible. Instead less or nonvolatile forms are recommended.
39. Photosensitive herbicides as well as volatile soil applied herbicides need soil-incorporation or light irrigation after application.
40. In preparing herbicide solution for field application, the amount of herbicide calculated to treat a specific area and volume of water needed must be added consequently (as water-herbicide-water) to the sprayer tank, thus herbicide is first dissolved in certain amount of water then spray solution may be then completed by adding water up to the final volume consumed in calibration. The herbicide-water mixture must then be thoroughly mixed by hand shaking of knapsack sprayers or spray solution must be kept agitated during spraying operation. The pressure, sprayer ground speed, boom height and the same nozzle type used in calibration must all be set the same as were in calibration. If all factors are kept the same then the herbicide solution must run-out by finishing the sprayed area without any shortage or spray solution left in the sprayer tank. In this case distribution of the herbicide solution is considered as uniform and equally applied over the sprayed surface; otherwise some problems in weed control may be resulted.
41. Consider that no herbicide gives 100% killing of all weeds, some weed species specified on the label as sensitive to certain herbicide may be left uncontrolled and the opposite is also true. Therefore, selective herbicides may show some overlapping up to certain extents in their weed control spectrum of broad- and narrow-leaved weeds.
42. Soil applied herbicides are influenced by edaphic factors including; soil pH or soil reaction, mechanical and structural analysis, leachability, microorganism population, organic matter content and height of soil water table.
43. Activity of soil-applied herbicides is affected by seed dormancy, hardness of weed seed coat, weed seed population and richness of seed bank, seed bank species composition and microbe's population...
44. Nonselective herbicides may be selectively used if directed only toward weeds and contact between these and crop plant is prevented. In this case the herbicide is not selective but rather than selectively applied.
45. Consider that certain herbicides working on photosynthesis need high light intensity associated with high temperature (De Vleeschauwer et al., 1992) for effective weed control (e.g. paraquat, diuron, cycloxdim) while others exhibit photo degradations (e.g.

- glyphosate) and need to be applied in cloudy or foggy days, early in the morning or late in the evening.
46. Keep observing treated weed population, switch to other herbicide of different mechanism of action and family or change weed control method once observed that some plants of one or more weed species start tolerating the herbicide used.
 47. Weed races or herbicide resistance or persistence and dominance of certain weed species are results of selection pressure of the agricultural practices employed. To prevent development of such conditions frequently change the existing agricultural practices.
 48. Any herbicide traces left in the sprayer tank may cause toxicity to sensitive crops; therefore it is always recommended that herbicides sprayers must not be used for application of other pesticides even though were thoroughly washed or carefully cleaned.
 49. Higher rate of application than that specified on herbicide label may cause changes in method of herbicide action, instead of giving a systemic action, translocated herbicide kills by contact action since high application rate kills phloem tissues and then no more translocation to the below ground regenerative organs occurs and thus perennials are quickly re-vegetate after treatment with translocated herbicides.
 50. Chemical drift could be substantially reduced by selecting the nozzle type that deliver large droplet size (more than 100 micron) but providing adequate coverage at the intended application rate and sprayer pressure, avoidance of herbicide application where wind current speed exceeding 10 miles per hour, and temperature is high, avoid application of volatile herbicides and ester forms of phenoxy herbicides when air temperature is high, avoid using of high vapor pressure herbicides, lower the nozzle height to be closer to or above weed vegetation, incorporation of volatile soil applied herbicides, smoking, timing of spray operation either early in the morning or late in the evening since high relative humidity result in slow evaporation of droplets and decrease drift, selection of nozzles work at low pressure (swirl chamber, flood jet), allow enough time for herbicide absorption before rain occurs, and by adding drift control agents.
 51. Failure in herbicide application may be resulted from loss of herbicide solution by heavy rain or irrigation, high rainfall occurs after application and wash-off the herbicide from leaf surface, failure of uniform coverage, herbicide precipitation (suspensions) in sprayer tank during spraying, wrong time of herbicide application, wrong physiological or morphological growth stage at which weeds or crop plants are treated and no or wrong sprayer calibration.
 52. Highly volatile herbicides should not be applied when air temperature is high, temperature may increase loss of herbicide through volatiles, and at the same time may activates other herbicides to become more toxic and cause crop injuries even though are used at normal recommended rates of application.
 53. There should be enough time allowed for foliage applied herbicide absorption after its application. This period is different from one herbicide to another but generally six hours are at least required for most herbicides to be absorbed through foliage parts and thus farmers should ensure that no rain occurs during this period when apply herbicides.

6. Conclusion

Herbicide application in the field is a skill needs full consideration of all plant, herbicide and environmental factors if a successful weed control is the ultimate farmer aim. Failure in

weed control or crop injury is mainly due to human errors at which failure in or wrong sprayer calibration is a common mistake. Weed identification, size of weed problem exist, critical period of weed competition, weed density, selection of proper herbicide, rate and time of herbicide application, herbicide persistence, development of herbicide resistant weeds and environmental pollution are among factors to be considered and determine the success or failure of weed control operation. However, chemical control is usually integrated with other methods of weed control in any successful weed management program.

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Herbicides are much more than just weed killers. They may exhibit beneficial or adverse effects on other organisms. Given their toxicological, environmental but also agricultural relevance, herbicides are an interesting field of activity not only for scientists working in the field of agriculture. It seems that the investigation of herbicide-induced effects on weeds, crop plants, ecosystems, microorganisms, and higher organism requires a multidisciplinary approach. Some important aspects regarding the multisided impacts of herbicides on the living world are highlighted in this book. I am sure that the readers will find a lot of helpful information, even if they are only slightly interested in the topic.

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