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A REVIEW

Plant origin herbicides: chemistry, mode of action and weed management

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Abstract : Plant origin herbicides or allelomones are major source of natural herbicides to combat the weed problem in current organic and sustainable agriculture. Some of the secondary metabolites extracted from plant origin provide lead molecules *viz.*, 1, 8-cineole, leptospermone, artemisinin, sorgoleone and benzoquinones act as templates or analogs to produce new synthetic chemical herbicides. Various plant products had sufficient quantities of allelomones that affect the growth and development of weeds directly, however, these effects are concentration dependent. Herbicidal activity of plant aqueous extracts of sorghum, rice, maize, sunflower, eucalyptus and some of the medicinal plants and other plants were explained to control the weeds in different situations. Combined applications of these plant origin aqueous water extracts with reduced rates of synthetic herbicides could be an economic and effective weed management practices in organic and sustainable agriculture to minimize the herbicide load in soil.

Key Words : Plant origin herbicides, Chemistry, Weed management

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INTRODUCTION

Herbicides continue to be a key component in most of the integrated weed management systems. Extensive and continuous use of synthetic herbicides could lead to serious threats to both environment and public health. Usage of synthetic herbicides is becoming more restrictive due to various problems *viz.*, residual toxicity, reduction in the choice of succeeding crops, development of herbicide resistant weeds and source for carcinogenic and mutagenic effects on human beings and animals (Rial-otero *et al.*, 2005) However, herbicide industry continuously searching for more effective, economical and environmentally safer herbicide formulations. The need for current sustainable and organic agricultural production system has also generated demand for effective and alternate plant based natural herbicides to combat the weed problem from the natural product data base. Duke *et al.* (1997) suggested four approaches for identifying synthetic organic herbicides *i.e* screening of large number of synthetic organic molecules, synthesizing analog of patent herbicides that do not fall within the boundaries of the existing patent, designing of new herbicide molecule based on molecular target site *i.e.* bio rational approach and screening of natural products for herbicidal activity.

There is great incentive to discover biologically potent natural products from higher plants that are as good as or better than synthetic agrochemicals. The potential wealth of natural plant based chemicals was relatively untapped and chemical structures were not identified. Phytotoxicity of plant products could lead to find out new herbicide molecules and to plan environmental friendly weed management strategies. The use of natural products for weed control has become increasingly popular, particularly in organic and sustainable agricultural systems. As the demand increases for cultivation of crops under sustainable agriculture and organic farming lead to less usage of synthetic chemical herbicides and attention is focused on reducing reliance upon synthetic herbicides and find out natural ways of weed management.

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Allelopathy is a natural and environment friendly phenomenon, which proved to be a useful tool for weed management and thereby increase the crop yield (Putnam *et al* ., 1983). Chemicals produced with allelopathic influence are known as allelochemicals and most of them are classified as secondary metabolites (Rice, 1984). These metabolites were produced from the metabolism of carbohydrates, fats and amino acids through acetate or shikimic acid path way. Thousands of secondary metabolites obtained from plants provide diverse and challenged structures, which act as natural herbicides, appear to have more potential herbicides with better selectivity to crops (Vyvyan, 2002). Allelochemicals produced by plants used as natural herbicides and these allelomones have good herbicidal activity between the concentrations of 10^{-5} to 10^{-7} M (Macias, 1995). Allelochemicals, which have sufficient herbicidal activity used as herbicides directly to control the weeds, while other products with lower herbicidal activity may be served as chemical templates for development of synthetic herbicides.

Most of the plant based products destroy the target weed through contact action and in some instances, required less than half an hour after application of plant based herbicides to show wilting symptoms on target weeds. The magnitude of damage caused by plant products on weeds depends on application time, number of applications and concentrations of natural products (Neal, 1998). Mostly these products are used as non-selective post-emergent herbicides or burn down products (Young, 2004). The plant products derived from secondary metabolism often have complex carbon skeletons with higher molecular weights than synthetic herbicides. Plant products tend to be rich in oxygen and nitrogen with more number of chiral centers and sp^3 hybridized carbons with more number of ring structures. Such type of diversity is useful to synthesize new class of herbicides based on the carbon structures from lead molecules found in natural allelomones (Dayan *et al.*, 1999). Further, plant products are rapidly degraded in the natural environment due to short half-life period and low amount of heavy atoms. The negative allelopathic effects of any crop or weed residue (or) allelomones can be used to control the weeds or to develop new green herbicides (Oudhia and Tripathi, 1996). There are two fundamental approaches to use the plant origin herbicides for weed control is the chemistry of natural lead molecules/ templates used for development of new synthetic herbicides and these plant based herbicides were used directly as green herbicides to control the weeds in different crops.

Lead molecules for development of new synthetic herbicides:

Lead molecules isolated from natural secondary metabolites/ allelomones from different plants used as templates for synthesis of new synthetic herbicides to control weed management. Some of the plant derivatives are highly phytotoxic to target weeds. The synthetic herbicides produced based on lead molecules of plant based secondary metabolites were discussed hereunder.

1, 8- cineole :

Essential oils and their constituents act as potential and ecologically acceptable natural herbicides with novel modes of action for weed management, particularly with 1,8-cineole (*1S,4S-1-isopropyl-4-methyl-7-oxabicyclo[2.2.1]heptanes*) is a monoterpenoid of many aromatic plants (*Salvia leucophylla and Eucalyptus citridora*) known to be highly phytotoxic to monocotyledon and some dicotyledon weeds. It is significantly reduced the germination and growth of weeds due to inhibition of mitosis (Romagni *et al.*, 2000). The ester derivatives of cineole showed increased activity compared to hydroxyl or carboxylic acid cineole (Barton *et al.*, 2010). Structural modification of monoterpene, 1, 8-cineole led to the development of a commercial herbicide, cinmethylin (*1R, 4S)-4-isopropyl-1-methyl-2-(2-methylbenzyloxy)-7-oxabicyclo [2.2.1] heptane*) (Fig. 1) with more physical and biological properties including improved herbicide selectivity and persistence in soil.

1,8-Cineole   Cinmethylin

Fig. 1: Molecular structure of 1, 8 cineole and its synthetic analog cinmethylin

Cinmethylin gave an excellent control of *Echinochola crus-galli* (L.) Beauv before emergence from soil to the 3rd leaf stage when it was applied @ 100 g a.i ha^{-1} in rice (Rao and Rao, 1990), however it has phytotoxic effect on in rice seedlings at 75g *a.i* ha^{-1} (Subramanyam *et al*., 2007).

Leptospermone :

Manuka oil, the essential oil distillated from manuka tree (*Leptospermum scoparium* J.R. and G. Frost) and it acts as natural pre-emergence herbicide @ 3 l ha^{-1} to control grassy weeds like large crab grass. Also, it acts as good post-emergence activity in combination with lemon grass oil. The main ingredient responsible for herbicidal activity in manuka oil is leptospermone (*2,2,4,4-tetramethy l-6-(3 methylbutanoyl) cyclohexane -1,3,5-trione*), a β-triketone and it was stable in the soil up to 7 days after its application (Dayan *et al.*, 2011).

The mode of action of leptospermone had similar to that of synthetic herbicide sulcotrione (*2-(2-chloro-4-(methyl sulfonyl) benzyl) cyclohexane-1-3-dione*) (Fig. 2) and mesotrione as these two synthetic herbicides inhibit p-hydroxy phenyl pyruvate dioxygenase, a key enzyme responsible for biosynthesis of tocopherols and plastoquinones. Due to inhibition of enzyme activity causes deleterious effect on biosynthesis of carotenoids and chlorophyll in plants (Pallett *et al.*,1998) Leptospermone is also present in *Callistemone citrinus* (Curtis) Skeels and it was commercially modified by the Syngenta Pvt. Ltd.USA as synthetic derivative, mesotrione (Callisto®) which is 100 times more potent than parent compound to control broad leaf weeds in *Zea mays* (Cornes, 2005).

Fig. 2: Molecular structure of leptospermone and its synthetic analog sulcotrione

Artemisinin :

Artemisinin (*6S,9R,10aR)-9-(7,8,9 trioxabicyclo [4.2.2] decane)-3,6,9 trimethyldecahydrooxepino[4,3,2-ij] isochromen- 2(3H)one*) (Fig. 3) is a sesquiterpene lactone obtained from *Artimisia annua* L. It is an effective antimalarial drug cum potent growth inhibitor (Di Tomasco and Duke, 1991). The exact mechanism to control the plants is still unknown however, laboratory studies indicate that artimisinin may kill the target plants by the same mechanism as it kills the *Plasmodium falciparum* Welch (Kohler *et al.*, 1997).

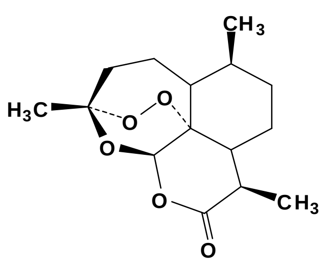

Fig. 3: Molecular structure of artemisinin

Artemisinin @ 5 µM concentration inhibited the root induction in *Vigna radiata* under laboratory conditions similar to glyphosate application at same dose due to inhibition of peroxidase enzyme activity (Chen *et al.*, 1991). Artemisinin and its derivatives significantly reduced the root growth and chlorophyll content in weeds (Stiles *et al.*, 1994 and Dayan *et al.*, 1999). Artechter is a derivative of artemisinin, which had inhibitory effect on the roots than shoot growth and it was highly phytotoxic to dicotyledon weeds where as artemisinin was more phytotoxic to monocotyledon weeds (Bagchi *et al.*, 1997). Dehydrozaluzanin is another sesquiterpene lactone obtained from different family members of the compositae, which inhibits the growth of weeds similar to a synthetic herbicide triasulfuron (Macias *et al.*, 2000).

Sorgoleone :

Sorghum root exudates are known to contain phytotoxic natural product benzoquinone compound, sorgoleone (*2-hydroxy-5-methoxy-3-((8Z,11Z)-pentadeca-8,11,14-trienyl) cyclohexa-2,5-diene-1,4-dione*) and analogs from their root hair as oily droplets (Fig. 4). It can accumulate up to 20 µg of exudate/mg of root dry weight (Dayan *et al.*, 2010) however, sorgoleone production was quite variable. Some of the sorghum cultivars produced up to 15 ìg of sorgoleone/g fresh root weight. It acts as potent inhibitors of electron transport in photo system-II similar to synthetic herbicides diuron and atrazine with respect to similar binding sites at molecular level (Nimbal *et al.*, 1996) and its inhibits the enzyme hydroxyl pyruvate dioxygenase activity (Meazza *et al.*, 2002). It has no effect on the photosynthesis of older plants, but inhibits the photosynthesis of newly germinated seedlings and it can be translocated through acropetally in older plants (Duke, 2010). The half-life of sorgoleone is around 77 days and it was strongly adsorbed on soil colloids than the many soil applied synthetic herbicides due to its hydrophobic nature.

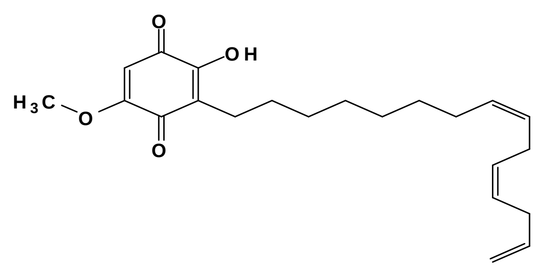

Fig. 4: Molecular structure of sorgoleone

Sorgoleone production is high in young developing plants of sorghum particularly at 5 days old seedlings to 10 days old seedlings and beyond, the production of sorgoleone is declined. The optimum temperature for root growth of sorghum and sorgoleone production was 30 ^{0}C and sorgoleone levels were significantly reduced at temperatures below 25^{0}C and above 35^{0}C (Dayan, 2006). Sorgoleone at 40 ppm incorporated in soil significantly reduced the fresh weight of several broad leaf weeds and same concentration as post-emergence application also inhibits the growth of weed species (Wetson and Czarnota, 2001).

Benzoquinones :

Benzoquinones are well known natural allelochemicals present in the plants as secondary metabolites. It includes mainly *2, 4-dihydroxy-(2H)-1, 4-benzoxazin-3-(4H)-one* (DIBOA) and its *methoxy* analog (DIMBOA), which are considered as successful template to design natural herbicide models (Macias *et al.*, 2006).

The herbicidal activity of DIBOA (Fig. 5) was seven times more inhibitory to root growth and four times more inhibitory to shoot growth than BOA. Under laboratory conditions, DIMBOA @ 0.7 mM inhibits the root growth of wild oat (*Avenue fatua* L.) by 50 % (Zheng *et al.,* 2007). Further, the derivatives of DIMBOA showed the greatest selectivity to rice seedlings and higher herbicidal activity to *Echinocloa crus-gall* and it was 15 times more selective than commercial herbicide propanil (Macias *et al.,* 2010). The mode of action of these compounds inhibits the mitochondrial function by interfering with both electron transport and mitochondria ATP activity including inhibition of germination and shoot growth (Burgos and Talbert, 2000).

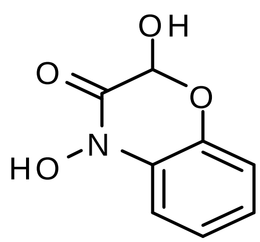

Fig. 5: Molecular structure of DIBOA

Scope of plant origin herbicides directly used as herbicides:

Plant products in the form of aqueous extracts, plant residues, dry powders of crops and other plants used as natural herbicides directly to suppress the growth and development of weeds in different crops or non-cropped areas. Study of allelomones of major field crops provides valuable information to identify alternative weed management practices in organic agriculture. Allelopathic potential of sorghum water extract has been demonstrated in recent years including other plants such as maize, rice, sunflower and eucalyptus.

Sorghum :

Sorghum (*Sorghum bicolor* L.) is one of the important cereal crops produces different types of allelomones, which act as natural herbicides. Sorghum residues produce highly phytotoxic chemicals which are more effective to suppress the growth of annual grassy weeds like *Echinocloa* spp. than broad leaf weeds (Lovett, 1989) and reduced the population of common purslane (*Portulaca oleracea* L.) and smooth crab grass [*Digitaria ischaemum* (Schreb) Exmunl] by 70 and 80 per cent, respectively due to presence of p-hydroxybenzoic acid and p-hydroxybenzaldhyde (Putnam and Defrank, 1983). The important phytotoxins present in sorghum plant are gallic acid, proticateuic acid, syringic acid, vanillic acids, p-coumeric acid, benzoic acid, p-hydroxybenzoic acid, ferulic acid, p-hydroxy benzaldehyde and sorgoleone (Netzly and Butler, 1986).

The short name of sorghum water extract is 'sorgaab', which is very effective in controlling the weeds similar to the synthetic chemical herbicides. Sorgaab is obtained after soaking of leaf bits in distilled water for 24 hours at room temperature at a ratio of 1:10 (w/v) and filtered through 10 and 60 mesh sieve (Cheema and Khaliq, 2000). Post-emergence application of sorgaab @ 6 l ha^{-1} to 12 l ha^{-1} combined with fenoxaprop-p-ethyl @ 375 g ha^{-1} reduced the weed biomass by 87 per cent in sunflower (Khaliq *et al.*, 2002) and sorgaab alone or in combination with reduced dose of s-metolachlor or pendimethalin is very effective to control the weeds in mungbean [*Vigna radiata* (L.) Wilczek] (Cheema *et al.*, 2003). The concentrated sorghum water extract @ 12 l ha^{-1} along with pendimethalin @ 0.5 kg ha^{-1} as pre-emergence resulted in the lowest density of purple nutsedge (*Cyperus rotundus* L.) and *Trianthema portulacastrum* in cotton (*Gassypium hirsutum* L.) (Cheema *et al.*, 2002). Three sprayings of sorgaab at 20, 30 and 40 DAS of mungbean significantly reduced the density and dry weight of weeds by 31.58 and 44.11 per cent, respectively which were at par with pre-emergence application of pendimethalin @ 1.0 kg ha^{-1} (Cheema *et al.*, 2001). Post-emergence application of isoproturon @ 600 g ha^{-1} along with sorgaab @ 12 l ha^{-1} reduced the total weed dry weight by 91 per cent and it was effective as isoproturon @ 1000 g ha^{-1} in wheat (*Triticum aestivum* L.) (Jamil *et al.*, 2005). Post-emergence application of reduced dose of bromoxynil + MCPA @ 250 g *a.i* ha^{-1} along with *sorgaab* @ 12 l ha^{-1} were effective in reducing total weed density in wheat, which was comparable with full dose of herbicide application (Sharif *et al.*, 2005).

Maize :

Corn gluten meal is a natural pre-emergence herbicide for control of weeds in turf grass by reducing the germination of many broad leaf and grassy weeds. It is a by-product of processing of maize (*Zea mays* L.) kernels to make maize starch and syrup in wet milling process. Application of corn gluten meal prevents the sprouting of weed seeds and inhibition of normal root growth in most of the common weeds *viz.*, *Digitaria sanguinalis, Polygonum pensylvanicum, Taraxacum officinale, Amaranthus retroflexus, Portulaca oleracea, Chenopodium album, Echinochloa crus-galli* and *Cynodon dactylon* due to presence of dipeptides which disrupt the cell division at the root tip (Cox, 2005). Corn gluten meal incorporation 400 g/m^2 reduced the weed density by 82 % over control. However, survival of vegetable seedlings like onion, sugar beet, radish, bean, carrot, pea and lettuce were significantly reduced at all the rates of corn gluten meal application (Mc Dade and Christians, 2000). However, it was not effective to control monocot weeds in strawberry (Dilley *et al.*, 2002). Corn gluten meal is also manufactured as "grift" to apply as post-emergence herbicide, which effectively abrading the weed seedlings just like fine sand to control the summer annual grassy weeds in organically grown row crops

(Forcella *et al.*, 2011). Corn gluten hydrolysate is a water soluble extract of corn gluten meal, a by-product of corn in wet milling process, which is advantageous and more active than corn gluten meal to suppress the weed growth (Christians, 1993).

Rice :

Numerous secondary metabolites such as phenolic acids, flavonoids, terpenoids etc have been identified as potent allelochemicals from rice tissues and root exudates. Momilactone B, 3-isopropyl-5-acetoxycyclohexane-2-one-1 and 5,7,4-trihydroxy-3,5-dimethoxy flavones are mainly produced from living tissues of rice plant whereas momilactone B and phenolic acids are produced from rice straw (Kong, 2008). Application of rice straw extract @ 3.47 to 6.95 g/l in combination with fusilade @ 40 g feddon^{-1} were most effective to suppress the weed growth as well as increasing yield of soybean [*Glycine max* (L.) Merr], however, at higher concentration of extract @ 13.9 g l^{-1} significantly reduced the growth of weeds, but phytotoxic to soybean (Kawather *et al.*, 2006 and Rokiek *et al.*, 2006). The concentration of allelochemicals varies with cultivars of rice. Aqueous extract prepared from straw of rice varieties BPT-5204 and Ponnai reduced the weed biomass by 47.68 and 45.43 per cent, respectively in water hyacinth, *Eichhornia crassipes* (Mart) Solms (Kathiresan and Dharabharathi, 2008). Rice husk extract showed inhibitory effect on germination and growth of barnyard grass due to presence of allelomones *viz.*, 9-octadecanoic acid, 7-octadecanoic acid, 5, 8, 11-heptadecatrionic acid and androstan-17-one (Jonghan *et al.*, 2005).

Mixing of powdered rice straw @ 125 to 500 g m^{-2}, three months before sowing of cucumber (*Cucumis sativus* L.) was more effective in suppressing the growth and development of broad and narrow leaf weeds than intact straw due to presence of phenolic acids *viz.*, cinnamic acid, salicylic acid, vanillic acid, p-hydroxybenzoic acid, 2, 5-dihydroxybenzoic acid, ferulic acid, o-coumaric acid and p-coumaric acid present at higher concentrations in grounded rice straw (Shahawy *et al.*, 2006). Application of rice bran compost @ 2 kg m^{-2} at 7 days after sowing of vegetable crops significantly controlled the number and dry weight of weeds and it was more efficient in reducing the weed emergence and dry weight of broad leaf weeds than grassy weeds (Khan *et al.*, 2007).

Sunflower :

Sunflower (*Helianthus annuus* L.) is one of the important allelopathic crops and it influences the growth and development of neighboring plants due to production of potent allelochemicals. The aqueous extract of sunflower inhibits the dry weight of broad leaf weeds up to 75 per cent compared to control (Anjum and Bajwa, 2005). The important allelomones found in the sunflower were annuionones A, B, annuolide E, leptocarpin and heliannuols considered as natural herbicides (Macias *et al.*, 2002). Soil incorporation of sunflower residue significantly reduced the density of weeds by 66 per cent (Anaya *et al*., 1990). The root and shoot extracts of sunflower @ 25 % significantly reduced the germination and root growth of carrot grass *Parthenium hysterophorus* L. due to presence of phenols and heliannuols, which are responsible for reduced germination and growth (Javaid *et al.*, 2006) due to disruption of cellular metabolism (Bogatek *et al*., 2005). Sunflower water extract could be used as pre and post emergence herbicide to manage the weeds. Application of sunflower water extracts as pre-emergence at 25 DAS + 35 DAS in wheat suppressed the growth of small canary grass (*Phalaris minor* L.) lambs quarter (*Chenopodium album* L.) and wild oat (*Avena fatua* L.) over the control (Naseem *et al.*, 2009).

Eucalyptus :

The allelopathic effect of *Eucalyptus* spp. have been reported by several workers due to release of sufficient quantities of allelochemicals such as phenyl propanoids, quinines, coumarins, tannins, phenolic acids, glycosides and cyanogenins (Einhellig, 1986). Alves *et al*. (1999) suggested that the use of allelopathic potential of eucalyptus to control the weeds. Aqueous extract of leaves of *Eucalyptus citridora* L. reduced the growth rate, germination and radical growth of *Raphanus sativus* L (Calegare *et al*., 1991). Leaf extract of eucalyptus also inhibits the germination of blue pimpernel and lambs quarter with increasing concentrations (Mukhopadhyay *et al*., 1995). Mulching of eucalyptus leaf litter @ 2 t ha^{-1} resulted in the lowest weed density and dry matter production of weeds, which was at par with pre-emergence application of fluchloralin @ 1.5 kg ha^{-1} + hand weeding in greengram (Natarajan *et al.*, 2003).

Combined application of crop water extracts :

Combined application of plant products alone or in combination with reduced dose of synthetic chemical herbicides may be less expensive and reduced the synthetic herbicide load in environment and thereby reduced recommended dose of synthetic herbicides up to 25 to 50 per cent. Sorghum and sunflower water extracts each at 18 l ha^{-1} in combination with reduced dose of glyphosate @ 767 g *a.e.* ha^{-1} applied as direct spray in cotton reduced the density and dry weight of purple nut sedge by 78 and 95 per cent, respectively and the same crop water extracts in combination with bromoxynil + MCPA @ 50 g ha^{-1} reduced the total weed density by 88 and biomass by 95 per cent and grain yield of wheat was enhanced by 35 per cent over the control (Iqbal *et al.*, 2010). Herbicide use can be reduced by 75 per cent through integration with sorgaab + sunflower water extract each at 18 l ha^{-1} without compromising the yield and net benefit for the management of wild oat (*Avena fatua* L.) and small canary grass (*Phalaris minor* L.) in wheat (Mushtaq *et al.*, 2010).

Combined application of sorghum and sunflower water extracts each at 18 l ha^{-1} with reduced dose of metribuzin + fenoxaprop by 70 per cent in wheat (Razzaq *et al.*, 2010) and pendimethalin by 50 per cent in sunflower (Awan *et al.*,2009). Crop water extracts of sorghum, sunflower, mustard and rice each at 15 l ha^{-1} in combination with pendimethalin @ 600 g ha^{-1} were applied as pre-emergence significantly reduced the density and dry weight of weeds, particularly purple nutsedge (*Cyperus rotundus* L.), which was comparable with full dose of pendimethalin @ 1200 g ha^{-1} in canola, (*Brassica napus* L) (Jabran *et al.*, 2010). Combined application of water extracts of rice, sorghum, sunflower and each at 15 l ha^{-1} along with half the recommended dose of butachlor @ 600 g ai ha^{-1} reduced the dry weight of barnyard grass [*Echinochloa crus-galli* (L.) Beauv] and flat sedge (*Cyperus iria* L.) by 75 and 67 per cent, respectively and it was comparable with full dose of application of butachlor @ 1200 g ha^{-1} in rice (Rehman *et al.*, 2010).

Other plants :

In addition to the above, many documented evidences of plant based products from other plants were also available in the literature for weed management in different crops (Table

Table 1: Allelochemicals and mode of action of some plants

Plant	Allelochemicals/ Aqueous extracts	Inhibition of	Reference
Brassica spp.	Caffeic, ferulic, vanilic acids and isothiocyanates	Germination and growth of weeds	Norsworthy *et al*. (2005)
Tobacco (*Nicotiana tabacum* L.)	Scopoletin hydroxyl benzoic acid	Photosynthesis biosynthesis of indole acetic acid	Einhellig, (1986) Lee and Skoog, (1965)
Sesamum (*Sesamum indicum* L.)	Haulm extract	Protein and chlorophyll synthesis	Chandrasekhar *et al*. (1998)
Rye (Secale cereal)	DIBOA , BOA	Mitochondrial function	Burgos and Talbert (2000)
Lavender intermedia cv. grasso	Leaf and stem extracts coumarin and 7-methoxy coumarin)	Germination of *Lolium rigidum* Gaudin	Timothy *et al.* (2009)
Saururaceae (*Houttuynia cordata* Thumb.)	Aqueous extract of dry powder	Germination and growth of *Echinochloa* spp. and *Monochoria* in rice	Sugitomo *et al.* (2006).
Cassia uniflora L.	Aqueous extract	chlorophyll and carotenoid synthesis in *Parthenium hysterophorus* L.	Knox *et al.* (2006).
Rosemary pepper (*Lippia sidoides* Cham)	Aqueous extract	Tuber emergence and vigour of *Cyperus rotundus* L.	Silveira *et al.* (2010).
Chinese rice flower (*Aglaia odorata* Lour)	Dried leaf pellets as mulch	Germination and emergence barnyard grass (*Echinocloa colonum* L)	Laosinwattana *et al.* (2009).
Kava root (*Piper methysticum* L.)	Mulch	Growth of *Echinochloa crus-galli* (L.) Beauv, *Monochoria vaginalis* (Burm f.) Kunth and *Paspalum distichum* L.	Yuichi *et al.* (2003).
Tagetes minuta L	Leaf powder	Germination of rice weeds	Batish *et al.* (2007)
Albizia lebbek (L.) Benth	Green leaf manure	Germination of maize weeds	Nandakumar and Swaminadhan (2010).
Withania somnifera (L.) Dunal	Root or leaf extract (withaferin-A)	Protein synthesis and cytotoxic effect	Kalthur *et al.* (2009)
Anisomeles indica (L.) Kuntze	Mulch	*Phalaris minor* L. and other weeds associated with wheat.	Batish *et al.* (2007)
Tagetes erecta L	Soil incorporation	Germination and growth of carrot grass	Shafique *et al.* (2011).
Canna indica L.	dried powder	Germination and emergence of weeds in rice	Lin *et al*. (2009)
Lantana camara L. *Hyptis suaveolens* (L.) Poit.	Aqueous extract of fresh or dry leaves	Germination of *Parthenium hysterophorus* L.	Arunkumar *et al.* (2008).
Abutilon spp.	Aqueous extract	Germination of *Amaranthus* spp., *Parthenium hysterophorus* L. and *Phylhanthus madaraspatensis* L.	Vasuki and Jagannadhan (2010)
Datura metal L.	Incorporation of crushed shoots	Germination and growth *Parthenium hysterophorus* L.	Javaid *et al.* (2010)
Breynia retusa L.	Foliar spray	Chlorosis and necrosis *Parthenium hysterophorus* L.	Rani *et al.*(2006).
Black radish (*Raphanus niger* L.)	Isothiocyanates	Johnson grass (*Sorghum halepense* L.)	Uremis *et al*. (2009)

1), however, these allelochemicals / aqueous extracts of plants should be further evaluated for its herbicidal activity.

Natural oils and acids :

Directed application of citronella oil extracted from *Cymbopogon winteranius* L @ 1500 l ha^{-1} had more rapid inhibitory effect on growth of common rap weed (*Senecio jacobaea* L.) similar to synthetic herbicide clopyralid @ 0.2 kg ha^{-1} or 2,4-D @ 2.3 kg ha^{-1}, especially at seedlings stage of weed (Dixon and Clay *et al.,* 2001) and it is very effective to defoliates the herbaceous perennial weeds (Clay *et al.,* 2005). Application of 200-grain vinegar (20% acetic acid) @ 636 l ha^{-1} recorded weed control efficiency of 83 per cent in sweet corn, however, the phytotoxicity of vinegar on sweet corn was overcome by 4 weeks after its application (Evans and Bellinder, 2009). Early post-emergence application of citric acid @ 5 % + garlic extract @ 2 % significantly reduced the broad leaf weeds, whereas acetic acid @ 30 % is very effective to control the narrow leaf weeds at early stages of weeds Hussain *et al.,* 2009).

Limitations :

Allelomones which are isolated from plant origin act as herbicides have some limitations as outlined by Khanh *et al.* (2007). They are :

– Isolation of allelomones obtained from plants origin is complex due to their multiple chiral centres
– Allelomones are degraded in nature before reaching the target site
– Shorter residual time in the environment.
– Further, plant based herbicides do not have specific mode of action and systemic activity as that of synthetic herbicides (Dayan and Duke, 2010).
– Allelochemicals are very active under laboratory studies, often lose their activity in soil due to their instability, adsorbed by soil particles and soil organic matter immediately (or) these plant origin herbicides are highly water soluble compounds and rapidly leached down from the root zone of the target species.
– Absorption and translocation of natural products by the target plant is limited (Dayan *et al.,* 1999).

Future line of work :

Further research is needed on plant origin herbicides to elucidate the following aspects for effective utilization to manage the weeds or designing new herbicide molecules with specific site of action.

– There is a need of simple and quick instrumentation techniques for isolation and purification of lead compounds or allelochemicals from plant origin including mode of action these products for designing new synthetic herbicides.
– Allelopathic effect of plant origin herbicides alone or in combination with reduced dose of synthetic herbicides may be investigated for effective and economic weed management in different crops.
– Development of genetically engineered allelopathic varieties in different field crops may be carried out to suppress the weed growth due to the production of natural herbicide molecules within the plants through transgenic techniques or biotechnological approaches.
– The mechanism of adsorption and degradation of allelochemcials in soil may be studied in detail to know the herbicidal activity/ selectivity mechanism of allelomones.

Conclusion :

Plant origin herbicides offer new opportunities for development of cost effective and environmentally safer green herbicides for management of weeds in agriculture. Plant based natural herbicides/allelomones have been used as lead molecules to identify the new synthetic herbicides or templates for designing new molecular target sites. Some of the crop / weed aqueous water extracts alone or in combination with reduced rates of synthetic herbicides were very effective for controlling weeds in organic or sustainable agriculture and thereby, protecting the environment including soil health. Transgenic or biotechnological approaches may be evolved to produce the own natural herbicide molecules within the crop or varieties itself to control the associated weeds. There is a scope for efficient utilization of on farm resources like aqueous plant extracts of crops and weeds including residue are used as green herbicides to control weeds in cropped and non-cropped areas.

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