

Eco-Friendly Weed Control Options for Sustainable Agriculture

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ABSTRACT

Background: Weeds are unwanted plants playing a very important role in different eco-systems and many of them cause enormous direct and indirect losses. The losses include interference with cultivation of crops, loss of biodiversity, loss of potentially productive lands, loss of grazing areas and livestock production, erosion following fires in heavily invaded areas, choking of navigational and irrigation canals and reduction of available water in water bodies. Weed management takes away nearly one third of total cost of production of field crops. In India, the manual method of weed control is quite popular and effective. Of late, labour has become non-availability and costly, due to intensification, diversification of agriculture and urbanization. The usage of herbicides in India and elsewhere in the world is increasing due to possible benefits to farmers and continuous use of the same group of herbicides over a period of time on a same piece of land leads to ecological imbalance in terms of weed shift and environmental pollution. The complexity of these situations has resulted in a need to develop a wholistic sustainable eco-friendly weed management programme throughout the farming period. **Objectives:** This study reviews the different approaches used in sustainable weed control options. **Conclusion:** Sustainable farming has the ability to save the natural resources for the future and develop the farm in the little expense, a transition to sustainable weed control is required for environmental, social and economic reasons and sustainable weed management is socially acceptable, environmentally benign and cost-effective.

Key words: Sustainable agriculture, weed control options, eco-friendly environment

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INTRODUCTION

Weeds are considered to be a potential pest causing more than 45% loss in yields of field crops, when compared to 25% due to diseases, 20% due to insects, 15% due to storage and miscellaneous pests and 6% due to rodents. Weed management takes away nearly one third of total cost of production of field crops. In India, the manual method of weed control is quite popular and effective. Of late, labour has become non-availability and costly, due to intensification, diversification of agriculture and urbanization. The usage of herbicides in India and elsewhere in the world is increasing due to possible benefits to farmers. At the same time, the continuous use of the same group of herbicides over a period of time on a same piece of land leads to ecological imbalance in terms of weed shift, herbicide resistance in weeds and environmental pollutions. Treatments of herbicides for controlling aquatic weeds in a pond also reduce dissolved oxygen and pH and increase biological oxygen demand¹. Herbicide application may also kill species of bacteria, fungi and protozoa that combat

disease causing microorganisms, thereby upsetting the balance of pathogens and beneficial organisms and allowing the opportunist, disease causing organisms to become a problem². The complexity of these situations has resulted in a need to develop a wholistic sustainable eco-friendly weed management programme throughout the farming period. Sustainable development is the management and conservation of the natural resource base and the orientation of technological and institutional change in such a manner as to ensure the attainment and continued satisfaction of human needs for present and future generations. Such sustainable development conserves land, water, plant and animal genetic resources, is environmentally non-degrading, technically appropriate, economically viable and socially acceptable³. With respect to the environment, society and economics, sustainable agriculture would, (1) Not harm the environment from pollution, (2) Not be reliant on non-renewable inputs or degrade renewable ones, (3) Nourish people with non-toxic, healthy food and other useful feed stocks and (4) Provide a fair, steady,

return on effective investment in labor and capital. Sustainable weed management is the use of weed control methods that are socially acceptable, environmentally benign and cost-effective. An attempt has been made to review the different approaches used in sustainable weed control options, in this study.

OBJECTIVES OF SUSTAINABLE WEED MANAGEMENT

There are several basic objectives of the sustainable weed management. The main objectives are:

- To make best use of the resources available for weed control
- To develop cultivation methods that manage weeds and improve soil quality and to determine the impact of weed management systems
- To minimize use of non-renewable resources like herbicides and to use of renewable energy and recycled mineral resources
- To protect the health and safety of farm workers and animals, local communities and society from the application of chemicals
- To protect and enhance the environment and natural resources
- To protect the economic viability of farming operations
- To provide sufficient financial reward to the farmer to enable continued production and contribute to the well-being of the community
- To produce sufficient high-quality and safe food
- To build on available weed control technology, knowledge and skills in ways that suit local conditions and capacity

APPROACHES INVOLVED IN SUSTAINABLE WEED MANAGEMENT

There are three different approaches involved in sustainable weed control management. The different approaches are reviewed in the context of the cultural, mechanical and biological methods, respectively.

Cultural approaches

Proper crop stand: Crop population, spatial arrangement, right method and time of sowing, adequate seed rate and the choice of cultivar (variety) are essential to limit the weed growth. Any crop variety that is able to quickly shade the soil between the rows and is able to grow more rapidly than the weeds will have an advantage in weed management. Studies have shown that narrow row widths and a higher seeding density will reduce the

biomass of later-emerging weeds by reducing the amount of light available for weeds located below the crop canopy. Similarly, fast growing cultivars can have a competitive edge over the weeds. Planting pattern is a cost effective technique that modifies the crop canopy structure and micro-climate enhances crop competitiveness in weed suppression, improves the resource use efficiency and maximizes crop productivity⁴. It was reported that combination of early sowing (October 25) with quicker growing wheat var (PB 154, 343, 542) significantly smothered *Phalaris minor*⁵. Rice variety PR 108 exhibited greater smothering effect on weeds but PR 118 obtained maximum grain yield as compared to PR 108, 114, 116 grown under puddled conditions. The index of competition was lower in the cultivars Avarodhi and Pant G114 as compared to the cultivar Radhney in Chick pea⁶. Closer spacing, early planting and increasing the fertilizer rates are observed to increase crop yields and reduce weed populations in barley and wheat under small farming systems of semi-arid regions⁷. The plant population and dry matter production of weed *Tagetes* sp. were significantly lower in the narrow spacing than wider spacing and control⁸. The plant population of 50 plants m⁻² was found to be significantly superior to 33 and 25 plants m⁻² as it recorded significantly less weed dry matter and highest grain yield compared to other plant population levels⁹. Planting pattern with closer spacing of 60×20 cm with 83,333 plants ha⁻¹ proved to be very effective in suppressing weeds, by recording the least density of grasses, sedges and broad leaved weeds in sweet corn¹⁰.

Green manure *in situ*: A practice of ploughing or turning into the soil undecomposed green manure crops in the same field where the crop is grown. Green manure crops are commonly associated with organic agriculture and are considered essential for annual cropping systems that wish to be sustainable. Traditionally, the practice of green manuring can be traced back to the fallow cycle of crop rotation, which was used to allow soils to recover. Green manures usually perform multiple functions that include soil improvement and soil protection. In addition to soil improvement, green manuring is also used for weed suppression in cropping systems. Raising green manure *Sesbania aculeata* in the preceding off-season and ploughing *in situ* before puddling reduced the weed counts and increased the weed control index in the succeeding rice crops due to smothering effect of green manure on the emergence and growth of weeds¹¹.

Sowing of green manure seeds in between rice row, serves as a green manure and checks weed growth¹². The weed control efficiency was higher when maize was raised with green manure (cowpea) as intercropping¹³. In rice-wheat cropping systems, inclusion of *Sesbania* in summer resulted in least grasses and sedges in the succeeding crops¹⁴.

Intercropping: Growing of two or more generally dissimilar crops simultaneously on the same piece of land, in distinct row arrangement is known as intercropping. Intercropping and cover cropping are practices that increase diversity in the cropping system and enhance the utilization of resources such as light, heat and water. These practices can also help to suppress weeds and increase the likelihood of being able to reduce herbicide use in the cropping system. Alternatively, in organic or other systems where herbicides are not used, intercropping and cover cropping can reduce the yield loss potential and provide stability in the system. Research and experience from around the world have shown that intercropping and cover cropping systems tend to suppress weeds better than sole cropping systems¹⁵. Maize+Cowpea intercropping system recorded the highest weed control efficiency of 90.6% at 60 days after sowing. It was followed by maize+blackgram intercropping system¹⁶. The highest weed control efficiency, test weight and grain yield were found intercropping of blackgram with maize followed by manual weeding¹⁷. The grain yield, productivity ratio index, production efficiency and weed control efficiency were highest under maize+blackgram (2:1) for maize; however weed smothering efficiency of maize was highest under maize+blackgram (1:1)¹⁸. Dual cropping of *Sesbania aculeata* with drum seeded rice reduced total weed density and weed biomass as compared to other method of seeding¹⁹.

Crop rotation: Crop rotation is an important component of integrated weed management. The choice and sequencing of crops affect long term weed population dynamics and consequently weed management. Crop rotation is a planned sequence of crops growing in the same field year after year. Rotating crops adds diversity to the cropping system, increasing the sustainability of the system. Crop rotation provides the foundation for long-term weed management. Planting a wide variety of crops with varied characteristics reduces the likelihood that specific weed species will become adapted to the system and become problematic. The success of rotation systems for weed

suppression appears to be based on the use of crop sequences that employ varying patterns of resource competition, allelopathic interference, soil disturbance and mechanical damage to provide an unstable and frequently inhospitable environment that prevents the proliferation of a particular weed species¹⁵. Crop rotation can also slow the development of herbicide resistant weeds²⁰. The crops like sorghum, maize, barley, rye, sweet clover, sunflower, rape seed, soybean, alfalfa, cowpeas and hemp has smothering effect on various weed species through crop interference. Soybean and sunflower planted without tillage into desiccated rye mulch give over 90% reduction in the biomass of *Chenopodium album*, *Amaranthus retroflexus* and *Ambrosia artemisiifolia* compared to tillage and no rye. Mungbean-mustard cropping sequence resulted in high return and benefit-cost ratio than fallow mustard, by recoding least weed counts and weed biomass²¹.

Organic manures: A byproduct of the processing of plant and animal matter that has sufficient nutrient capacity to have value as fertilizer. Pressmud is one of the byproducts of the sugar industry. Pressmud is obtained in sugar factories to a tune of 2% of the weight of sugarcane crushed. Pressmud contains sizable quantity of macro and micro nutrients, besides 20-25% of organic carbon. In addition to the manurial value of pressmud, it destroys the weed seeds and seedlings due to reduced soil pH and allelochemicals produced from the native microbes of pressmud. Significant weed control and increased the yields of rice were reported from pressmud 10 t ha⁻¹ applied alone and the same was reported to synergistically interact with herbicide²². Application of pressmud at higher dose of 20 t ha⁻¹ performed superior by suppressing weed growth and favourably influencing growth and yield characters of rice²³. Pressmud incorporation at 10 t ha⁻¹ before puddling and azolla inoculation at 1 t ha⁻¹ on 7 days after transplanting contributed lesser weed counts and highest weed control index in succeeding rice crops due to the destruction of weed seeds and seedling¹¹. Application cane pressmud and neem cake reduced the weed seed bank of *Cyperus rotundus*, *Echinochloa colonum* and *Trianthema portulacastrum* in maize, due to reduced pH and phytotoxic properties of organic manures^{24,25}.

Mechanical approaches

Off-season ploughing: Ploughing operations carried out in the off-season with the help of tractors or bullock drawn implements known as off-season ploughing, before the crops are sown or transplanted. Off-season

ploughing was very effective in reducing the weed population in succeeding rice crop as tubers and weed seeds are exposed to scorching sun and a highly unfavourable environment, with eventual destruction of their perennation²⁶. Summer ploughing increased the total buried weed seed population by 3-4 times compared to no-ploughing²⁷. Off-season ploughing twice at 45 days interval was found to be superior in reducing the population of weeds; *Cyperus rotundus*, *C. difformis*, *Sphenoclea zeylanica* and *Fimbristylis littoralis* and highest weed control index in succeeding rice crops. Mechanical destruction of existing weed vegetation in the summer and exposure of reserves of weed seeds or propagules and subsequent scorching contributed for superior performance of summer ploughing in controlling weeds during succeeding crop seasons¹¹.

Soil solarization: Soil solarization is a method of hydrothermal disinfection accomplished by covering moist soil with transparent polyethylene (TPE) film during the hot summer months. Solarization during the hot summer months can increase soil temperature to levels that kill many disease-causing organisms (pathogens), nematodes and weed seed and seedlings. It leaves no toxic residues and can be easily used on a small or large scale. Soil solarization also improves soil structure and increases the availability of nitrogen and other essential plant nutrients. The basic phenomenon helping weed control upon soil solarization is build up of lethally high temperatures in top soil where most of the dormant and viable weed seeds are present. The possible mechanisms of weed control by soil solarization are breaking dormancy of weed seeds and solar scorching of emerged weeds and direct killing of weed seeds by heat. Soil solarization increases soil temperatures by 8-12°C over the corresponding non-mulched soil²⁸. Rhizomes of perennial weeds may be controlled by solarization, if they are not deeply buried. Solarization for two successive years was most effective in suppressing the perennial weeds. Soil solarization with the use of 0.05 mm transparent polyethylene sheets for 40 days was effective in controlling weeds than the use of 0.1 mm thickness polyethylene sheet and the lesser duration of soil solarization. Soil solarization with 0.05 mm thickness for 40 days recorded significantly higher pod yield of ground nut and least weed seed reserves in the top 5 cm soil²⁹.

Stale seed bed: It is the technique in which the weed seeds are allowed to germinate by rain or wetting and killing them (at 1-2 flushes of the weeds) before sowing

seeds of main crops. At this stage a shallow tillage or a non-residual herbicide like paraquat may be used to destroy the dense flush of young weed seedlings. This may be followed immediately by sowing a desired crop. The main objective with this technique is that most of the weeds that have the potential to germinate, because of their placement in the upper 1" to 2" of the soil, will usually do so within two weeks after the soil is prepared. Adequate soil moisture and temperature (at least 50°F at a depth of 2") must be present. The technique can be utilized in early spring, when the weather is still too cold for proper seed germination. Several passes are made with a rototiller or plow and then weed seeds are allowed to germinate as weather permits. By tilling, the farmer increases the chance of weed seed germination by the same method as one would for favorable vegetable/crops. The fine soil allows weed seed to grow rapidly by allowing the seed to open and the roots to spread easier than in compacted soil. Deep tilling will also bring dormant seed to the surface for germination. Some species of plant are known for seeds that can lay deeply buried in the soil for years before favorable conditions allow germination. Spike tooth harrow is a very useful implement for destroying the emerging weeds during the preparation of stale-beds. Soybean sowing, using stale seedbed techniques, by killing the first or second flush of weeds resulted in higher soybean yield³⁰. Adopting stale seedbed techniques either for 7 or 14 days (by keeping field drained and destruction of weeds by letting in water on 14th day) significantly reduced the population of grassy and broad leaved weeds and improved grain and straw yield of wet seeded rice compared to normal seed bed³¹.

Use of weeders: Now a days, use of mechanical weeders in agricultural operations is increasing because of non-availability of labours for weeding. The cost of the weeding operations is also reduced by using the machineries for weeding. The machineries like mini-weeders, power tillers, mini-tractor drawn rotavator are used for weeding in wider spaced crops like sugarcane, cotton and orchards. Since the wider spacing of 5-6 feet is practiced Sustainable Sugarcane Initiatives (SSI), mini-tractor drawn rotavator can be used for effective controlling all types of weeds in sugarcane. Cono weeder is used for controlling the wet land weeds and getting more yields in the System of Rice Intensification (SRI). The mini weeder and power tillers are used for controlling different types of weeds in cotton crop. Moreover, different types of weeding implements are available for weeding operations in

various field and horticultural crops. Small farm implements and machine i.e., power tiller, marker and cono weeder played very imperative role in controlling weeds, enhancement of productivity and reduction in drudgery in SRI³². The cono weeder incorporation of dhaincha and azolla resulted in higher weed control during early stages of rice crop.

Mulching: Mulches are coverings placed on the surface of the soil. Mulching smothers the weeds by excluding light and providing a physical barrier to impede their emergence. Any material such as straw, plant residues, leaves, loose soil or plastic film can be used as a mulching material. Such materials as straw, bark and composted material can provide effective weed control. Producing the material on the farm is recommended since the cost of purchased mulches can be prohibitive, depending on the amount needed to suppress weed emergence. An effective but labour-intensive system uses newspaper and straw. Two layers of newspaper are placed on the ground, followed by a layer of hay. It is important to make sure the hay does not contain any weeds seeds. Organic mulches have the advantage of being biodegradable. Cut rye grass mulch spread between planted rows of tomatoes and peppers was more economic than cultivation. Materials such as black polyethylene have been used for weed control in a range of crops in organic production systems. Plastic mulches have been developed that filter out photosynthetically active radiation but let through infrared light to warm the soil. These infrared transmitting mulches have been shown to be effective at controlling weeds. The new approach of using rice straw for controlling weeds in different crops indicated that rice straw can be used for mulch, which benefits in preventing weed growth as well as supplies organic matter for N-fixation by heterotrophic N-fixing microorganism³³. News papers and black polythene are recommended for the environmental friendly and sustainable control of weeds and realizing good yields of edible pea³⁴. Surface application of rice residues at 6 and 7 t ha⁻¹ significantly reduced population, dry matter production and leaf area index of *Phalaris minor* as compared to straw removal and incorporation treatments, in wheat^{35,36}.

Biological approaches

Allelopathic plants: The concept of allelopathy is receiving increased attention in the search for weed control strategies. Allelopathy is any direct or indirect effect by one plant, including micro-organisms, on another through production of chemical compounds

that escapes into the environment to influence the growth and development of neighboring plants³⁷. Plant releases chemicals that show allelopathic potentiality are called allelochemicals or allochemicals³⁸. It covers a wide range of chemicals used by plants or organisms. Generally different plant organ such as plant tissues, including leaves, flowers, fruits, stems, roots, rhizomes, seeds and pollen are the main sources of allelochemicals of donor plants are in stressed or competing with neighboring plants, that released through crop-environmental ecological process³⁹. Allelochemicals or natural compounds have more benefits over synthetic compounds as they have novel structure and short half-life, therefore considered safe of environmental toxic⁴⁰. Therefore, allelopathy mechanism can be applicable as a component of sustainable weed management. There are many plant species have allelopathic potential to control the aquatic weeds effectively. Rice cultivar ADT 36 was moderately allelopathic and reduced the weed biomass by 33.4 and 32.0% in laboratory bioassay and micro pond, respectively. Allelopathic cultivars of rice can control both monocot and dicot weeds under field conditions with some selectivity observed amongst such weeds, suggesting that certain compounds with selective action might be implicated in rice allelopathy^{41,42}. Weed population was lower at all doses of rice straw incorporated and it can also be utilized for producing new group of natural herbicides⁴³. Dry leaf powder and flower powder of *Parthenium hysterophorus* at 0.5% (w/v) kills water hyacinth within one month⁴⁴. An Indian medicinal herb *Coleus amboinicus/aromaticus* shows remarkable allelopathic inhibition of water hyacinth. The aquatic weed of *Eichhornia crassipes* can be effectively controlled by the integrated approach of releasing the insect agents *Neochetina* spp., with an adequate inoculation loads of 2 insects plant⁻¹ followed by the spraying of aqueous leaf powder extract of *C. amboinicus/aromaticus* at 25% concentration, 10 days later on the weed canopy⁴⁵. A number of crop plants with allelopathic potential can be used as cover, smother and green manure crops for managing weeds by making desired manipulations in the cultural practices and cropping patterns. These can be suitably rotated or intercropped with main crops to manage the target weeds selectively. Sunflower was reported to inhibit the growth of weeds *Sinapis arvensis* and *Setaria viridis* in terms of root and shoot length and seedling dry weight⁴⁶. The list of allelopathic crops and weeds to interfere with different weeds are given in Table 1 and 2.

Table 1: Allelopathic crops to interfere with different weeds

Crop	Weeds
<i>Sorghum bicolor</i>	<i>Abutilon theophrasti</i> , <i>Amaranthus retroflexus</i> and <i>Portulaca oleracea</i>
<i>Oryza sativa</i>	<i>Monochoria vaginalis</i> and <i>Echinochloa crusgalli</i>
<i>Triticum aestivum</i>	<i>A. retroflexus</i>
<i>Triticum speltoides</i>	<i>Avena fatua</i>
<i>Stylosanthes guianensis</i>	<i>Desmodium adscendens</i>
<i>Capsicum annum</i>	<i>Solanum nigrum</i> , <i>A. retroflexus</i> and <i>Chenopodium album</i>
<i>Secale cereale</i>	<i>E. crusgalli</i> and <i>Epilobium ciliatum</i>
<i>Helianthus annuus</i>	<i>E. colonum</i>
<i>Coleus amboinicus/aromaticus</i>	<i>Eichhornia crassipes</i>

Table 2: Allelopathic weeds to interfere with other weeds

Weeds	Weeds
<i>Acalypha indica</i>	<i>Eichhornia crassipes</i>
<i>Trianthema portulacastrum</i>	
<i>Parthenium hysterophorus</i>	
<i>Sesbania grandifolia</i>	
<i>Ottelia alismoides</i>	
<i>Argemone maxicana</i>	<i>Cyperus rotundus</i>
<i>Eupatorium adenophorus</i>	<i>Lantana camara</i>
<i>Mikania micrantha</i>	<i>Cyperus sp.</i> , <i>Imperata cylindrica</i>
<i>Imperata cylindrica</i>	<i>Echinochloa colonum</i> , <i>Phalaris minor</i> and <i>Portulaca oleracea</i>

Bio-fertilizers: Bio-fertilizers are defined as preparations containing living cells or latent cells of efficient strains of microorganisms that help crop plants' uptake of nutrients by their interactions in the rhizosphere when applied through seed or soil. They accelerate certain microbial processes in the soil which augment the extent of availability of nutrients in a form easily assimilated by plants. Azolla is a free-floating water fern that floats in water and fixes atmospheric nitrogen in association with nitrogen fixing blue green alga *Anabaena azollae*. Azolla fronds consist of sporophyte with a floating rhizome and small overlapping bi-lobed leaves and roots. Dual culturing of azolla in rice fields had the added benefit of suppressing weed growth besides fixing atmospheric nitrogen. Since it formed a mat over the surface, it reduced the entry of sunlight and aeration into soil thereby suppressing weed growth. The addition of azolla in rice fields suppressed the weeds of *Echinochloa crusgalli* and *Cyperus difformis* and the degree of suppression increased with increase in per cent of azolla cover and water depth⁴⁷. Application of pressmud at 10 t ha⁻¹+azolla at 1 t ha⁻¹ recorded the least weed count and highest weed control index in rice crop, as the thallus growth formed a thick mat on the surface of water, curtailing the interception of light by weed seeds and seedlings¹¹.

Insect bio-control agents: Bio-control of weeds is the deliberate use of natural enemies to reduce the densities of the weeds economically or aesthetically tolerable limits. Insects are important in biological control because of their, (1) Great variety and numbers, (2) High degree

of host specialization, (3) Intimate adaption to their host plants, (4) Availability of a range of natural enemies suited to particular ecological situations and (5) Ease with which they can be handled. There are two kinds of biological control: Classical and inundative. In classical biological, once the agents are well established there is no need to make further releases as they persist forever. But, in inundative biological control large quantities of agents are released to control the target weeds. Biological agents are increasingly being seen as a feasible solution to the problem. The research effort in the use of fish to control excessive aquatic weed growth in irrigation canal has steadily gained ground in recent years⁴⁸. The list of weed species controlled by insect agents is given in Table 3.

Bio-herbicides: Weeds can be controlled by pathogens like fungi, bacteria, viruses and virus like agents. Among the classes of plant pathogens, fungi have been used to a larger extent than bacteria and virus or nematode pathogens. A bio-herbicide is a preparation of living inoculums of plant pathogens formulated and applied in a manner analogous to that of an herbicide in an effort to control or suppress the growth of weed species. The development of a bio-herbicide involves three major phases, (1) Discovery, (2) Development and (3) Deployment⁴⁹. The discovery phase involves the collection of diseased plant material, isolation of the causal organism, demonstration of Koch's postulates, identification of the pathogens, culture of the pathogens on artificial media and maintenance of the pathogen culture in short-term and long-term storage.

Table 3: List of weed species controlled by insect agents

Weed species	Agents used to control
<i>Salvinia molesta</i>	<i>Cyrtobagous salviniae</i> <i>Paulinia acuminata</i>
<i>Eichhornia crassipes</i>	<i>Neochetina eichhorniae</i> <i>N. bruchi</i> <i>Orthogalumna terebrantis</i> <i>Sameodes albigitallis</i>
<i>Alternanthera philoxeroides</i>	<i>Agasicles hygrophila</i>
<i>Ludwigia adscendens</i>	<i>Altica cyanea</i>
<i>Pistia stratiotes</i>	<i>Namangana pectinicornis</i>
<i>Opuntia</i> spp.	<i>Dactylopius ceylonicus</i> <i>D. opuntiae</i> <i>Dactylopius tomentosus</i> , <i>D. indicus</i>
<i>Lantana camara</i>	<i>Ophiomyia lantanae</i> <i>Crocosema lantana</i> , <i>Teleonemia scrupulosa</i>
<i>Parthenium hysterophorus</i>	<i>Zygomma bicolorata</i>
<i>Cyperus rotundus</i>	<i>Bactra verutana</i> <i>Athesapaeuta cyperi</i>
<i>Orabanche</i> spp.	<i>Phytomyza orobanche</i>
<i>Tribulus terrestris</i>	<i>Microlarinus hypiriformis</i> , <i>M. laireyui</i>
<i>Solanum elaeagnifolium</i>	<i>Frumenta nephalomicta</i>
<i>Hydrilla</i> , <i>Azolla</i> , <i>Lemna</i> , <i>Potamogeton</i>	<i>Ctenopharyngodon idella</i>
Algae	<i>Tilapia</i> sp.

The development phase involves the determination of optimum conditions for spore production, determination of optimum conditions for infection and disease development, determination of host range, elucidation of mechanism of action of the pathogen and/or toxin and quantification of the efficacy of the bio-herbicide as control option. The final phase, deployment, often involves close collaboration between researchers, farmers and the industrial sector for the production, possible commercialization and use of bio-herbicides, formulation, fermentation, regulating aspects, marketing and implementation are essential aspects of this phase.

Herbicide-resistant weed biotypes will eventually develop after repeated applications of the same herbicides in a given field. For example, glyphosate resistant *Lolium rigidum* developed after repeated use of glyphosate in an orchard to control grass weeds⁵⁰ as herbicide resistant becomes more problematic with many common weeds, strategies using bio-herbicides will become more important in maintaining adequate weed control in conventional systems. The potential for successful use of bio-herbicides in managing herbicides-resistant biotypes was demonstrated where growth of an imazaquin-resistant common cocklebur biotype originating soybean field was suppressed with the mycoherbicides, *Alternaria helianthi*⁵¹. The fungus *Colletotrichum gleosporioides* attack cuscutta⁵² and has been used to control cuscutta selectively in soybean⁵³. *Fusarium oxysporum* was found to be the best resulting in killing of inoculated water hyacinth in about 15 days⁵⁴. The list

different bio-herbicides available for controlling weeds are given in the Table 4.

Herbicide resistant crops: Herbicide resistance is the inherited ability of the plant to survive and reproduce following exposure to a dose of herbicide that would normally be lethal to the wild type. In a plant, resistance may occur naturally due to selection or it may be induced through such techniques as genetic engineering. The adoption of Genetically Modified (GM) crops has increased dramatically during the last 10 years and currently over 52 million hectares of GM crops are planted world-wide. Approximately 41 million hectares of GM crops planted are herbicide-resistant crops, which includes an estimated 33.3 million hectares of herbicide-resistant soybean. Herbicide-resistant maize, canola, cotton and soybean accounted for 77% of the GM crop hectares in 2001. However, sugarbeet, wheat and as many as 14 other crops have transgenic herbicide-resistant cultivars that may be commercially available in the near future. There are many risks associated with the production of GM and herbicide-resistant crops, including problems with grain contamination, segregation and introgression of herbicide-resistant traits, market place acceptance and an increased reliance on herbicides for weed control.

Integrated weed management: One of the definitions of Integrated Weed Management (IWM) implies methods of controlling weed that require no herbicide or rational use of herbicides⁵⁵. IWM includes

Table 4: List of microorganisms used in bio-herbicides and their target weeds and ecosystems

Microorganism	Target weed	Ecosystem	Commercial product
Foliar/stem fungal pathogens			
<i>Biopolaris sorghicola</i>	<i>Sorghum halepense</i>		Biopolaris
<i>Colletotrichum gleosporioides aeshynomene</i>	<i>Aeschynomene viriginica</i>	Rice, soybean	Collego
<i>Colletotrichum gleosporioides f.sp. malvae</i>	<i>Malva pusilla</i>	Wheat, horticultural crops	Biomal, Mallet
<i>Colletotrichum gleosporioides f.sp. cuscutae</i>	<i>Cuscuta</i> spp.	Soybean	Lubao
<i>Colletotrichum gleosporioides</i>	<i>Hakea sericea</i>	Mountain meadows	Hakatak
<i>Colletotrichum truncatum</i>	<i>Sesbania exaltata</i>	Soybean, cotton, rice	Coltru
<i>Colletotrichum coccodes</i>	<i>Abutilon theophrasti</i>	Maize, soybean	Velgo
<i>Phytophthora palmivora</i>	<i>Morrenia odorata</i>	Citrus groves	De Vine
<i>Alternaria cassiae</i>	<i>Cassia obtusifolia</i>	Soybean	CASST
<i>Alternaria destruens</i>	<i>Dodders</i>	Cranberry	Smolder
<i>Puccinia canaliculata</i>	<i>Cyperus esculentus</i>	Rice, horticultural crops	Dr.Biosedge
<i>Cercospora rodmani</i>	<i>Eichhornia crassipes</i>	Water ways, impoundments	ABG 5003
<i>Chondrostereum purpureum</i>	<i>Prunus serotina</i>	Forest	Biochon
<i>Cylindrobasidium leave</i>	<i>Acacia</i> spp.	Forest, rangelands	Stumpout
<i>Nectria ditissima</i>	Red alder	Forest	PFC-Alderkill
Soilborne fungal pathogens			
<i>Sclerotinia sclerotiorum</i> and <i>S. minor</i>	<i>Taraxacum officinale</i>	Turf	Formulation development
<i>Rhizoctonia solani</i>	<i>Euphorbia esula-virgata</i>	Rangelands	Formulation development
<i>Fusarium solani</i> f.sp. <i>cucurbitae</i>	<i>Cucurbita texana</i>	Cotton, soybean	Formulation development
<i>Fusarium oxysporum</i> f.sp. <i>erythroxyli</i>	<i>Erythroxylum coca</i>	Illicit narcotic crops	Formulation evaluation
Non-pathogenic soilborne fungi			
<i>Trichoderma virens</i>	Several	Row and horticultural crops	Formulation evaluation
Foliar bacterial pathogens			
<i>Xanthomonas campestris</i> pv. <i>poae</i>	<i>Poa annua</i>	Turf, athletic fields	Camperico
<i>Streptomyces hygroscopicus</i>	General vegetation	Row and horticultural crops	Biophos
<i>Pseudomonas syringae</i> pv. <i>tagetis</i>	Composite weeds	Maize, soybean	Field evaluation
<i>Pseudomonas syringae</i> pv. <i>phaseolicola</i>	<i>Pueraria lobata</i>	Non-crop lands, pastures	Field testing
<i>Pseudomonas syringae</i> strain 3366	<i>Epilobium aungustifolium</i>	Cranberry	Formulation development
<i>Ralstonia solanacearum</i>	<i>Solanum nigrum</i>	Non-crop lands, pastures	Formulation development
Non-pathogenic bacteria			
<i>Pseudomonas fluorescens</i> D7	<i>Bromus tectorum</i>	Cereal grain crops	Formulation development
Plant viruses			
<i>Tobacco mild green mosaic virus</i> U2	Tropical soda apple	Non-crop lands, pastures	Formulation development

more than one method of control viz., seed purity, crop varieties, spacing and methods of planting, cultivations, soil solarization, intercropping, crop rotation, water management, manure application, biological control and herbicides. According to FAO, "the integrated campaign against pests 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. Integrating fish culture and dual culture of azolla in transplanted rice is observed to compliment weed control in transplanted rice⁵⁶. Off-season ploughing and mulching the inter row space enhanced the weed control in combination with herbicide in cotton⁵⁷.

BENEFITS OF SUSTAINABLE WEED MANAGEMENT

The benefits are reviewed in the context of the environment, society and economics, (1) Improved soil

and water conservation, (2) Mitigation of global warming, (3) Enhanced biodiversity, (4) Reduction of persistent pollution, (5) Increased food nutrient density, (6) Reduced toxic load in adults and children who eat organic, (7) Better conditions for farm workers, (8) Competitive yields, (9) Price premiums, (10) Direct-to-consumer marketing channels, (11) Lower input costs, (12) Higher per farm income, (13) Improved resilience or lower volatility, (14) Energy savings and (15) Income from carbon markets.

CONCLUSION

As we know the sustainable farming has the ability to save the natural resources for the future and develop the farm in the little expense, a transition to sustainable weed control is required for environmental, social and economic reasons. Fortunately, sustainable farming is a robust business model, delivering superior economics over conventional farming on a wide variety of metrics such as crop yields, gross and net income per acre, cost of inputs, per farm income and more. As society

provides the financial and organizational capital to re-create agriculture, the living soils, plants and animals will respond, over time, to support us. Each acre converted to organic, sustainable methods is one acre closer to a societal tipping point for sustainability-or at least one less acre as a source of harm.

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