Weed Management

Weeds and their Control Methods

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Weeds have been existing on the earth ever since the man started domesticating/cultivating plants and animals around 10,000 B.C. Weeds have been recognized as a problem since then and the battle against weeds is a never ending one and often the costliest agronomic input for successful crop production. Between humans and continuing food supply, there stand four natural hazards, e.g. weather, weeds, insect pests and plant diseases. Sometimes these hazards work independently and many times they work hand in hand. Weeds are the most underestimated crop pests in tropical agriculture although they cause maximum reduction/loss in the yields of crops than other pests and diseases. Of the total annual loss of agricultural produce from various pests in India, weeds roughly account for 37%, insects for 29%, diseases for 22% and other pests for 12% (Yaduraju, 2006). They decrease quantity and quality of produce/food, fibre, oil, forage/fodder, animal products (meat and milk) and cause health hazards for humans and animals. Thus weed control is indispensable in every crop production system.

1. UNDERSTANDING ABOUT WEEDS TOWARDS EFFECTIVE WEED CONTROL

Knowledge of weed seed characteristics, morphology, ontogeny, nature of competition and degree of association with crops are pre-requisite for suggesting some efficient weed control measures. It makes the users/scientists quite acquainted with the nature and spectrum of weeds existing in the crop fields and accordingly guides them to adopt certain measures. Identification and naming of a particular weed based on its genus, species or certain biological characters may not be much useful to users since weed control usually, unless specific weed problem in certain area, aims at composite weed culture and not on individual species of weeds. Therefore, some common characteristics of the species, which are clearly visible and easily understandable by users, are to be exploited for making of their classes/groups and for recommending suitable control measures.

Weed life cycle or ontogeny

Weed life cycle or ontogeny has made weeds annual, biennial and perennial, three main/broad groups, which are further sub-divided. The knowledge of spectrum of life cycle of weeds is of immense use towards recommending their control measures. **i) Annual weeds :** weeds, which usually germinate, grow and produce seeds within a season/year and then die-up are called annual weeds. Annual weeds usually do not take more than a season to complete their life cycle under Indian (sub-tropical) field situation. For example, *Galinsoga parviflora, Amaranthus viridis/retroflexus, Bidens pilosa, Trianthema portulacastrum, Chenopodium album/murale*, *Solanum nigrum, Digera arvensis, Melilotus indica/alba*, *Argemone mexicana*, *Parthenium hysterophorus, Phalaris minor, Avena fatua/ludoviciana*. They may be summer season, rainy/wet season and winter season annuals. **ii) Biennial weeds :** weeds, which complete their life cycle in two seasons/years and normally live more than one but less than two seasons/years are biennial weeds. They form rosette and remain vegetative in the first season/year and produce flowers and set seeds in the second season/year. Some biennial weeds are *Daucus carota* (wild carrot), *Tribulus terrestris* (puncture vine), *Cichorium intybus* (chicory), *Cirsium vulgare* (bull thistle) and *Senecio jacobaea* (tansy ragwort). **iii) Perennial weeds :** weeds, which grow for more than two years before they wither away or die-up, are perennial weeds. They flower for the first time in the second year of their growth and then flower each year regularly and grow indefinitely from the same root system. They propagate mainly through vegetative means, although have sizable amount of seeds comparable with annuals. They may be simple herbaceous, creeping herbaceous or woody plants. Generally the control of perennial weeds is more difficult than the control of annual weeds. Many times even deep tillage cannot reach to the deep roots of perennials and dig out their perennating structures. Systemic herbicide even sometimes cannot reach to the roots and vegetative structures lying deeper in soil. They should be controlled in fallow or lean season with deep summer tillage combined with suitable systemic herbicide which can translocate all through the plant system and reach quickly to the under-ground perennating structures.

1.1 Seed characteristics/plant morphology

Based on seed characteristics/plant morphology, weeds have been classified from the viewpoint of weed control particularly by herbicides. **i) Monocotyledones/ monocot weeds :** Monocotyledones have seeds, which cannot be split into two halves. They are a) grasses and b) sedges with annual, biennial or perennial habits. **a) Grasses :** Several grass weeds are *Phalaris minor, Cynodon dactylon, Digitaria abyssinica* (=*scalarum*), *Digitaria sanguinalis/adscendens, Polypogon monspeliensis, Avena fatua/ludoviciana/sterilis, Commelina sp, Cynotis sp*. **b) Sedges:** Sedges are mostly perennial except a few, for example, *Cyperus iria/difformis /compactus/compressus, Fimbristylis miliacea/ littoralis/ dichotoma/tenera, Scirpus supinus* var *lateriflorus*, which are annual. **ii) Dicotyledones/dicot weeds :** Dicotyledones have seeds, which can be splitted into two halves and may be annual, biennial or perennial. The majority weeds have broad and often toothed or divided leaves with netted venation. They have distinct petioles and blades and may be arranged in basal rosettes or along the stem singly, in pairs or rarely in whorls. For example, *Amaranthus viridis/ retroflexus /hybridus/spinosus, Bidens pilosa, Galinsoga parviflora, Trianthema portulacastrum /monogyna, Chenopodium album/murale, Rumex dentatus/ crispus/ obtusifolius/acetosella, Solanum nigrum, Digera arvensis, Tribulus terestris, Melilotus indica/alba/parviflora, Argemone mexicana, Sonchus oleraceous/ arvensis, Parthenium hysterophorus* etc.

1.2 Crop-weed association

Some weeds remain associated with certain crops. They have seasonal-biasedness and/or crop-biasedness. Crop microclimate also plays role towards species-wise weed distribution and overall abundance, growth and competition of weeds. Usually in crop field, annual weeds pose major competition because of their quick multiplication through seeds from soil and initial rapid growth and vigour. Although a good pre-emergence herbicide can take care of them to a great extent, periodicity of their germination (repeated flushes of germination) by virtue of variable dormancy in their seeds many a time nullifies/defies this measure and additional/extra control measures are required to be adopted/followed. Many annual grass and broad-leaved weeds except some grassy weeds having similar growth pattern with graminaceous cereal and millet crops, complete their life cycle well ahead of crop maturity and subside. But, certain perennials such as *Cyperus rotundus* remains consistent enough in growth for a longer period than annuals, sometimes up to crop maturity and poses similar competition as that of annual weeds if it had a sizable population close or similar to that of composite culture of annual weeds. The degree of competition, however, varies across crops. Their competition in one-one situation remains as bad as that offered by composite culture of annual weeds, which infest invariably every crop. Continuous application of pre-emergence herbicides in crops alters annual-perennial balance in favour of perennial weeds, which being not controlled by pre-emergence herbicides becomes rampant in crop fields. Notwithstanding, annual weeds offer the lion’s share of competition with crops in majority crop-field situations at the early part of crop growth and remain as the main dominating weeds constituted of composite flora of plants.

Based on their association with crops, weeds are classified as:

i) **Seasonal/Season-bound**, which grow in a specific season of the year irrespective of crop species grown (Figure 1). Majority season-bound weeds are annual in nature. Of course, perennials do come up and compete for their vegetative growth during a season, but reproductive stage may switch over to next season. In that case the period of their major vegetative growth is taken as their growing season. For example, *Sorghum halepense* is a summer perennial weed, whereas *Cirsium arvense* is a winter perennial one. Many seasonal annual weeds are also seen to grow in the transition period between seasons and certain degree of overlapping in their growth across the seasons takes place. However, this does not adequately support them to be designated as a different season weed. This may be visualized from their growth which remains somehow stunted and different when they grow in an unusual season of their growth. Thus seasonal weeds in our tropical climates are summer/*zaid*, rainy-season and winter weeds (Figure 1).

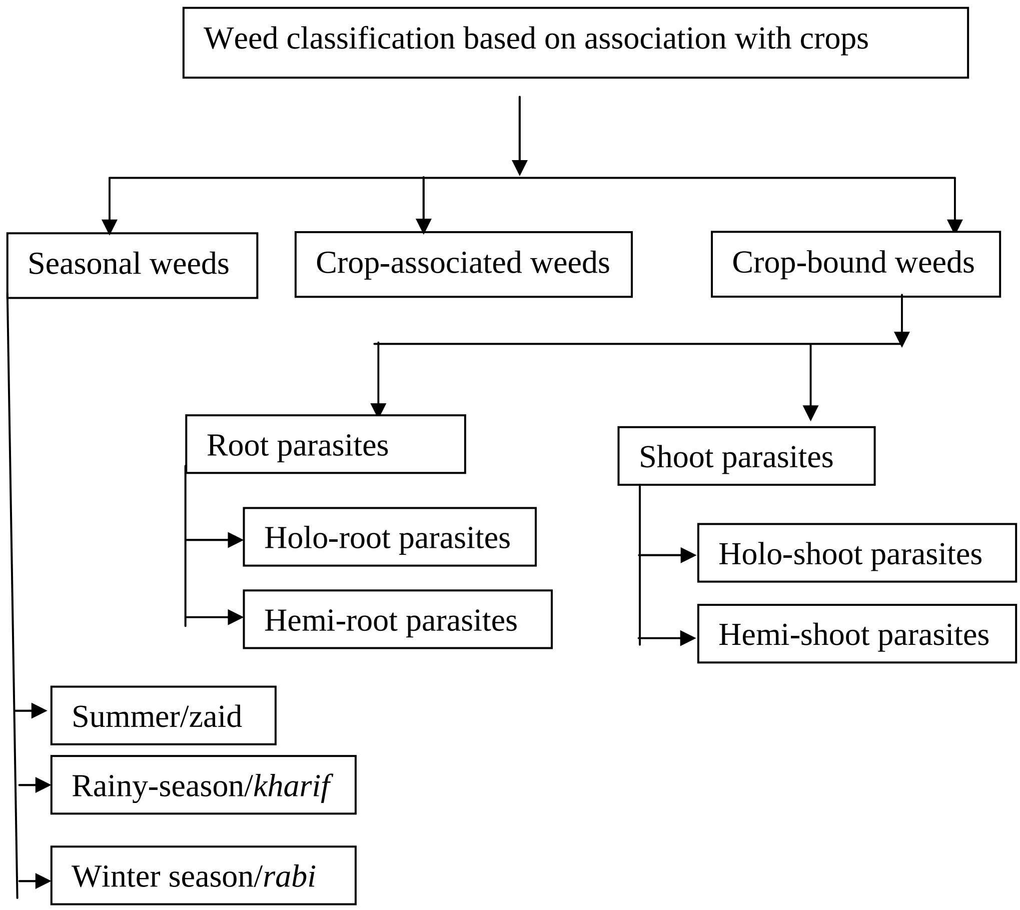

Fig. 1: Classification of weeds based on association with crops

ii) Crop-bound, which do not produce their own food by themselves and, therefore, necessarily parasitize partially or wholly a crop for their food and survival, e.g. *Cuscuta sp, Orobanche sp, Striga sp, Loranthus longiflorus, Cassytha filiformis*. They remain dependent upon crops and other wild hosts for food. Crop rotation can be of immense use against them, but longer viability in many parasitic weed seeds defies short-term crop rotation measure. Crop-bound weeds because of their large/huge species diversity also infest a large number of crops of economic importance. Unlike autotroph weeds, which affect the crops indirectly by removing nutrients, water from soil or competing with crop plants for space and light, the parasitic weeds affect crop growth directly by sharing/taking away food from the crops. They thus form a parasitic class of weeds based on nutritional habit or nature of competition and may again be classified (Figure 1) on the basis of parasitism on roots and shoots in the following ways :

Based on root-parasitism :

a) Total root/holo-root parasite : They take away food from the host-roots and do not have any other source of gathering food. Therefore, they are also called "obligate root-parasite." For example, *Orobanche sp* (on tobacco, tomato, fababean, chickpea, mustard, etc).

b) Partial root/hemi-root parasite : Initially they depend upon host-roots for their food and living (sub-terranean/under-ground stage in case of *Striga*), but later after emergence from soil, they are green, chlorophyllous and can produce their own food. For example, *Striga hermonthica/asiatica(=lutea*) on sorghum, maize and *Striga gesneroides* on cowpea.

Based on shoot/stem-parasitism :

a) Total stem/holo-stem parasite : They take away food from the host-shoot/stem and do not have any other source of gathering food. Therefore, they are also called "obligate shoot/stem-parasite." For example, *Cuscuta campesstris/chinensis/epilinum* (on alfalfa, niger and linseed, respectively). Earlier *Cuscuta* was the only parasitic genus of the autotrophic family *Convolvulaceae*. But now-a-days *Cuscutaceae*, a separate family has come into being for this genus.

b) Partial stem/hemi-stem parasite : Initially they depend upon the host-shoot/stem for their food, but later for becoming green and chlorophyllous, can produce their own food. For example, *Loranthus longiflorus* is a green colour plant (on mango and other trees) and *Cassytha filiformis* (on orange, eucalyptus and other trees). *Cassytha filiformis* has circumnutation anticlock-wise like *Cuscuta* but is much greener than *Cuscuta*.

iii) Crop-associated, which remain associated with certain crops like crop-bound weeds but do not parasitize the crop plants. Crop-bound weeds and crop-associated weeds are recognized separately although both of them are crop-specific and may be trapped by a single crop rotation. Crop-associated weeds are not parasitic like crop-bound weeds, but there are certain reasons why they remain associated with certain crops, e.g. for specific microclimate requirement, weeds mimicking with crops (Figure 1&2). This basic/primary knowledge about weeds is highly necessary for suggesting herbicides or other weed control measures as applicable.

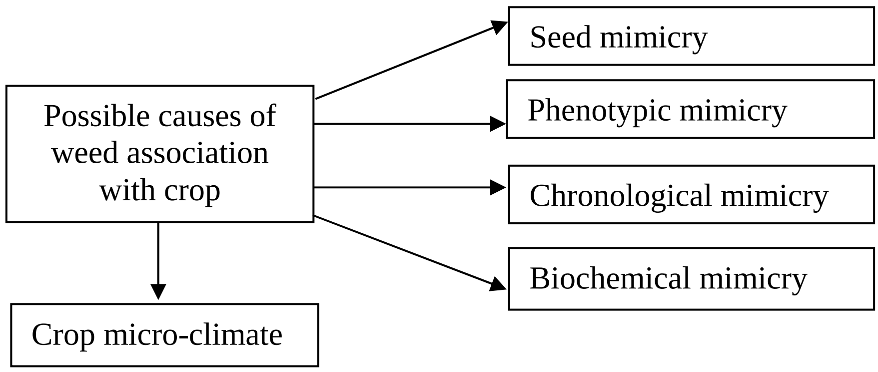

Fig.2: Possible causes of weed association with crops

a) Specific micro-climate requirement : Some weeds for their higher growth and survival, require shady, cool and moist habitat and therefore, they associate themselves where such situation available (Figure 2). *Cichorium intybus, Coronopus didymus* is associated with berseem and lucerne for the same reason.

b) Weed mimicry with crops : Mimicry in artificial system/arena could be defined as an art of pretending to be what an individual is really not. But in natural system, some plants pretend in various forms to maintain their survival and continue existence. Pitcher plant (Venus fly trap), sundew etc. cannot synthesize protein of their own and, therefore, pretend in some sorts to attract insects and extract protein out of their body. In crop fields too, some weeds mimick with crop plants in various forms to ascertain their existence and perpetuation with crops. Weeds may mimick with crops in the following four ways (Figure 2). **i) Vegetative/phenotypic mimicry :** Some weeds have similar morphology (leaf, stem) as that of the associated crop plant and therefore, it is difficult to identify and separate out them from crop plants until anthesis/inflorescence occurred. It is called "vegetative/ phenotypic mimicry" particularly at the seedling and early vegetative stage (Figure 2). As a result, they remain unweeded even by trained farmers/labourers and are harvested along with crops. For example, *Oryza sativa* var *fatua, Oryza longistaminata* (Wild rice), *Echinochloa colona/crus-galli* (jungle rice/barnyard grass) in rice, *Avena fatua/ludoviciana, Phalaris minor/paradoxa* in wheat, *Loranthus sp* in tea, *Saccharum spontaneum* (Wild cane) in sugarcane and *Sorghum halepense* (Wild sorghum) in sorghum. **ii) Seed mimicry :** These weeds have seeds similar in shape, size and even to some extent by weight to that of some crop seeds called "seed mimicry" (Figure 2). For example, seeds of *Lolium temulentum, Agrostemma githago* resemble wheat seed, *Avena fatua* seeds resemble cultivated oat seeds, *Commelina sativa* seeds resemble flax seeds, *Rottboellia cochinchinensis* (Itch grass) seeds resemble rice seed (upland) and *Cichorium intybus* seeds resemble berseem seeds. They are also called "satellite weeds." **iii) Chronological mimicry :** These weeds have height and ripening time similar to that of the crop plants associated called "chronological mimicry" (Figure 2). For example, *Phalaris minor/paradoxa* has almost similar maturity time with wheat crops and as a result, they are harvested along with crop and contaminate wheat grains. They are sown again with wheat in the next year. **iv) Biochemical mimicry :** A crop plant is normally tolerant to a herbicide selective to it. A weed associated with the crop although controlled by it may develop resistance to that herbicide through biochemical and physiological alterations/modifications on continuous exposure to it in course of time and behaves like the tolerant crop. As a result, that weed may remain associated with the crop as long as that herbicide or herbicide with similar mode of action continues to be applied in that crop. This is biochemical mimicry (Figure 2). This means that the weed which was earlier susceptible now mimicking the crop plants through biochemical means.

2. CONCEPTS OF WEED CONTROL/MANAGEMENT

Generally preventive/prophylactic and curative measures are two broad concepts/approaches of controlling pests and diseases. The curative measure applies methods to kill the pests or causal organisms and thus bring them under control. In weed science it may include control as well as eradication. Thus, prevention, control and eradication were used to be used as three basic concepts of weed control earlier. However, management as another concept has been a fore-runner among weed control/management concepts/approaches in recent years and considered to be the most desired approach/concept of weed control/management in modern era. Thus control/management of weeds has several facets/ aspects such as mechanical & manual, cultural/ ecological/cropping & competition, biological, chemical and allelopathy (Figure 3). Zimdahl (1999) reported that weed prevention, control, eradication and management are different concepts and each uses or combines technologies differently.

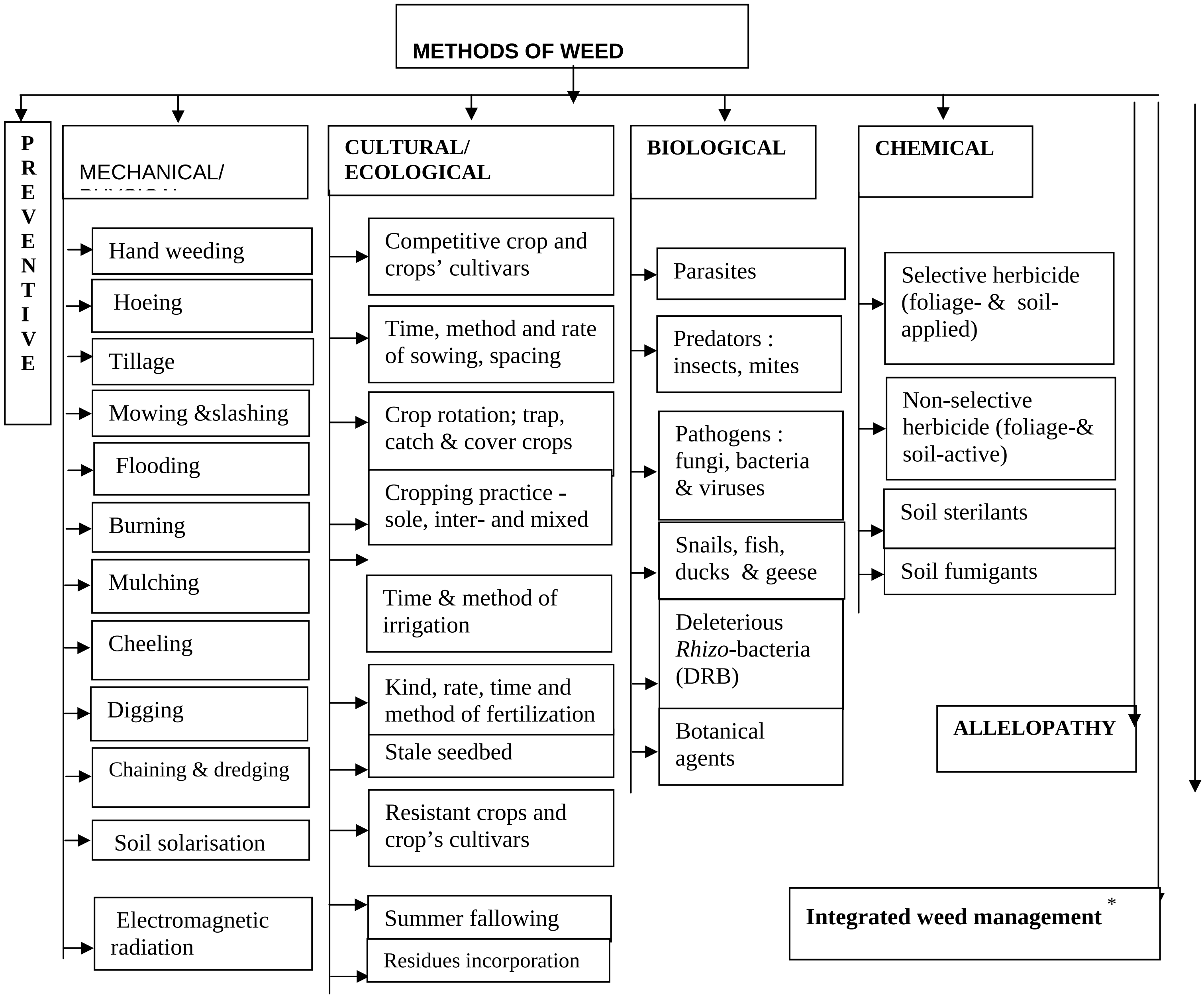

Fig. 3. Methods of weed control/management (*Integrated weed management although considered as a method of weed management, is basically a concept behind weed management, or in other words, "a method of methods," which put together two or more methods, e.g. preventive, physical, cultural, biological, chemical, allelopathy in mutual and compatible way to work better and more efficiently towards weed management)

2.1 PREVENTION

Prevention is a concept as well as a method of weed control/management. The popular saying, “prevention is better than cure” of Medical Science could be bit modified to “prevention is better than intervention” in Weed Science. First prevention means stopping weeds from infesting an area. It advocates not permitting a weed alien to an area (which is not yet infested with it) to come/enter into and infest that area. The area could be of any dimension, a block, a district, a state or a country. However, the success of weed prevention decreases *vis-à-vis* difficulty in achieving it increases if the size of area increases. In true sense, it was earlier envisaged/ intended towards prevention of exotic weeds. Secondly, in crop field situation, prevention highlights on the aspects how best the seed reservoir/bank could be exhausted, *albeit* complete exhaustion is a rare possibility. In this situation, preventing weeds to emerge from soil and grow vigorously and/or preventing existing weeds to come to seeds, tubers, rhizomes or other propagules for dissemination are considered to be preventive approaches. The weed control/management measure adopted last year, in fact, may be a preventive approach for the coming year. Even certain cultural practices/methods such as stale seedbed; competitive crop & cultivar; time, method & rate of sowing; spacing; irrigation; time, method & rate of fertilization; intercropping; crop rotation; cover crops; etc have bearing towards reducing growth and seed production of weeds. Thus prevention requires a set of practices rather than a single practice to tackle the introduction and spread of weeds. Their individual effect is small, but the impact is enormous when the very/same practices followed together for a long period under certain situation.

Impact assessment/quantification of prevention approach should focus on the combined effects of all practices adopted together rather than that of a single practice. In certain agro-ecosystems/crop field situation, a single option of prevention not attended may mar the effect of all other practices carefully attended towards prevention. This makes impact analysis on quantitative term difficult and prevention a more qualitative aspect. The measures/options normally suggested towards prevention of weeds seem to be simple and easy, but difficult to execute/follow and achieve the result compared with control. They individually incur costs less than or similar with several control options. However, weed prevention as a whole (considering a combined effect of all options) is a more difficult task to achieve than control.

2.1.1 Preventive measures/methods

The preventive measures (Figure 3) usually do not offer remedy over the already existing population and diversity of weeds in the crop fields, but they focus on the prevention of further introduction of weeds from different external sources/agents as well as perpetuation of weeds in the forth-coming years from the existing stands of weeds in crop fields. Therefore, an understanding of the mechanisms of reproduction and survival of weeds as well as the agents for their dispersal constitutes the very basis of preventive measure. Accordingly the success of preventive measure lies on the biology, reproduction and dissemination behaviour of weeds and how rigorous a measure is adopted to prevent the spread of weeds. Several weed prevention measures usually discussed in the text books of weed science include only the curtailment of sources from which weed seeds get accumulated in soil over the years and enrich soil seed bank and makes weed control process a never ending one. They make weed control measures adopted every year useful for a short period and, therefore, repetitive on time scale.

i) Pure and clean crop seeds and seed certification

Always use pure and clean crop seeds, which do not add seeds of the existing or new weed species to the soil seed bank. It acts as an insurance/check against increasing weed (both existing and new weeds) problem in the long run. It reduces seed rain and further dissemination of weeds. Seeds should be certified and purchased from some authentic sources. The local market seed should be neglected or must be cleaned properly before sowing. Separation can be made using physical differences among seeds such as shape, size, colour, weight, texture, electrical properties) or by using air-screen cleaner, specific gravity separator (differentiating seeds based on size, shape, surface area, specific gravity). Weed seeds thus separated should be burnt and in no case put into soil, manure pits or animal feed. The effect of unclean crop seeds towards weed population build-up may not be visualized immediately, but its cumulative effect over the years may be enormous (Table 1). In wheat, seed rate being normally 100 kg/ha, an admixture by weed seeds to the level of 1% as sometimes recommended for certified certain crop seeds, will put exactly 1 kg weed seed in one hectare. Rezene (1984, 1985) reported that increasing weed problem of maize is mainly due to impure maize seeds being purchased from local market and sown in the field without cleaning. In India, *Phalaris minor* contamination to the tune of 3-4 g per kg of wheat seed has been observed in the market available wheat seeds. *Phalaris* problem cropped up gradually because of admixture since mid-sixties when Mexican dwarf varieties of wheat carrying *Phalaris* seeds were introduced in India. Therefore, use of certified seeds (Table 2) which have certain standard should be propagated among farmers (Agrawal, 1995; Jaya Kumar and Jagannathan, 2003). Seed certification is vested with the Central and States Government who control the agencies entrusted with seed certification. In India National Seed Corporation (NSC) has been given the responsibilities of certifying seeds produced by its approved growers. Certain weed species have been designated as objectionable (a noxious weed whose seed separation is difficult once mixed with crop seeds) under the Indian Seed Act, 1966 and their maximum permissible limits and the permissible limits of total (composite) weed seeds in foundation and certified seeds of crops have been assigned (Table 2).

Table 1. Impurity of farmer's crop seed from different sources (Bengtsson, 1983)

Crop	Other crop seed (%)	Weed seed (%)	Inert matter (%)	Weed seed (No./kg crop seed)	
				Avena sp	*Lolium sp*
Wheat	0.6	1.4	0.8	84	439
Barley	0.6	1.3	1.9	800	692
Teff	0.0	2.1	0.3	103	118
Broad bean	0.2	0.7	0.0	0	0
Field pea	0.8	1.2	0.6	247	139
Linseed	0.2	5.6	4.1	276	691

Table 2. Some objectionable weed species and crops with which associated and their maximum permissible limits and total weed seed permissible limits in the foundation and certified seeds of crops

SN	Crops	Objectionable weeds as applicable	Permissible weed seed admixture limits			
			Objectionable weeds **(no./kg)**		Total weeds **(no./kg)**	
			Foundation seed	Certified seed	Foundation seed	Certified seed
1.	Rice	Wild rice or red rice (*Oryza sativa* var *fatua*)	2	5 or 0.01(%)	10	20 or 0.1(%)
2.	Wheat	Field bind weed (*Convolvulus arvensis*) or littleseed canarygrass (*Phalaris minor*)	2	5 or 0.01(%)	10	20 or 0.1(%)

SN	Crops	Objectionable weeds as applicable	Permissible weed seed admixture limits			
			Objectionable weeds **(no./kg)**		Total weeds **(no./kg)**	
			Foundation seed	Certified seed	Foundation seed	Certified seed
3.	Barley	---	--	--	10	20
4.	Oat	Wild oat (*Avena fatua/ludoviciana*)	2	5	10	20
5.	Maize	---	None	None	None	None
6.	Sorghum	---	--	--	5	10
7.	Pearl millet	---	--	--	10	20
8.	Black gram	---	--	--	5	--
9.	Green gram	---	--	--	--	10
10.	Gram/chick pea	---	--	--	None	None
11.	Grass pea	---	--	--	5	10
12.	Lentil	---	--	--	10	20
13.	Pigeon pea	---	--	--	--	10
14.	French bean, peas, groundnut	---	--	--	None	None
15.	Mustard, rapeseed, taramira	Mexican poppy (*Argemone mexicana*)	5	10 or 0.1(%)	10	20 or 0.5(%)
16.	Soybean	---	--	--	5	10
17.	Sunflower	Wild sunflower	None	None	5	10
18.	Linseed	---	--	--	5	10
19.	Niger	---	--	--	10	20
20.	Safflower	Wild safflower	None	None	5	10
21.	Sesame	---	--	--	10	20
22.	Cotton	---	--	--	5	10
23.	Jute	---	--	--	10	20
24.	Egyptian clover/ berseem	Chicory (*Cichorium intybus*)	5	10 or 0.05 (%)	10	20 or 0.5(%)
25.	Lucerne/alfalfa	Dodder (*Cuscuta spp*)	5	10 or 0.05 (%)	10	20 or 0.5(%)
26.	Fenugreek	White sweet clover (*Melilotus alba*)	2	5 or 0.1(%)	10	20 or 0.2(%)
27.	Lettuce	Wild lettuce (*Lactuca serriola*)	2	5 or 0.1(%)	5	10 or 0.2(%)
28.	Cucurbit	Wild cucurbit (*Cucurbita spp*)	None	None	None	None
29.	Amaranth	Wild amaranth	5	10	10	20
30.	Lady's finger/okra	Wild lady's finger/okra (*Abelmoschus spp*)	None	None	None	None
31.	Potato (TPS)	---	--	--	--	10

Source : Agrawal, 1995 and Jaya Kumar & Jagannathan, 2003 compiled by the Author

ii) Stale seed bed

Stale seedbed technique is a cultural-cum-preventive measure. It is cultural from the point of view of pre-sowing 2-3 tillage invariably adopted by farmers since long time to prepare a good seed bed and to control early flushes of weeds. It is preventive from the view-point of its effect, which exhausts soil seed bank and early flushes of weeds (discussed under cultural methods; **section 3.3**).

iii) Well-decomposed farm yard manure (FYM)/compost

Fresh or undecomposed farm yard manure/compost is a source through which weed seeds are added to soil. Therefore, it should be always well-decomposed/well-rotten and free from weed seeds. However, it is very difficult and time consuming to ascertain a well-decomposed FYM free from weed seeds. Even a well-decomposed FYM may contain viable weed seeds undecayed, half-decayed or at various stages of decomposition. The only way for making compost, FYM free from viable weed seeds is fermentation. The cattle and other livestock also cannot completely digest the weed seeds and pass viable weed seeds along with the dung (Table 3). Therefore, fodder/forage containing enough weed seeds should be properly cooked or ensiled before given for feeding. Harmon and Keim (1934) observed that most weed seeds became non-viable within one month of storage in cow manure due to heating and decomposition. However, some weed seeds, namely *Abutilon theophrasti* Medic, *Convolvulus arvensis*, *Melilotus sp* showed some viability, 2%, 4% and 22%, respectively even after storage in cow manure for one month. In the wake of organic farming, the use of organic matter cannot be stopped rather the fermentation process needs to be improved or other superior methods of composting explored.

Table 3. Percentage of viable weed seeds passed by animals based upon total number of seeds fed (Harmon and Keim, 1934)

Sl. No.	Weed seeds	Percentage of viable seeds passed by					Mean
		Calves	Horse	Sheep	Hogs	Chickens	
1.	***Convolvulus arvensis (Field bind weed)***	22.3	6.2	9.0	21.0	0.0	11.7
2.	*Melilotus sp* (Sweet clover)	13.7	14.9	5.4	16.1	0.0	10.0
3.	*Lepidium virginicum* (Virginia pepperweed)	5.4	19.8	8.4	3.1	0.0	7.3
4.	***Abutilon theophrasti (Velvet leaf)***	11.3	4.6	5.7	10.3	1.2	6.6
5.	*Rumex altissimus* (Smooth dock)	4.5	6.5	7.4	2.2	0.0	4.1
6.	*Polygonum pensylvanicum* (Pennsylvania smartweed)	0.3	0.4	2.3	0.0	0.0	0.6
Mean		9.6	8.7	6.4	8.8	0.2	6.7

iv) Clean farm machineries and farm animals

The farm machineries like tillage and harvest implements are another source from which weed seeds get into crop field. They should be cleaned properly and the soil sticking/adhered to the implements particularly ploughs, tractors must be removed before it is carried to another field. Accordingly similar treatment may be given to the farm animals since several weed seeds adhere/entangle with the furs and skins of animals by means of some hook like structures and disperse. These are very small efforts towards weed prevention and have hardly been ever evaluated or quantified.

v) Clean irrigation channels and water or alternative irrigation method/system

Irrigation water carries soil and weed seeds to a crop field. Some sub-surface (drip) and over-head (sprinkler) irrigation systems may be installed as per feasibility and applicability in crops, soil and climatic conditions. Also equally important are the irrigation channels, which should be kept clean and weed free. Weedy irrigation channels, apart from dispersal of weeds, cause choking/plugging and wastage of valuable water. Irrigation water also needs to be clean or treated.

vi) Clean farm bunds, roadsides, fences and other non-crop areas

Weeds on farm bunds, paths/roads and fences should be controlled occasionally always before they go for flowering to avoid weed perpetuation in the field. Similarly weeds not controlled by measures adopted should be removed from the field before they flowered.

vii) Sand, soil from an infested area should not be transported and used to a clean or cultivated area.

viii) While up-rooting crop seedlings, weed seedlings up-rooted may be removed before crop seedlings are taken to main field. In transplanted crops like vegetables, rice, this may be an important mechanism of spread of weeds. Otherwise, weed control has to be exercised in the nursery.

ix) Weed/plant quarantine laws

An enactment is always required to check movement of noxious and pernicious weeds such as *Striga sp, Orobanche sp, Parthenium hysterophorus, Eichhornia crassipes, Chromolaena (=Eupatorium) odoratum, Salvinia molesta, Lantana camara* etc. It could be both inter-state and inter-country movement. Weed law prevents dissemination by manual, physical or mechanical ways of weed species in general and noxious weeds in particular across regions, states or countries. It also prevents farmers from using mislabelled or contaminated crop seeds. Weed law exists only in Karnataka in India, which declares *Parthenium hysterophorus* as a noxious weed. It should be enacted across states and countries and should include most of the noxious weeds. Again noxious weeds can be prohibited ones (having seed as well as vegetative propagation and difficult to control) and restricted ones (objectionable in cropping areas but controlled).

Weed Quarantine Law enforces isolation of an area where a serious weed has established and prevents further movement of the weed into a non-infested area. To achieve this, import of weed seeds separately or as admixture with crop, should be prevented strictly. To enforce the laws, a number of quarantine stations across the length and breadth of a country requires be operational in places from which possible entry of weeds through food grains, feed and other means is apprehended. Airports for prevention of inter-country/inter-continental movement and rail stations, bus stops, for checking the intra-country/inter-state movement of weed seeds should have a strong regulatory authority of which at least a member should be weed scientist, preferably weed biologist. All noxious weeds of the world should be identified and enlisted before declaring weed laws.

Similarly Plant Quarantine (Regulation of Import into India) Order was enacted/issued in 2003 and till June 28, 2006 nine Amendments have been incorporated into it. This imposes regulation on the import of plants, plant products, soil, earth, clay, compost, sand, peat, sphagnum moss, germplasm, transgenics or genetically modified organisms, live insects, microbial cultures, wood or timber. No consignment of plants and plant products such as seeds of coarse cereals, pulses, oilseeds and fodder seeds and seeds/stock materials of fruit plants for propagation, if found infested or infected with a quarantine pest or contaminated with noxious weed seeds shall be permitted to be imported. Pest risk analysis (PRA) and fumigation towards disinfection/ disinfestation as applicable will be pursued well before shipment of the product or in certain cases before unloading the materials in India. The order/law if functions properly may prevent entry of exotic weeds including noxious and invasive weed species into India in future.

2.2 ERADICATION

Eradication means complete elimination or removal of all live weeds/wild plants/plants including their seeds and vegetative propagules from certain area. It is taken to the belief that once a weed is eradicated from an area, it will not reappear unless introduced. Eradication is very difficult to achieve or hardly achieved in terms of complete exhaustion of seed bank and vegetative propagules of weeds from soil. On the contrary, very high dose of soil sterilants and fumigants applied for the sake of eradication unnecessarily leads to soil and water pollution. That's why it is not or rarely desirable and its adoption is discouraged now-a-days on the ground of high cost, difficulty in accomplishment and for urges in maintaining bio-diversity for pest management in crop fields.

Eradication brings about temporary or long sterilization effect of soil. Better it is advised to apply/try in small areas such as vegetable and rice nurseries, flower beds and in industrial and factory premises, where immediate residue may not likely cause hazard. Eradication may lead to more soil erosion from the treated area. Therefore, management of weeds to certain extent rather than their eradication is advocated and exercised. However, it may be adopted in certain crop fields if the reasons are justified, e.g. for perennial (*Cyperus rotundus, Cynodon dactylon, Convolvulus arvensis, Cirsium arvense* etc.) and parasitic weed control in some arable lands and noxious and invasive weed control in non-crop situations. Its adoption is justifiable around oil refineries, industrial and factory premises, housing complexes and railway tracts for fear of fire hazards from the existing/growing weeds. Eradication may also be adopted in and around farm yards where harvested farm produces are kept for threshing and further processing. For eradication programme, whatever chemicals opted should be non-selective and should act through soil since soil needs to be sterilized. Several soil sterilants, e.g. methyl bromide, metham, EPTC, $NaClO_3$, chloropicrin (tear gas) and dazomet (DMTT) are recommended for the purpose. They are of course out-dated and their rate of application is very high. Therefore, certain triazines (e.g. simazine, atrazine), phenylureas (e.g. linuron, diuron) or even phenoxyalkanoic acids (e.g. 2,4,5-T but banned in India) may be used for the purpose, but the dose should be much higher than recommended for usual weed control in the crop fields. For example, in crop field, simazine (triazines) is used @ 1.0-2.0 kg/ha depending on soil type, soil pH and organic matter content, but the same as a soil sterilant, may be used as high as 40 kg/ha or more on pathways, roadsides, fence lines, industrial and factory premises and other non-crop areas.

2.3 CONTROL

Earlier there used to be spoken of three major concepts, *viz*., prevention, eradication and control of weeds. People did not think much about management of weeds. They use to use "control" to mean control of weeds and definitely not to mean management of weeds. Unlike weed prevention, control is exercised normally after the weed problem arises/exists (Zimdahl, 1999) or known to users from previous history of weed infestation in a certain area/crop field. Control is easier to practise than prevention and eradication and can be put/made to work well with short-term economic or cultural planning goals. However, prevention and eradication require long-term thinking and planning. That is why weed control options have been adopted widely among people. The methods/tools, severity of weed infestation in terms of population, species diversity and age/stage of growth, production systems and capital invested greatly affect the degree/level of weed control achieved in a farm. Generally when a single option/method is exercised towards control of pests/weeds, it is more a control than management aspect of pests/weeds. Employing one single method, e.g. herbicide, managing a weed population to the desired density or economic threshold level is hardly/rarely possible unless other options tried or exercised. Sometimes a pesticide/herbicide may even kill pests/weeds to the level of 100 per cent, which assumes to be as good as eradication. Therefore, for management necessarily more than one or several options/methods should be tried to bring down weed population below economic threshold value. Thus control remained as an old concept and in recent years it has got a different connotation, e.g. management. Management has become more popular because it has some significant bearing over control in terms of maintaining bio-diversity and for preventing sudden insurgence of other pests/weeds etc. However, control still bears significance when many farmers use only herbicide to control weeds in crops. For example, to control *Phalaris minor* or *Avena ludoviciana* in wheat, farmers resort mainly to herbicides in north-western wheat belt of the country. We talk of management of weeds much, management is hardly executed.

2.4 MANAGEMENT

Gradual change in the concept of weed control has taken place in the world in phased manner. Emphasis has gradually shifted from eradication to control and recently from control to management of weeds particularly under crop-field agro-ecosystems. However, "control" remains implicit in "management." Management means to maintain/manage a population below a threshold level. Behind management, the principle is that let all pests be present, but under certain control. To exercise management, one has to exercise control over pest population so that it does not multiply to such a density which would be damaging to crop plants and incur considerable loss in yield. Thus management is necessarily a control *plus*, which includes control plus certain other options to manage pests/weeds. Also management is wider than control and cannot be synonymous with control. Therefore, management is more complex and difficult to achieve than control and they differ in philosophy behind coining them.

3. METHODS OF WEED CONTROL/MANAGEMENT

3.1 PREVENTIVE MEASURES/METHODS (discussed in section 2.1.1)

3.2 PHYSICAL (MANUAL AND MECHANICAL) METHODS

i) Hand pulling/hand weeding

Hand weeding (Figure 3) effectively controls annual weeds having erect and upright growth, while weeds growing prostrate, rosette and horizontal get frequently cut/torn off at the base/soil surface on pulling by hands and may rejuvenate/regenerate from tap roots left inside the soil. Therefore, manual labourers use small implements, e.g. khurpi, to remove them along with roots and thus it could be both mechanical as well as manual in nature. This loosens soil surrounding the crop rhizosphere and enhances crop growth and yield. However, hand weeding is time-consuming, labour-intensive, back-breaking and often costlier than

chemical method. Hand weeding at the later growth stages of crop does not provide much benefit rather it inflicts/encourages damage to crops, for example, lodging, breakage of stalk/stem and branches, tearing of leaves.

ii) Hand hoeing

Hand hoeing is a post-planting intercultural operation, faster and require less manpower than hand weeding. It is effective more against annual weeds than against perennial weeds since it cannot control under-ground vegetative structures of the perennial weeds. Line sowing is a pre-requisite for it. It may leave unweeded some weeds growing within crop rows. Hoeing, however, should not be adopted late, which may equally damage weeds and crop plants both.

iii) Tillage

Tillage is the manipulation of soil with tools and implements for loosening the surface crust and bringing about conditions favourable for the germination of seeds and growth of crops (Figure 3). It includes both primary (disc plough, mouldboard plough etc.) and secondary tillage (cultivator, disc harrow etc.) which have different objectives and usually primary tillage is followed by secondary tillage to bring about a fine tilth. The main objectives of tillage are to provide a good seed bed and a root bed for smooth germination and better root growth and subsequent rapid seedling establishment and to reduce/control initial flushes of weeds by means of exhausting weed seed bank. It also reduces population of perennial weeds by exhausting food reserves of the vegetative structures/propagules. Tillage brings about alterations in the physical, chemical and biological properties of soil and thus, it favours crop growth and influences competition behaviour. Frequent tillage encourages proliferation and perpetuation of annual weeds more, whereas no/zero-tilled fallow land experiences more perennial weeds. Generally shallow and frequent pre-sowing tillage followed by irrigation is highly useful for controlling annual weeds (Das and Yaduraju, 2001), whereas deep tillage during the hot summer months is beneficial for the control of perennial weeds like *Cyperus sp, Cynodon dactylon* etc. Deep summer tillage also reduces disease and insect pest problem by exposing them to the sun.

iv) Mowing and slashing

The concept behind mowing and slashing is prevention of weed seed production and dissemination through concurrent control of the existing weeds or wild vegetation (mainly their top/tall growth) usually under non-crop situations such as canal bunds, farm roads, parks and lawns. Thus controlling existing weed/wild vegetation is the cause and prevention of weed seed production and dissemination is effect and this makes mowing and slashing mechanical/physical-cum-preventive measures. In fact, in this spirit, all options exercised to control weeds have inherent weed prevention aspect. Mowing and slashing should be carried out before weeds start setting seeds. They are more useful for controlling annual weeds than perennial weeds since they cut mainly tall growth of weeds and horizontal, prostrate and under-ground growth remain usually uncontrolled. Mowing by sickle mower, rotary mower is also recommended for weed control in widely spaced fruits and plantation crops.

v) Flooding

Flooding creates anaerobic condition, which prevents weed seed germination and root respiration of already germinated weeds and kills plants by reducing oxygen supply for growth. The growing habit and nature of weeds may also be exploited for their control by flooding. For example, *Alhagi camelorum*, a xerophyte cannot grow and tolerate flooding and, therefore, it is likely to be controlled if flooded. *Convolvulus arvensis* (field bind weed) is killed by flooding in rice. It could be followed if cost economics permits. In rice, greater the depth of flooding, lower is the weed infestation. Standing water 3-10 cm immediately after transplanting for 30 days and 10-20 cm for 20-25 days after direct-sown rice reached the seedling stage are useful for controlling weeds. However, weed species differ in their tolerance to flooding (Table 4). Maintaining required depth of water is equally difficult and cost-incurring.

Table 4. Germination of weed seeds after storage in fresh water (Bruns and Rasmussen, 1953, 1957 & 1958)

Sl.No.	Weed species	Duration of storage and germination
1.	*Convolvulus arvensis* (Field bind weed)	After 54 months, 55 % germinated
2.	*Cirsium arvense* (Canada thistle)	After 36 months, about 50 % germinated
		After 54 months, none germinated
3.	*Amaranthus retroflexus* (Redroot pigweed)	After 33 months, 9 % still sprouted
4.	*Agropyron repens* (Quack grass)	After 27 months, none sprouted
5.	*Echinochloa crus-galli* (Barnyard grass)	After 2 months, less than 5 % germinated
		After 3 months, less than 1% germinated
		After 12 months, none germinated
6.	*Cardaria draba* (L.) Desv. (Hoary cress)	After 2 months, germination dropped to 5% or less
		After 19 months, none germinated
7.	Russian knapweed	After 30 months, 14% of seeds still sound
		After 5 years, none germinated
8.	*Halogeton glomeratus* (M. Bieb)C.A.Meyer (Halogeton)	After 3 months, less than 1% germinated
		After 12 months, none germinated

vi) Burning, flaming and heating

Burning/fire, flaming and heating work on the principle/concept of both control/management and prevention of weeds or wild plants. Burning is practised mainly under non-crop situation towards non-selective control of weeds or unwanted vegetation. It could be an economical and practical means. It also destroys weed seeds along with insect pests and diseases. Flaming, on the contrary, could be used both selectively and non-selectively. Flame is directed towards the ground and injury to crops is avoided. Crop plants can withstand heat of the burner, whereas small succulent weeds cannot. Flaming causes rupture of the weed cells rather than combustion of plants. The effect of flaming is visualized after few hours of treatment. Row planting is necessary for its selective adoption in crops. Crop plants should be taller than weeds. It has been used successfully for selective weed control in alfalfa, cotton, sugarcane and soybean.

Heating soil through solarization or residue burning is another aspect for weed control in crops in recent years. It may be executed before sowing of crops. It, however, warrants soil disturbance of any kind. Due to burning, a particular stratum of soil gets burnt/ sterilized and weed seeds of that stratum are likely destroyed. Therefore, any kind of soil stirring may disturb this stratum and bring sub-soil carrying weed seeds up. Heating through soil solarization has been discussed later separately.

vii) Cheeling and digging

Cheeling simply means cutting and scraping of the top growth of weeds by the cheel hoe at the soil surface. Digging in small scale may be carried out to remove the under-ground vegetative structures from the deeper layer of soil if found perennial weeds really problematic in certain area. It is highly labour-intensive, cost-incuring and time-consuming method. It may not be feasible for a large area. It is not at all advocated for the control of annual weeds.

viii) Chaining and dredging

Chaining and dredging are obsolete control measures for aquatic weeds. Herbicide has replaced them. Chaining means pulling a heavy chain through the bottom of a ditch by two tractors moving on either bank of the ditch. The heavy chain, by its rubbing action cuts and up-roots the aquatic weeds, which later floats on the surface and gets collected down the stream by nets and hooks. Dredging, on the contrary, is the mechanical pulling of weeds along with their shallow roots and rhizomes covered in mud. It is adopted to remove sub-merged and emerged aquatic weeds.

ix) Mulching

Mulching (Figure 3) may broadly be categorized into i) live mulch (cover crop, inter-crop, green manure crop, etc) and ii) dead mulch. Dead mulch could be a) organic mulches such as i) residue mulch (dry residues of plants/crops, e.g. straw/stover, groundnut shells, sawdust, grass clippings, bark from treads, etc.), ii) organic matter mulch, e.g. compost, FYM; b) synthetic mulch, e.g. polyethene film, polyester sheet, latex and starch resin spray mulches; c) soil mulch (no material put to the surface, but few centimeters of surface is disturbed mainly to prevent capillary evaporation in dry semi-arid areas). Dead mulch may be applied before and after crop sown. If it is adopted simultaneously/concurrently with crops, line sowing preferably in wider row-space is a pre-requisite. It cannot be practised in broadcast crop. Mulching is best-suited to wide-row field crops, e.g. cotton, sugarcane, maize, fruit crops, e.g. citrus, banana, grape and plantation crops, e.g. tea, coffee, rubber etc.

Almost all mulches except polyethene film are bad conductors of heat. They get heated up on receiving short-wave solar radiation, but transmission or conduction of heat is very less. They prevent sunlight from reaching to soil covered by it and to germinating weeds, whose photosynthesis inhibited causing them to die. They also provide an effective barrier to weed emergence. Even the germinated weeds, find it difficult to penetrate the thick layer of mulch. Mulching is very effective against most annual weeds and some perennial weeds such as *Cynodon dactylon*, *Sorghum halepense*.

x) Soil solarization

The basic principle/phenomenon behind soil solarization is that light received from the sun is in the form of electromagnetic short waves, which easily pass through the transparent colourless polyethene films and reach to soil. As a result, earth/soil is heated up and emits long-wave terrestrial radiation, which, however, cannot pass through transparent polyethene films and results in build-up or trapping of heat (Katan *et. al*., 1976; Yaduraju, 1997). A decrease in the heat loss of soil through evaporation and convection is the main cause of increase in soil temperature by transparent polyethene films. Water droplets formed on the inner surface, highly reduce the transmittance of transparent polyethene films to long-wave terrestrial radiation and induce increased green house effect. Air is a bad conductor of heat and, therefore, its insulation effect should be minimized or nil by laying plastic films very close to the soil. A good land preparation ensuring fine tilth and smooth and even surface of soil is a pre-requisite to reduce air spaces in between the polyethene film and soil for effective solarization. Surface soil temperature may increase up to 55-60^{O}C due to solarization during hot summer months (Kumar et. al., 1993), which proves lethal to many weed seeds and vegetative propagules, insects, nematodes and disease pathogens and causes them to die.

Solarization for a minimum period of 2 weeks during hot summer months (May and June in India) is sufficient to control weeds, but it may be continued to several weeks together for prolonged effect. It may control weeds in crops in the wet-season (*kharif*) as well as subsequently in the winter (*rabi*). It also controls soil-borne plant pathogens like *Fusarium, Verticillium, Pythium, Rhizoctonia, Sclerotium, Phytophthora* (Abdel Rahim et. al., 1988; AlMasoum et. al., 1998). Combination of solarization and herbicide, however, would be the best choice towards weed control (Yaduraju et. al., 1999). Among winter weeds, wild oat and *Phalaris* are effectively controlled, but *Cyperus sp* and *Melilotus sp* not. Thinner (25-50 μ thickness) and white transparent polyethenes are more effective than thicker (200-400μ) and black polyethenes. It is, however, a costly affair in field crops, which are usually not cash crops. It also, like herbicide, warrants any sort of disturbance/stirring of soil by tillage or other means once solarization has been undertaken.

3.3 CULTURAL/ECOLOGICAL METHODS

Fryer (1983) stated that a good crop is the best weed killer. Cultural/ecological methods (Figure 3) exploit crop's competitiveness, growing environment and management practices towards producing a good/healthy crop. Farmers should adopt a good crop husbandry, which results in or aims at boosting up of initial growth of crop and then crop itself would be equipped with enough competitive advantages against weeds.

i) Crop species

A crop must have initial vigorous growth to become more competitive against weeds. It should germinate and grow faster than weeds and form a closed plant stand and enough canopy coverage rapidly, which imposes shading effect and makes weeds gradually weaker in competition. Crops having good weed smothering ability should be opted for cultivation and a good smother crop has several other benefits/merits apart from weed control (Delorit and Ahlgren, 1967). Cowpea is more competitive with higher weed smothering capability than green gram or black gram. Similarly barley (Pavlychenko and Harrington, 1934; Pavlychenko, 1937; Bell and Nalewaja, 1968a, 1968b) is more competitive than wheat. Cousens *et. al.* (1991) observed that barley, against wild oats, was more competitive than wheat at Long Ashton (South-West England), but the reverse was true at Brooms Barn (eastern England).

Sorghum possesses allelochemical HCN (hydrocyanic acid) in shoot and foliages and allelopathic to *Abutilon theophrasti*, *Amaranthus hybridus*, *Setaria viridis, Bromus pectinatus* (Putnam, 1985), while in maize major source of allelochemicals is root exudates and maize is allelopathic to *Chenopodium album*, *Amaranthus retroflexus*. The allelochemicals add to their competition potential/behaviour with weeds. Cereals because of their tall stature prove more competitive against short-stature weeds (e.g. wheat more competitive to/against *Melilotus indica/alba, Spergula arvensis, Coronopus didymus, Fumaria parviflora, Polygonum plebeium, Oenothera biennis, Sisybrium irio* etc.; maize and sorghum against *Commelina benghalensis, Digera arvensis, Trianthema portulacastrum /monogyna* etc) than short-statured pulses and legumes and oilseeds. Similarly, Rao and Shetty (1981) observed pearl millet, maize and cowpea by virtue of their growing habit showed high weed smothering ability over other crops, namely pigeon pea and castor. Kolbe (1977) reported similar variation in the competitive ability of crops by virtue of their growing habit.

ii) Crop variety/cultivar

Crop cultivars too vary in their ability to compete with weeds, basically on the same principles as crop plants do. Sandhu *et. al.* (1981) reported that greater the height of a crop genotype, greater was weed suppression. Gill and Mehra (1981) also observed significant reduction in density, dry weight and height of *Phalaris minor, Chenopodium album* and

Melilotus indica in association with tall wheat genotype (C 306) compared to 3-gene dwarf variety (WL 1562). Greater competitive ability of WH 291 and HD 2285 than HD 2009 and S 308 against wild oat (*Avena ludoviciana* Dur.) was reported under late-sown condition (Balyan and Malik, 1990), whereas in normal sown wheat, WH 147 followed by WH 283 was more competitive to wild oats than rest of the varieties (Malik and Balyan, 1990). Pawar (1994) observed that a semi-dwarf variety of wheat, Kundan (HD 2285) performed better than C 306, a tall variety, under sub-optimal levels of irrigation and N and had an equal competitive ability to suppress weeds as that of C 306. In rice too, tall and dwarf cultivars showed a wide range of variation in their competitive abilities against weeds (Ghosh and Sarkar, 1975; Sarkar and Ghosh, 1977; Moody and De Datta, 1977). Under conditions of varying K (Siddiqi *et. al.*, 1985) and P (Konesky *et. al.*, 1989) availability, barley cultivars exhibited considerable difference in competitive ability with wild oats. Rao and Shetty (1976) observed that weed growth in compact genotype of pigeon pea (var. HY 34) was 37% higher than in spreading variety (ST 1).

ii) Sowing of Crop (Time, method and rate of sowing and row spacing)

Time of sowing of crops influences weed competition. If initial big flush of weeds germinating at one point of time is bypassed through manipulation of the time of sowing of a crop, a little earlier or later than its normal time of sowing, the crop may germinate and have initial growth under almost weed-free or less weedy environment. For example, weeds pose more competition when wheat is sown on October than on November or December (Kolar and Mehra, 1992). Similarly late planting of wheat in December than its normal sowing in mid November in North and North-western India reduces *Phalaris minor* problem (Yaduraju and Ahuja, 1992). Similarly maize, cotton sown 15 days before the onset of usual monsoon rains with pre-sowing irrigation proved beneficial towards reduction of weed competition.

Line sowing normally encounters less weed infestation and provides more ease of controlling them than broadcasting. In the summer season, furrow planting of crops is also useful for reducing weed growth. In wheat, FIRBS (furrow-irrigated raised bed system) is of recent introduction from CIMMYT, Mexico and has been found useful in reducing overall weed competition in wheat mainly on the raised bed, but the furrows get highly populated with weeds. *Cris-cross* sowing in wheat and transplanting in rice are other planting methods, which generally encounter less weed problem.

Seeding rate and per cent viability and germination of seeds usually determine crop density and normally higher the density of a crop, lower is weed competition and *vice-versa*. The crop density, however, cannot be increased arbitrarily and infinitely since every crop has an optimum population beyond which intra-specific competition among crop plants may begin. Also economics of increasing seed rate and benefit over weed competition reduction *vis-a-vis* crop yield enhancement are to be worked out. Increasing wheat plant density by reducing row spacing from 20 cm to 15 cm could reduce the dry weights of *Lolium* and *Phalaris* by 11.9% and 18.3%, respectively (Angiras and Sharma, 1993). Similarly an increase in wheat seed rate from 100 to 150 kg/ha was beneficial in higher *Phalaris minor* density plots since they recorded yield increase greater (10.5-16.9%) than in weed free situation (4.8-4.9%) (Duary, 1998). Similarly row spacing, for example, closer row-space reduces weed competition in crops. Rogers *et. al.* (1976) observed that for obtaining maximum yield of cotton planted in narrow row spacing of 53 cm, the period of weed control was 6 weeks, whereas the period of weed control was 14 weeks when cotton was planted in wider row spacing of 106 cm.

iii) Crop rotation

Crop rotation is considered as a "panacea" as for controlling several insect pests, diseases and weeds under crop field ecosystems so for maintaining soil health and sustained crop production. It is highly effective against parasitic weeds such as *Striga hermonthica/asiatica* (mainly in sorghum and maize), *Orobanche ramosa* (in *Brassicas* & solanaceous crops), *Orobanche cernua* (in tobacco), *Orobanche crenata* (in faba bean), *Cuscuta chinensis* (in alfalfa), *Cuscuta epilinum* (in linseed), *Cuscuta campestris* (in niger) (Parker, 1979b; Parker and Riches, 1993) and crop-associated weeds like *Avena ludoviciana/fatua* and *Phalaris minor* (in wheat), *Cichorium intybus* and *Coronopus didymus* (in Egyptian clover/berseem), *Echinochloa colona/crusgalli* (in rice) (Gupta, 1998). For example, mustard/gobhi sarson, vegetable pea, potato, Egyptian clover/berseem if adopted in sequence after rice during winter season, *Phalaris* problem could be reduced to a great extent in North-western wheat belt of India (Singh and Singh, 2006).

Trap and catch crops : Trap and catch crops should be included in crop rotation particularly for controlling parasitic weeds *Striga* and *Orobanche*. There is no trap or catch crop of *Cuscuta*. Trap crops are nothing but false hosts, which exude striga germination stimulants and induces striga seed germination, but after germination, striga may die-out for want/lack of attachment with the roots of a suitable host. This is called suicidal germination. Cotton, soybean, sunflower, cowpea, jute, pigeon pea, chick pea, kenaf and groundnut are trap crops for striga. Trap crops are usually not sacrificed but harvested as a crop. Catch crops, on the contrary, are parasitic weed-susceptible varieties of a crop or crops, which are grown and ploughed under/buried into soil prior to the flowering of parasitic weeds and sowing of a crop of principal interest. Normally a catch crop is sacrificed since it is ploughed under. To become successful, the temperature and moisture regime must be favourable to encourage striga germination when catch crop is present. Sudan grass (*Sorghum sudanense*) is a very effective catch crop and growing it just for 5 weeks before cutting and sowing sorghum in the stubble reduced the infestation of *Striga hermonthica* in East Africa so long as the growing conditions, especially moisture condition allowed the cultivation of Sudan grass and sorghum within one season (Last, 1961). Catch cropping, however, often faces problem of shortness of the growing season (Parker, 1979b).

iv) Cropping practice

Compton (1982) stated that an inter-cropping system to become efficient in terms of production and weed control, must balance the reduction in the economic value of principal crop against the economic value and weed control value of inter-crop. It is generally held that inter-cropping or mixed cropping is more remunerative than sole cropping under rainfed, unirrigated conditions, but under assured irrigation, sole crop may prove superior on yield output. Several inter-croppings like sugarcane + green gram/black gram, maize + soybean/black gram, sorghum + cowpea/desmodium, wheat + gram are reported beneficial towards weed control. Intercropping short-season crops (e.g. maize, melon) with longer-season crops (e.g. yam, cassava) prevents weeds from adapting to the growth cycle of either of the crops (Akobundu, 1978). Low-growing crops (melon, sweet potato) with maize, cassava and yam as inter-crops suppressed weed growth in Nigeria. Maize + green gram (Table 5) is also a useful combination (Bantilan and Harwood, 1973; Moody, 1973 &1979).

Table 5. Mean weed biomass (t/ha) growing in assoiation with sole-cropped and inter-cropped maize and mung bean (Bantilan and Harwood, 1973)

SNo.	*Treatments*	Mean weed biomass (t/ha) under sole cropping		Mean weed biomass (t/ha) under intercropping (maize + mung)
		MAIZE	Mung	
1.	Unweeded	2.06	0.85	0.28
2.	Inter-row cultivation	1.96	0.78	0.42
3.	Butachlor (0.6 kg/ha)	1.26	0.15	0.15
4.	Butachlor (1.2 kg/ha)	0.71	0.31	0.08
5.	Butachlor (2.4 kg/ha)	0.35	0.03	0.04
6.	Hand weeding	0.06	0.02	0.03

v) Irrigation time and method

Wheat is normally sown with a pre-sowing irrigation in north-and north-western India, but it is seen that major flush of *Phalaris minor* germination takes place only after first irrigation given at 3 WAS (weeks after sowing) at CRI (crown root initiation) stage of wheat. On the contrary, germination of *Avena ludoviciana* (wild oats) starts along with wheat. Therefore, the philosophy is that if the first irrigation is delayed beyond 3 WAS, there won't be much germination of *Phalaris* under late irrigation and even though it takes place, wheat plants which have grown up enough by that time may take care of them. Thus *Phalaris minor* competition may be reduced considerably. However, wheat yield loss due to late first irrigation must be equated with gain in weed control front. The delay in first irrigation also needs to be standardized. If economics permits, may be adopted. Irrigation methods, e.g. border strip, check basin, ridge and furrow, FIRBS (furrow-irrigated raised bed system), drip and sprinkler also have varying weed smothering ability.

vi) Fertilizers (kind, time, method and rate)

Unger (1984) reported *Centella asiatica* occupying 35% of the vegetation in non-fertilized plots, was completely suppressed by fertilizer. Appropriate fertilization considering the kind of fertilizer and time, method & rate of application may alter crop-weed balance in favour of crop.

The N-, P- and K-fertilizers affect weed diversity and species distribution. Nitrogen influences grassy weeds more (Carlson and Hill, 1985), whereas P and K influence broad-leaved weeds, namely *Melilotus alba/indica/parviflora, Chenopodium album, Medicago denticulata* much. However, tall-growing wheat plants supplied with enough N may smother their growth (Williams, 1976; Das and Yaduraju, 1999a &1999b). Acidic fertilizers like ammonium sulphate, ammonium chloride, urea may acidify the soil and discourage leguminous weeds.

Addition of N to wild oat-infested wheat increased the density of wild oats panicles and decresed wheat yield (Carlson and Hill, 1985; Wimschneider *et. al.*, 1990). Split N application in that situation incurred more yield loss due to wild oats. The N-, P- and K-fertilizers need to be banded, side-dressed or placed below the crop rows (Yaduraju and Ahuja, 1992, 1997) before sowing and there should not be any contact between fertilizer and crop seeds.

Generally higher the rate of fertilizer/N application, lower is the weed growth. In wheat, *Phalaris minor* growth was reduced when N was applied at 150 kg/ha than at 120 kg/ha (Gautam, 1992). Similarly *Striga* germination reduced drastically at higher concentration of N in soil. Saraswat (1989) reported the growth of perennial *Chara zeylanica* decreased with increased levels of N and the doses 90 kg N/ha and above recorded no increase in growth.

vii) Stale seedbed

Stale seedbed technique dictates that a field should be irrigated first and then it is ploughed on optimum moisture status and levelled thoroughly. Crop is withheld from sowing and the field is left as such for about a week or more to allow enough germination of weeds, which later will be controlled by a non-residual herbicide, e.g. paraquat, glyphosate, glufosinate-ammonium, or by shallow cultivation. Engstroem (1974) reported that weed population was reduced by 40-50% and wheat grain yield increased by 50.7% in stale seedbed compared to conventional seedbed. The land was prepared 3-4 weeks before sowing with minimum soil disturbance followed by paraquat application. Subsequent application of hand weeding or herbicide (MCPA) was again useful towards drastic reduction of weed growth.

viii) Crop plants' resistance to weeds and herbicides

Crop plant's resistance could be of two types, e.g. a) crop cultivar's resistance to some parasitic weeds of which it is host (host plants' resistance)s, and b) crop cultivar's resistance to some effective non-selective herbicides (herbicide resistant crop or transgenics). In recent years some varieties of crops resistant to *Striga*, *Orobanche* and *Cuscuta* have been developed (Table 6) or on the anvil (Narayana, 1989; Kumar and Kondap, 1992). Similarly researches on transgenic crops have geared up very fast in the world particularly by the Multinational Companies and as a result, a number of transgenic crop varieties have evolved within a short period of hardly 7-8 years (Table 7) using biotechnological tools.

Table 6. Crop's varieties resistant to some parasitic weeds

SN	Parasitic weed species	***Crops and resistant varieties***	Country
1.	**Striga hermonthica**	Sorghum (S 1561, S 1477, S 1511 - from ICRISAT, Hyderabad, India)	Africa
2.	*Striga hermonthica*	Sorghum [Yeju (ICSV 111), Gobiye (P 9401), Abshir (P 9403), Jigurty, Key # 8574 (from Sirinka Agric. Research Centre, Sirinka, Woldiya, Ethiopia)]	Africa (Ethiopia)
3.	*Striga hermonthica*	Maize (HR 2001, Gibe 1)	Africa (Ethiopia)
4.	**Orobanche sp**	Mustard (Durgamani* shows mild resistance in India); Fababean (F-402); Pepper (Maor, Odem)	--
5.	**Cuscuta sp**	Alfalfa (LLC 6* and LLC 7* - moderately tolerant); greengram (M 2*); blackgram (T 9*)	India

* Varieties reported herein are not transgenics or genetically modified rather they show as such or in-built tolerance.

Table 7. Some transgenic crops of the world

Crops	Transgenics	***Herbicides***	Country and year
1. Cotton (*Gossypium hirsutum*)	BXN COTTON	Bromoxynil	USA, 1997
	LIBERTY LINK COTTON	Glufosinate-AM	USA, 2000
	ROUNDUP READY COTTON	Glyphosate	USA, 1997
	19-51a COTTON	Sulfonylureas	USA, 1997
2. Soybean* (Glysine max*)	LIBERTY LINK SOYBEANS	Glufosinate-AM	USA, 1998; Brazil,1998-99
	ROUNDUP READY SOYBEANS	Glyphosate	USA, Brazil, Argentina, 1997
	STS SOYBEANS	Sulfonylureas	USA, 1993
3. Tobacco (*Nicotiana tabacum*)	BXN TOBACCO	Bromoxynil	Europe,1997-98
	Chlorsulfuron-resistant tobacco	Chlorsulfuron	
	Asulam-resistant tobacco	Asulam	
4. Maize* (Zea mays*)	LIBERTY LINK CORN	Glufosinate-AM	USA, 1997
	ROUNDUP READY CORN	Glyphosate	USA,Canada, 1998
	IMI CORN	Imidazolinones	USA, 1997; Australia1998-99
	SR CORN	Sethoxydim	USA, Brazil,1997
5. Rice* (Oryza sativa*)	LIBERTY LINK RICE	Glufosinate-AM	USA, 2000-01; Asia, 2000-01
6. Sugarbeet (*Beta vulgaris*)	LIBERTY LINK SUGARBEET	Glufosinate-AM	Europe, 1999-2000
	ROUNDUP READY SUGARBEET	Glyphosate	Europe, 1997-98
7. Canola (*Brassica carinata*)	BXN CANOLA	Bromoxynil	Europe,1995
	LIBERTY LINK CANOLA	Glufosinate-AM	Canada, Europe, 1995
	ROUNDUP READY RAPE	Glyphosate	Canada, 1997
8. Rapeseed	Glyphosate-resistant rapeseed	Glyphosate	
9. Tomato	Glyphosate-resistant tomato	Glyphosate	
10. Potato	Asulam-resistant potato	Asulam	

ix) Summer fallowing

Fallowing is a cheap and effective practice of weed control (Moody, 1975). Fallowing during summer accompanied by 3-4 tillage (of which the first one should be a deep tillage) exposes weed seeds, under-ground vegetative structures of perennial weeds (e.g. *Cyperus* *rotundus, Cynodon dactylon, Digitaria abyssinica* (~ *scalarum*), *Cirsium arvense* or *Convolvulus arvensis*), insects, pathogens, nematodes to the hot sun and kill them by solarization. Mere fallowing, however, may not yield a good result.

x) Residue incorporation into soil

Crop residue management research either through incorporation or by burning has been taken up in significant scale towards nutrient recycling under integrated nutrient management system. It has hardly been investigated towards crop or weed allelopathy and on weed management aspect. Its short-term effect may not be instantaneously visualised, but long-term effect may be enormous. There are reports that crop residues of lentil are phytotoxic to wheat and of sunflower and mustard to several crops (Putnam, 1983, 1985). Similarly sorghum is allelopathic to wheat and *Phalaris minor* and sweet potato to cowpea, but mung/green gram, urdbean/black gram and cowpea are stimulatory to the growth of wheat.

3.4 BIOLOGICAL CONTROL OF WEEDS

3.4.1 Definition

Biological control (Figure 3) is defined as "the control of an organism (weeds, insects or pathogens in agriculture) employing another living organism to a population lower than what naturally occurs in the absence of introduced/employed organism" (Gupta, 1998). They have just prey-predator relationship. The biological agents normally employed for the purpose could be parasites, predators (insects, mites), pathogens (fungi, bactieria, viruses), deleterious *Rhizobacteria* (DRB), herbivorous fish, other animals (ducks and geese, snails) and botanical agents (competitive plants, crops or weeds) as applicable under a situation.

3.4.2 Biological *Versus* Chemical Control

Neither chemical nor biological method as such is a full-proof strategy for weed control. Considering composite culture of weeds present in the crop fields, chemical control may prove superior to biological control. On the contrary, biological control on certain fronts as for controlling certain problem and invasive weeds under non-crop situations is more effective than chemical control. Therefore, a comparison has been made in Table 8.

Table 8. Comparison between chemical and biological methods of weed control

SN	Chemical control of weeds	Biological control of weeds
1.	Chemical control may leave residues in dangerous level in the crop produce.	iv) Biological control, on the contrary, does not leave any harmful residue in crops.
2.	Ill-effect/pollution of herbicide to the environment (soil and water).	It does not pose pollution to environment.
3.	It may lead to development of resistance to herbicide by weeds.	No resistance development by weeds.
4.	It may exert negligible and invisible phytotoxicity to crops even though the herbicide is selective. Phytotoxicity is apparent at higher doses of a selective herbicide or wrong herbicide application.	It does not exert any phytotoxicity to crop plants.
5.	Preponderance of perennial weeds in crop field due to constant use of herbicides.	No preponderance of perennial weeds.

SN	Chemical control of weeds	Biological control of weeds
6.	Chemical control is a destructive method and may become a grave problem to man and environment in the long run.	Biological control is more ecological, eco-friendly and economic in the long run.
7.	It is repetitive and not self-perpetuating over the years.	It is self-perpetuating if the bio-agent selection is proper and they could adapt well to that climate.
8.	Maintaining plant/weed biological diversity on earth is quite difficult by chemical method since certain herbicide may result in 100% kill or eradication of weeds.	It likely helps to maintain the biological diversity on earth since it does not envisage complete eradication of weeds.

3.4.3 Advantages and Disadvantages of Biological Control

3.4.3.1 Advantages

i) Biological control is environmentally benign/eco-friendly since it does not lead to environmental pollution.

ii) It is economical in the long run, although initially monetary investment is high.

iii) It is self-perpetuating/self-sustaining except bioherbicides. Classical biological control does not need to introduce insects/bio-agents repeatedly in every year or every crop season and, therefore, relatively permanent and longer lasting.

iv) It preserves bio-diversity since weed control by biological means/agents is not achieved to the level of 100%.

v) It is effective in areas inaccessible to man. That weed wherever found even in dense forest, high mountains, is likely to be controlled particularly by insect bio-agents.

3.4.3.2 Disadvantages

i) It requires/incurs higher initial cost.

ii) Screening and identification of bio-agents if not proper, they may damage the economic crops or they may control weed plants of economic interest in other places. For example, *Zygogramma bicolorata* Pallister (Mexican beetle) and *Epiblema strenuana* Walker (gall-forming insect) meant for parthenium (*Parthenium hysterophorus* L.) control also feed on sunflower and niger, respectively. Test for host specificity of the bio-agent by means of multiple choice and starvation tests, therefore, should be conducted rigorously. The bio-agent should be introduced to a large number of crop plants on which it does not feed on. In that case, since the specific weed is not there, it may die out of starvation, but won't feed on crop plants. This is starvation test. Similarly several species of the weed in question as well as other related species of different weeds may be given for feeding to the bio-agent to test its multiple choices in feeding habit.

iii) Biological control has limited use/adoption in a crop field, which usually witnesses a composite culture of weeds. It is in most cases weed-specific and the weed is managed at a lower density. Controlling a single weed unless it is rampant having widely distributed in large areas and highly damaging to crop or ecosystem, is of less use/benefit.

iv) It is slow in action initially. Release/introduction of bio-agent and its subsequent establishment in the field and multiplication to build up the desired level of population for causing significant damage to weed take time and, therefore, the process of control of weed goes slow initially. On the contrary, the weed which usually comes up along with crop must have enough growth (in terms of population and dry weight) by that time and might have inflicted/caused significant damage to crop plants. Also in many instances the damaging stage/life cycle of bio-agents (namely insects) and the susceptible stages of weeds do not coincide properly and it makes its adoption in crops less efficient.

v) Weeds are not eradicated, but managed at a lower density. The bio-agents employed feed on mainly foliage (not the whole plant or all plant parts). Certain bio-agents (namely insects), of course, eat up flowers, fruits and seeds of the weeds. Biological control, therefore, cannot be of much help towards weed eradication. Equally it is unsuitable for adoption in the crop field where the need is to minimize weed competition *vis-à-vis* to prevent them from going to seeds.

vi) The biological control warrants the use of other pesticides such as insecticide, fungicide in the crop, which may kill the bio-agents or hamper its activity.

vii) The span of activity of bio-agent in most cases is small/narrow, whereas weeds may grow all through the year. For example, *Parthenium hysterophorus* grows all through the year, but *Zygogramma bicolorata*, the bio-agent is active only during rainy season for a period of 2-3 months starting from July. It goes for wintering during cold season.

3.4.4 APPROACHES TO BIOLOGICAL CONTROL OF WEEDS

3.4.4.1 Classical/Inoculative approach

Classical/inoculative approach involves the release of bio-agents (insects, pathogens) just for once in the belief that it will readily adapt to the prevailing climate and multiply enough to keep pace with the multiplication rate of weed in question. Therefore, repeated release of bio-agent unless failed, is not advocated. No augmentation and large-scale mass production of the bio-agent are pactised. In this approach, a small amount of inoculum (pathogen) or a small number of insects, say, one insect per 20-40 weeds or 1 insect per 3-5 m^2 area based on the assessment of weed problem and prevailing situation, is initially released in the standing population of weeds and allow it to multiply and feed on the weeds.

3.4.4.1.1 Steps for introduction/release of bio-agents (mainly for exotic/introduced weeds)

The following steps are to be adopted while introducing insect bio-agents :

i) First assess area-wise gravity of the problem of the weed for which bio-agent is to be introduced.

ii) Survey all native organisms (insects, diseases pathogens, vertebrate pests etc.) that attack the weed in the area where the bio-agent is to be introduced.

iii) Find out the origin of that weed geographically and organisms those attack it there.

iv) Search for natural enemies in its place of origin or native land.

v) Test for host specificity of the bio-agent by means of multiple choice and starvation tests.

vi) Importation of the specific bio-agent based on performance of the bio-agent in above-mentioned tests.

vii) Further testing and screening of the natural enemies for parasites in quarantine.

viii) Adaptability test and based on that, mass rearing of the bio-agents in the place where to be introduced.

ix) Release and assessment of the effect of bio-agent on that weed.

3.4.4.2 Augmentative/Inundative/Bio-Herbicide Approach

Inundative approach pursues *in vitro* augmentation of the pathogen inoculum and its culturing in artificial medium in the laboratory on the belief that target weeds may fall susceptible to it when applied in a large concentration (considering the number of active bio-agent molecules) over its existing population. This inoculum is bio-herbicide. Bio-herbicides are native pathogens mostly fungi and hence called mycoherbicide. Several inoculums such as fungi, bacteria, parasitic nematodes, viruses having tested control ability over a weed species may be applied/sprayed like herbicides (Table 9).

Table 9. Mycoherbicide products in use in the world

SN	Product, year & country	Bio-herbicide description	Target weeds and diseases caused	Crop where used and reference
1.	DeVine, 1981, USA	*Phytophthora citrophthora* p.v. *palmivora*. Soil-borne pathogen and can remain for 3-4 years in soil by one spray	*Morrenia odorata* (Strangler vine), (Lethal root-rot)	Citrus, USA; (Kenny, 1986)
2.	Collego 1982, USA	*Colletotrichum gleosporioides* f. sp. *Aeschynomene*	*Aeschynomene virginica* (Nothern joint vetch), (Stem and foliage blight)	Rice and soybean, USA; (Bowers, 1982)
3.	Biomal, Canada	*Colletotrichum gleosporioides* f. sp. *Malvae*	*Malva pusilla* (Round-leaved mallow), (Anthracnose)	Cotton, Canada; (Makowski and Mortenson, 1992)
4.	Biomal No. 1 & 2	*Colletotrichum gleosporioides* f. sp. *Malvae*	*Malva pusilla* (Round-leaved mallow), (Anthracnose)	Wheat and small-grain crops in USA
5.	Lubao II	*Colletotrichum gleosporioides* f. sp. *Cuscutae*	*Cuscuta sp* (Dodder)	--
6.	VELGO	*Colletotrichum coccoides*	*Abutilon theophrasti*	Cotton, Canada
7.	ABG 5003	*Cercospora rodmanii*	*Eichhornia crassipes*, (Leaf spot)	Water-ways, USA
8.	CASST	*Alternaria cassiae*	*Cassia obtusifolia, Cassia occidentalis & Cassia alata* (Blight disease)	Cotton, soybean & groundnut, Florida, USA; various crops in Australia
9.	DR.BIO SEDGE	*Puccinia canaliculata*	*Cyperus esculentus*	--
10.	Product F	*Fusarium oxysporum*	*Orobanche sp*	Sunflower
11.	--	*Fusarium oxysporum* f. sp. *Cannabis*	*Cannabis sativa*	--
12.	Bipolaris	*Bipolaris sorghicola*	*Sorghum halepense* (Johnson grass)	--
13.	--	*Exerchitum turcicum*	*Sorghum halepense* (Johnson grass)	--
14.	--	*Colletotrichum orbicular*	*Xanthium spinosum*	Australia
15.	--	*Colletotrichum truncatum*	*Sesbania exaltata*	Soybean,

				Mississippi, USA
16.	--	*Colletotrichum gleosporioides*	*Hypericum perforatum* (St. John's wort)	Australia
17.	--	*Alternaria cressa*	*Datura stramonium* (Jimson weed)	Israel, USA
18.	--	*Fusarium moniliformae*	*Datura stramonium* (Jimson weed)	--
19.	--	*Septoria sp*	*Convolvulus arvensis* (field bind weed)	Maize & potato, Greece
20.	--	*Rumularia subelis*	*Rumex obtusifolius*	--

Bioherbicides are sprayed in every season on the target weed in crop field. The bio-agent generally remains active only on concurrent weed population. Then they wither away without any cyclic perpetuation unlike what happens in classical bio-control. However, in some cases, the pathogen may remain active for 3-4 years e.g. soil-borne pathogen *Phytophthora citrophthora* p.v. *palmivora* for the control of *Morrenia odorata* (Strangler vine) in citrus.

3.4.5 BIO-AGENTS FOR BIOLOGICAL CONTROL

Some important bio-agents along with the weed species controlled by them are enlisted below and discussed.

i) Insects

a) **Opuntia sp** ***(Prickly pear)***

The cochineal insect *Dactylopius ceylonicus* Green (= *indicus* Green) was introduced for controlling *Opuntia vulgaris* Miller (~ *monacantha* Willdenow) Haworth in southern India around 1863 (Goeden, 1978) and this could be first successful biological control involving insects. Another species, *Dactylopius tomentosus* (Cochineal scale insect) recovered around 40,000 hectares of land infested with *Opuntia dillenii* in India (Narayanan, 1954). This insect, however, did not attack other species of *Opuntia*. In Australia, *Cactoblastis cactorum* (Cactus moth) introduced from Argentina and *Daclytopius opuntiae* (Cochineal insect) from USA were found very effective for controlling *Opuntia*. The larvae of *C. cactorum* tunnel through the plants and eventually destroy all above-ground parts. They also penetrate underground bulbs and roots and thus help entry of bacterial and fungal parasites such as *Cleosporium anatum* E & E, *Phyllosticta concava* Seav., *Montegnella opuntiorum* Speg. through the tunnels. *Cactoblastis cactorum* was also introduced in Hawaii and proved very effective.

b) *Lantana camara* (Lantana)

Lantana camara got introduced to Hawaiian Islands around 1860. It invaded large areas of rangelands there. Among several insects introduced in 1902 and later, *Crocidosema lantana* Busck (Tortricid moth), *Agromyza lantanae* (Seed fly) and *Thecla echion* and *Thecla bazochi* (Lycaenid butterfly) were very effective in controlling *Lantana*. Insects have effectively controlled *Lantana* in India, Australia and Fiji too. *Teleonemia scrupulosa* (Lac bug) has been found most effective against *Lantana*. *Hypena jussalis* Guenoe in Hawaii, *Uroplata girardi* Pic. and *Octotoma scabripennis* Guerin in Australia also achieved success in controlling *Lantana camara.*

c) *Parthenium hysterophorus* (Parthenium)

Among a dozen of bio-control agents (insects and pathogens) introduced in Australia and India, *Zygogramma bicolorata* Pallister and *Epiblema strenuana* have been found most effective in controlling parthenium.

i) *Zygogramma bicolorata* Pallister (Mexican beetle) : It is highly effective but its maximum span of activity is 2-3 months (July – September) and has slow dispersal. It goes for wintering (perpetuation) during winter season and as a result, the beetle is not available all through the year while parthenium proliferates all the year round. It is multivoltine (2-3 generations/year in Mexico, 4 or more generations/year in Australia) and adults can live for 2 years. It also feeds on sunflower, but not a pest of sunflower.

ii) *Epiblema strenuana* : It is a gall-forming insect feeds on buds of *Parthenium* and has long dispersal range up to 20 km. The fecundity is 100-1300 ova/female. Ova are laid on stems and leaf under-surface. Small larvae are leaf miners and then bore into stems and a gall (10-15 mm) is formed by the plant. Pupation is in gall and life cycle is 30-40 days. It is multi-voltine (2-3 generations/year in Mexico, 4-6 generations/year in Australia).

d) Eichhornia crassipes (Water hyacinth)

i) *Neochetina eichhorniae* Warner : The larvae of *Neochetina* tunnel through the petioles and stems and thus open the way for soft-rotting bacteria. They are highly effective if *Eichhornia* is pre-treated with a growth retardant.

ii) *Neochetina bruchii* : *Neochetina bruchii* is another insect found effective in Australia.

E) *Cuscuta sp (*DODDER*)*

i) *Melanagromyza cuscutae* and ii) *Smicronyx cuscutae* (in Africa) controlled dodder effectively.

F) *SALVINIA MOLESTA*

Successful biological control of *Salvinia molesta* was reported in 1974 by the grasshopper (*Paulinia acuminata*) in Lake Kariba, Zambia (Bennett and Woodford, 1980). The success of controlling *Salvinia* has also been reported from Papua New Guinea (Akobundu, 1987). *Salvinia* control through *Cyrtobagous salviniae* in Australia has added another dimension in biological control of weeds since 1980.

g) ***Alternanthera philoxeroides* (Mart.) Griseb (Alligatorweed)**

Alligatorweed, a highly prolific aquatic weed has been controlled by *Agasides hygrophylla* and *Agasides connexa* Boheman (Flea beetle) in southern USA (Florida). The feeding efficiency of the insects increases if the weed is pre-treated with 2,4-D or diquat, which softens the foliage for insect attack.

h) ***Hypericum perforatum* L. (St. John’s wort)**

St. John’s wort is a rangeland weed and also found here and there on the roadside. *Chrysolina hyperici* (Leaf-eating beetle) in Australia and New Zealand and *Chrysolina quadrigemina* Suffrian in western USA have been found effective in controlling St. John’s wort.

i) ***Cyperus rotundus* (Purple Nutsedge)**

Bactra verutana Zeller (Moth borer) controlled *Cyperus rotundus* in India, Pakistan and USA.

j) ***Ludwigia sp***

Haltica cyanea Web (Steel blue beetle) is reported to control *Ludwigia parviflora/octavalvis* (in rice fields).

k) ***Imperata cylindrica* (Thatch grass/Alang alang)**

Orseoliella javanica (Gall midge) controls *Imperata cylindrica*.

ii) Mites

Among the mites, *Tetranychus desertorum* Banks against *Opuntia stricta* Haw. (Prickly pear) and *Aceria chondrillae* Can. (Gall mite) against the weeds *Chondrilla juncea* L. have been found effective in Australia. Another mite, *Orthogalummna terebrantis* Wal. has been tried against *Eichhornia crassipes* (Water hyacinth).

iii) Cattle, Goats, Sheep and Donkeys

Grazing by cattle, goats, sheep, donkeys etc. in pastures and fallow lands is a kind of natural control of unwanted floras and vegetation. *Senecio jacobaea* L. (Tansy ragwort) and *Rubus fruticosus* L. (Blackberry) have been effectively controlled by sheep in the pastures of Australia (Schmidl, 1977). Sheep are more effective than goats since goats selectively feed on floras. Similarly buffaloes are more voracious eater than cows. Cattle and buffaloes are more effective in controlling emergent aquatic weeds, e.g. *Eleocharis sp, Phragmites communis* (Reed), *Typha sp* (Cattails) than goats and sheep because the latter animals do not enter into water bodies.

iv) Ducks and Geese

Ducks and geese have also been experimented for aquatic weed control in rice culture, cotton (Crafts, 1975), strawberries, mint and some other crops. The geese prefer seedlings of grass weeds. However, ducks/geese and fish and/or snail cannot be introduced simultaneously in the same rice culture, since ducks and geese may be predators of fish and snail.

v) Manatees

Manatees (*Trichechus sp*) is a large plant eating sea mammal and had been introduced in Florida waterways for weed control. It, however, cannot breed in fresh water and therefore, is restricted to saline/salty water.

vi) Fish

Several herbivorous fish such as *Cyprinus carpio* L. (Common carp), *Ctenopharyngodon idella* Val (White amur/Chinese grass carp), *Tilapia mossambica* (Sunfish), have been introduced and found useful for aquatic weed control in ponds, waterways and in lowland rice ecosystem. Chinese grass carp is a voracious eater/feeder and eats more than its body weight daily. It may grow at a rate of 5 kg/year and attains 50 kg or more body weight at its full size (Gupta, 1973). It proved highly effective for aquatic weed control in many countries including India.

vii) Snails

A large fresh water snail, *Marisa cornuarieties* L. and some other snails in Florida and Puerto Rico have been evaluated for the control of several submerged aquatic weeds and algae. *Marisa cornuarieties*, however, proved most effective. *Marisa* feeds on the roots of *Eichhornia crassipes* (Water hyacinth) and *Pistia stratiotes* (Water lettuce) and the leaves of *Salvinia molesta*. It, however, attacks rice seedlings and *Trapa natans* (Water chestnut) and, therefore, should not be introduced in rice fields where water chestnut, a plant of economic value grows.

viii) Deleterious *Rhizobacteria* (DRB)

The *Rhizobacteria* usually colonize around the rhizosphere of certain weeds and decrease their root growth and proliferation. As a result, the weeds remain stunted and cannot exert enough competition to crop plants. The *Rhizobacteria* possessing this attribute is called “deleterious *Rhizobacteria* (DRB).” Research on deleterious *Rhizobacteria* is still in its infancy, but some experiments showed their potential towards growth inhibition of weeds. A number of bacteria have been identified towards control of certain weeds in some crops (Table 10).

Table 10. Biological control of weeds through *Rhizobacteria*

Rhizobacteria	Weeds	Ecosystems
Enterobacter	*Bromus tectorum*	Cereals
Enterobacter	*Amaranthus sp*	Row crops
Pseudomonas	*Setaria viridis*	Cereals and range lands
Pseudomonas	*Calamagrostis canaderosis* Var *Canadensis*	Forest nursery
Pseudomonas	*Bromus japonicus*	Cereals
Pseudomonas	*Abutilon theophrasti*	Cereals
Pseudomonas fluorescens	*Aegilops cylindrica, Sisymbrium, Amaranthus*	Cereals
Xanthomonas	*Bromus secalinus, Aegilops cylindrical*	Cereals
Agrobacterium,	*Euphorbia esula*	Range lands
Flavobacterium	*Euphorbia esula*	
Erwinia herbicola	*Setaria sp*	Row crops

ix) Botanical agents (BAs)

Botanical agents are the plants which suppress/depress the growth of other plants grown in vicinity or in close proximity by means of allelopathy and competition. They are highly competitive and gradually replace the weed in question. They are harmless plant and can displace harmful plants (weeds). This has been widely demonstrated to replace parthenium (*Parthenium hysterophorus* L.) in Bangalore, Karnataka, India. A large number of ruderal flora/weeds, namely *Cassia sericea*, *Tagetes minuta*, *Mirabilis jalapa*, *Tephrosia purpurea, Cassia obtussifolius*, *Cassia occidentale* have been found allelopathic to parthenium (Mahadevappa, 1997). Among them, *Cassia sericea* has been extensively studied and found highly effective in replacing the parthenium. *Panicum purpurascens* Raddi is also found competitive against *Typha sp* in marshy land.

3.5 ALLELOPATHY AND ALLELOCHEMICALS

3.5.1 Definition

Allelopathy is derived from two Greek words, “allelon or allelo” means “mutual or each other” and “pathos or patho” means “suffering or to suffer.” Molisch (1937) coined the term allelopathy, which includes all stimulatory and inhibitory reciprocal biochemical interactions among plants including microorganisms. Some authors, however, prefer to describe it purely an inhibitory effect of one plant species upon another. Rice (1974) too opined the same. However, an allelochemical that inhibits the growth of some plants or microorganisms at certain concentration may stimulate the growth of same or different plants or microorganisms at its lower concentration. Therefore, this biochemical interaction cannot be solely an inhibitory phenomenon. That is why Rice later (Rice, 1984) inclined to the same definition of allelopathy as propounded by Molisch (1937).

3.5.2 Kinds of allelopathic interactions

Allelopathy may be alloallelopathy and autoallelopathy, true and functional allelopathy (Aldrich, 1984) and concurrent/direct and residual allelopathy. Alloallelopathy is inter-specific chemical co-action, whereas autoallelopathy intra-specific chemical co-action. The cases of alloallelopathy are : maize is allelopathic to *Chenopodium album, Amaranthus retroflexus*; sorghum to *Abutilon theophrasti, Amaranthus hybridus, Setaria viridis, Bromus pectinatus* ; rye to *Digitaria sanguinalis, Ambrosia artemisiifolia, Chenopodium album* ; cucumber to *Echinochloa crusgalli, Amaranthus retroflexus* ; and sweet potato to *Cyperus rotundus, Cyperus esculentus* (Putnam, 1985). The cases of autoallelopathy are : wheat, alfalfa, cowpea, rice, apple, clover and sweet potato are autotoxic. The soil where these crops were previously grown, is inhibitive to their growth when replanted or their residues proved autotoxic to them when incorporated. Similarly *Trifolium repens* (weed) has autotoxicity.

True allelopathy refers to the release into the environment of chemical compounds that are toxic in the forms they are produced by the plants, but functional allelopathy is the release into the environment of compounds that are toxic after chemical modification by microorganisms. Concurrent/direct allelopathy refers to instantaneous direct effect of released toxins from the living plants to another growing in vicinity, whereas residual allelopathy is the effect obtained on the plants growing in succession from the decaying residues, leaf litters, stems, roots of the previous plants. Concurrent allelopathy is differently called as "live plant effect," e.g. sorghum suppresses many weeds growing in vicinity. Live barley plants and their root exudates are more inhibitory than aqueous leachates of dead roots (Overland, 1966). This might support the concept of active metabolic secretion of allelochemicals by the live/standing plants. Lentil residues are phytotoxic to wheat and sunflower and mustard residues to several crops (Putnam, 1983, 1985). Similarly sorghum is allelopathic to wheat and *Phalaris minor* and sweet potato to cowpea. These are example of residual allelopathy.

3.5.3 Application of allelopathy in weed management

i) Development of novel biopesticides, namely herbicides, insecticides or fungicides from allelochemicals or allelopathic agents assumes paramount importance.

a) Bialaphos, a microbial toxin/allelochemical is found in a bacterium *Streptomyces hygroscopicus*. Its synthetic analogue glufosinate-AM is extensively used for weed control in cropped and non-crop situations.

b) From *Salvia sp* (sage), 1,8-cineole is released, which has phytotoxic effect. Cinmethylin is a synthetic herbicide and has structural similarity with it. Cinmethylin controls annual grasses and some broad-leaved weeds and is recommended for weed control in rice.

c) A natural herbicide AAL-toxin is a metabolite produced by *Alternaria alternata* f. sp. *Lycopersici*, a pathogen (fungus) causing stem canker of tomato (Zimdahl, 1999).

ii) A number of crops have been reported with their alleged allelopathic effects and attempts have also been made to find crop cultivars with a competitive allelopathic basis (Putnam, 1985; Rice, 1979 & 1984; Thompson, 1985). Therefore, adoption of crops or crop's cultivars more allelopathic to weeds may reduce the cost of weed control in particular and the cost of cultivation as a whole. For example, sorghum residues have been applied to control weeds in subsequent rotational crops (Putnam, 1885).

iii) Application of the residues of allelopathic crop plants as mulches or adoption of an allelopathic crop in rotational sequence and allowing the residues to remain in the field has enough importance to bring down weed population to lower level.

iv) Utilizing a companion crop/plant ((Putnam, 1885; Zimdahl, 1999) that is selectively allelopathic to weeds and does not interfere appreciably with crop growth has enough bearing towards weed control in the fields. In several intercropping situations such as sorghum + cowpea, maize +cowpea/soybean and agro-forestry/agro-silvi-pastoral systems, a clear advantage in weed control is obtained, but it requires to be authenticated and quantified through enough research.

3.6 CHEMICAL METHOD OF WEED CONTROL

A proper technical know-how is a pre-requisite for successful adoption of chemical method of weed control so-called herbicide technology (Figure 3). One has to exercise a lot of caution while using the herbicide for uniform application as well as higher herbicide efficiency. Herbicide selectivity and its dose, time and method of application are of paramount importance/consideration before applying to a crop.

3.6.1 Usefulness of chemical method/Herbicides

i) Herbicide is the most potent single tool towards weed management if used judiciously on the prescribed guidelines. It on global basis has the highest consumption, production and market share among all pesticides.

ii) Herbicides particularly pre-emergence ones control weeds right from the beginning of their germination and thus prove to be more efficient than many other methods of weed control.

iii) Herbicides can control weeds having morphology similar to crop plants, e.g. *Phalaris minor*, *Avena fatua/ludoviciana*, *Lolium temulentum* etc in winter cereals like wheat, barley and cultivated oat easily and efficiently than other methods. Even trained manual labourers cannot identify these weeds growing in intra-row position at the early seedling stage and leave them unweeded. This is revealed when they come to flower by means of the difference in their inflorescence.

iv) Most herbicides prove to be more economical than mechanical & manual methods particularly where manual labourer costs higher.

v) They can substitute mechanical control of weeds in many situations and hence reduce mechanical damage (stalk breakage, lodging, up-rooting, root damage, etc) to crops.

vi) They control weeds where other methods is difficult to execute, e.g. in wet & marshy soils under humid conditions, within or between narrow-rows of crops.

vii) Herbicides prove to be the most important tool for weed management under minimum and zero tillage. Similarly under tilled conditions, the number of tillage could be reduced by applying herbicides, and thus they save labour and energy.

viii) They offer greater flexibility/resilience on the choice of crop management system. For example, using herbicide one needs not to depend much on crop rotation, intercropping etc towards weed management.

3.6.2 Limitations of chemical method/herbicides

i) Herbicides may cause inadvertent/unintentional injury to crop and other non-target vegetation in an area by faulty application techniques (using inappropriate herbicide, its dose & spray volume, spraying in windy days, etc). It is even true for a good selective herbicide since selectivity is crop-specific, climate- and soil-specific, dose-dependent and dependent on time and method of application, etc.

ii) Most herbicides are narrow-window ones (i.e. window of application is narrow). This dictates that they, except their requisite time of application, cannot be applied at any time or at any growth stages of crop like insecticides or fungicides seeing incidence of the pests. Once that time of application elapses or is over, their selectivity margin goes down and prove risky for application in that crop. On the contrary, wider window herbicides, which could be applied all through the growth stages of a crop, are rarely available in the world.

iii) Many herbicides are narrow-spectrum ones (i.e. the spectrum of weed kill is narrow). In fact, no herbicide gives 100% control not because of herbicide per se but for other factors, e.g. weed species variation and tolerance, spray techniques (volume rates, sprayer type, degree of spray overlapping, etc.), soil condition (moisture, organic matter content, temperature, etc.) and climatic condition (temperature, relative humidity, sunshine, etc.), which readily interact with herbicide. Therefore, herbicide alone cannot be a sole and full-proof strategy for weed control. This necessarily recommends other herbicides or other methods of weed control preferably hand weeding is followed after or integrated with it for effective and long lasting weed management/control.

iv) Chemical method may be less economic under small and fragmented holdings of the farmers.

v) It poses high risk towards adoption in crops particularly by illiterate farmers. Proper technical know-how of the herbicide is the pre-requisite for its application to crop to ensure crop safety. Farmers are required to be trained for its correct use.

vi) Herbicide residues left in soil may cause soil and water pollution concurrently or in the long run. Residues of atrazine has been detected in the well water long back in USA, in ground water at IARI, New Delhi (personal communication) and long continued use of paraquat, a non-residual herbicide caused havoc phytotoxicity in Thailand (Fryer et. al., 1975).

vii) Herbicides may pose toxicity to other non-target organisms such as soil micro-flora and micro-fauna, vertebrate animals and crops grown in succession. Atrazine applied to maize has been found phytotoxic to wheat grown in rotation and similarly metribuzin at 0.5 kg/ha in sandy loam soil caused phytotoxicity to wheat (personal communication).

viii) They may be the cause for concern and threat on their long and continued use to human health and safety.

ix) Continuous use of herbicides particularly narrow-spectrum ones may cause weed flora shift. For example, continuous use of benthiocarb in rice-field has resulted in spontaneous increase in the population of broad-leaved weeds like *Monochoria vaginalis* (Burm) and *Sphenoclea zeylanica* Gaertn. (Mukhopadhyay, 1992; Raju, 1998). Speedy proliferation of *Ischaemum rugosum* in rice has happened mainly due to uninterrupted use of butachlor. The broad-leaved weed domination in wheat has changed to grass weed (*Avena ludoviciana and Phalaris* minor) domination due to continuous use of 2,4-D or other phenoxyalkanoic acids in the world (Crafts, 1975). Several broad-leaved weeds and sedges have, of late, become very important in the crop fields due to continuous use of predominantly grass killer herbicides (ISWS, 2000). For instance, *Commelina, Cyanotis, Euphorbia, Xanthium, Parthenium, Acalypha, Physalis, Cyperus* (*rotundus*) *etc.* in soybean ; and *Cyperus (iria, difformis or esculentus), Fimbristylis, Scirpus, Ludwigia, Monochoria, Marsilea, Sphenoclea etc.* in rice have assumed serious proportions.

x) Continuous use of the same herbicides or group of herbicides having similar mode of action may cause insurgence of herbicide-resistant weeds (Urech *et. al*., 1997). The same reason applies to *Phalaris minor* developed resistance to isoproturon in India (Malik and Malik, 1994; Malik *et. al.*, 1995; Yaduraju and Singh, 1997).

xi) Continuous use of broad-spectrum herbicides in crop-fields may cause preponderance of perennial weeds in the long run. *Cyperus rotundus* and *Cynodon dactylon* problem under high herbicide-used zero tillage; *Cynodon dactylon, Cyperus rotundus, Sorghum halepense, Sacchurum spontaneum* L. infesting large areas of field crops (Mukhopadhyay, 1992); and *Cirsium arvense* and *Convolvulus arvensis* preponderance in wheat in parts of Punjab and

Haryana (Singh *et. al.,* 1992) are good examples.

3.6.3 Herbicide Classification

In India nearly 144 pesticides molecules are registered and about 65 technical grade materials are manufactured. However, in the world nearly 400 herbicides have been developed under different chemical families/classes. They differ widely in their physical, chemical and biological properties. They are selective or non-selective to crops and have wide or narrow spectrum of weed control activity. All herbicides do not have equal coverage/acreage across the countries of the world or even within the states of a country since crop-specificity has to be satisfied before their application. Therefore, herbicides have been classified in a number of ways considering their different aspects, which are as follows.

3.6.3.1 Herbicide classes/families based on use/miscellany

Herbicide classes based on a number of uses/miscellanies have been given in Figure 4.

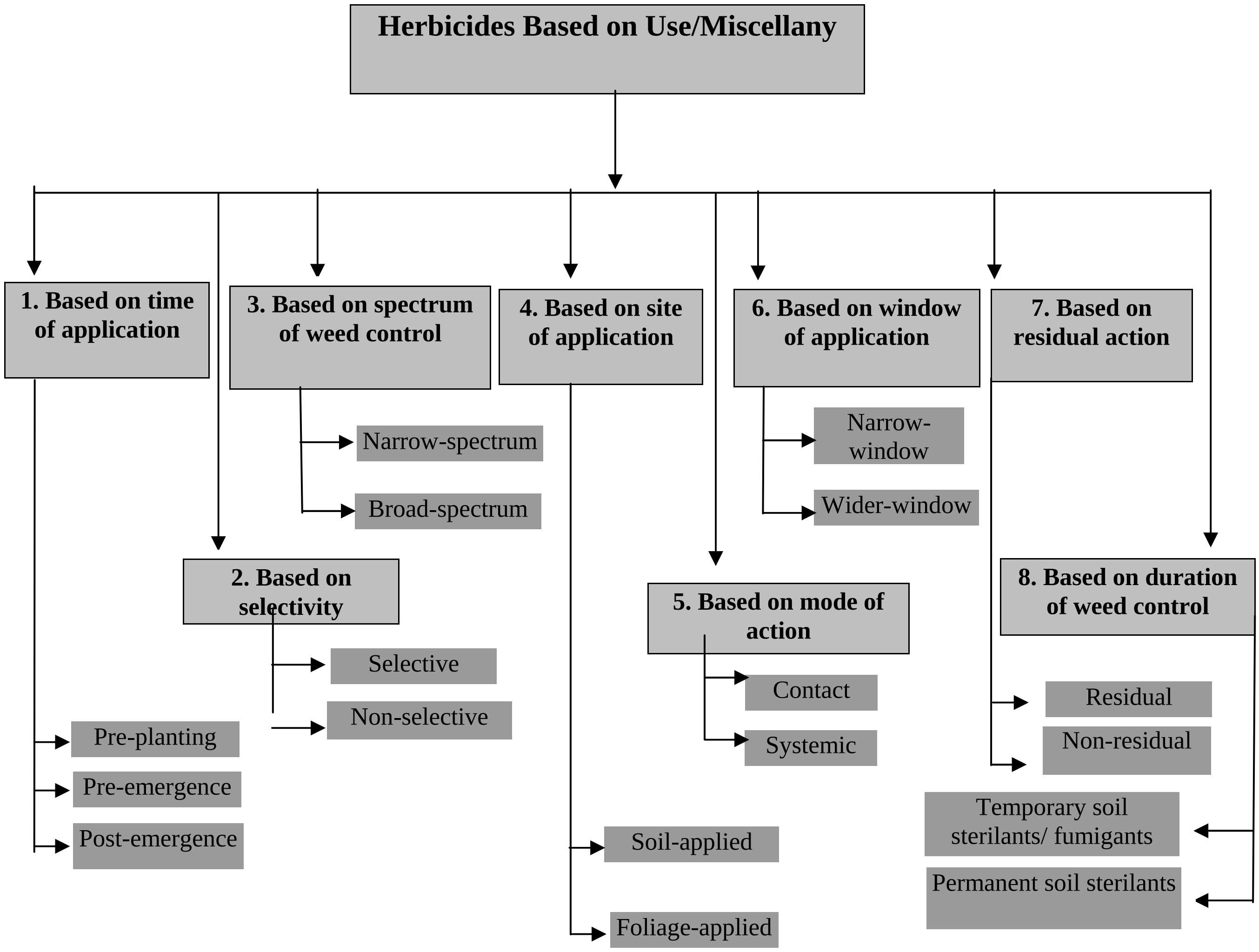

Fig. 4 . Classification of herbicides based on use or miscellany

i) Based on time of application

a) **Pre-planting :** Pre-planting herbicides (Figure 4) are applied in finally-prepared levelled soil one day before or just before planting of a crop followed by stirring/wrecking of soil by onion-hoe or by some secondary tillage implements to ensure incorporation of the herbicide. They usually have higher vapour pressure/volatility Fluchloralin, trifluralin and EPTC are good examples of PPI herbicides.

b) **Pre-emergence :** Pre-emergence herbicides (Figure 4) are applied 1-2 days after planting or immediately after planting of a crop but before the emergence of crop. Although the emergence of crop is taken into consideration, the emergence of weeds is equally important for designating many herbicides pre-emergent. Several pre-emergence herbicides are pendimethalin, atrazine, alachlor, metolachlor, butachlor, nitrofen, oxadiazon, clomazone, chlorimuron-p-ethyl, etc.

c) **Post-emergence/post-transplanting :** Post-emergence herbicides (Figure 4) are applied after the emergence of a crop and weeds both, although on principle it is after the emergence of crop. Several post-emergence herbicides are 2,4-D, butachlor, atrazine, isoproturon, fluazifop-p-butyl, fenoxaprop-p-ethyl, clodinafop-propargyl, chlorsulfuron, sulfosulfuron, lactofen, tralkoxydim, etc.

ii) Based on selectivity

a) **Selective :** The herbicide which kills selectively a particular species/group of plants (weeds) in a mixed stand/population of plants (crop and weeds) is called a selective one (Figure 4). All pre-planting, pre-emergence and post-emergence herbicides meant for application in crops are selective ones.

b) **Non-selective** :The herbicide which kills indiscriminately species/group of plants irrespective of weeds and crop is called a non-selective one. Paraquat, glyphosate, glufosinate-ammonium, acrolein, picloram, amitrole, chlorfenac/fenac, metham, sodium chlorate ($NaClO_3$) are examples of non-selective herbicides (Figure 4).

iii) Based on spectrum of weed control

a) **Narrow-spectrum** : Narrow-spectrum herbicides control a particular group of weeds, *viz*., grasses, broad-leaved or sedges. Their range of activity (spectrum of control) is narrow (Figure 4). For example, 2,4–D, diclofop-methyl, flufenacet, fluazifop-p-butyl, fenoxaprop-p-ethyl, clodinafop-propargyl, etc.

b) **Broad-spectrum** : Broad-spectrum herbicides control a wider array of weeds constituting grasses, broad-leaved and/or sedges (Figure 4). Their range of activity (spectrum of control) over the population of weeds is broad. For example, metribuzin, isoproturon, chlorsulfuron, atrazine, pendimethalin, etc.

iv) Based on surface/site of application

a) **Soil-applied/soil-active :** Soil-applied/soil-active herbicides (Figure 4) are applied to soil or active through soil and kill germinating or sprouting weed seeds, rhizomes, stolons, tubers, corms, etc.. All pre-planting and pre-emergence herbicides, *viz*., fluchloralin, trifluralin, pendimethalin, metribuzin, atrazine, simazine, alachlor or EPTC, recommended for crops are basically soil-active ones.

b) **Foliage-applied/foliage-active :** Almost all post-emergence herbicides (Figure 4), which are usually applied to the canopy/foliage of plants on principle could be foliage-active ones. Paraquat, diquat, glyphosate, 2,4–D, fenoxaprop-p-ethyl, clodinafop-propargyl, tralkoxydim, isoproturon, sulfosulfuron, tribenuron-methyl, flufenacet, chlorsulfuron, metsulfuron-methyl, etc are good example of this kind of herbicides.

v) Based on mode of action

a) **Contact (but limited/restricted mobility) :** Contact herbicides (Figure 4) on principle should control weeds by means of contact with germinating seeds, radicles/roots and/or plumules/shoots/foliages. However, contact herbicides are not purely contact in nature. They have at least some degree of mobility, may be restricted within a leaf, a petiole etc. Bromoxynil, ioxynil, paraquat, diquat, propanil are ideal examples of contact herbicides.

b) **Translocated/systemic :** Translocated herbicides (Figure 4) move from the site of application (soil, plant foliage) to site of action, where they inhibit/jeopardize a particular or a number of bio-chemical reactions and bring about the ultimate herbicidal effect. For example, pendimethalin, trifluralin, fluchloralin, 2,4–D, isoproturon, glyphosate, glufosinate-ammonium, atrazine, metribuzin, nitrofen, etc.

vi) Based on window of application

a) **Narrow-window herbicide :** Narrow-window herbicides (Figure 4) have length/range of time of application highly reduced/limited to just before sowing or from sowing to before emergence of crop or at a specific time after crop emergence as post-emergence. They are, therefore, pre-planting, pre-emergence or post-emergence herbicides, e.g. trifluralin, fluchloralin, pendimethalin, fenoxaprop-p-ethyl, clodinafop-propargyl, sulfosulfuron, tralkoxydim etc. Once a crop is left untreated at the specified period, almost all these herbicides cannot be used again in other growth stages of that crop.

b) **Wider-window herbicide :** Wider-window herbicides (Figure 4) as desired should have length/range of time span of application wider, for example, from before sowing or after sowing to longer period of crop growth may be up to 40 days after emergence of crop in certain cases. They, therefore, are herbicides with extended period of activity along the crop growth cycle. In fact, there is hardly any herbicide in the world today, which is wider-window in true sense. Atrazine and butachlor because of their pre- and post-emergence activities may loosely be held as wider-window herbicides. Chlorimuron-p-ethyl can be used as PPI, pre-emergence or post-emergence in a few crops particularly soybean and may be assumed to be a wider-window herbicide for soybean.

vii) Based on residual action in soil

a) **Non-residual :** Non-residual herbicides (Figure 4) usually leave no or less residue in soil and get quickly inactivated or metabolized upon falling in soil. They do not have extended period of activity in soil. Paraquat, diquat, glyphosate, clodinafop-propargyl, DSMA and amitrole are non-residual herbicides. Amitrole has both symplastic and apoplastic movement.

b) **Residual :** Residual herbicides (Figure 4) after application usually maintain their phytotoxic effect in soil for a considerable period of time but not the whole crop growing season. Therefore, they offer good control of weeds in crops for sufficient period at least for the critical period of weed competition. Atrazine, pendimethalin, isoproturon, fluchloralin, trifluralin, 2,4-D, metribuzin, simazine, alachlor, EPTC – all are residual ones.

viii) Based on duration of weed control (mainly under non-crop situation)

a) **Temporary soil sterilant/fumigant :** Temporary soil sterilants (Figure 4) sterilize the soil for relatively short period of time usually for 15-16 weeks. They are basically fumigants. High volatility is always preferred for fumigant's action. Methyl bromide (MB), metham (vapum®), carbon disulfide (CS_2), chlorfenac, chloropicrin/tear gas (CCl_3NO_2), methyl isothiocyanate, dazomet (DMTT) are good examples of temporary soil sterilant or fumigant.

b) **Permanent soil sterilant :** Permanent soil sterilants (Figure 4) remain active in soil for relatively long period of time, sometimes for two or more seasons/years. Triazines, phenylureas (e.g. linuron) or sodium chlorate ($NaClO_3$) at very high dose act as permanent soil sterilant. They are recommended mainly for industrial and non-crop areas.

3.6.3.2 HERBICIDE CLASSES/FAMILIES BASED ON CHEMISTRY

A detailed organic classification of herbicides is given below.

i) **Acetamides (Amides) :** Diphenamid, napropamide, allidochlor, pronamide, chlorthiamid, perfluidone, propanil, acetochlor, alachlor, butachlor, metolachlor, metazachlor, propachlor, prynachlor, pretilachlor, benzoylprop-ethyl, flamprop-methyl/isopropyl (R-isomer), diflufenican

ii) Aliphatics (aldehydes) : Acrolein

iii) **Aliphatic acids :** MCA, TCA, dalapon

iv) **Azoles :** Bentazon, clomazone, oxadiazon, methazole, pyrazoxyfen, benazolin, amitrole, amitrole-T, carfentrazone, sulfentrazone

v) **Benzoic acids :** 2,3,6-TBA, 2,3,5,6-TBA, dicamba, tricamba, chloramben, chlorthal-dimethyl/ DCPA*

vi) **Benzonitriles/nitriles :** Dichlobenil, bromoxynil, ioxynil, chloroxynil, diphenatrile, cyanazine[*]

vii) Benzylethers/Cineoles : Cinmethylin

viii) **Bipyridiliums :** Diquat, paraquat, cypermequat, reglone

ix) **Carbamates & thiocarbamates :** Asulam, metham, sulfallate, barban, propham/IPC, chloropropham /CIPC, EPTC, diallate, triallate, butylate, pebulate, vernolate, benthiocarb

x) **Cyclohexanediones :** Alloxydim, clethodim, cycloxydim, sethoxydim, tralkoxydim

xi) **Dinitroanilines :** Benefin/benfluralin, butralin, fluchloralin, pendimethalin, nitralin, oryzalin, dipropalin, dibutalin, trifluralin

xii) **Dinitrophenols :** DNOC, DNAP/dinosam, DNBP/dinoseb, PCP, Na-PCP

xiii) **Diphenylethers :** Nitrofen, acifluorfen, oxyfluorfen, fomesafen, lactofen

xiv) **Heterocyclic compounds:** pyridate, MH, norflurazon, pyrazon, clopyralid, picloram, triclopyr, fluoroxypyr, dithiopyr, thiazopyr, fluridone, pyrichlor, quinclorac, quinmerac, dazomet/DMTT

xv) **Imidazolinones & imidazolidinones:** Buthidazole, imazamethabenz, imazapyr, imazaquin, imazethapyr, imazamox

xvi) Mercurics : PMA

xvii) **Organic arsenicals :** CA (cacodylic acid), CMA, MSMA, DSMA, MAMA

xviii) **Organophosphorus :** Fosamine-AM, glyphosate, sulfosate, glufosinate-AM, amiprofos-methyl, butamifos, anilofos, piperofos, DMPA(Zytron®), bensulide

xix) **Phenoxy (~ aryloxy) phenoxy propionates :** Diclofop-methyl, fluofenprop,fenoxaprop-p-ethyl, fluazifop-p-butyl, haloxyfop-2-ethoxyethyl, quizalofop-p-ethyl, clodinafop-propargyl

xx) **Phenoxyalkanoic acids :** 2,4-D, 2,4,5-T, MCPA, 2,4-DB, MCPB, dichlorprop/2,4-DP, mecoprop/MCPP, 2,4,5-TP/silvex/fenoprop

xxi) **Phenoxyethyl sulphates/phosphates :** 2,4-DES/sesone/disul-sodium, 2,4,5-TES, MCPES, 2,4-DEP, Erbon

xxii) **Phenylalkanoic acids :** Fenac/chlorfenac

xxiii) **Phenylureas :** Fenuron, monuron, diuron, linuron, isoproturon, chloroxuron, metoxuron, chlortoluron, metobromuron, methabenzthiazuron

xxiv) **Phthalic & phthalamic acids :** Flumiclorac-pentyl, flumioxazin, endothall, chlorthal-dimethyl[*], Naptalam/NPA[*]

xxv) **Pyrazoliums :** Difenzoquat

xxvi) **Pyrimidinyl-thiobenzoates :** Pyrithiobac-Na, bispyribac, pyriminobac-methyl, pyribenzoxim

xxvii) **Sulfonylureas :** Nicosulfuron, bensulfuron-methyl, chlorimuron-ethyl, chlorsulfuron, metsulfuron-methyl, primisulfuron-methyl, sulfometuron-methyl, triasulfuron, triflusulfuron

xxviii) **Triazines :** Atrazine, simazine, cyanazine[*], ametryn, simetryn, atratone, simetone, hexazinone, metribuzin, metamitron

xxix) **Triazolopyrimidine sulfonanilides :** Flumetsulam/DE 498, cloransulam-methyl, dicosulam, metosulam

xxx) **Uracils :** Bromacil, isocil, lenacil, terbacil

3.6.4 HERBICIDE RECOMMENDATION FOR FIELD CROPS

Herbicides tested for selectivity and recommended for effective weed control across crops in the country and those fairly available in the market have been summarized in Table 11.

Table 11. Herbicide recommendation towards weed control in crops

Crops	***Herbicides***	Dose (kg/ha)	Application time and remarks
Rice Nursery	Butachlor	1.0-1.5	Pre-emergence at 5-6 days after sowing (DAS); If moisture is less in soil, irrigation should follow immediately.
	Benthiocarb	"	--- do ---
	Pendimethalin	"	--- do ---
	Pretilachlor (S)	0.3-0.4	Pre-emergence at 3-5 DAS.
Direct-seeded Upland Rice	Butachlor	1.0-1.5	To be applied before emergence of crop; One hand weeding at 30-35 DAS will supplement herbicide treatment.
	Benthiocarb	"	--- do ---
	Pendimethalin	"	--- do ---
	Pretilachlor (S)	0.3-0.4	Pre-emergence at 3-5 DAS.
	Oxadiazon	0.5-0.75	Pre- or early post-emergence for controlling annual grasses, sedges and some broad-leaved weeds.
	Metsulfuron-methyl	0.010-0.015	Post-emergence at 30-35 DAS; basically a broad-leaved weed killer and recommended as a substitute of 2,4-D.
	Bentazon	1.0-2.0	Post-emergence at 30-35 DAS; basically a broad-leaved weed killer, but controls *Cyperus esculentus*, a problematic sedge; could be a substitute of 2,4-D.
Direct-seeded Puddled and Transplanted Rice	Butachlor	1.0-1.5	Pre-emergence at 3-5 days after transplanting (DAT) on saturated soil; No irrigation or standing water impounded for at least 3 days after treatment.
	Benthiocarb	"	--- do ---
	Pendimethalin	"	--- do ---
	Pretilachlor (S)	0.3-0.4	Pre-emergence at 3-5 DAT
	Anilofos	0.4	--- do ---
	Metsulfuron-methyl	0.010-0.015	Post-emergence at 30-35 DAS; basically a broad-leaved weed killer and recommended as a substitute of 2,4-D.
	Bentazon	1.0-2.0	At 30-35 DAT where broad-leaved weeds and sedges particularly Cyperus esculentus pose problem; could be a substitute of 2,4-D.
	2,4-D	0.5	To be applied at 30-35 DAT

	2,4-D	0.75-1.0	To be applied at 35-40 DAS/DAT, where broad-leaved weeds and sedges dominant. Field is to be drained before application and re-flooded after 2-3 days.
	Oxadiazon	0.5-0.75	Pre- or early post-emergence; soil surface should not be disturbed after its application.
Wheat	Isoproturon	0.75-1.0	At 30-35 DAS; cheap and highly economical herbicide; controls both grass and broad-leaved weeds; however, in Punjab, Haryana and Western U.P. of India, where *Phalaris minor* has developed resistance to this herbicide, it should not recommended for its control, but for controlling other weeds, its application in mixture with other herbicides or followed-by application may be advocated. The followed-by application, however, proves superior to tank-mix application.
	Clodinafop-propargyl	0.06-0.08	At 30-35 DAS; exclusively a grass killer herbicide and recommended for resistant *Phalaris minor* control; however, recently a large number of biotypes of *Phalaris minor* have shown cross-resistance to it in different parts of Punjab and Haryana and, therefore, its use may be restricted to areas where cross-resistance has not occurred; for broad-spectrum control of weeds, it should be followed by 2,4-D or isoproturon rather than its mixture with 2,4-D or isoproturon, which causes slight phytotoxicity to wheat.
	Sulfosulfuron	0.02-0.04	At 30-35 DAS; basically a grass killer and used against resistant *Phalaris minor*; can also control some broad-leaved weeds; for broad-spectrum control of weeds, it should be followed by 2,4-D or isoproturon rather than its mixture with 2,4-D or isoproturon, which causes slight phytotoxicity to wheat.
	FENOXAPROP-P-ETHYL	0.10-0.12	At 30-35 DAS; exclusively a grass killer one and recommended for resistant *Phalaris minor* control, however, its efficacy on resistant *Phalaris minor* has been a matter of controversy and, therefore, better not recommended; for broad-spectrum control of weeds, it should be followed by 2,4-D or isoproturon rather than its mixture with 2,4-D or isoproturon, which causes slight phytotoxicity to wheat.
	Diclofop-methyl	1.0	At 30-35 DAS; basically a grass killer and may be used against resistant *Phalaris minor*.

	Pendimethalin	1.0	Pre-emergence at 1-2 DAS; the surface soil must have adequate moisture when applied; controls annual grasses but not wild oat; may be used against resistant *Phalaris minor* too.
	Chlortoluron	1.5-2.0	Pre-emergence; controls annual grasses and broad-leaved weeds; to be applied to moist soil; not to be recommended for sandy soil, some wheat varieties may get injured.
	Metsufuron-methyl	0.004-0.008	At 30-35 DAS; exclusively a broad-leaved killer; could be a substitute of 2,4-D, which causes ear malformation in some wheat varieties, e.g. Arjun (HD 2009), Kundan.
	2,4-D	0.4-0.5	At 30-35 DAS; exclusively a broad-leaved killer with some sedge killing action; should not be used in sensitive varieties of wheat, e.g. Arjun (HD 2009), Kundan.
	Bentazon	1.0-2.0	At 25-30 DAT where broad-leaved weeds and sedges particularly *Cyperus esculentus* are dominant; it may substitute 2,4-D ; not to be applied if rain expected within eight hours.
Maize/ Sorghum/ Pearl millet	Atrazine	1.0-1.5	Pre-emergence at 1-2 DAS; broad-spectrum herbicide but basically a broad-leaved killer; early post-emergence application within 2 weeks after emergence in maize or at 20-25 DAS in sorghum is also recommended.
	Pendimethalin	1.0-1.5	Pre-emergence at 1-2 DAS; broad-spectrum, but basically a grass killer herbicide.
	Alachlor (use only in maize)	2.0-2.5	Pre-emergence at 1-2 DAS; broad-spectrum, but basically a grass killer; its use in sorghum may cause crop phytotoxicity.
	Metolachlor	1.0-1.5	Pre-emergence at 1-2 DAS; broad-spectrum, but controls mainly grasses; does not control *Rottboellia cochinchinensis*, but controls *Cyperus esculentus*; moist soil is a pre-requisite for its action.
	Atrazine + pendimethalin	0.75+0.75	Pre-emergence at 1-2 DAS; The tank-mix application controls a broad-spectrum of weeds and render maize field almost weed free.
	Atrazine + alachlor	0.75 +1.0	--- do ---
	Atrazine + metolachlor	1.0+1.0	--- do ---
	2,4-D	0.75	Post-emergence at 30-35 DAS.
	Bentazon	1.0-2.0	Post-emergence at 2-3 leaf-stage of maize; controls broad-leaved weeds effectively, but *Cyperus esculentus* moderately.

Pigeonpea/ Blackgram /Greengram	Fluchloralin	1.0	Applied as pre-plant incorporation (PPI) into soil; sprayed into soil before sowing of a crop followed by slight stirring of surface soil for incorporation into soil to reduce vapourization.
	Pendimethalin	1.0	Pre-emergence at 1-2 DAS;
	Alachlor	1.0	--- do ---
Chickpea/ Lentil/Pea	Fluchloralin	1.0	Applied as pre-plant incorporation (PPI) into soil; sprayed into soil before sowing of a crop followed by slight stirring of surface soil for incorporation into soil to reduce vapourization.
	Pendimethalin	1.0	Pre-emergence at 1-2 DAS.
Soybean	Metribuzin	0.50	Pre-emergence at 1-2 DAS.
	Pendimethalin	0.75-1.0	--- do ---
	Chlorimuron-ethyl	0.012	--- do ---
	Clomazone	0.75-1.0	--- do ---
	Alachlor	1.0-2.0	--- do ---
	Metolachlor	0.75-1.0	Pre-emergence at 1-2 DAS; broad-spectrum, but cannot control *Rottboellia cochinchinensis*, but controls *Cyperus esculentus*; soil moisture is a pre-requisite for its desired activity.
	Fenoxaprop-p-ethyl (Whip Super®)	0.06-0.08	Post-emergence at 14-21 DAS; only a grass killer one.
	Bentazon	0.8-1.0	Applied as post-emergence. It controls broad-leaved weeds and sedge.
	Metribuzin followed by lactofen	0.50 & 0.09 resp.	Metribuzin pre-emergence at 1-2 DAS followed by lactofen post-emergence at 14-20 DAS.
Rapeseed & Mustard	Fluchloralin	1.0	Applied as pre-plant incorporation (PPI) into soil; sprayed into soil before sowing of a crop followed by slight stirring of surface soil for incorporation into soil to reduce vapourization.
	Pendimethalin	1.0	Pre-emergence at 1-2 DAS.
	Isoproturon	0.75-1.0	--- do ---
	Oxadiazon	0.50	--- do ---
Groundnut/ Sunflower	Pendimethalin	1.0	Pre-emergence at 1-2 DAS.
	Fluchloralin	1.0	Applied as pre-plant incorporation (PPI) into soil; sprayed into soil before sowing of a crop followed by slight stirring of surface soil for incorporation into soil to reduce vapourization.
	Alachlor	1.0-2.0	Pre-emergence at 1-2 DAS.
	Oxadiazon (in sunflower)	0.5-1.0	Pre-emergence; to be applied on moist soil.
Sugarcane	Atrazine	2.0	Pre-emergence at 1-2 days after transplanting (DAT).

	Atrazine + Alachlor	1.0+2.0	--- do ---. The tank-mix application controls a broad spectrum of weeds and provides a long weed-free condition.
	Metribuzin	1.0-1.5	--- do ---
	2,4-D	1.0	Post-emergence at 35-40 DAT.
Cotton	Fluchloralin	1.0	As PPI treatment; to be incorporated into soil before sowing.
	Pendimethalin	1.0	Pre-emergence at 1-2 DAS on moist soil.
	Diuron	0.5-0.75	Pre-emergence; not to apply in coarse sandy soil; crop damage imminent if seeds are treated with systemic insecticide.
	Trifluralin	0.5-1.0	As PPI treatment; to be incorporated into surface soil immediately after application.
	Alachlor	1.5-2.0	Pre-emergence if nutsedge (*Cyperus sp*) is a problem.
	Metolachlor	0.75-1.0	Pre-emergence at 1-2 DAS; broad-spectrum, but does not control *Rottboellia cochinchinensis*, however, *Cyperus esculentus* is controlled; moist soil required for its activity; effect usually does not persist more than 30 days.
Potato	Pendimethalin	1.0	Pre-emergence at 1-2 days after planting (DAP); moisture in soil is essential for activity.
	Metribuzin	0.5	--- do ---
	Paraquat	0.5	Post-emergence at 5% sprouting of potato; delay in spraying beyond 5% sprouting may cause phytotoxicity to potato plants.
	Isoproturon	0.75-1.0	Pre-emergence at 1-2 DAP.
Tomato/ Brinjal	Pendimethalin	1.0	To be applied before transplanting followed by irrigation; one hand weeding at 35-40 DAT is supplementary to herbicide.
	Fluchloralin	1.0	--- do ---
	Metribuzin (in tomato only)	0.5	--- do ---. Avoid contact with tomato plants.
	Alachlor	2.0	Pre-emergence to weeds; to be applied before transplanting followed by irrigation; controls annual grasses and some broad-leaved weeds; one hand weeding at 35-40 DAT is highly useful.
Cabbage/ Cauliflower/ Knolkhol	Pendimethalin	1.0	To be applied before transplanting followed by irrigation.
	Fluchloralin	1.0	--- do ---
	Trifluralin	1.0	--- do ---
`	Pendimethalin	1.0	To be applied before transplanting followed by irrigation.
	Fluchloralin	1.0	--- do ---
	12	0.25	--- do ---
	Alachlor	1.0-2.0	Pre-emergence to weeds; application followed by irrigation and then transplanting done; one hand weeding at 35-40 DAT would be useful.

	Bentazon	1.0-1.5	Applied as post-emergence to control broad-leaved weeds and sedges.
Beet/Radish/ Carrot	Pendimethalin	1.0	To be applied after sowing but before emergence of weeds.

3.7 INTEGRATED WEED MANAGEMENT (IWM)

3.7.1 Rationale/Relevance of IWM

Weed management should aim at maximization of profit by reducing the risk of damage to crops and environment (soil and water). A large number of herbicides since their discovery has been evaluated and recommended (Table 11) for a large number of crops in India. They have replaced or in some cases supplemented traditional practice of hand weeding towards weed control and economization of overall production cost. The chemical method *albeit* proved more promising, has led to many problems such as weed flora shift, insurgence of herbicide-resistant weeds, gradual population built-up/preponderance of perennial weeds and inhibition in growth of non-target micro-flora besides residue problem in environment and marked reduction in tillage practice. Even the spectrum of weeds killed by herbicides, in most cases, is narrow. Herbicide, therefore, cannot be a sole and full-proof strategy. Thus, no single method, e.g. manual & mechanical, biological or chemical, could reach to the desired level of weed control efficiency in certain location or across locations mainly because of the vast diversity of weeds in crop fields. There also occurs a continuous dynamics both in population and biomass accumulation of weeds in crop-field ecosystem on temporal scale mainly due to changes brought about by man in crop cultivation/management practices (Das, 2001). It has been witnessed that today's weed of minor importance assumed importance gradually and became a major weed of regional or national concern in course of time. All these have led to the evolution of integrated weed management (IWM), which means maintaining/managing a population below a threshold level, which may not cause substantial economic damage to crops (Figure 5). IWM is a method whereby all economically, ecologically and toxicologically justifiable methods are employed to keep the harmful organisms below the threshold level of economic damage, keeping in the foreground the conscious employment of natural limiting factors (Jaya Kumar and Jagannathan, 2003). The concept is that it uses a variety of technologies in a single weed management with the objective to produce optimum crop yield at a minimum cost taking into consideration ecological and socio-economic constraints under a given eco-system. It is thus a more holistic approach for weed management in crops or cropping system combining two or more control methods (Noda, 1977). Weed biologists' contributions could be of immense value towards evaluation of the ecological factors that govern weed abundance, describe conditions and times when weeds are most vulnerable to management tactics, providing information to predict accurately the response of weeds to various controls, and elucidating the functional links between environment, weeds, crops, and other species.

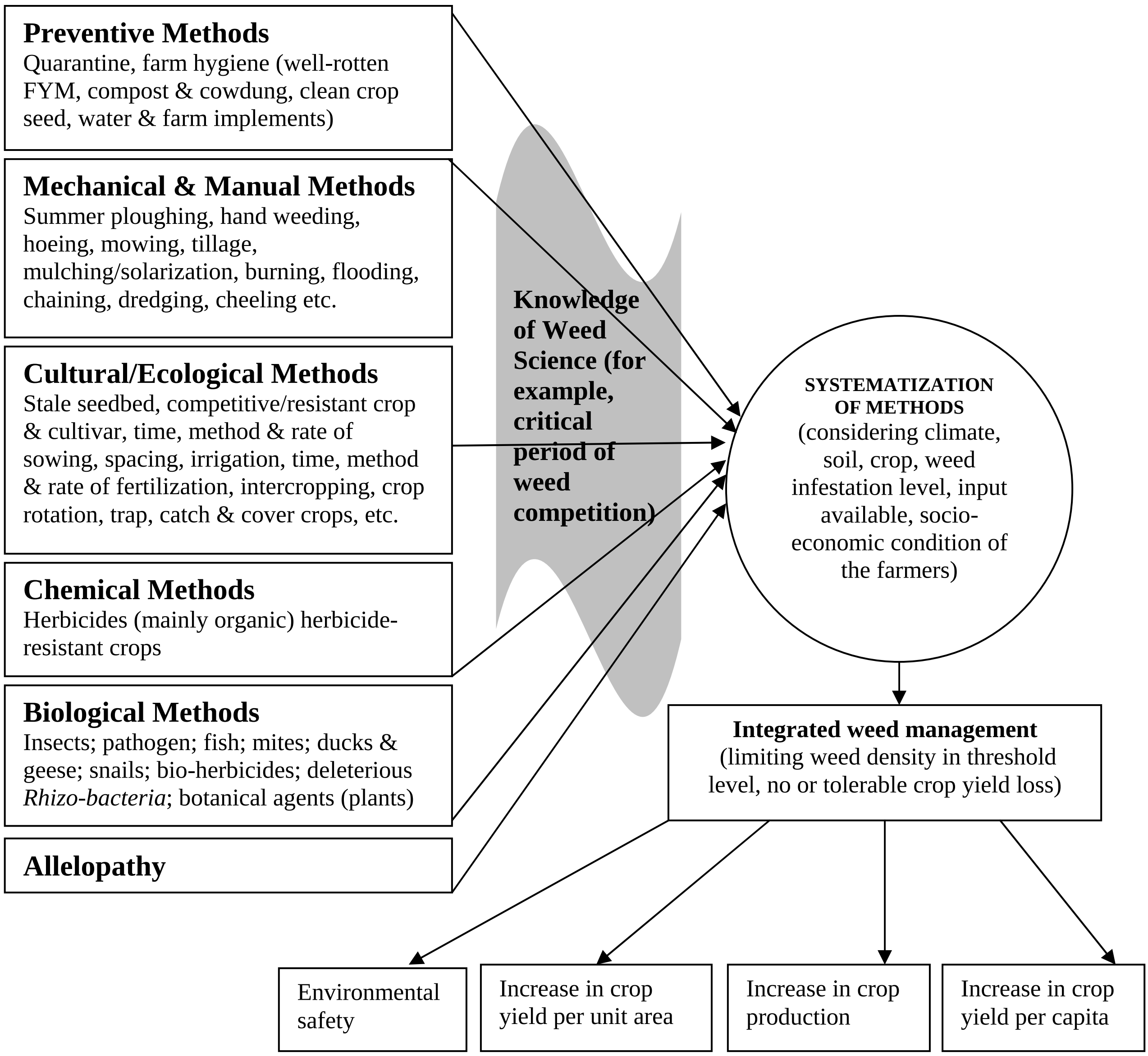

Figure 5. Schematic diagram of the integrated weed management system (Noda, 1977; modified by the author)

3.7.2 Usefulness/Advantages

i) IWM is considered a more practical approach more effective in the long run since combination of methods will take care of weeds in totality and prevents seed production of weeds and enrichment of soil seed bank.

ii) It provides longer and continuous control of weeds than any individual method since it normally overcomes the existing lacunae of individual method of weed control applied in isolation.

iii) It may reduce or eliminate the chance of occurrence of weed flora shift, herbicide-resistant weeds, preponderance of perennial weeds etc. in an agro-ecosystem.

iv) It is environment- or eco-friendly. Ill-effects on soil micro-flora & micro-fauna and degradation to environment (soil and water) through herbicide residues could be reduced by adopting IWM, which advocates using herbicides at the lowest possible rates.

v) It may to some extent be complementary to integrated pest management (IPM) through continuous control of weeds, which otherwise allow/cause many insect pests and diseases to harbour upon them.

vi) It may generate higher net income/return in the long run particularly under higher cropping intensity.

vii) It is much useful under high cropping intensity.

viii) It has enough flexibility/resilience that it can incorporate innovative and practical experiences of the farmers.

ix) It is developed for a whole farm, which includes field bunds, irrigation channels, roads/paths, and other non-crop surroundings on the farm and, therefore, prevents possible dispersion of weeds from adjoining bund, roads, channels etc.

3.7.3 Limitations/Disadvantages

i) An IWM approach may not be uniformly applicable to all crops across locations. It is highly site-specific and crop- or cropping system-specific based on a host of factors comprising of soil, crops, climate and production/management practices adopted.

ii) Integrating methods of weed control mutually compatible, supportive to each other and matching the diversity of weed species is not an easy task, but requires a lot of researches to be carried out on-farm for suitability/compatibility and economics and then proper refinement of the results for implementation and social acceptance. Otherwise, it cannot be a successful IWM strategy.

iii) A model IWM designed for certain situation may not be operative constantly or repetitive over the years since the relative importance of the methods under integration may vary at degrees in course of time based on weed species and population distribution and overall weed infestation. Need may arise in between to incorporate a new method or exclude an already existing method for a workable integration of weed control methods under certain situation.

iv) It is more of a concept and as such not a method of weed control in true/pure sense. Its efficiency may vary based on fluctuation in the efficiency of weed control methods integrated over time and space.

v) Integration of different methods of weed control may incur higher cost and may not evolve desired result on weed control front in the initial years and users may give up hope on IWM.

3.7.4 IWM Approach

Integrated weed management combines rational adoption/use of direct and indirect weed control strategies to take care of weeds in totality (i.e. to match the diversity of weed species in a situation). Direct weed control strategies include physical (manual & mechanical) and chemical means. Physical (manual & mechanical) means which prove useful towards integration and weed management are tillage/land preparation, deep summer tillage for management of perennial weeds in the off-season, manual weeding by hand tools or weeders, mechanical weeding by animal- or power-drawn weeders, mulching and soil solarization. Chemical mean includes effective use of herbicides (pre-emergence herbicides with adequate moisture, post-emergence herbicides (selective/non-selective with directed spray), selective herbicide for intercropping situation. It is fact that herbicide is an important component in IWM, but their doses should be restricted to low enough, which may not cause environmental degradation. Indirect control implies cultural or agronomic practices including weed management strategies designed to promote crop yield and suppress weeds (Bhowmik and Inderjit, 2003). These may include options like crop species & variety (competitive and adaptable high-yielding varieties to resist weed competition); ecological suppression of weeds by changing cropping systems or using sound crop rotation and/or better crop management techniques (e.g. optimum time, method & rate of sowing and spacing that provides optimum plant population and enhances crop growth; kind, time, method & rate of fertilization (precision in placement & timing of fertilizer); water management (time & method of irrigation); use of bio-agents. Integration of weed control methods should necessarily be based on their suitability, compatibility and feasibility under a specific crop-weed situation. Each method included has its own role to play in the overall weed management programme and its impact must be analyzed in relation to yield loss and weed population growth, subsequent spread, and possible future weed shift (Bhowmik and Inderjit, 2003). The methods chosen should be mutually compatible enough with each other, must support each other and match the diversity of weed species present in a crop field or a situation. They should be favourable to crop growth, but unfavorable to weeds (i.e. they must favour crop growth at the cost of weed growth) and should give effective and long-lasting/continuous control of weeds under a certain situation. Bhowmik and and Inderjit (2003) opined that if the component practices in IWM are to be considered viable, sustainable and environmentally safe, they must be evaluated in relation to the following guidelines :

What does the IWM component contribute to :

- Development of weed species abundance to reduce interference with crop.
- Dominance of a species in the composition of existing weed flora.
- Substitution of a species in the composition of existing weed flora.
- Change in succession of species.
- Change in genetic structure of the targeted species.
- Acceptance of weed management system in relation to environment.
- Enhanced profitability.
- Improvement of overall pest management at the farm level.
- Social acceptance of practices those are appropriate to stake holders.

Altieri and Liebman (1988) once reported that the present day literature on IWM is off track. There are very few papers dealing with the actual concept of IWM. They, however, put forward some considerations to follow while designing an IWM system. For example, i) crop monocultures seldom use all the environmental resources available for plant growth. The resulting ecological niches, therefore, are susceptible to invasion by weeds and should be protected; ii) weed populations are either active as photosynthesizing plants or dormant seeds. Thus the seed bank as well as the above-ground vegetation should be considered when determining weed abundance; and iii) the cropping pattern can be a powerful agent in reducing weed densities by preemption of environmental resources to crop plants. Such practices reduce selection pressure on weed communities and populations.

3.7.5 Probable IWM Across Crops

Probable IWM for different crops follows. These, however, require to be tested for a crop across situations differing in soil & climatic conditions and agronomic practices & cropping system/pattern followed. The refinement of the IWM practices, therefore, has to be made crop-wise and location-wise on temporal scale. The pre- and post-emergence herbicides across crops and their doses and time of application have been duly given in Table 11 and they may be referred/recommended on their requirement in a certain/specific crop.

i) Rice

a) Direct-seeded upland rice

Direct-seeded upland rice cultivation is gradually increasing in south-east Asia. It encounters heavy weed competition compared to direct-seeded puddled lowland rice or transplanted rice. Weed management is the most important consideration for successful cultivation of rice in this culture. The following can be considered towards IWM in this situation.

i) Good crop husbandry (deep summer tillage to control perennial *Cyperus*; land preparation by repeated ploughing on receipt of summer rain or stale seed bed to control annual weeds; clean rice seed free from seeds mainly of *Echinochloa colona, E. crusgalli and Cyperus difformis/iria*, reducing or avoiding basal nitrogen application) + pre-emergence herbicide (pendimethalin, butachlor, benthiocarb, anilofos, pretilachlor) at reduced rates + beushening/blind tillage + hand weeding later at 40-45 DAS.

ii) Good crop husbandry (deep summer tillage with residue incorporation and/or green manuring; good land preparation & stale seed bed; clean seed; reducing or avoiding basal nitrogen application + post-emergence herbicide (propanil, bentazon, 2,4-D) or hand weeding or cultivation at 30-35 DAS.

b) Direct-seeded puddled lowland rice

This rice culture being a lowland puddled situation experiences less weed competition compared to direct-seeded upland rice. In this culture, pre-germinated seeds are broadcast into puddled soil with standing water. The puddling followed by shallow standing water (5-10 cm) after emergence of crop reduces weed competition to a great extent. Beushening/blind tillage is not practised and hand weeding and cultivation prove impractical. Therefore, herbicides and other cultural practices need to be adopted. High seed rate reduces weed infestation to some extent. Residue incorporation with water hyacinth, parthenium and/or green manuring prove promising. Their combinations with herbicide may play a workable role.

i) Good crop husbandry (puddling, high seed rate, shallow standing water (5-10 cm), residue incorporation and/or green manuring) + pre-or post-emergence herbicides at reduced rates followed by hand weeding (in case of pre-emergence herbicide at 30-35 DAS), otherwise late (at 40-45 DAS in case of post-emergence herbicide).

c) Transplanted lowland rice

i) Good crop husbandry (summer ploughing, residue incorporation and/or green manuring, effective puddling/ land preparation, clean seedling/nursery management, shallow standing water (5-10 cm) + pre-emergence herbicide + hand weeding or rotavation at 30-35 DAT (days after transplanting). If *in situ* green manuring is practised concurrently with rice transplanted, pre-emergence herbicide should be selective to both rice and green manure crop. Otherwise, post-emergence herbicide may be adopted after incorporation of green manure crop into soil. Row transplanting necessarily becomes the pre-requisite for *in situ* green manuring in transplanted rice culture. A few centimeters of standing water during this growing period of rice helps the weed control process in a large way.

ii) Good crop husbandry (as mentioned above + high-density planting or skip row planting) + pre-emergence herbicide + fish cultivation under lowland condition (rice-cum-fish culture).

iii) Good crop husbandry (as mentioned above + high-density planting or skip row planting) + hand weeding at 15-20 DAT + post-emergence herbicide at 30-35 DAT.

ii) Wheat and barley

Stale seedbed, pure & clean crop seed, higher seed rate, closer row spacing, criss-cross sowing, skip row planting, fertilizer (mainly N and its high rate of application and placement along crop rows), zero tillage (under rice-wheat system) or FIRBS (furrow-irrigated raised bed system), soil solarization in the previous summer season - all have definite role in the overall weed management for wheat and barley. Their integration, however, should be mutually compatible and environmentally safe.

a) Good crop husbandry (stale seedbed, pure & clean crop seed, change in time of sowing, higher seed rate or closer row spacing, skip row planting /zero tillage (under rice-wheat system)/ FIRBS) + post-emergence herbicide (broad-spectrum or herbicide mixture). Usually post-emergence application proves more effective than pre-emergence application particularly for *Phalaris minor* and *Avena ludoviciana* (wild oat) control in wheat. If *Phalaris minor* has developed resistance to isoproturon, post-emergence clodinafop-propargyl, fenoxaprop-*p*-ethyl or sulfosufuron may be recommended in mixture or followed by application with 2,4-D, isoproturon or metsulfuron-methyl for broad-spectrum weed control. However, followed by application proves superior to tank-mixes or ready-mixes. Otherwise, separate hand weeding needs to be employed after application of clodinafop-propargyl, fenoxaprop-*p*-ethyl or sulfosufuron for broad-leaved weed control. Recently cross-resistance to clodinafop-propargyl, fenoxaprop-*p*-ethyl and to a very small degree to sulfosulfuron by *Phalaris minor* biotypes has been reported. This poses an alarming situation as far as cross-resistant *Phalaris biotypes* are concerned. Suitable herbicides alternative to these herbicides, therefore, need to be evaluated to control those cross-resistant *Phalaris* biotypes. Crop rotation, e.g. *rice - mustard/pea* instead of *rice – wheat* sequence may prevent the resistant as well as susceptible *Phalaris minor* to appear in the field.

b) Good crop husbandry (as mentioned above) + pre-emergence herbicides, namely pendimethalin (broad-spectrum or herbicide mixture) + hand weeding [for controlling problematic weeds namely *Convolvulus arvensis* (field bind weed), *Asphodelus tenuifolius* (wild onion), *Cirsium arvense* (Canada thistle), *Carthamus oxyacantha* (wild safflower) and *Cannabis sativa* (bhang)] later.

iii) Maize and sorghum

Good crop husbandry practices in maize and sorghum include land preparation/tillage; stale seed bed; time of sowing of crops (sowing in the last week of June with irrigation to suppress over-all weed growth under North-Indian condition or sowing in early July to reduce *Striga* infestation under Ethiopian condition); ridge & furrow methods of planting; optimum plant population (50,000-55,000 plants/ha in case of hybrids & 35,000-40,000 plants/ha for open-pollinated varieties of maize); fertilizer (mainly N) management (placement along the crop rows, higher N dose for *Striga* control, split application at the critical stages); management for stem borer, shoot fly (very important towards maintaining optimum plant population); intercropping with soybean, green gram & black gram (mainly with maize) or cowpea (with sorghum); wheat residue incorporation (6.0 t/ha). Thus the following IWM practices can be formulated.

a) Good crop husbandry (suitable combination of those mentioned above) + pre-emergence herbicide (atrazine, pendimethalin or atrazine + pendimethalin at reduced rates) + hand weeding at 35-40 DAS for broad-spectrum control of weeds. Of course, atrazine + pendimethalin mixture is highly capable of controlling a broad-spectrum of annual weeds in maize and sorghum. Sometimes *Cyperus rotundus/esculentus* (sedges) which are not controlled by these pre-emergence herbicides dominate in maize and sorghum fields after complete control of the annual weeds. Then hand weeding at 35-40 DAS proves highly beneficial.

b) Soil solarization during hot summer months + good crop husbandry (suitable combination of those mentioned above but no tillage/zero tillage after solarization) + pre-emergence herbicide (if required) + hand weeding (with little soil disturbance) at 35-40 DAS. Soil solarization with transparent polyethene film although proves effective, its high cost discourages its use mainly in the non-cash field crops.

iv) Pulses

Both rainy-season (*kharif*) and winter (*rabi*) pulses have generally short stature and slow growth at the beginning. Weeds compete faster at this stage and surpass the growth of crops. In absolute sense, application of a pre-emergence herbicide (Table 11) accompanied/followed by a hand weeding at 30-35 proves quite effective towards weed management in most pulses particularly winter pulses. In wet season pulses, periodicity of weeds is more frequent and, therefore, the number of hand weeding may possibly be increased to two depending on the growing duration of crops. The role of hand weeding is mainly to reduce competition from late-coming perennial sedges, e.g. *Cyperus rotundus* and grasses, e.g. *Cynodon dactylon*. There are post-emergence herbicides recommended for certain pulses (e.g. soybean) and their application may substitute hand weeding in those pulses, but not to be encouraged. Post-emergence herbicide application is less efficient than hand weeding on perennial grass and sedge control and often proves phytotoxic to crops even though they are selective. That is why, unlike cereals, post-emergence herbicide application is not encouraged in pulses and oilseeds. Several practices, e.g. soil solarization, mulching, repeated summer cultivation with irrigation, stale seedbed, crop residue incorporation along with several non-monetary inputs (appropriate variety, time, method & rate of sowing, placement and timing of fertilizers, etc) do influence weed competition in pulses. They may be suitably included in the integrated weed management schedule to maintain/contain weed population below threshold level. Thus based on periodicity and severity of weed infestation, the following may be advocated :

a) Wet season (*kharif*) pulses (cowpea, green gram, black gram, pigeon pea, soybean, French bean)

i) Repeated summer cultivation with irrigation and residue (wheat, maize) incorporation + stale seed bed + appropriate crop husbandry (non-monetary inputs) + pre-emergence herbicide (at low rate) + hand weeding at 30-35 DAS.

ii) Good crop husbandry (mentioned above) + pre-emergence herbicide + hand weeding at

30-35 DAS or post-emergence herbicides at selected pulses, e.g. soybean.

b) Winter season (*Rabi*) pulses (chick pea, pea, lentil, grass pea etc)

i) Good crop husbandry (mentioned above) including higher seed rate, maize/sorghum residue incorporation + pre-emergence or pre-plant incorporated herbicide + hand weeding at 30-35 DAS (for problematic weeds).

v) Oilseeds

a) Good crop husbandry (earthing-up for groundnut) + pre-emergence herbicide (early post-emergence herbicide namely isoproturon for mustard and rapeseed if required) + hand weeding at 30-35 DAS (for problematic weeds)

vi) Cotton

There are both rainfed and irrigated cotton in India. The wider row-space of cotton accompanied by its initial slow growth encounters heavy weed infestation during wet season (*kharif*). Growing high yielding varieties which require higher fertilization again adds extra weed problem/competition with cotton crop. Under this circumstance, weeds grow vigorously and establish quickly and eventually shade cotton growing slowly. Mechanical weeding is difficult in heavy cotton soils. Chemical and cultural methods need to be combined suitably towards better weed management. Several options like deep ploughing, timely sowing, paired-row cultivation allowing inter-space between paired rows for intercropping with green gram, black gram, lady's finger, onion, raddish etc., ridge & furrow method for sowing on the ridge and allowing furrow for irrigation, closer inter-row space by suitably adjusting intra-row spacing, fertilizer band application, etc have been found promising. There are also several pre-emergence/pre-planting herbicides recommended for cotton (Table 11) and their adoption would help to remove initial weed competition in cotton. Of them diuron is the most promising pre-emergence herbicide and is loosely held as "cotton herbicide." However, it should not be applied in sandy soil in high rainfall areas. Rain after application of diuron may affect cotton germination. Pre-planting herbicides like trifluralin or fluchloralin needs to incorporated into soil immediately after application. Both pre-emergence and pre-planting herbicides should be applied to soil having sufficient moisture for greater efficacy. Therefore, the following IWM combination may work well in cotton.

a) Good crop husbandry (suitable combination of the practices mentioned above as feasible and compatible) + pre-emergence or pre-plant incorporated herbicide + hand weeding at 35-40 DAS. Since cotton is a widely-spaced crop, hoeing/scraping of weeds may also be practised at the early stages (at 15-20 DAS) to replace or supplement the application of pre-emergence/pre-planting herbicides.

vii) Sugarcane

Sugarcane is the longest duration field crop grown for a period of 12 months (*ekshali*) or 18 months (*adshali*) in India. Its germination takes about one month. It gets heavily infested with weeds right from the germination to about 3-4 months. Weed competition at the early stages of sugarcane affects tillering, cane elongation, number of millable canes, cane yield and sucrose content. Recently parasitic *Striga sp* has also started infesting sugarcane.

Several options towards IWM of sugarcane could be blind hoeing (before cane sprouts to control weeds already emerged or on the process of germination), intercropping (with green gram/soybean/chick pea/black gram very useful), spreading filter pressmud as a manure and soil amendment (decrease fresh germination as well as growth of the germinated ones), flaming (effective concurrently but very costly), manual weeding/ mechanical weeding/ hoeing (by bullock-drawn blade hoe, weeder) or earthing-up (controls weeds as well as provide anchorage to sugarcane plants) and herbicides (Table 11). An IWM approach to sugarcane is as follows :

a) Good crop husbandry (timely planting with optimum population of setts; ridge furrow method; spreading filter pressmud or blind hoeing) + pre-emergence herbicide + hand weeding / mechanical weeding/ hoeing or earthing-up at 35-40 DAS and later.

b) Good crop husbandry (timely planting with optimum population of setts; ridge furrow method; intercropping with black gram/soybean/groundnut) + pre-emergence pendimethalin (0.75-1.0 kg/ha) or thiobencarb (1.0 -1.5 kg/ha) + earthing-up after harvest of the intercrop.

viii) Potato

In potato, land preparation and timely planting assume enough significance towards crop germination and weed control. Four-five thorough ploughings make a field well pulverized and provide fine seed bed to potato. Ridge planting followed by earthing-up or flat planting followed by ridging or earthing-up is the most important practice which keeps potato free of weeds. If it is done twice, would be the best. Hand weeding may be adopted to control weeds wherever required/applicable until 7-8 weeks after transplanting depending on the variety and growth of potato. Optimum fertilization with all three major nutrients (N, P & K) and split application of N & K may also be useful towards boosting up of crop growth & yield and smothering of weeds. Increased fertilization, however, induces lodging in potato. A number of herbicides (Table 11) have also been recommended for potato.

a) Good crop husbandry (suitable combination of those mentioned above) + pre-emergence herbicide + small-scale earthing-up or ridging (under ridge planting).

b) Good crop husbandry (ridge planting) + paraquat at 2-5% sprouting of potato (post-emergence) + small-scale earthing-up/ridging or hand weeding at 30-35 DAS (under ridge planting).

c) Good crop husbandry + pre-emergence herbicide or paraquat at 2-5% sprouting of potato (post-emergence) + earthing-up at 35- 40 DAS (under flat sowing).

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