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REVIEW ARTICLE

Herbal herbicide: A low-cost and eco-friendly tool for weed management in smallholder farming

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ABSTRACT

Weeds have been recognized as a major biotic constraint towards achieving higher crop productivity as well as quality. With the current crop protection measures, weeds cause nearly one-third of the crop losses among all the crop pests. The effective approach to combat the weed menace is the need-based use of herbicides. Because of widespread growing concern over the environmental aspects of commonly used herbicides as well as their untimely availability, development of weed resistance, *etc*., the need for the use of conveniently available and biodegradable herbicides is very much imperative. Researchers currently search for novel alternatives to the synthetic herbicides, which would be biodegradable and environment-friendly. Common plants and their metabolites become a source of compounds that can be utilized directly as natural herbicides or as lead structures for the herbicide discovery. These herbal herbicides in judicious combination with other weed management methods would be a potential tool to combat weed menace, especially by the smallholder farmers in rural areas in general, and organic or natural farming in particular.

Keywords: Crop losses, Herbal herbicide, Integrated weed management, Organic farming, Smallholder farmer, Weeds

INTRODUCTION

Weeds have been one of the major impediments to crop production since the dawn of human civilization. A significant quantum of crop harvest is lost each year due to inadequate, ineffective and untimely weed management. Huge losses in crop yields as well as crop quality take place due to weeds, which have an impact on food security and safety. The extent of crop yield losses varies due to weeds, depending on the crop and related agro-ecological conditions. In India, the average annual yield losses due to various crop pests are projected to be approximately ₹ 600 billion (Singh 2005), with weeds alone responsible for the greatest losses. However, weed damage to crops receives less attention than the damage from other pests. Weeds have a direct impact on crop productivity and quality, and they also substantially reduce the input use efficiency. The uncontrolled weeds utilize most of the expensive inputs like fertilizers and irrigation water that would otherwise be used to maximize the potential yield (Yaduraju and Mishra 2004 and 2005). Gharde *et al.* (2018) estimated total actual economic loss of about USD 11 billion due to weeds alone in 10 major crops of India *viz.* groundnut (35.8%), soybean (31.4%), greengram (30.8%), pearlmillet (27.6%), maize (25.3%), sorghum (25.1%), sesame (23.7%), mustard (21.4%), direct-seeded rice (21.4%), wheat (18.6%) and transplanted rice (13.8%) using the data from 1581 on-farm research trials conducted by ICAR - All India Coordinated Research Project on Weed Management between 2003 and 2014 in major field crops in different districts of 18 states of India. They found that potential yield losses were high in case of soybean (50–76%) and groundnut (45–71%). Greater variability in potential yield losses were observed among the different locations (states of India) in case of direct-seeded rice (15–66%) and maize (18–65%).

A clear understanding and knowledge regarding weeds and their management can be helpful in addressing certain challenges related to food security and safety. In India, various weed control methods are in use, based on the socio-economic conditions of farmers. Manual weeding is still the most common way to manage weeds in the country although it is tiresome, time-consuming, ineffective, and

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practically uneconomical. There is also a declining trend on the use of draught animals for land preparation and intercultural operations. Wage rates have been increasing dramatically over the last two decades. The reduced labour availability at the peak time of agricultural operations compels the farmers to look for alternative weed management options as the farmers frequently fail to address the weed problems with their current weed management techniques. Significant crop losses occur due to either delayed weeding or omitted weeding. As a result, there is a greater need for low-cost, time-saving, and effective weed management solutions under various agro-ecological situations (Duary and Mukherjee 2013). To deal with the weed problems, the intense use of herbicides is being preferred by farmers during recent years. But exclusive reliance on the use of synthetic herbicides has resulted in emerging environmental concerns, including herbicide residue in soil, water and plants (especially fruits and vegetables); toxicity to animals and humans; shift in weed flora; and evolution of resistant weeds (Mukhopadhyay 1992 and 1993, Gautam and Mishra 1995, Duary 2010).

Innovations and interventions are imperative for effective weed management so as to eliminate or avert the environmental risks and health concerns. Since the herbicides have the relatively higher potential to cause unfavourable environmental contaminants, there is a growing need for using the environmentally safer herbicides which would be either equally or even more effective and selective than the currently available synthetic herbicides. Researchers have been searching for novel, bio-degradable and environment-friendly alternatives to the synthetic herbicides. In this context, herbal herbicides can play a greater role. There has been an increasing interest in the use of allelopathic plants for weed management at the national and international levels. The compounds released by these allelopathic plants (allelopathic chemicals/allelochemicals) can either be directly utilized for weed management or alternatively their chemical contents be utilized for developing new herbicides with novel chemistries. As an essential prerequisite of the sustainable agricultural practices, the inputs currently provided by non-renewable chemical resources should be replaced by the biologically based renewable and naturally available products. To make the weed management solutions more sustainable and eco-friendlier, there is a need to judiciously switch from using chemical herbicides to that of the herbal herbicides or phytochemicals with herbicidal properties.

CONCEPT OF HERBAL HERBICIDE

There exist many plant species in and around our surroundings. Some of these have allelopathic potentials. There is a range of plants that herbivores do not graze, browse, nibble or relish in other ways, and these plants are also not afflicted with insects and pathogens. These plants include those with the aromatic, cosmetic, antibiotic, empirical remedial, medicinal, preservative, repellent, and other properties. These plants, in whole or in part, have herbicidal and other properties. These plants exude attractants (water/alcohol soluble products) or release some active chemicals into the environment through exudation, leaching or decomposition (Kumar and Varshney 2009), which inhibit the germination and growth of nearly all types of annual weeds both in transplanted and direct-sown crops in both aerobic and anaerobic soils. The bioactive compounds or phytochemicals or plant extracts with herbicidal properties are called herbal herbicides, also known as phytoherbicides (Bhowmick *et al.* 2016). Moreover, the herbal herbicides will act as natural herbicides for combating the weed problems in organic and sustainable agricultural systems. **Table 1** lists some examples of such plants although it is not the exhaustive one.

TYPES OF HERBAL HERBICIDES

Herbal herbicides from plant extracts

Plant extracts are excellent candidates to replace synthetic compounds that render toxic and carcinogenic effects. Hence, plants extracts can be used in various ways, including food industries (Balasubramaniam *et al.* 2022; Ramakrishnan *et al.* 2022), human health benefits and medicines (Abubakar and Haque 2020; Proestos 2020), antimicrobial purposes (Alzoreky and Nakahara 2003; Gonelimali *et al.* 2018; Palombo 2011), and also as herbal herbicides (Hasan *et al.* 2021). Aqueous plant extracts of several plant species have shown good potency against many weed species as herbal herbicides (Carrubba *et al.* 2020, Caser *et al.* 2020, Elisante *et al.* 2013, Hasan *et al.* 2021, Perveen *et al.* 2019, Wang *et al.* 2019). Such water-based extracts are considered easy to prepare and less damaging to the environment as compared to the chemical herbicides.

Herbal herbicides from plant allelochemicals

Plants often produce a class of semiochemicals called allelochemicals or phytotoxins which inhibit the growth of nearby plants while allelopathy refers to the

Table 1. Common plant sources having herbicidal properties

Scientific name	Common name	Family	Salient features	References
Ailanthus altissima	Tree of heaven	Simaroubaceae	Deciduous tree	Kozuharova *et al.* (2022)
Acacia auriculiformis	Sonajhuri	Fabaceae	Evergreen tree	Bhowmick *et al.* (2016)
Adhatoda vasica	Vasaka	Acanthaceae	Small evergreen, sub-herbaceous bush	De and De (2000)
Ailanthus altissima	Tree of heaven	Simaroubaceae	Deciduous tree	Heisey (1997)
Andrographis paniculata	Kalmagha	Acanthaceae	Annual herbaceous plant	Nagaraja and Deshmukh (2009)
Annona squamosa	Ata	Annonaceae	**S**mall, well-branched tree or shrub	De and De (2000)
Antigonon leptopus	Sandwich island climber / Anantalata	Polygonaceae	Flowering plant	De and De (2000); Mandal and De (2005)
Azadirachta indica	Neem	Meliaceae	Tree	De and De (2000)
Centaurea diffusa	Diffuse knapweed	Asteraceae	Herbaceous, perennial weed	Quintana *et al.* (2009)
Calotropis gigantean	Akand	Apocynaceae	Large shrub or small tree	De and De (2000); Bhowmick *et al.* (2014), Bhowmick *et al.* (2016)
Chromolaena odorata	Bitter bush	Compositae	Weed	Nornasuha and Ismail (2013)
Cymbopogon nardus	Citronella grass	Cardiopteridaceae	Herb	Somala *et al.* (2022)
Cymbopogon citratus	Lemon grass	Poaceae	Fast growing, perennial aromatic grass	De and De (2000)
Drimys winterii	Winter's bark or canelo	Winteraceae	Slender tree	Verdeguer *et al.* (2011)
Eucalyptus sp.	Eucalyptus	Myrtaceae	Large tree	Bhowmick *et al.* (2016)
Holarrhena antidysenterica	Kurchi	Apocynaceae	Medicinal herb	De and De (2000); Mandal and De (2005)
Ipomoea batatus	Sweet potato	Convolvulaceae	Dicotyledonous plant	De and De (2000)
I. carnea	Ban kalmi	Convolvulaceae	Vine	De and De (2000)
Lantana camara	Lantana	Verbinaceae	Perennial herb	Darana (2013)
Leucas aspera	Set drone	Lamiaceae	Annual herb	Islam and Kato-Noguchi (2013)
Mikania micrantha	Bitter vine	Asteraceae	Perennial herbaceous vine	Nornasuha and Ismail (2013)
Nigella sativa	Black caraway	Ranunculaceae	Annual herb	Zribi *et al.* (2018)
Peumus boldus	Chilean plant	Monimiaceae	Evergreen tree	Verdeguer *et al.* (2011)
Senna (*Cassia*) *tora*	Sickle pod	Caesalpinaceae	Annual leguminous weed	Dolai *et al.* (2015); Bhowmick *et al.* (2016)
Tabarnaemontana coronaria	Siulicop	Apocynaceae	Medicinal plant	Mandal and De (2005)
Tagetes erecta	Mexican marigold	Asteraceae	Annual plant	Dolai *et al.* (2015); Wichittrakarn *et al.* (2013)
T. patula	French marigold	Asteraceae	Annual plant	Ramachandra Prasad *et al.* (2010)
Vitex negundo	Nisinda	Lamiaceae	Large aromatic shrub	De and De (2000)

direct or indirect chemical effect of one plant on the germination, growth or development of neighboring plants (Cheng and Cheng 2015). Some of the important chemically diverse plant allelochemicals include alkaloids, phenols, terpenoids, glucosinolates, isothiocyanates, steroids, proteins, purine-based compounds, macrocyclic polyethers, *etc*. (**Table 2**). There are several crop varieties like rice, wheat, sorghum which have the ability to suppress weed by allelopathy (Jabran 2017; Masum *et al*. 2018; Shamsur *et al*. 2019). The phenomenon of allelopathy can be practically utilized for weed control in the form of crop rotations, intercropping, allelopathic mulches, and a spray of allelopathic plant water extracts. Sorghum (*Sorghum bicolor*) and sunflower (*Helianthus annuus*) are well known allelopathic crops, which contain a number of allelochemicals that are toxic to weeds (Bajwa *et al*. 2015; Cheng and Cheng 2015; Jabran *et al*. 2015; Shamsur *et al*. 2019; Sathishkumar *et al.* 2020).

The majority of past allelopathic research has focused on the detrimental effects of living plants or their residues on plant growth. Recent research on identifying novel secondary products isolated from plants, as phytochemicals with allelopathic potential (Cragg and Newman 2013; Ndam *et al*. 2014), offer promising scope for the biological control of weeds as well. The synthetic herbicide 'mesotrione' (callisto®), is derived from leptospermone, a compound isolated from the bottle brush plant (*Callistemon citrinus*) (Araniti *et al*. 2015). The ability to develop more herbicides from allelopathic compounds is limited by several factors. Allelopathic

Table 2. Allelochemicals for inhibiting weed seed germination and weed seedling growth

Allelochemicals	Allelopathic plants	Target weeds	References
Ailanthone	Tree-of-heaven (*Ailanthus altissima*)	*Lepidium sativum, Raphanus sativus, S. officinalis, S. rosmarinus*	Caser *et al.* (2020)
Alkaloids	Jimson weed (*Datura stramonium*)	*Cenchrus ciliaris, Notonia wightii*	Lovett and Potts (1987)
Artemisinin	Sweet wormwood (*Artemisia annua*)	*A. retroflexus, I. lacunose, P. oleracea, A. annua, Lemna minor, Pseudokirchneriella subcapitata*	EI Bazaoui *et al.* (2011)
Catechin	Spotted knapweed (*Centaurea stoebe*)	*Arabidopsis thaliana, Festuca idahoensis*	Bais and Kaushik (2010)
1, 8- cineole	Purple sage (*Salvia leucophylla*), Eucalyptus (*Eucalyptus* sp.)	*E. crus-galli, Cassia occidentals, Lolium rigidum*	Topal *et al.* (2007); Subramanyam *et al.* (2013)
Glucosinolates*, Isothiocyanates**	Brassicaceous plants (*Brassica* sp.)*, Radish (*Raphanus sativus*)**	*S. aspera, M. inodora, A. hybridus, E. crus-galli, A. myosuroides, C. bursapastoris, C. arvensis, Cuscuta* spp.*, D. carota, H. incana, S. polyceratium*	Soltys *et al.* (2013)
Juglone	Black Walnut (*Juglans nigra*)	*S. arvensis, C. arvense, Papaver rhoeas, Lamium amplexicaule, Triticum vulgare, Hordeum vulgare*	Julien and Griffiths (1998)
Leptospermone	Lemon bottlebrush (*Callistemon citrinus*), Broom tea-tree or manuka tree (*Leptospermum scoparium*)	*E. crus-galli, D. sanguinalis, Setaria glauca, Avena sativa, Brassica juncea, Rumex crispus*	Dayan *et al.* (2011); Soltys *et al.* (2013)
Momilactone	Rice (*O. sativa*), Moss (*Hypnum plumaeform*)	*E. colona, A. lividus, D. sanguinalis, P. annua*	Motmainna *et al.* (2021)
Pelargonic acid	Rose Geranium (*Pelargonium roseum*)	*Digitaria ischaemum, Physalis angulata, Amaranthus spinosus, Cyperus esculentus*	Webber *et al.* (2014)
Polyacetylenes	Russian knapweed (*Centaurea repens*)	*T. aestivum, Glycine max, L. minor*	Minto and Blacklock (2008)
Quinones	*Black cumin* (*Nigella sativa*)	*S. lycopersicum*	El-Najjar *et al.* (2011)
Sarmentine	Long pepper (*Piper longum*)	*E. crus-galli, A. retroflexus, D. sanguinalis, Leptochloa filiformis, Taraxacum* sp. *C. album, P. annua, I. purpurea, S. arvensis, R. crispus*	Dayan *et al.* (2011)
Sorgoleone	Sorghum (*Sorghum bicolor*)	*P. minor, C. didymus, C. rotundus, S. nigrum, A. retroflexus, A. atrtemisifolia, C. obtusifolia*	Subramanyam *et al.* (2013); Thi *et al.* (2015)

compounds tend to be short-lived in the environment, complex and unpredictable (Schandry and Becker 2020; Zhang *et al.* 2021). Additionally, they are often non-selective in their control, expensive to synthesize, and in some cases, present potential mammalian toxicity with carcinogenic and allergenic concerns (Clemensen *et al.* 2020; Wink 2018). Despite these limitations, the herbicides based on allelopathic compounds often represent novel target sites in managing pesticide resistance, and they are water soluble and are perceived as more environmentally benign as compared to the chemical herbicides (Clemensen *et al.* 2020; Macias *et al.* 2003; Nishida 2014).

Several plant-based compounds possess a specific inhibiting activity against weed growth without causing any detrimental impact on crops due to differences in sensitivity to a specific receptor in different plant species or families (Hasan *et al.* 2021). The target-oriented phytotoxic compounds may lead to chlorosis or burning of leaves, reduction in chlorophyll content, cellular respiration, oxidative damage, plant growth reduction, mitotic inhibition, etc. (Hasan *et al.* 2021; Muñoz *et al.* 2020). However, hardly any systematic study has been conducted to elucidate the biochemical or physiological pathway followed by a range of plant extracts used as herbicidal agents.

EVIDENCE-BASED BIO-EFFICACY STUDIES FOR WEED MANAGEMENT USING HERBAL HERBICIDES

In a study on the wet season rice, *Calotropis* was found to be more effective than mechanical weeding at 30 days after transplanting (DAT).

Ipomoea and *Antigonon* also reduced weed growth, whereas higher grain yields were achieved with the use of *Annona*, followed by *Vitex* and *Holarrhena*, which were significantly superior to *Azadirachta*, pretilachlor and *Adhatoda*. The usage of *Adhatoda* was found to be as good as mechanical weeding (MW) and weed-free treatments. *Calotropis*, *Ipomoea* and *Antigonon* were found to be less effective in producing higher grain yield of rice (De and De 2000), whereas the use of *Ipomoea*, *Vitex*, MW (30 DAT) and *Cymbopogon* was equally effective as the weed-free check with minimal weed density at 42 DAT (Mandal and De 2001; Mandal *et al*. 2002). Next best treatments were the usage of *Calotropis* and *Annona*, which remained significantly superior to butachlor. Use of *Vitex* registered minimum weed biomass and remained at par with weed-free check and MW, and it was superior to butachlor. *Ipomoea* and *Calotropis* lowered the weed biomass in an equally manner as butachlor, and were followed by *Cymbopogon* and *Annona*. Similar results of *Annona* were also reported earlier (De and De 2000).

In a study, green leaves of the selected plants (150-200 kg/ha) were chopped, macerated and incorporated into the soil at the time of final puddling in transplanted rice or land preparation in other crops (Mandal and De 2005; Mandal *et al*. 2002). It was observed that incorporation of chopped and macerated leaves of *Tabernaemontana* caused 34% yield advantages and ranked second best in terms of net returns, whereas *Holarrhena* and *Antigonon* had fetched net returns exceeding those attained with MW (Mandal and De 2005). Hence, *Antigonon*, *Holarrhena* and *Tabernaemontana* may replace the traditional MW methods in rapeseed.

One hand weeding (HW) at 15 DAT in combination with two rounds of cono weeding (CW) at 25 and 35 DAT was found comparable with the pre-emergence (PE) application of pretilachlor 500 g/ha at 1 DAT followed by (*fb*) CW twice at 25 and 35 DAT, and use of herbal extract (water extract of *Calotropis* stem and leaf at 50 ml/l) at 1 DAT (PE) *fb* CW twice at 25 and 35 DAT, in the system of rice intensification (SRI). An integrated approach involving MW (CW), manual weeding (HW), and/or herbicide (pretilachlor) in judicious combination with the herbal herbicide (*Calotropis*) would be effective for sustainable weed management to improve rice productivity (Bhowmick *et al*. 2014).

Nagaraja and Deshmukh (2009) studied the phytotoxic effect of *Andrographis paniculata* (king of bitter / kirata / kalmagha) on growth and metabolism of *Parthenium hysterophous*. They reported that the powdered leaves, stems and roots of *Andrographis* could adversely affect the growth and physiology of *Parthenium* up to 60 days after sowing (DAS). Hence, *Andrographis* may be a suitable herbal herbicide against *Parthenium*.

Field experiment was conducted to find out a suitable solution for managing *Parthenium* with the use of different bio-agents including Mexican beetle (*Zygogramma bicolorata*) at 35 nos./plant, sowing of Mexican marigold (*Tagetes erecta*) along with *Parthenium* in 50 : 50 proportion, sowing of sickle pod (*Cassia tora*) in 50 : 50 proportion, and inoculation of Brinjal Mosaic Virus (BMV). The beetle insect and BMV did not exhibit satisfactory performance whereas *C. tora* and *T. erecta* significantly minimized weed growth possibly due to the release of allelochemicals. Because of widespread availability of sicklepod and marigold, common people can easily use these plants for controlling the obnoxious weed *Parthenium* (Dolai *et al*. 2015). *Parthenium* intensity was reduced in association with the plant species *C. tora* and *T. erecta* (Pawar *et al.* 2010). French marigold (*T. patula*) did not allow *Parthenium* to grow with it (Ramachandra Prasad *et al*. 2010). *T. erecta* displays strong allelopathic and herbicidal potential on seed germination and seedling growth of wild peas (*Phaseolus lathyroides*) as reported by Wichittrakarn *et al.* (2013). Furthermore, aqueous extracts from leaf may have a greater inhibitory effect on seed germination and seedling growth, *fb* those of root, flower and stem extracts.

Essential oil of *Peumus boldus* at all concentrations of 0.125-1.000 µl/ml is highly phytotoxic against annual weeds such as *Amaranthus hybridus* and *Portulaca oleracea* by inhibiting their seed germination and seedling growth whereas that of *Drimys winterii* only affects germination of *Portulaca* at the highest concentration (0.5-1.0 µl/ml). This suggests the possible use of essential oil from *P. boldus* as a natural herbicide for weed management in tropical and subtropical crops (Verdeguer *et al*. 2011).

Since aqueous methanol extract of *Leucas aspera* can significantly inhibit the seedling growth of timothy, jungle rice and barnyard grass, *Leucas* plant extract may have allelopathic properties (Islam and Kato-Noguchi 2013). Leaf extract of *Lantana camara* inhibits the germination per cent of *Bidens pilosa*, and leaf extracts at 1, 5 and 10% concentrations are comparable with MW and synthetic herbicide oxyfluorfen, but higher and significantly different as compared to lantana leaf extracts at 20% concentration (Darana 2013). Aqueous leaf extract and leaf debris of *Chromolaena odorata* and *Mikania micrantha* incorporated into the soil shows significant effect on total germination, germination indices and seedling growth of *Ageratum conyzoides* both in the laboratory and greenhouse conditions (Nornasuha and Ismail 2013).

According to Sondhia and Varshney (2009), significant inhibition of growth of major world's worst weeds (*P. hysterophorus*, *Vicia sativa*, *Ischaemum rugosum*, *Convolvulus arvensis*, *Echinochloa colona*, *Lathyrus sativa*, *Phalaris minor*, *Cyperus rotundus*, *Avena ludoviciana*, *etc*.) is possible with the use of phytochemicals / extracts isolated from different plants / weeds at the concentration range of 0.5-5.0 ppm and complete inhibition at 5-10% extracts. Crude ethanol extracts (70%) from the leaves of *Chromolaena odorata* as an early post-emergence application exhibit the highest inhibitory activity on the germination and growth of *Echinochloa crus-galli* seedlings (Poonpaiboonpipat *et al.* 2021).

Ghosh *et al.* (2020) studied with different botanical extracts of *Tectona grandis* (leaf), *Eucalyptus cameldulensis* (leaf), *Bambusa vulgaris* (root and leaf), *Calotropis procera* (young twigs), *Cucumis sativus* (matured plants), and young plants of *Parthenium hysterophorus*, *Blumea lacera*, *Ageratum conyziodes*, *Ocimum sanctum*, *Physalis minima*, *Cyperus difformis* and *Echinochloa colona* in mixed combination with 0.25% Tween 80 surfactants. In rapeseed and soybean, *Eucalyptus* leaf extract gives 11.2% higher seed yield over weedy check. Botanical treatments like *Ageratum conyzoides* extract gives higher growth and yield in sesame and blackgram while *Ocimum sanctum* extract among the botanicals in greengram displays higher harvest index, oil content and also soil nutrient status. Botanicals are reported to inhibit mostly the grassy weed species and give higher yields due to weed management with the help of natural phenol based allelochemicals (Ghosh *et al.* 2015 and 2020). Annual planning for weed management along with the use of botanical herbicides in integration with the MW is more eco-safe and cost-effective option for weed management under the system of crop intensification (Ghosh *et al.* 2015).

In a study with different intercrops for weed management in cotton under rainfed condition, the relative neighbour effect (RNE) value for each intercrop was assessed to correlate the abundance of different allelochemicals released from intercrops with their bio-efficacies for weed suppression. As evidenced from the RNE values, intercrops with high levels of phenolic, terpenoid, and other allelochemicals specific to sunnhemp, pearl millet, and sesame can be positively correlated with weed suppression. An effective weed management in cotton is possible if it is intercropped with pearl millet, sesame and sunnhemp due to the combined effect of allelochemicals (fatty acids, fatty acid methyl esters, terpenoids and phenolics) released from those intercrops which proved to be toxic to the weed flora. (Verma *et al.* 2021). Allelopathic compounds of wild plants (*Tithonia diversifolia* and *Thevetia peruviana*) may be an effective alternative for promoting growth and imparting resistance of tomato crop (Fangue-Yapseu *et al.* 2021).

The allelopathic potential of certain weed and crop species can influence the growth and distribution of associated weeds and the yield of desired plants (Inderjit and Keating 1999). For example, *Ailanthus altissima* produces an allelopathic compound called alianthone, which inhibits the growth of other plants (Heisey 1997) like garden cress (*Lepidium sativum*), redroot pigweed (*Amaranthus retroflexus*), yellow bristlegrass (*Setaria pumila*), barnyard grass (*Echinochloa crusgalli*), pea (*Pisum sativum* cv. *Sugar Snap*) and maize (*Zea mays* cv. *Silver Queen*). Likewise, several plant secondary metabolites (allelochemicals) possess good herbicidal activity. These allelochemicals provide novel chemistries that can be manipulated in order to produce commercial herbicides (Bhowmick and Mandal 2001). Some examples of commercially developed herbicides (based on natural chemistry) are 'cinmethylin' (a herbicidal analogue of 'cineole', widespread in plants), 'benzazin' (based on the natural product 'benzoxazinones'/'hydroxamic acids' derived from poaceaeous plants), 'quinclorac' (based on 'quinolinic acid' from *Nicotiana tabacum*), *etc*. (Hatzios 1987). One more important example is 'leptospermone', which is a purported thermochemical in lemon bottlebrush (*Callistemon citrinus*). Although it has been found to be too weak as a commercial herbicide, a chemical analog of it, 'mesotrion' (trade name 'callisto'), has been found to be effective. It is sold to control broadleaved weeds in corn but also seems to be an effective control for crabgrass in lawns. Corn gluten meal (CGM) is used for the natural PE weed control in turfgrass, which reduces germination of many broadleaved weeds and grasses (McDade and Christians 2000).

These examples demonstrate that the structures of naturally occurring phytotoxins can serve as leads for the synthesis of new successful herbicides. Thus, the secondary metabolites of plant species with allelopathic activities offer an excellent potential to develop new herbicide formulations or as a guide towards identifying active compounds to obtain natural / herbal herbicides. Greater research efforts need to be made to study the effect of plant-derived compounds or the allelopathic effect of phytochemicals for identifying them as herbal herbicides. Till then, the commonly available plants may be utilized directly by the rural farmers for successful weed management in different crops and cropping systems.

PROSPECTS AND LIMITATIONS OF USING HERBAL HERBICIDES

Use of herbal herbicides for weed management may have certain prospective benefits (Bhowmick *et al.* 2016). Some of these are as follows:

1. They don't necessarily display a toxic effect on the non-target organisms including human beings and animals.
2. There is limited scope for the development of resistance in weeds.
3. There is no scope for the residue build up in the environment.
4. They are bio-degradable.
5. They may act as plant growth promoters in addition to their herbicidal activities.
6. Smallholder farmers can easily explore the use of herbal herbicides as per natural and local availability.
7. Weed control techniques are inexpensive.

Despite having multiple benefits, use of herbal herbicides may be constrained for widespread adoption by the farmers because of certain limitations (Bhowmick *et al.* 2016), including (1) slow rate of weed suppression or extermination by herbal herbicides, (2) their variable efficacies or sometimes even little or negative toxicity and instability under field conditions (based on soil and environmental conditions), (3) possible requirements for bulk applications for improving field effectiveness and performance, (4) lack of specific mode of action and also no systemic activity (limited absorption and translocation) unlike synthetic chemical herbicides, (5) inadequate research efforts for the discovery and development of novel herbal herbicides with greater bio-efficacies, and (6) requirements for need-based integration with synthetic herbicides and other tactics for broad-spectrum weed control.

CONCLUSION

Weed-related crop losses are still very common and can place a huge financial strain on farmers. Herbicide usage minimizes crop-weed competition effectively and increases farm labor efficiency, but it comes out with the risks in terms of environmental pollution, human health hazards, herbicide resistance development, and much reliance on inputs that must be purchased. New eco-friendly alternatives are required to combat the threat of weeds as they continue to evolve resistance to synthetic herbicides. Therefore, proper attention must be placed on using non-chemical weed control methods, ranging from adjusting crop cultivation systems to biological ones, as well as developing, identifying, and employing herbal herbicides. The potential use of secondary plant products as natural or herbal herbicides has initiated scientific curiosity in light of recent developments in plant biochemistry. Although it may or may not control all kinds of weeds, rural farmers can readily use such natural plant sources as herbal herbicide. Thus, herbal herbicides should be viewed as complementing adjuncts in an integrated weed management (IWM) system rather than as a current replacement for broad-spectrum herbicides and other weed control strategies. The IWM strategy using herbal herbicides and other techniques in a strategic combination would be a cost-effective and environmentally acceptable solution resolve to the weed problems and related issues in smallholder farming in general, and organic or natural farming systems in particular.

REFERENCES

Abubakar AR and Mainul Haque. 2020. Preparation of medicinal plants: Basic extraction and fractionation procedures for experimental purposes. *Journal of Pharmacy & Bioallied Sciences* **12**(1): 1–10.

Alzoreky NS and Nakahara K. 2003. Antibacterial activity of extracts from some edible plants commonly consumed in Asia. *International Journal of Food Microbiology* **80**(3): 223–230.

Bais HP and Kaushik S. 2010. Catechin secretion & phytotoxicity: Fact not fiction. *Communicative and Integretive Biology.* **3**: 468–470.

Bajwa AA, Mahajan G and Chauhan BS. 2015. Non-conventional weed management strategies for modern agriculture. *Weed Science* **63**(4): 723–747.

Balasubramaniam VG Ramakrishnan SR and Antony U. 2022. Opportunities and Challenges of Plant Extracts in Food Industry. In: *Plant Extracts: Applications in the Food Industry*.(Eds. Mir SA, Manickavasagan A and Shah MA). Academic Press.

Bhowmick MK and Mandal BK. 2001. Biotechnological approaches to the management of weeds in Indian agriculture. *Science and Culture* **67**(9-10): 275–280.

Bhowmick MK, Dhara MC, Ghosh RK and Duary B. 2014. Productivity improvement through weed management under the System of Rice Intensification in West Bengal. Pp. 85–86. In: *Proceedings of "Environmental Biology and Ecological Modelling*", Feb. 24-26, 2014, Department of Zoology, Centre for Advanced Studies, Visva-Bharati, Santiniketan, Birbhum, West Bengal, India.

Bhowmick MK, Duary B and Biswas PK. 2016. Herbal herbicide: A potential tool of weed management for rural farmers. Pp. 55–62. In: *Essays on Indian Economic Problems* (Ed. Chattopadhyay PK). Renu Publishers, Mohan Garden, New Delhi, India.

Carrubba A, Labruzzo A, Comparato A, Muccilli S and Spina A. 2020. Use of plant water extracts for weed control in durum wheat (*Triticum turgidum* L. subsp. *durum* Desf.). *Agronomy* **10**(3): 364.

Caser M, Demasi S, Caldera F, Dhakar NK, Trotta F and Scariot V. 2020. Activity of *Ailanthus altissima* (Mill.) swingle extract as a potential bioherbicide for sustainable weed management in horticulture. *Agronomy* **10**(7): 965.

Cheng F and Cheng Z. 2015. Research progress on the use of plant allelopathy in agriculture and the physiological and ecological mechanisms of allelopathy. *Frontiers in Plant Science* **6**: 1020.

Clemensen AK, Provenza FD. Hendrickson JR and Grusak MA 2020. Ecological implications of plant secondary metabolites - Phytochemical diversity can enhance agricultural sustainability. *Frontiers in Sustainable Food Systems* **4**: 233.

Cragg GM and Newman DJ. 2013. Natural products: a continuing source of novel drug leads. *Biochimica et Biophysica Acta* **1830**(6): 3670.

Darana S. 2013. Allelopathic activity of *Lantana* leaf extract (*Lantana camara*) on the weed in tea (*Camellia sinensis*). Pp. 341–345. In: *Proceedings of 24th Asian-Pacific Weed Science Society Conference,* Oct. 22-25, 2013, Bandung, Indonesia.

Dayan FE, Hower JL, Marras PJ, Ferrera D and Koivunen M. 2011. Manuka oil, a natural herbicide with pre-emergence activity. *Weed Sci*ence **59**: 464–469.

Dayan FE, Owens DK, Watson SB, Asolkar RN and Boddy LG. 2015. Sarmentine, a natural herbicide from piper species with multiple herbicide mechanisms of action. *Frontier of Plant Science* **6**: 222.

De GC and De P. 2000. Effect of phytoherbicides on transplanted *kharif* rice. Pp. 40. In: *Proceedings of National Seminar on "Development and Use of Biofertilizers, Biopesticides and organic Manures,*" Nov. 10-12, 2000, B.C.K.V., Kalyani, West Bengal, India.

Dolai A K, Ghosh RK and Bhowmick M K. 2015. Field performance of some bioagents in suppressing *Parthenium hysterophorus* L. *Environment & Ecology* **33**(2): 635–638.

Duary B. 2010. Recent advances in herbicide resistance in weeds and its management. *Indian Journal of Weed Science* **40**(3&4): 124–135.

Duary, B. and Mukherjee, A. 2013. Distribution pattern of predominant weeds of wet season and their management in West Bengal, India. Pp. 191–199. In: *Proceedings of 24th Asian-Pacific Weed Science Society Conference*, Oct. 22-25, 2013, Bandung, Indonesia.

El Bazaoui A, Bellimam MA and Soulaymani A. 2011. Nine new tropane alkaloids from *Datura stramonium* L. Identified by GC/MS. *Fitoterapia* **82**: 193–197.

Elisante F, Tarimo MT and Ndakidemi PA. 2013. Allelopathic effect of seed and leaf aqueous extracts of *Datura Stramonium* on leaf chlorophyll content, shoot and root elongation of *Cenchrus ciliaris* and *Neonotonia wightii*. *American Journal of Plant Sciences* **4**(12): 2332–2339.

El-Najjar N, Gali-Muhtasib H, Ketola RA, Vuorela P, Urtti A and Vuorela H. 2011. The chemical and biological activities of quinones: Overview and implications in analytical detection. *Phytochemical Review* **10**: 353–370.

Fabrizio A, Mancuso R, Lupini A, Giofre SV, Sunseri F, Gabriele B and Abenavoli MR. 2015. Phytotoxic potential and biological activity of three synthetic coumarin derivatives as new natural-like herbicides. *Molecules* **20**(10): 17883–17902.

Fangue-Yapseu GY, Mouafo-Tchinda RA, Fomekong KM, Effa Onomo P and Djocgoue PF. 2021. Allelopathic effect of three wild plants (*Azadirachta indica*, *Tithonia diversifolia* and *Thevetia peruviana*) on tomato (*Lycopersicum esculentum* Mill.) growth and stimulation of metabolites involved in plant resistance. *American Journal of Plant Sciences* **12**: 285–299.

Gautam KC and Mishra JS. 1995. Problems, prospects and new approaches in weed management. *Pesticides Information* **XXI** (1): 7–19.

Ghardea Y, Singh PK, Dubey RP and Gupta PK. Assessment of yield and economic losses in agriculture due to weeds in India. *Crop Protection* **107:** 12–18.

Ghosh RK, Ghosh A, Mondal D and Bandyopadhyay P. 2020. Expediency of botanical herbicides in organic green farming for sustainable productivity of agricultural crops in alluvial soils of India. P. 17. In: *Proceedings of ISWS Biennial Conference on "Weed Management for Enhancing Farmers' Income and Food Security*", 5-7 February 2020, ICAR-CCARI, Goa, Indian Society of Weed Science, India.

Ghosh RK, Shamurailatpam D, Ghosh A, Sentharagai S, Labar A, Nongmaithem D, Jana PK, Ghosh S and Kole RK. 2015. Use of botanical herbicides in system intensification. *Indian Journal of Weed Science* **47**(4): 401–407.

Gonelimali FD, Lin J, Miao W, Xuan J, Charles F, Chen M and Hatab SR. 2018. Antimicrobial properties and mechanism of action of some plant extracts against food pathogens and spoilage microorganisms. *Frontiers in Microbiology* **9**: 1639.

Hasan M, Ahmad-Hamdani MS, Rosli AM and Hamdan H. 2021. Bioherbicides: An eco-friendly tool for sustainable weed management. *Plants* **10**(6): 1212.

Hatzios KK. 1987. Biotechnology applications in weed management: Now and in the future. *Advances in Agronomy* **41**: 325–375.

Heisey RM. 1997. Allelopathy and the secret life of *Ailanthus altissima*. *Arnoldia* **57**(3): 28–36.

Inderjit and Keating KI. 1999. Allelopathy: Principles, procedures, processes and promises for biological control. *Advances in Agronomy* **67**: 141–231.

Ines Z, Ghezal N, Sbai H, Richard G, Fauconnier M L and Haouala R. 2018. Biochemical composition of Tunisian *Nigella Sativa* L. at different growth stages and assessment of the phytotoxic potential of its organic fractions. *Plant Signaling & Behaviour* **153**(2): 205–212.

Islam AKMM and Kato-Noguchi H. 2013. Isolation and characterization of allelopathic substance from *Leucas aspera*. Pp. 338–340. In: *Proceedings of 24th Asian-Pacific Weed Science Society Conference,* Oct. 22-25, 2013, Bandung, Indonesia.

Jabran K, Mahajan G, Sardana V, and Chauhan BS. 2015. Allelopathy for Weed Control in Agricultural Systems. *Crop Protection* **72**: 57–65.

Jabran K. 2017. *Manipulation of allelopathic crops for weed control*. Cham: Springer International Publishing. http://link.springer.com/10.1007/978-3-319-53186-1.

Julien MH and Griffiths MW. 1998. *Biological Control of Weeds. A World Catalogue of Agents and Their Target Weeds,* CAB International: Wallingford, UK.

Kozuharova E, Pasdaran A, Al Tawaha AR, Todorova T, Naychov Z and Ionkova I. 2022. Assessment of the potential of the invasive arboreal plant *Ailanthus altissima* (Simaroubaceae) as an economically prospective source of natural pesticides. *Diversity* 1**4**: 8, 680

Kumar L and Varshney JG. 2009. Utilization of weeds as a source of potential allelochemicals. pp. 21–22. In: *Proceedings on National Consultation on Weed Utilization*, Oct. 20-21, 2009, Directorate of Weed Science Research, Jabalpur, Madhya Pradesh, India.

Lovett JV and Potts WC. 1987. Primary effects of allelochemicals of *Datura stramonium* L. *Plant Soil* **98**: 137–144.

Macias FA, Martin D, Oliveros-Bastidas A, Varlea RM, Simonet AM, Carrera C and Molinillo JMG. 2003. Allelopathy as a new strategy for sustainable ecosystems development. *Biological Sciences in Space* **17**(1): 18–23.

Mandal B and De G C. 2001. Efficiency of herbal leaves on transplanted *kharif* rice weed management. Pp. 161–163. In: *Proceedings of National Seminar on 'Frontiers of Crop Management'* (Eds. Mukhopadhyay SK, Ghosh D.C and De GC), Feb. 1-3, 2001, Institute of Agriculture, Visva-Bharati, Sriniketan, West Bengal, India.

Mandal B and De GC. 2005. Studies on herbal herbicides in controlling weeds in rapeseed and mustard. *Journal of Interacademicia* **9**(2): 292–295.

Mandal B, De P and De GC. 2002. Efficiency of herbal leaves on weed management of transplanted *kharif* rice. *Journal of Interacademicia* **6**(1): 109–112.

Masum SM, Hossain MA, Akamine H, Sakagami JI, Ishii T, Gima S, Kensaku T and Bhowmik PC. 2018. Isolation and characterization of allelopathic compounds from the indigenous rice variety 'Boterswar' and their biological activity against *Echinochloa crus-galli* L. *Allelopathy Journal* **43**(1): 31.

McDade MC and Christians NE. 2000. Corn gluten meal - a natural preemergence herbicide: effect on vegetable seedling survival and weed cover. *American Journal of Alternative Agriculture* **15**(4): 189–191.

Minto RE and Blacklock BJ. 2008. Biosynthesis and function of polyacetylenes and allied natural products. *Progress of. Lipid Research* **47**: 233–306.

Motmainna M, Juraimi AS, Uddin MK, Asib NB, Islam AKM and Hasan M. 2021. Assessment of allelopathic compounds to develop new natural herbicides: A review. *Allelopathy Journal* **52**: 21–40.

Mukhopadhyay SK. 1992. Emerging problems and advances in weed management. Pp.1-16. In: *Proceedings of 79th Indian Science Congress*. Part II. Presidential Address (Agric. Section), Baroda.

Mukhopadhyay SK. 1993. Scope and limitation of the application of biotechnology in integrated weed management. Pp. 221-224. In: *Proceedings of International Symposium.* Indian Society of Weed Science, Hisar, India, Nov. 18-20, 1993, Vol. **I**

Muñoz M, Torres-Pagan N, Peiro R, Guijarro R, Sanchez-Moreiras AM and Verdeguer M. 2020. Phytotoxic effects of three natural compounds: Pelargonic acid, carvacrol, and cinnamic aldehyde, against problematic weeds in Mediterranean crops. *Agronomy* **10**(6): 10.3390/agronomy10060791.

Nagaraja TG and Deshmukh SM. 2009. Phytotoxic effect of *Andrographis paniculata* on metabolism of *Parthenium hysterophorus* L. *Journal of Biopesticides* **2**(2): 165–167.

Ndam LM, Mih A, Fongod A, Tening A, Tonjock R, Enang JE and Fujii Y. 2014. Phytochemical screening of the bioactive compounds in twenty (20) Cameroonian medicinal plants. *International Journal of Current Microbiology and Applied Sciences* **3**(12): 768–778.

Nishida R. 2014. Chemical ecology of insect–plant interactions: Ecological significance of plant secondary metabolites. *Bioscience, Biotechnology, and Biochemistry* **78**(1): 1–13.

Nornasuha Y and Ismail BS. 2013. Comparative allelopathic effects of *Chromolaena odorata* (L.) King & Robinson and *Mikania micrantha* H.B.K. on *Ageratum conyzoides.*Pp. 407–411. In: *Proceedings of 24th Asian-Pacific Weed Science Society Conference,* Oct. 22-25, 2013, Bandung, Indonesia..

Palombo EA. 2011. Traditional medicinal plant extracts and natural products with activity against oral bacteria: Potential application in the prevention and treatment of oral diseases. *Evidence-based Complementary and Alternative Medicine* 2011.

Pawar SU, Jadhav AS, Patil MG, Deshmukh DD and More SR. 2010. Influence of suppressing bio-agent plant species on *Parthenium hysterophorus* L. intensity. In: *Proceedings of Third International Conference on Parthenium.* IARI, New Delhi, India.

Perveen S, Yousaf M, Mushtaq MN, Sarwar N, Khaliq A and Hashim S. 2019. Selective bioherbicidal potential of *Delonix regia* allelopathic leaf extract on germination and seedling growth of field bindweed and wheat. *Applied Ecology and Environmental Research* **17**(1): 511–519.

Poonpaiboonpipat T, Krumsri R and Kato-Noguchi H. 2021. Allelopathic and herbicidal effects of crude extract from *Chromolaena odorata* (L.) R.M.King and H.Rob. on *Echinochloa crus-galli* and *Amaranthus viridis*. *Plants* **10**: 1609.

Proestos C. 2020. The benefits of plant extracts for human health. *Foods* **9**(11). /pmc/articles/PMC7696850/.

Quintana N, El Kassis EG, Stermitz FR and Vivanco JM. 2009. Phytotoxic compounds from roots of *Centaurea diffusa* Lam. *Plant Biosystems* **4**(1): 9–14.

Ramachandra Prasad TV, Denesh, GR, Ananda, N, Sushilkumar and Varshney JG. 2010. *Parthenium hysterophorus* L.– a national weed, its menace and integrated management strategies in India. Pp. 13–20. In: *Proceedings of Third International Conference on Parthenium.* IARI, New Delhi, India..

Sathishkumar A, Srinivasan G, Subramanian E and Rajesh P. 2020. Role of allelopathy in weed management: A review. *Agricultural Reviews* **41**(4): 380–386.

Schandry N and Becker C. 2020. Allelopathic plants: Models for studying plant–interkingdom interactions. *Trends in Plant Science* **25**(2): 176–185.

Shamsur R, Sahazad B, Bajwa AH, Hussain S, Rehman A, Cheema SA, Abbas T, Ali A, Shah L, Adkins S and Li P. 2019. Utilizing the allelopathic potential of *Brassica* Species for sustainable crop production: A review. *Journal of Plant Growth Regulation* **38**(1): 343–356.

Singh A. 2005. Ensuring food security. Pp 1–8. In: *Integrated Pest Management – Principles and Applications.* (Eds. Singh A, Sharma OP and Garg DK), CBS Publishers & Distributors, New Delhi, India.

Soltys D, Krasuska U, Bogatek R and Gniazdow A. 2013. Allelochemicals as bio-herbicides -present and perspectives. Pp. 517–542. In: *Herbicides— Current Research and Case Studies in Use* (Price AJ and Kelton JA, Eds.). InTech: Rijeka, Croatia.

Somala N, Laosinwattana C and Teerarak M. 2022. Formulation process, physical stability and herbicidal activities of *Cymbopogon nardus* essential oil-based nanoemulsion. *Scientific Reports* **12**: 10280.

Sondhia S and Varshney JG. 2009. Weeds as a source of biopesticides. Pp. 15–16. *Abstracts. National Consultation on Weed Utilization* (Eds. Varshney JG and Sushilkumar), Oct. 20-21, 2009, Directorate of Weed Science Research, Jabalpur, Madhya Pradesh, India..

Subramanyam D, Srinivasulu D, Sumathi V and Sajitha K. 2013. Plant origin herbicides: chemistry, mode of action and weed management. *International Journal of Agriculture Science* **9**(1): 413–422.

Thi HL, Hyuk P and Ji PY. 2015. Allelopathy in *Sorghum bicolor*: A review on environmentally friendly solution for weed control. *Research Crop* **16**: 657–662.

Topal S, Kocacaliskan I, Arslan O and Tel AZ. 2007. Herbicidal effects of juglone as an allelochemical. *Phyton* **46**: 259–269.

Verdeguer M, Garcia-Rellan D, Boira, H, Perez, E, Gandolfo, S. and Blazquez MA. 2011. Herbicidal activity of *Peumus boldus* and *Drimys winterii* essential oils from Chile. *Molecules* **16**: 403–411.

Verma P, Blaise D, Sheeba JA and Manikandan A. 2021. Allelopathic potential and allelochemicals in different intercrops for weed management in rainfed cotton. *Current Science* **120**(6): 1035–1039.

Wang C, Wu B and Jiang K. 2019. Allelopathic effects of Canada goldenrod leaf extracts on the seed germination and seedling growth of lettuce reinforced under salt Stress. *Ecotoxicology* **28**(1): 103–116.

Webber CL, Taylor MJ and Shrefler JW. 2014. Weed control in yellow squash using sequential post directed applications of pelargonic acid. *HortTechnology* **24**: 25–29.

Wichittrakarn P, Teerarak M and Laosinwattana C. 2013. Allelopathic potential of *Tagetes erecta* Linn; optimal extraction solvent and its partial separation of active compounds. Pp. 653–659. In: *Proceedings of 24th Asian-Pacific Weed Science Society Conference*, Oct. 22-25, 2013, Bandung, Indonesia..

Wink M. 2018. Plant secondary metabolites modulate insect behaviour-steps toward addiction? *Frontiers in Physiology* **9:** 1–9.

Yaduraju NT and Mishra JS. 2004. Eco-friendly approaches for weed management. Pp. 196–218. In: *Advances in Plant Protection Sciences* (Eds. Prasad D and Singh A eds.). Akansha Publishing House, New Delhi, India.

Yaduraju NT and Mishra JS. 2005. Status and prospects of integrated pest management strategies for obnoxious weeds. In: *Integrated Pest Management – Principles and Applications.* Vol. **1** (Eds. Singh A, Sharma OP and Garg DK). CBS Publishers & Distributors, New Delhi, India.

Zhang Z, Liu Y, Yuan L, Weber E and van Kleunen M. 2021. Effect of allelopathy on plant performance: A meta-analysis. *Ecology Letters* **24**(2): 348–362.