

Allelopathy of Medicinal Plants: Current Status and Future Prospects in Weed Management

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Abstract

An attempt has been made in this article to accumulate and elucidate the literatures about the allelopathic potentiality of medicinal plants, and its role on the development of bio-herbicides for eco-friendly weed management strategies to conserve bio-diversity and ecological balance. This review paper has been prepared by comprehensive studies of various published research articles, books and proceedings available in the world literature. The farmers of different countries use several weed management techniques in order to minimize the deleterious effect of weeds. Among them most commonly used practice is application of herbicides due to its high efficacy and cost effectiveness, less time-consuming nature, flexibility and easy accessibility, and more rapid out return. Although use of synthetic herbicides in the crop fields has increased the crop production as well as the productivity by reducing the weed infestation, over time it causes a number of environmental hazards. Hence, to avoid these detrimental effects of synthetic herbicide, a lot of efforts have been dedicated by the researchers to search the novel natural plant products mainly allelochemicals and try to apply them as a tool for the development of bio-degradable natural herbicides. This paper intended to reflect the current state of allelopathic medicinal plants and their potentiality to develop eco-friendly and natural product-based herbicides for sustainable agriculture, and to invite further debate on this issue.

Keywords

Allelochemicals, Medicinal Plants, Natural Products, Bio-Herbicides, Sustainable Weed Management

1. Introduction

Among the deleterious pests of crops, weeds rank the first as it causes severe loss of crop yields, which is even more than the combined losses caused by plant pathogens and insect pests worldwide. Around 33% - 53% crop produce is damaged if weeds are not controlled in the crop fields [1] [2] [3]. Even after adopting conventional weed control techniques, 13% - 30% of crop produce is lost from the farmers' fields [1] [4] [5].

Since the inception of first commercial herbicide in 1940s farmers are using thousand tons of herbicide every year to control weeds across the globe. Excessive use of synthetic herbicide lead to a tremendous environmental hazards [6] [7] [8] including development of herbicide resistant weed biotypes [9]. Therefore, for the sake of pollution free earth ecosystem and sustainability in crop productivity, conventional agriculture has to be improved by limiting the use of synthetic agrochemical including chemical herbicides. Researchers around the world are therefore now searching for new natural plant products to develop biodegradable and cost effective herbicides for sustainable weed management.

The impact of plants upon neighboring plants or their associated micro-flora and/or macro-flora by the production of allelochemicals is known as allelopathy [10]. Allelopathic substances are released into the surrounding environment (atmosphere or rhizosphere) through a number of ways [11], and upon release may suppress the germination, growth and establishment of neighboring plants, even the donor species itself either directly by affecting their physiological properties [12] [13], or indirectly by modifying the rhizosphere soil properties through influencing the microbial biomass carbon and microbial community [14] [15] [16]. Thus, allelopathic substances play a vital role in regulating the structure of plant communities [17], and thus could be used as lead for biodegradable herbicide production [18] [19].

Medicinal plants have a great history as a source of potential therapeutic agents, which have been incorporated into modern medicine [20] [21] [22]. There are about 422,000 flowering plant species in the world, out of which 52,885 plant species are considered medicinal plants [23]. Of these, the biological activity of only about 6% has been screened, with 15% having been phytochemically evaluated [24] [25] [26]. On the other hand, there are about 400,000 secondary metabolites in plants [27], of which only a few have been examined for their biological or herbicidal activities [28]. The biological or herbicidal potentialities of rest of the compounds are still unexplored. The present study reviews the present status and future prospects of allelopathic medicinal plants in controlling major crop weeds for sustainable agricultural production.

2. Allelopathic Activities of Medicinal Plants

Medicinal plants are considered as an important source of secondary metabolites that usually have a number of biological functions. It has been reported that medicinal plants species possess strong allelopathic potential [11] [29] [30] [31].

Many researchers around the world are now showing their keen interest on medicinal plants for searching new natural plant products, [32]-[37]. Islam and Kato-Noguchi [38] stated two reasons for this increasing interest: 1) the easier screening process of phytotoxic plants from medicinal plants and 2) the possibility to have more bioactive compounds in medicinal plants than other plants. Fujii *et al.* [39] carried out the first comprehensive studies of allelopathic medicinal plants. They evaluated 387 Japanese medicinal plants and observed that a considerable number of those have growth inhibitory potential [39] [40] [41]. Azizi *et al.* [42] examined 56 aromatic medicinal plants of 22 families from Iran for their allelopathic potential and found 51 species inhibited the seedling growth of lettuce. Gilani *et al.* [43] also evaluated 81 medicinal plant species of Pakistan and reported 78 as allelopathic potential inhibiting the root growth of lettuce. Mardani *et al.* [44] recently evaluated the allelopathic potential of 83 Iranian medicinal plants and observed more than 80% root growth suppression of lettuce by *Peganum harmala*, *Berberis vulgaris*, *Artemisia aucheri* and *Ferulago angulata*. Amini *et al.* [45] investigated the allelopathic potential of 68 medicinal and wild plant species belong to 19 plant families grown in Iran. Among the examined plant species, stigma and style of *Crocus sativus*, leaves of *Artemisia kopetdaghensis*, *Mentha piperita*, *Zhumeria majdae*, *Ferulago subvelutina*, flowers bud of *Eugenia caryophyllata*, flower of *Perovskia abrotanoides*, fruits of *Melia azedarach* and *Ruta graveolens* had the strongest inhibitory effects on lettuce seedling growth. Islam *et al.* [46] on the other hand, examined the allelopathic properties of 55 tropical medicinal plant species of Bangladesh representing 32 different families. All the medicinal plant species except *Garcinia mangostana* (Clusiaceae) and *Schleichera oleosa* (Sapindaceae) showed allelopathic potential. Moreover, among the plant species, *Citrus aurantifolia* (Rutaceae), *Moringa oleifera* (Moringaceae), *Annona muricata* (Annonaceae), *Aegle marmelos* (Rutaceae), *Cinnamomum tamala* (Lauraceae) and *Azadirachta indica* (Meliaceae) completely (100%) inhibited the growth of *Raphanus sativus*. From two different studies Piyatida and Kato-Noguchi [47] and Suwitthayanon *et al.* [48] evaluated 25 medicinal plants of Thailand and reported that the extract obtained from *Cymbopogon nardus*, *Piper retrofractum*, *Piper sarmentosum*, *Rhinacanthus nasutus* and *Tinospora tuberculata* possessed the highest allelopathic potential against the seedling growth of lettuce. Qasem [31] examined 30 medicinal plant species of Jordan for their herbicidal activities against *Amaranthus retroflexus* and *Chenopodium murale* in laboratory and glasshouse conditions. In laboratory study, the aqueous extracts of *Alhagi maurorum*, *Capparis spinosa*, *Citrullus colocynthis*, *Lavandula officinalis*, *Origanum syriacum*, *Rhus coriaria*, *Ricinus communis*, *Rosmarinus officinalis* and *Teucrium polium* either prevented seed germination or reduced seedling growth. Whereas, in glasshouse experiment addition of 2 g kg⁻¹ dried shoot material of *L. officinalis* or *R. officinalis* to the potted soil mixture was highly toxic to weed germination and growth, and addition of 16 g kg⁻¹ of *C. spinosa*, *R. coriaria*, and *T. polium* severely reduced

weed growth. Many other researchers for example, Khanh *et al.* [49], Azizi and Fujii [32], Khan *et al.* [50], Anjum *et al.* [51], Laosinwattana *et al.* [52], Islam and Kato-noguchi [53] Islam and Kato-Noguchi [54], Khan *et al.* [55], Islam and Kato-Noguchi [56], Islam *et al.* [57], Islam and Kato-Noguchi [58], Itani *et al.* [59], Baličević *et al.* [60], Qasem [61] and Algandaby and El-Darier [62] worked with several medicinal plants species and observed that most of the species possessed strong allelopathic properties and inhibited the growth of test plant species with different inhibition values.

3. Scope of Using Natural Plant Products in Weed Management

Since the inception of agriculture, different types of natural plant products have been used to control pests mainly insect and disease organisms. More evidences have been found in the world literature about the use of natural product as fungicides, insecticides, and other pesticides than as herbicides [63]. Although natural product based herbicides for weed control strategies have not yet been as successful as like other pesticides, however, there have some notable success stories [64]. Nowadays, the use of allelopathic medicinal plants has been suggested as a viable option for alternative weed management in sustainable agriculture [65] [66] [67]. Yang and Tang [68], described two ways of plant utilization for weed management: 1) the active compounds are isolated, identified and chemically synthesized; if possible, these compounds or their active analogs are produced by the chemical industry, 2) plant tissue or a crude product of the plant, such as aqueous or organic extract is used directly. The last one is more labor intensive, but is often economically and ecologically sounds, and does not require sophisticated technology, and thus is suitable for the farmers in developing countries and also for organic farming.

Duke *et al.* [19] proposed three approaches to select the sources of natural products for the discovery of potential herbicides: 1) to obtain pure compounds from other scientists, 2) to obtain biological material that has not previously been studied, and 3) to use ethnobiological and/or chemical ecology clues. However, ethnobotanical knowledge showed better performance only in case of pharmaceutical, rodenticide and insecticide discovery, but not for phytotoxins. In this backdrop chemical ecology provides some important clues. They suggested two chemical ecology approaches to identify phytotoxic plants: a) allelopathic activity has been the most common approach; an example of this strategy is the discovery of sorgoleone from allelopathic sorghum species [69] [70], b) the second approach is to examine compounds on that plant species have sequestered to avoid autotoxicity, for examples, artemisinin and hypericin [71].

4. Prospects and Status of Allelopathic Plants in Weed Management

The allelopathic plants have been suggested as a viable option for alternative weed management under sustainable agriculture [65] [66] [67] [72] [73]. These

plants could be exploited in weed management through a number of processes. For example, use them as cover/smother crops [74] [75] [76], rotational/companion crops [77], application of their extracts [78] [79] [80] [81], incorporation of their residues or their different parts as mulch [82] [83] [84], application of allelopathic substances as natural herbicides [82] [85], use of allelopathic plant extracts with lower herbicide doses [79] [86] [87] or development of allelopathic crop cultivars through breeding program [88] [89].

Substantial number of reports has been documented in the literature about the successful use of allelopathic plants, their extracts/residues, or the allelopathic substances into the crop fields as a substitute of synthetic herbicides to control weeds. Mushtaq *et al.* [90] opined that herbicide use could be reduced by 75% through integration with sorghum and sunflower extracts without compromising yield and net benefits for cost-effective and eco-friendly control of wild oat and canary grass in wheat. Xuan *et al.* [91] found that alfalfa pellets at 1 - 2 t·ha⁻¹ completely inhibited the emergence of *Dopatrium junceum*, *Lindernia pyxidaria* and *Elatine triandra*, and also reduced the number and dry weight of emerged *Echinochloa oryzicola*. Hong *et al.* [92] worked with ten allelopathic higher plants (*Ageratum conyzoides*, *Bidens pilosa*, *Blechnum orientale*, *Eupatorium canabium*, *Euphorbia hirta*, *Galactia pendula*, *Leucana glauca*, *Melia azedarach*, *Morus alba*, and *Tephrosia candida*) and revealed that all the species at 2 t·ha⁻¹ significantly reduced paddy weed growth and promoted the rice growth and yield. Among those species, *B. pilosa* and *T. candida* showed the highest potential to reduce more than 80% weeds and to increase rice yields by up to 20%. Many other examples are found in the literatures that are potential to control weeds [49] [89]. From another field experiment in Thailand, Laosinwattana *et al.* [52] reported that the powders of the *Aglaia odorata* leaves inhibited the emergence and growth of *Digitaria adscendens*, *Trianthema portulacastrum*, and *Amaranthus gracilis* at a dosage of 1 t·ha⁻¹. A bioherbicide PORGANIC™ was then developed from the leaf extracts of this plants, which had significant inhibitory effects on *Echinochloa crusgalli* and *Sphenoclea zeylanica* at a dosage of 10 kg·ha⁻¹ [93].

Xuan *et al.* [94] demonstrated that allelopathic plant extracts performed better than synthetic herbicides to control weeds. They observed that Japanese alfalfa variety (Rasen) inhibited 80% total weed biomass and promoted 81% rice yield when compared with the control (without any weed and fertilizer management). In contrast, herbicide treatment suppressed 75% paddy weeds but increased rice yield by only 10%, and those for hand weeding were about 70% and 25%, respectively.

As stated earlier, an increasing number of weeds are now gaining resistant to several synthetic herbicides. Therefore, it is much difficult to control them through synthetic herbicides. Allelopathic plants showed promising results in controlling those weeds. In Japan, *Rotala indica* showed strong resistance to some common herbicides. Application of alfalfa and rice byproducts at the rate

of 1 - 2 t·ha⁻¹ could completely inhibit the emergence of this noxious weed, and *A. conyzoides*, *B. pilosa*, *G. pendula*, *L. glauca* and *Piper methysticum* inhibited significantly *R. indica* at the same dose [94].

Xuan *et al.* [94] also reported that 70% - 80% weed reduction could be attained through the incorporation of 1 - 2 t·ha⁻¹ of strong allelopathic plants. Although the inhibitory activity of allelopathic plant biomass is dose-dependent, they suggested not exceeding the limit above 2 t·ha⁻¹. Otherwise, it will be laborious and costly. The most important obstacle to use plant biomass is that it needs water for decomposition. Therefore, it is very difficult to apply plant biomass in highland areas where water crisis exists. To overcome this problem many researchers currently focuses on allelopathic substances rather than the plant itself. They stated that if allelopathic substances with stronger activity on weeds are deployed as a tool for new natural herbicides development, the burden from plant residue application could be minimized.

Sorgoleone, an isolated allelochemicals exudate from *Sorghum* root hair, has been characterized as a potent bio-herbicide. It is phytotoxic to broadleaf and grass weeds at concentrations lower than 10 µM [95] [96]. Post-emergent foliar application of Sorgoleone, at a similar concentration to labelled field rates of Atrazine (0.6 kg *a.i.* ha⁻¹), inhibited growth of most of the small-seeded broad-leaf weeds [97]. Pre-emergence soil applications were also toxic to certain small-seeded weed species [98]. The allelochemicals of tomato *e.g.*, tomatine and tomatidine also reduce the growth of weeds, pathogenic fungi at a satisfactory level [99].

Several types of allelochemicals for examples, phenolics, terpenoids, alkaloids, coumarins, tannins, flavonoids, steroids and quinines are involved in the phytotoxic activities of the allelopathic plants [28] [72]. Recently, a number of compounds extracted from higher plants, such as cineole, benzoxazinones, quinolinic acid and leptospermones, have been commercially applied in crop fields to control weeds such as Benzoxazinones and Quinolinic acid by BASF, Germany; Cineole as Cinmethylen by Shell, USA; Letospermones as Triketones by Zeneca, Letospermones as Mesotrione by Syngenta AG [73] [100] [101] [102]. A brief description of the natural products (plant extracts or essential oils) commercially used in the crop fields is summarized in **Table 1**.

Moreover, these herbicides are not quite enough to control a vast number of weeds, and also not effective to all weeds. Therefore, searching of new natural plant products effective for weed control is very crucial. Isolation and identification of new natural plant products might lead to the development of new natural herbicides.

5. Challenge for Medicinal Plant Allelopathy in Weed Management

Although selection and/or identification of allelopathic plants from medicinals plants are much easier than other group of plants, isolation and identification of

Table 1. Examples of commercial products containing natural products used for weed management in organic agriculture [102] [103] [104] [105].

Products	Components
Callisto [®] , Tenacity [®] , Lumax [®] , Lexar [®] , Halex GT [®] , Camix [®] , Calaris [®] , Callisto Xtra [®] or Elumis [®]	Leptospermonone (1-hydroxy-2-isovaleryl-4,4,6,6-tetramethyl cyclohexen-3,5-dione) which is produced by the roots of the <i>Callistemon citrinus</i>
WeedBan [™] , Corn Weed Blocker [™]	Corn gluten meal
Bioscape Bioweed [™]	Corn gluten meal, soybean
Scythe [™]	Pelargonic acid (57%), related short chain fatty acids (3%), 30% paraffinic petroleum oil (30%)
Burnout [™] , Biorganic [™] , Poison Ivy Defoliant [™]	Clove oil (12% - 18%), sodium lauryl sulfate (8% - 10%), acetic acid, lecithin, citric acid (30%), mineral oil (80%)
Bioorganic [™]	Clove oil (5%), 2-phenethyl propionate (5%), sesame oil (4%) and sodium lauryl sulfate (0.5%)
AllDown [™]	Citric acid (5%), acetic acid, yucca extracts, garlic oil (0.2%)
Interceptor [™]	10% pine oil
Weed Zap [™]	Clove oil or cinnamon oil (30%), vinegar (70%)
Weed-A-Tak [™] , Repellex [®]	Citric acid (32%), clove oil (8%), cinnamon oil (8%), 2-phenethyl propionate, lecithin. It may contain thyme oil, and wintergreen oil
Moss & Algae Killer [™] Naturell WK Herbicide [™] , DeMoss [™] , Mosskiller [™]	Potassium salts of fatty acids (40%)
Organic Weed & Grass Killer [™]	Citrus oil (70%)
GreenMatch O [™] , Nature's Avenger [™]	D -Limonene (70%), castor oil (1% to 4%), emulsifiers (18% to 23%)
GreenMatch EX [™]	Lemongrass oil (50%) and a mixture of water, corn oil, glycerol esters, potassium oleate and lecithin
Matran II [™]	Clove oil (46%), wintergreen oil, butyl lactate, lecithin
Eco-Exempt [™] , Eco-Smart [™]	2-Phenethyl propionate (21.4%), clove oil (21.4%)
Basta [®] , Buster [®] , Challenge [®] , Finale [®] , Harvest [®] , Ignite [®] , Rely [®] , Liberty [®]	Phosphinothricin [PPT or glufosinate = L- 2-amino-4-(hydroxymethylphosphinyl) butyric acid]
PORGANIC [™]	Leaf extracts of <i>Aglaia odorata</i>

strong allelopathic substance is laborious, time consuming and need very sophisticated equipment's. Hence, to date very few works have been conducted to isolate and characterize the allelopathic substances from allelopathic medicinal plants. A list of allelopathic substances isolated from different medicinal plants is given in **Table 2**. These substances showed strong phytotoxic potential against different target plant species under laboratory condition. However, their phytotoxic potential under field condition not yet reported. It is well known that even a substance showing strong phytotoxic activity on target plants in laboratory experiments, may not perform satisfactorily in the field conditions due to the influence of several soil factors like soil pH, organic carbon, organic matter and available nitrogen [136] [137] [138] [139]. Therefore, more emphasis should be

Table 2. Isolated compound of different medicinal plants and their phytotoxicity against test plant species.

Sl. No.	Plants species	Family name	Compound isolated	Phytotoxicity on test plants	Authors
1	<i>Citrus junos</i>	Rutaceae	Abscisic acid- β -d-glucopyranosyl ester	The concentrations required for 50% inhibition (IC_{50}) of the shoot and root growth of lettuce was 2.3 and 1.4 μ M, respectively.	Kato-Noguchi <i>et al.</i> [106]
2	<i>Hibiscus sabdariffa</i>	Malvaceae	Trimethyl allo-hydroxycitrate	IC_{50} value for the shoot and root growth of garden cress was 20.3 and 14.4 mM, respectively.	Suwitchayanon <i>et al.</i> [107]
3	<i>Ailanthus altissima</i>	Simaroubaceae	Ailanthone	IC_{50} value for the radicle elongation of garden cress was 0.7 mL L ⁻¹	Heisey [108]
4	<i>Leucas aspera</i>	Lamiaceae	3:2 mixture of two labdane type diterpenes [(rel 5S,6R,8R,9R,10S,13S,15S,16R)-6-acetoxy-9,13;15,16-diepoxy-15-hydroxy-16-methoxylabdane and (rel 5S,6R,8R,9R,10S,13S,15R,16R)-6-acetoxy-9,13;15,16-diepoxy-15-hydroxy-16-methoxylabdane]	IC_{50} value for the seedling growth of garden cress and barnyard grass ranges from 31 to 80 μ M.	Islam <i>et al.</i> [109]
5	<i>Hyptis suaveolens</i>	Lamiaceae	14 α -hydroxy-13 β -abiet-8-en-18-oic acid (suaveolic acid)	IC_{50} value for the growth inhibition of suaveolic acid for garden cress, Italian ryegrass, and barnyard grass were ranged from 76 to 1155 μ M.	Islam <i>et al.</i> [110]
6	<i>Mangifera indica</i>	Anacardiaceae	Methyl-3,4,5-trihydroxybenzoate (methyl gallate)	IC_{50} value for the growth inhibition of garden cress roots and shoots were 3.9 and 3.3 mM, and those of foxtail fescue roots and shoots were 1.5 and 9.5 mM, respectively.	Suzuki <i>et al.</i> [111]
7	<i>Castanea crenata</i>	Fagaceae	2 α ,3 β ,7 β ,23-tetrahydroxyurs-12-ene-28-oic acid	IC_{50} value for the shoot and root growth of barnyard grass was 2.62 and 0.41 mM, respectively	Tuyen <i>et al.</i> [112]
8	<i>Peganum harmala</i>	Nitrariaceae	Harmaline	Inhibiting root elongation of lettuce and amaranth by 31% and 47% at a 5 μ g mL ⁻¹ concentration	Shao <i>et al.</i> [113]
9	<i>Azadirachta indica</i>	Meliaceae	Nimbolide B and Nimbic acid B.	In case of Nimbolide B the IC_{50} value for growth inhibition of cress roots and shoots was 1.2 and 1.4 μ M and that of barnyard grass roots and shoots were 3.7 and 39 μ M, respectively. In case of Nimbic acid B the IC_{50} value for the cress roots and shoots were 5.7 and 9.4 μ M, respectively, and I_{50} of the barnyard grass roots and shoots were 29 and 210 μ M, respectively.	Kato-Noguchi <i>et al.</i> [114]
10	<i>Zanthoxylum limonella</i>	Rutaceae	Xanthoxyline	At a concentration of 2500 μ M, xanthoxyline completely inhibited seed germination and growth of Chinese amaranth, while seed germination, shoot and root length of barnyard grass were inhibited by 44, 72 and 88%, respectively by this compound.	Charoenying <i>et al.</i> [115]
11	<i>Aglaiia odorata</i>	Meliaceae	Odorine, Rocaglaol	Odorine at concentration of 8000 ppm showed 79% reduction of barnyard grass germination, and exhibited seedling growth inhibition at all tested concentrations (1000, 2000, 4000 and 8000 ppm). The IC_{50} value of Rocaglaol for garden cress and barnyard grass ranged from 0.09 to 2.5 μ M.	Kato-Noguchi <i>et al.</i> [103], Teerarak <i>et al.</i> [116]

Continued

12	<i>Orthosiphon stamineus</i>	Lamiaceae	13-epi-orthosiphol N	The IC_{50} value of this compound for seedling growth of garden cress and lettuce ranged from 41 to 102 $\mu\text{mol L}^{-1}$	Kato-Noguchi <i>et al.</i> [117]
13	<i>Asparagus officinalis</i>	Asparagaceae	p-Coumaric acid, iso-Agatharesinol and trans-Cinnamic acid	p-Coumaric acid and iso-Agatharesinol inhibited the shoot and root growth of asparagus, garden cress and ryegrass, at concentrations higher than 0.1 mM. The IC_{50} value for the root and shoot growth of these test plants ranged from 0.36 to 0.85 mM and 0.41 to 1.22 mM for p-Coumaric acid and iso-Agatharesinol, respectively. trans-Cinnamic acid inhibited the growth of asparagus seedlings at concentrations greater than 10 μM . The IC_{50} value of the compound for growth inhibition of asparagus was 24.1 - 41.6 μM .	Kato-Noguchi <i>et al.</i> [118], Kato-Noguchi <i>et al.</i> [119]
14	<i>Piper methysticum</i>	Piperaceae	5-hydroxy-4',7-dimethoxyflavanone (1); 5,7-dihydroxy-4'-methoxy-6,8-dimethyl flavanone (matteucinol, 2); a mixture of kavain and yagonin (3), and dihydro-5,6-dehydrokavain, 7,8-dihydrokavain, dihydromethysticin and methysticin (4).	The compound 1 and 2 exhibited the strongest inhibition on shoot elongation (IC_{50} value = 120.2 and 248.0 $\mu\text{g mL}^{-1}$, respectively), whilst compound 3 and 4 showed the highest root growth inhibition of radish (IC_{50} value = 7.7 and 15.7 $\mu\text{g mL}^{-1}$, respectively).	Van <i>et al.</i> [120]
15	<i>Helianthus annuus</i>	Asteraceae	4, 15-dinor-3-hydroxy-1(5)-xanthene-12,8-olide (sundiversifolide)	Inhibited the seedling growth of cat's-eyes by about 50% at a concentration of 30 ppm.	Ohno <i>et al.</i> [121]
16	<i>Ipomoea cairica</i>	Convolvulaceae	3-3' -5-Trihydroxy-4'-7-dimethoxyflavone and 3-3'-5-Trihydroxy-4'-7-dimethoxyflavone-3-O-sulfate	both these allelochemicals independently or jointly inhibited the seed germinations radish, Cucumber, Napa cabbage and <i>Ligularia virgaurea</i> (a weed)	Ma <i>et al.</i> [122]
17	<i>Chrysanthemum morifolium</i>	Asteraceae	Luteolin 7-O- β -glucuronide	At concentrations of 0.2 and 2.0 mM, the compound reduced the frond number and chlorophyll content of <i>Lemna gibba</i>	Beninger and Hall [123]
18	<i>Cymbopogon nardus</i>	Poaceae	Myrislignan, N-Octanoyl tyramine	IC_{50} value of Myrislignan for the shoot and root growth of garden cress was 429 and 517 μM , respectively. IC_{50} values of N-octanoyl tyramine were 426 and 444 μM for shoot and root growth of cress, and that for barnyard grass was 1430 and 450 μM , respectively.	Suwitchayanon <i>et al.</i> [124], Suwitchayanon <i>et al.</i> [125]
19	<i>Rumex maritimus</i>	Polygonaceae	2-Methoxystypandrone, 5,7-dihydroxyphthalide and altechromone A.	IC_{50} values of 2-Methoxystypandrone for growth inhibition of Garden cress was ranged from 5.8 to 11.8 μM . IC_{50} values for the growth inhibition of garden cress seedling growth were 1.73 - 2.48 mM for 5, 7-dihydroxyphthalide and 0.66 - 1.41 mM for altechromone A, respectively.	Islam <i>et al.</i> [126], Islam <i>et al.</i> [127]
20	<i>Caesalpinia mimosoides</i>	Fabaceae	Methyl gallate	IC_{50} values of methyl gallate for the growth of garden cress and barnyard grass ranged from 2.3 to 2.9 and 0.3 to 30.5 mM, respectively.	Boonmee <i>et al.</i> [128]

Continued

21	<i>Ginkgo biloba</i>	Ginkgoaceae	2-hydroxy-6-(10-hydroxypentadec-11-enyl)benzoic acid	The IC_{50} values of the compound for seedling growth inhibition for garden cress roots and shoots were 9.1 and 12 M, respectively, and that for timothy roots and shoots was 17 and 23 M, respectively. The activity of the compound was 10- to 52-fold that of nonanoic acid (a natural ester used for herbicide preparation) on those test species.	Kato-Noguchi <i>et al.</i> [129]
22	<i>Cucumis sativus</i>	Cucurbitaceae	9-hydroxy-4,7-megastigmadien-9-one (1); (6S,7E,9S)-6,9,10-trihydroxy-4,7-megastigmadien-3-one (2); (2S)-2,3-dihydro-2a-(4-hydroxy-3-methoxyphenyl)-7-methoxy-5-(1,2,3-trihydroxypropyl)benzofuran-3b-methanol (sisymbriofolin, 3)	The IC_{50} values for root and shoot growth inhibition of cress and barnyard grass were 2.4 - 29.3 μ M for compound 1 and 8.1 - 52.2 μ M for compound 2. The IC_{50} values of compound 3 for root and shoot growth inhibition of cress and barnyard grass were 16.5 - 34.2 μ M and 22.1 - 67.3 μ M, respectively.	Kato-Noguchi <i>et al.</i> [130], (Kato-Noguchi <i>et al.</i> [131])
23	<i>Rhinacanthus nasutus</i>	Acanthaceae	4-hydroxy-3-methoxybenzoic acid (vanillic acid)	The IC_{50} values of vanillic acid for growth inhibition of cress and lettuce were about 470 - 800 μ M and that for timothy and Italian ryegrass were 0.17 - 8.2 μ M, respectively.	Piyatida <i>et al.</i> [132]
24	<i>Tinospora tuberculata</i>	Menispermaceae	4-[(1E)-3-Hydroxyprop-1-en-1-yl]-2,6-dimethoxyphenyl b-D-glucopyranoside (syringing)	The IC_{50} values of syringing for root and shoot growth inhibition of garden cress and lettuce ranged from 78.2 to 412 μ M, and that of timothy and barnyard grass ranged from 9.8 to 73.2 μ M, respectively.	Kato-Noguchi <i>et al.</i> [133]
25	<i>Piper sarmentosum</i>	Piperaceae	3-phenylpropionic acid	The IC_{50} values of 3-phenylpropionic acid for cress and lettuce were 1.2 - 9.3 μ M and that of timothy and Italian ryegrass were 4.7 - 51.8 μ M, respectively.	Piyatida <i>et al.</i> [134]
26	<i>Onopordum acanthium</i>	Asteraceae	Elemanolide 11(13)-dehydromelitensin b-hydroxyisobutyrate	Inhibited the coleoptile growth of wheat.	Watanabe <i>et al.</i> [135]

given on evaluating the bioactivity of allelopathic substances or the allelopathic plant extracts in both laboratory and field condition. If the extracts or the isolated compound shows strong activity in both conditions only then it could be recommend for new natural herbicide development.

6. Conclusion

From the above discussion, it is clear that there is immense prospect of allelopathic medicinal plants for the isolation and identification of allelochemicals and applies them as a tool for new bio-herbicide development. On the other hand, issues such as environmental pollution, unsafe agricultural products, human health concerns, may be dealt appropriately if allelopathic medicinal plants or bio-herbicides developed from their allelochemicals are use in the crop fields for weed management instead of synthetic herbicides. Undoubtedly, these natural products based crop production system will continue to attract increasing attention and, ultimately, will play a major role in agricultural productivity in a most

sustainable way. However, before implication of allelochemicals as bio-herbicide the following points should be considered:

1) both laboratory and field experiments should be conducted exclusively, to study its interaction with various physical, chemical and biological properties of soil.

2) the physiological and ecological mechanisms of allelopathy for example, the movement of allelochemicals, its fate in soil, mode of action, selectivity etc. should be studied.

3) the impact of use of allelochemicals from agronomic and environmental point of view should be brought under consideration. However, allelochemicals are not always safe for the human and animals. There are some allelochemicals that are toxic to human beings and are carcinogenic, for example, AAL-toxin and fumonisin are toxic to mammalian cells [19]. Some other allelochemicals are reported to cause dermatitis [140].

If the identified allelochemicals satisfy the above three criteria then it could be used for the development of natural herbicides. Moreover, except very few limitation, natural product based agriculture is the only way to achieve sustainable crop production for the pollution free green earth ecosystems. Allelopathic medicinal plants could provide the clues to the researchers of that arena and still there is a lot of vacant space for the scientists to work with allelopathic medicinal plants. Therefore, in future more and more emphasis should be given by the researchers to isolate and identify the new allelopathic substances from the medicinal plants, examine their bioactivity under laboratory and field conditions, if satisfy both then recommend them to use as a tool for new natural herbicides development for the evergreen world.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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