

## **Plant Autotoxicity Review. Part 2: Families Caryophyllaceae to Leguminosae**

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### ABSTRACT

Autotoxicity is one of the reasons that causes the continuous cropping problem in plants. It not only inhibits the growth of plants but also leads to some soil borne diseases, causes autotoxic soil and low crop yields. In this paper, 32 plant species from 29 genera in 11 families causing autotoxicity have been briefly reviewed. Their autotoxicity leads to continuous cropping problem for agricultural crops or medicinal plants, or the difficulty in regeneration of forest plant species. The 11 families are: Caryophyllaceae, Casuarinaceae, Chenopodiaceae, Cistaceae, Crassulaceae, Cucurbitaceae, Fagaceae, Gentianaceae, Juncaceae, Labiatae and Leguminosae.

**Key words:** Autotoxicity, autotoxins, continuous cropping problem, crops, medicinal plants, forest plants, weeds

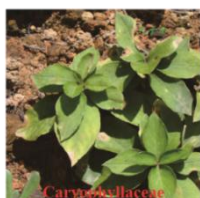
### 1. INTRODUCTION

Allelopathy includes harmful or beneficial effects of one plant on another plant through the production and release of chemical compounds into the environment (17). The autotoxicity is particular form of allelopathy. Autotoxicity occurs when a plant releases toxic chemical substances into the environment that inhibits its own germination and growth (14,19,26). Such autotoxicity reduces the intensity of intraspecific competition for scarce growth resource (e.g. water, nutrients, sunlight, space) under unfavourable environmental conditions (2).

Usually, monoculture of crops or medicinal plants leads to the decreased growth and yield in next season due to autotoxicity. Recently, numerous reports have proved the role of autotoxicity in replant failure and soil sickness. Soil sickness is an example of typical negative plant-soil feedback that reduces the quantity (yields) and quality of crop, when the same crop or its related species are grown successively on the same soil. In continuous monocropping systems, plants repeatedly release different kinds of autotoxins for many years, which gets accumulated resulting in significant changes in soil microorganisms species. Thus, autotoxicity could be partly responsible for soil sickness (23).

Autotoxicity occurs in wide range of taxonomically distant species (43). root exudates of *Cucumis melo*, *Eustoma grandiflorum* (Raf.) Shinn., *Pogostemon cablin* (Blanco.) Benth., *Phaseolus vulgaris* L. and *Glycine max* L. etc. (4,5,29,52,54) and the extract of *Casuarina equisetifolia* Forst, *Beta vulgaris*, *Chenopodium album* L., *Salsola kali* L., *Juncus effuses* L. and *Quercus ilex* L. causes autotoxic growth inhibition (12,19,25,32, 37,38,39).

In this paper, autotoxicity of plants from 11 families has been briefly reviewed. The 11 families are: Caryophyllaceae, Casuarinaceae, Chenopodiaceae, Cistaceae, Crassulaceae, Cucurbitaceae, Fagaceae, Gentianaceae, Juncaceae, Labiatae and Leguminosae. Based on this information of each plant, suitable measures could be taken accordingly to deal with the continuous cropping problems of the plants.



1. *Pseudostellariae heterophylla* (Miq.)

## 2. CARYOPHYLLACEAE

### 2.1. Genus *Pseudostellariae*

The problem of soil sickness in continuous cropping of major medicinal plant *Pseudostellariae heterophylla* was investigated. The autotoxicity potential of 2-years continuous monoculture was stronger than rice-*P. heterophylla* and soybean-*P. heterophylla* rotations. The autotoxicity of rice-*P. heterophylla* rotation soil was minimum. The autotoxic substances present in the rhizosphere soil of *P. heterophylla* were identified as benzoic, myristic, cinnamic and 2-butenic acids, etc. (30).



2. *Casuarina equisetifolia* Forst

## 3. CASUARINACEAE

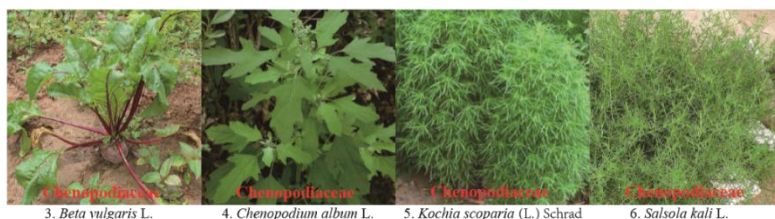
### 3.1. Genus *Casuarina*

*Casuarina equisetifolia* Forst is indigenous tree species in Australia and Polynesia and has been introduced to many countries in coastal plantations (44). However, difficulty in its regeneration and decline of productivity due to autotoxicity exists in *C. equisetifolia* plantations (57).

In 2018, seven compounds, 3 $\beta$ -(p-hydroxy-trans- cinnamoyloxy) olean-12-en-28-oic acid, 3-O-(E)-coumaroylerythrodiol, casuarmondol, alnusdiol, kaempferol, 3-O- $\alpha$ -L-rhamnopyranoside, 4'-trans-p-coumaroyl- kaempferol-3-O- $\alpha$ -rhamno-pyranoside and kaempferol, were isolated from the ethyl acetate extract of *C. equisetifolia* litter (47). Concurrently, the 12,13-dihydromicromeric acid, betulinic acid, 3-O-caffeoyl lupeol, catechins and epicatechin in *C. equisetifolia* roots inhibited seed germination and seedling growth. Specifically, the 12,13- dihydromicromeric acid was the most autotoxic (38).

The root aqueous extract from 15-years-old *C. equisetifolia* trees at 12.5-200 g/kg decreased the chlorophyll content and the carbohydrate accumulation of its seedlings (31,33). Besides the aqueous extracts of *C. equisetifolia* roots strongly decreased the IAA, GR, iPAs and ZRs in seedlings. At root extract concentrations of 1: 40-1: 5, the *C. equisetifolia* seedling leaf and seedling root IAA was decreased by 37.3-75.1 % and 26.8-57.0 % and the iPAs was decreased by 9.3-85.3 % and 10.6-86.7 %, respectively and the GA content was decreased by 4.7-59.2 % and 12.1-74.8 %, respectively (32).

Further researches showed that allelochemicals (quercetin-3- $\alpha$ -araboside and quercetin-3- $\beta$ -glucoside) damaged the function of PSII reaction center and decreased the photochemical electron transfer rate, which led to the structural damage of photosynthetic organs and functional degradation in photosynthetic ability (28), and the allelopathy mechanism of two compounds to *C. equisetifolia* was different. Generally SOD, CAT and POD activities treated by quercetin-3- $\alpha$ -araboside and quercetin-3- $\beta$ -glucoside at concentration (12.50 to 400.00 mg/L) first increased and then decreased (27).



## 4. CHENOPODIACEAE

### 4.1. Genus *Beta*

Sugarbeet (*Beta vulgaris*) extract are autotoxic to its own germination and growth. The extract > 1.00 % (w/v) inhibited the seed germination (18). The aqueous extract of sugarbeet plant contained p-hydroxybenzoic, p-coumaric acids, protocatechuic acid, vanillic acid, coumarin, vanilline, chichimec acid and camphor (19).

### 4.2. Genus *Chenopodium*

The mature plant aqueous extracts of *Chenopodium album* L. was assayed at 0, 2, 4, 6 and 8 % (w/v) for its effects on seed germination and early seedling growth. Germination (%) declined with the increase in concentration of, extract than control. At 8 % (w/v) concentration, the aqueous extract of *C. album* L. was very autotoxic and caused seed germination inhibition of 57 % (39).

### 4.3. Genus *Kochia*

The autotoxic phenolics and flavonoids were isolated and identified from summer cypress (*Kochia scoparia* (L.) Schrad) leaves. The radicle length of 10-day-old summer cypress seedlings was reduced by autotoxins, while the seeds germination was not affected (36).

### 4.4. Genus *Salsola*

Quercetin, ferulic and chlorogenic acids and small amounts of neochlorogenic and isochlorogenic acids were identified in the water extracts of fresh prickly saltwort (*Salsola*

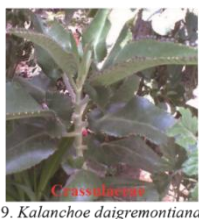
*kali* L.) leaves. All these phytotoxins significantly decreased the radicle length of prickly saltwort at 60 h at  $10^{-3}$  M concentration, whereas, this concentration did not inhibit the seed germination or radicle growth (37).



## 5. CISTACEAE

### 5.1. Genus *Cistus*

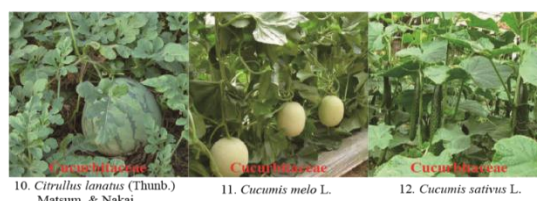
Some plants from *Cistus* family in low quantities are autotoxic. Essential oil of *Cistus albidus* L. is autotoxic to its own seedling growth, but had little effect on germination. A essential oil concentration  $>1.00$   $\mu\text{L}/\text{mL}$ , increased the mortality rate of *C. albidus* seedling. The mortality rate of *C. albidus* seedling was 64 % and 100 % at 10  $\mu\text{L}/\text{mL}$  and 100  $\mu\text{L}/\text{mL}$ , respectively (41). *Cistus ladanifer* L. (labdanum) was also allelopathic. The aqueous extract from its leaves, inhibited the germination and cotyledon emergence of *C. ladanifer* (3).



## 6. CRASSULACEAE

### 6.1. Genus *Kalanchoe*

Groner (16) determined the autotoxicity of aqueous extracts from the stems and leaves of older *Kalanchoe daigremontiana* and found that it reduced the plant growth. Established plants of *K. daigremontiana* inhibited the growth rate of daughter plantlets that fell within the radius of their root systems. Plantlets which were detached from their parent leaves and planted in fresh substrate increased in stem length at about twice the rate of sister plantlets grown in substrate that had been used previously to grow *K. daigremontiana*. Addition of water extracts of finely cut stems and leaves from older plants retarded the growth, similar to that observed in *Kalanchoe* roots. Inhibition is apparently caused by one or more water-soluble, allelopathic substances, which are secreted into the substrate through the roots of living plants and which are present in extracts from stems and leaves of older plants.



## 7. CUCURBITACEAE

Cucurbitaceae, the cucurbits family of flowering plants, contains 98 genera of food and ornamental plants (cucumbers, gourds, melons, squashes, pumpkins etc.). The soil sickness is often observed in cucurbit crops such as *Citrullus lanatus* (Thunb.) Matsum & Nakai, *Cucumis melo* and *Cucumis sativa* L., which decreased their yields.

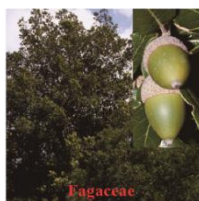
### 7.1. Genus *Citrullus*

Hao *et al.* (17) reported that autotoxicity may play an important part in the development of soil sickness in continuous cropping systems of watermelon (*C. lanatus*). Aqueous and methanol extracts of soil samples after 3 or 30 continuous cropping seasons with watermelon decreased the radicle elongation in watermelon in Petri dish cultivation. Plant dry weight decreased significantly in continuous cropping soil treatment with no difference among the treatments in nutrients contents, indicating that the growth reduction was due to autotoxicity, rather than competitive effects (17). Yu *et al.* (55) also showed that plant growth of watermelon was greatly inhibited by autotoxic substances released from the root tissue at 1 g per seedling. Root exudates of watermelon were autotoxic to its own radicle elongation and seedling growth. Phenolic acids were important autotoxins (17).

### 7.2. Genus *Cucumis*

Plant growth of muskmelon (*C. melo*) and *C. sativus* were greatly inhibited by the autotoxins released from the powered root tissue at a rate of 1 g per seedling. Root exudates of muskmelon and *C. sativus* were autotoxic to radicle elongation and seedling growth of the respective species (55).

The muskmelon root exudates were identified by HPLC and 7-autotoxic phenolic compounds (Gallic, phthalic, syringic, salicylic, ferulic, benzoic and cinnamic acids) were identified. All these significantly reduced the muskmelon seed germination and seedling growth at higher concentration (0.5 mmol/L) than control. The maximum inhibition of seed germination was caused by cinnamic acid, followed by benzoic and ferulic acids. Salicylic, syringic, gallic and phthalic acids showed stimulatory effects (0.05 mmol/L), while cinnamic, benzoic and ferulic acids inhibited all parameters (54). When the leaf extract of Hami melon (*C. melo* var. *saccharinus*) concentration reached 50 g/L and 90 g/L, the root length and numbers were inhibited significantly. The content of chlorophyll *a*, chlorophyll *b* and carotenoids were also decreased (60). In addition, Wang *et al.* (48) investigated that a phenolic compound [syringic acid (SA)] with autotoxicity to cucumber was 0.1  $\mu\text{mol g}^{-1}$  soil, which may exert negative effects on cucumber seedling growth by inhibiting the plant-beneficial microorganisms.

13. *Quercus ilex* L.

## 8. FAGACEAE

### 8.1. Genus *Quercus*

Li and Romane (25) reported that the aqueous soil extracts of *Quercus ilex* L. were autotoxic to seed germination. Aqueous extracts from *Quercus ilex* soil decreased the seedling biomass with increase in extract concentration. Besides, *Q. ilex* soil decreased the germination of *Q. ilex* and the poor seed regeneration was due to the inhibition of *Q. ilex* seed germination.

14. *Eustoma grandiflorum* (Raf.) Shinnars

## 9. GENTIANACEAE

### 9.1. Genus *Eustoma*

Maleic and benzoic acids were detected in the root exudates of medicinal plant prairie gentian [*Eustoma grandiflorum* (Raf.) Shinnars.]. Its growth of prairie gentian was drastically inhibited in nutrient solution without active carbon (AC) compared with those containing AC, the soil with AC at a rate of 60-kg · 10 acre<sup>-1</sup> could reduce autotoxicity of Prairie gentian (5).

15. *Juncus effusus* L.

## 10. JUNCACEAE

### 10.1. Genus *Juncus*

Ervin in 2000 (12) revealed that *J. effusus* possessed strong autotoxicity as evident from the substantial decreases in seedling biomass and chlorophyll a content and delayed second-leaf formation in plants exposed to the aqueous extract of dead aboveground *J. effusus* plant parts. The rapid decrease in production rates and senescence of aboveground plant parts, coupled with their slow decomposition, provide extremely high potential for autotoxicity in *J. effusus* dominated wetland ecosystems. *J. effusus* contains numerous chemicals, which are autotoxic. The autotoxins cycloartane triterpenes, cycloartane glucosides and 9,10-dihydrophenanthrene glucosides (15) were found in *J. effusus* plants. Many such compounds possess the allelopathic activities (23).



16. *Elsholtzia cypriani* (Pavol.) 17. *Pogostemon cablin* Blanco) Benth. 18. *Scutellaria baicalensis* Georgi

## 11. LABIATAE

The family Labiatae has many genera and species, and many of them are native to Mediterranean environments. They have many traditional uses, from cookery to phytotherapy. Plants from 3-genera (*Elsholtzia*, *Pogostemon* and *Scutellaria*) are autotoxic. The quality of *Pogostemon cablin* produced cannot be assured due to its autotoxicity (53). Besides, *Scutellaria baicalensis* suffers from serious replant problem, which causes substantial yield reduction after 2-3 years of continuous cropping (58).

### 11.1. Genus *Elsholtzia*

The autotoxicity of various organs of *Elsholtzia cypriani* (Pavol.) plants aqueous extracts on its own seed germination followed the order: flower > stem > leaf and their CE (comprehensive effect, CE < 0 means inhibition effect) were -0.64, -0.61 and -0.52, respectively. The autotoxic response of the aqueous extract of shoot parts of *E. cypriani* on 3 indexes followed the order: radicle length > seedling rate > germination rate and their CE were -0.73, -0.59 and -0.58, respectively (63).

### 11.2. Genus *Pogostemon*

*Pogostemon cablin* (Blanco.) Benth. (Patchouli), from south-east Asia is cultivated extensively in Indonesia, Philippines, Malaysia, China and Brazil. The aqueous extracts of patchouli plant had some autotoxic potential to reduce the plant height and root length of seedlings. (53). The aqueous extract from the rhizosphere soil also significantly inhibited the number, length, activity of roots and growth rate of stem cutting of patchouli (45). The

aqueous extract of root exudates of patchouli reduced the fresh weight at high concentration of the root exudates of patchouli was higher, the fresh weight of patchouli was reduced to 68.42 % (29).

Eight allelochemicals (Dibutyl phthalate as well benzoic, cinnamic, malonic, vanillic, salicylic, p-hydroxybenzoic and tetradecanoic acids) were isolated and identified from patchouli plants and their rhizosphere soil (51). The p-hydroxybenzoic acid (200  $\mu$ M) drastically reduced the plant height, root length and total fresh weight of patchouli by 77 %, 42 % and 70 %, respectively (53). Mechanism studies revealed that the MDA, SOD and POD, etc. activities was effected due to autotoxicity. The SOD and POD activities increased at low concentration, followed by decline at high concentration of roots and leaves extracts (1:10) (53). The aqueous extract from the rhizosphere soil also affected the activities of POD, PPO and IAAO in seedlings (43). The activity of MDA and POD increased 7.2 % and 201.1 % with E<sub>5</sub>W<sub>5</sub>, and increased 132.0 % and 177.9 % with E<sub>10</sub>W<sub>0</sub>, respectively (29).

### 11.3. Genus *Scutellaria*

This important medicinal plant *Scutellaria baicalensis* Georgi. performs poorly when continuously cropped in same land. Its roots release the major compound baicalin. Its concentration in soil, where *S. baicalensi* had been grown for 3 years was 0.97  $\mu$ g/g. The mortality and damping-off in its seedlings were high in soil collected from the *S. baicalensis* field (58).

## 12. LEGUMINOSAE

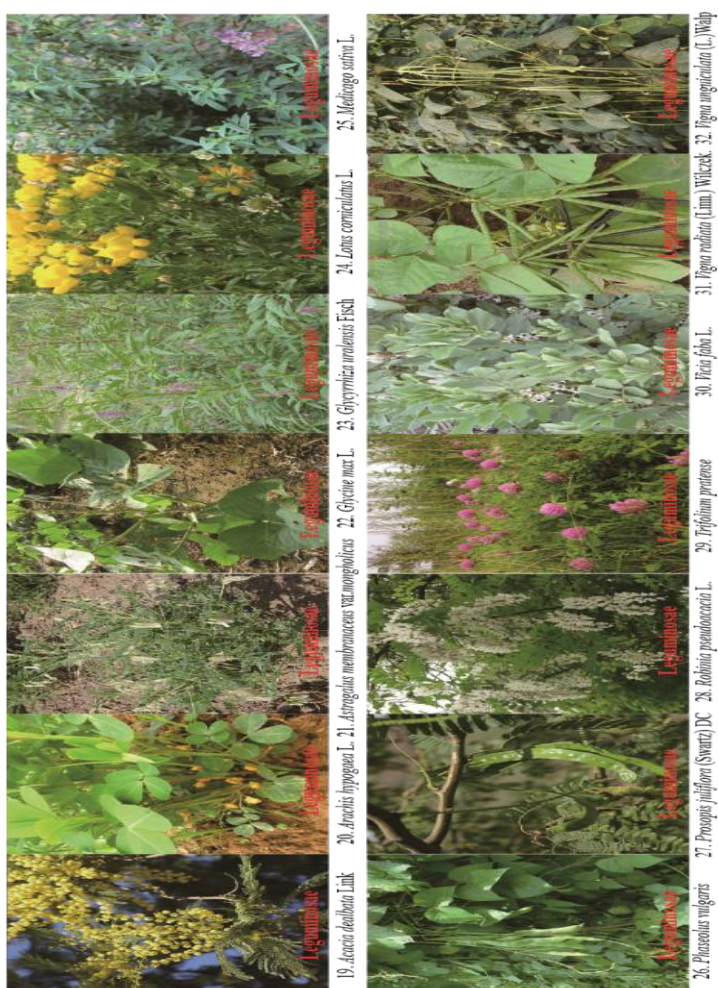
The Leguminosae, is very large and economically important family of flowering plants. The family is widely distributed, and is the third-largest land plant family in terms of number of species. Plants from its 13 genera (*Acacia*, *Arachis*, *Astragalus*, *Glycine*, *Glycyrrhiza*, *Lotus*, *Medicago*, *Phaseolus*, *Prosopis*, *Robinia*, *Trifolium*, *Vicia* and *Vigna*) had autotoxic effects.

### 12.1. Genus *Acacia*

Autotoxicity is observed in *Acacia dealbata* Link. The pods and leaves expressed autotoxic biological activity. The leaves and pods of this species significantly inhibited its own seed germination. In particular, germination was approximately 5 % due to direct contact with leaves and 20 % by the pod treatments. The case of pods is particularly interesting, because they remained under the tree canopy throughout the phenological cycle of *A. dealbata* and are also deposited under the canopy. This means that the pods can constantly release phytotoxic compounds (1). The major compounds detected in the methanol extract of soil collected under the *A. dealbata* canopy were fatty acids [hexadecanoic acid methyl ester, 9,12-octadecadienoic acid methyl ester and octadecanoic acid methyl ester]. Besides, 3-putative phytotoxic compounds found were: anthiaergosatin-5,7,9,22-tetraen 3-acetoxy, tetracyclo [11.4.0.0 (3,11). 0(7,11)] heptadeca-1(13),14,16-triene-4-carboxylic acid 14,17-dimethoxy-8-(2-hydroxy-1- methylethyl) and desmosterol (2).

Table 1. Autotoxic plants and their autotoxins

Family	Genus	Plant	Autotoxins	Reference
Caryophyllaceae	<i>Pseudostellaria</i>	<i>P. heterophylla</i>	Benzoic acid, Myristic acid, Cinnamic acid, 2-Butenoic acid Quercetin-3- <i>o</i> -araboside, Quercetin-3- $\beta$ -glucoside, 3- $\beta$ - <i>D</i> -Hydroxy- <i>trans</i> -sinanoyloxy)olean-12- <i>en</i> -28- <i>oic</i> acid, 3- <i>O</i> - <i>E</i> - coumaroylerythrodol, 3- <i>O</i> - $\alpha$ - <i>L</i> -thamnoxyranoside, Casuarinodiol, 4'- <i>trans</i> - <i>p</i> - coumaroyl-kaempferol-3- <i>O</i> - $\alpha$ - <i>D</i> -flamno-pyranoside, Alnusdiol, Kaempferol, 12, 13-dihydrochromoneic acid, Benylinic acid, 3- <i>O</i> -caffeoyl luteol, Catechins, Epicatechin	27,28, 38,47
Casuarinaceae	<i>Casuarina</i>	<i>C. equisetifolia</i>		
Clemnopoaceae	<i>Beta</i>	<i>B. vulgaris</i>	P-hydroxybenzoic acid, <i>p</i> -coumaric acid, Protocatechuic acid, Vanillic acid, Chetameic acid, Coumarin, Vanillin, Camphor	19
	<i>Salsola</i>	<i>S. kali</i>	Quercetin, Ferulic acid, Chlorogenic acid, Neochlorogenic acid, Isochlorogenic acid	37
Cyperitaceae	<i>Cyperus</i>	<i>C. nolo</i>	Galic acid, Phthalic acid, Syringic acid, Salicylic acid, Ferulic acid, Benzoic acid, Cinnamic acid	54
	<i>Eustoma</i>	<i>E. grandiflora</i>	Malic acid, Benzoic acid	5
Juncaceae	<i>Juncus</i>	<i>J. effusus</i>	Cycloartane, Triterpene, Cycloartane, Glucosides, 9,10-Dihydrophenanthrene glucosides	15
Labiatae	<i>Pogostemon</i>	<i>P. cablin</i>	Benzoic acid, Cinnamic acid, Malonic acid, Vanillic acid, Salicylic acid, <i>p</i> - hydroxybenzoic acid, Tetradecanoic acid, Dibutyl phthalate	51
	<i>Scutellaria</i>	<i>S. baicalensis</i>	Baicalin	58
Leguminosae	<i>Acacia</i>	<i>A. dealbata</i>	Hexadecanoic acid methyl ester, 9,12-Octadecadienoic acid methyl ester, Octadecanoic acid methyl ester, Anthraenosan-5,7,9,22-tetraen-3-acetoxy, Desmosterol, Tetraacyl[14,0(3,11)/0(7,11)]heptadeca-(1(3),14,16-triene-4- carboxylic acid, 14,17-Dimethoxy-8-(2-hydroxy-1-methylethyl)	2
	<i>Arachis</i>	<i>A. hypogaea</i>	<i>p</i> -hydroxybenzoic acid, Vanillic acid, Coumaric acid, Coumarin	22
	<i>Glycyh</i>	<i>G. max</i>	<i>m</i> -hydroxy-phenylacetic acid (MHPA)	42
	<i>Glycyrrhiza</i>	<i>G. wradensis</i>	Liquiritin, Isoliquiritigenin, Glycyrrhizic acid	40
	<i>Medicago</i>	<i>M. sativa</i>	Chlorogenic acid, Salicylic acid	11
	<i>Phaseolus</i>	<i>P. vulgaris</i>	Benzoic, Salicylic, Malonic acids	4
	<i>Vicia</i>	<i>V. faba</i>	Benzoic acid, Adipic acid, <i>p</i> -hydroxyphenylacetic acid	4
	<i>Vigna</i>	<i>V. unguiculata</i>	Phenylacetic acid, Cinnamic acid, 4-Hydroxybenzoic acid, Phthalic acids	21



### 12.2. Genus *Arachis*

Peanut (*Arachis hypogaea* L.) is autotoxic specie, the neutral fraction of its root extract severely inhibited the seedling growth. At 30 mg/L, it inhibits the plant height, shoot fresh weight and root fresh weight by 80 %, 73 % and 66 %, respectively. However, the activity of SOD, POD and the content of MDA in the leaf were increased (34). Four phenolic acids (p-hydroxybenzoic acid, vanillic acid, coumaric acid, and coumarin) were identified from the peanut rhizosphere soil. The combined concentration of vanillic acid and coumarin was from 0.067 to 0.314 µg/g (dry soil) during continuous cropping over 4-years, and this is why peanut had many culture problems in continuous cropping (22).

### 12.3. Genus *Astragalus*

The aqueous extract of medicinal plant *Astragalus membranaceus* (Fisch.) Bunge. and *Astragalus membranaceus* (Fish.) Bge. var. *mongholicus* (Bge.) showed autotoxicity (56,59). The aqueous extract of *A. membranaceus* var. *mongholicus* root, stem and leaf at 25 mg/mL significantly inhibited its own seed germination and seedling growth and the aqueous extract of stem was most effective (56,59). Ethyl acetate fraction of aqueous extract of *A. membranaceus* var. *mongholicus* roots showed strong autotoxicity on the growth of seedlings (62).

### 12.4. Genus *Glycine*

Among the grain legumes, some edible beans, for example, soybean (*Glycine max* L.), are used as vegetables and intensively cultivated in same land year after year. The production of these common bean plants and other perennial legumes declines in replanting conditions owing to autotoxicity. Autotoxicity due to root exudates is involved in growth reduction in soybean monocropping, which decreased the plant biomass and root triphenyl tetrazolium chloride (TTC)-reducing activity. The root exudates of soybean in reproductive growth stage are more autotoxic than vegetative growth stages (52). The autotoxin m-hydroxy-phenylacetic acid (MHPA) depressed the radicle growth of soybean. Soybean root meristematic cells showed less cytoplasm and fewer organelles, cell vacuolation and poorly developed irregular amyloplasts in root columella cells (42). Its root exudates of soybean increased SOD activity and POD activity of seedlings (52).

### 12.5. Genus *Glycyrrhiza*

*Glycyrrhiza uralensis* Fisch. is mainly distributed in Neimenggu, Xinjiang, Gansu, Shanxi provinces of China and is traditional medicine (35). Its plants growth is reduced in replanting, resulting in lower yield and medicinal quality. Its autotoxicity plays important role in the replant problem (24). Extract of *G. uralensis* rhizosphere soil showed autotoxic activity on its own seedlings. Liquiritin, isoliquiritigenin and glycyrrhizic acid isolated from the extract showed autotoxicity and their concentrations in dry soils were 2.32, 0.09 and 12.50 µg/g, respectively. When the concentrations of these compounds reached 200.00 µg/mL, root length of *G. uralensis* seedling were reduced by 21.89 %, 32.22 % and 45.04 %, respectively (40).

### 12.6. Genus *Lotus*

Aqueous extracts of birdsfoot-trefoil (*Lotus corniculatus* L.) were autotoxic to germination, root growth and shoot growth. The extract had a very strong inhibitory effect on the root development. The extract of birdsfoot-trefoil top had a much greater effect than the root extract (14).

### 12.7. Genus *Medicago*

Alfalfa (*Medicago sativa* L.) leaf extract is autotoxic to its own seed germination and root growth of seedlings (10). The leaf extracts of 8 % concentration reduced the alfalfa root length 50 % 48 h after the treatment (8). More than 1 g dry tissue/L leaf extract (g/L) was significantly inhibitory to the root growth, whereas, the leaf extract had no effect on hypocotyl growth. In 4-years alfalfa continuous cropping soil, alfalfa root length was reduced by 66 % (7). Chung *et al.* (11) identified the compounds chlorogenic acid (0.39 mg/g) and salicylic acid (0.03 mg/g) in alfalfa aqueous extract, only chlorogenic acid caused autotoxicity. Chlorogenic acid at 0.001 mol/L significantly inhibited the alfalfa seed germination, seedling elongation and the dry weight (11). Other researches also reported that the chemical root exudates released from alfalfa inhibited the germination, root growth, and caused swelling, curling and discolouration of roots (9).

### 12.8. Genus *Phaseolus*

Asaduzzaman and Asao (4) determined the growth of *Phaseolus vulgaris* L. in hydroponics either with or without activated charcoal addition. It was found that the number of *P. vulgaris* and the fresh mass were decreased significantly to 49-67 % without activated charcoal. The autotoxins in *P. vulgaris* root exudates were identified as benzoic, salicylic, and malonic acids (4).

### 12.9. Genus *Prosopis*

Mesquite (*Prosopis juliflora* (Swartz.) DC.) seed germination was 95 % when treated with 5 g/L pericarp aqueous extract. However, when treated with 60.00 g/L pericarp aqueous extract, mesquite seed germination was totally inhibited. Besides, the extract was inhibitory to the elongation of radicles and hypocotyls (49). The seed germination (%), radicle and hypocotyl lengths of mesquite were reduced significantly by mesquite leaf aqueous extract at 10 g/L to 60 g/L concentrations than control (50).

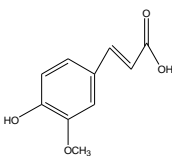
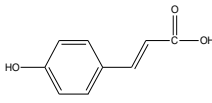
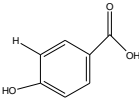
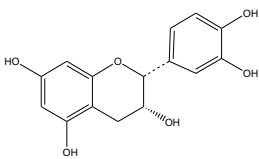
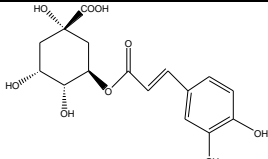
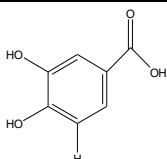
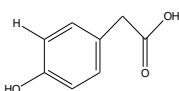
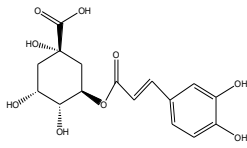
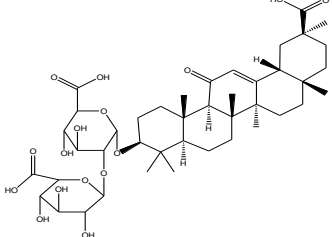
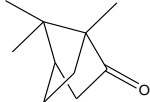
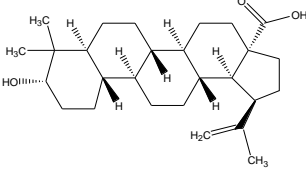
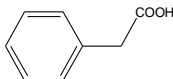
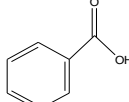
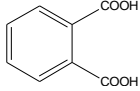
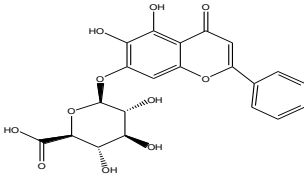
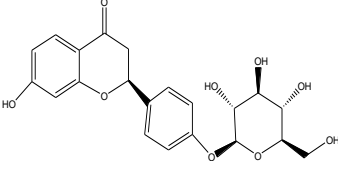
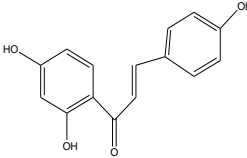
### 12.10. Genus *Robinia*

*Robinia pseudoacacia* rhizosphere soil and litter leachates completely suppressed the seed germination and seedling growth of *R. pseudoacacia* at 0.20 g DW/mL (46). *R. pseudoacacia* rhizosphere soil inhibited the *R. pseudoacacia* photosynthesis, greater the concentration, more was inhibition. Leachates of *R. pseudoacacia* soil inhibited the synthesis of chlorophyll *a* and chlorophyll *b* in leaves of *R. pseudoacacia* seedlings. Soluble sugar content and membrane permeability in seedling were affected slightly by *R. pseudoacacia* soil leachates, while MDA content increased slightly both in *R. pseudoacacia* rhizosphere soil and litter leachates (46).

### 12.11. Genus *Trifolium*

The aqueous extracts of red clover (*Trifolium pretense* L.) stems, leaves and flowers at 0.025-0.20 g/mL showed autotoxic effects to the seedling growth. At 0.20 g/mL, the RIs of red clover stems extracts on the length of seedling and roots were -0.34 and -0.60, respectively; the RIs of red clover leaf extracts on the length of seedlings and roots were -0.39 and -0.69, respectively; and the RIs of red clover flowers extracts on the length of seedlings and roots were -0.31 and -0.63, respectively (6).

Table 2. Chemical structures of autotoxins

Phenolic compounds			
			
Ferulic acid 37,54	p-coumaric acid 19	p-hydroxybenzoic acid 19,22,51	Epicatechin 38
			
Chlorogenic acid 11,37	Protocatechuic acid 19	p-hydroxyphenylacetic acid 4	Salicylic acid 11,51,54
Terpenoids			
			
Glycyrrhizic acid 40	Camphor 19	Betulinic acid 38	
Aromatic acids			
			
Phenylacetic acid 21	Benzoic acid 4,5,30,51,54,	Phthalic acid 21,54	
Flavonoids			
			
Baicalin 58	Liquiritin 40	Isoliquiritigenin 40	

### 12.12. Genus *Vicia*

*Vicia faba* L. is autotoxic. The compounds identified in *V. faba*, the benzoic acid and applied at 50  $\mu\text{M}$  significantly reduced the root length, shoot fresh and dry mass by 81 %, whereas, adipic and p-hydroxyphenylacetic acids decreased the root length to 87 % and 88 %, respectively (4).

### 12.13. Genus *Vigna*

The continuous cropping problem of cowpea (*Vigna unguiculata* (L.) Walp.) is mainly due to autotoxicity. The aqueous extracts of the seedlings of mung bean (*Vigna radiata* (Linn.) Wilczek.) decreased the seed vigour. index, seedling growth, chlorophyll content and POD activity. The autotoxicity varied in different mung bean varieties (61).

Four phenolic acids (phenylacetic, cinnamic, 4-hydroxybenzoic and phthalic acids), were isolated from the rhizosphere soil of cowpea. Cinnamic and 4-hydroxybenzoic acids inhibited the seed germination and seedling growth. Cinnamic acid at 0.1  $\text{mmol}\cdot\text{L}^{-1}$  could decreased the net photosynthetic rate of cowpea 3 d after treatment (21).

## 13. CONCLUSIONS

Autotoxicity is the main reason causing continuous cropping problem in important agricultural crops and medicinal plants. In this review, autotoxicity of 11 families (32 species) are summarized. Most of these species are crops (*Citrullus lanatus*, *Cucumis melo*, *Cucumis sativus*, *Arachis hypogaea*, *Glycine max*, *Vicia faba* and *Vigna unguiculata*, etc.) or medicinal plants (*Eustoma grandiflorum*, *Pseudostellariae heterophylla*, *Astragalus membranaceus*, etc.). Moreover, there are trees (*Casuarina equisetifolia* and *Acacia dealbata*). Owing to the economic importance, we mainly focussed on the autotoxicity of crops and medicinal crops. Infact, the autotoxicity of some invasive species might play an important ecological role. For example, the *A. dealbata* can release autotoxic compounds throughout its phenological cycle to help regulate intraspecific competition under its canopy. This phenomenon has ecological relevance to the invasive process of *A. dealbata* in its non-native range, because it improves the plant's performance and competitive capability. Detailed studies are needed to find links between the chemical compounds present in the plant and their dynamics after release into the soil.

The autotoxin isolation and identification studies showed that phenolic acids were the main autotoxins causing the autotoxicity of crop species. More autotoxins were found in medicinal plants and invasive weed species. The elucidation of autotoxins is not only important in solving the problem of continuous cropping problem, but also to find the new herbicidal chemicals. Therefore, the elucidation of autotoxins from more medicinal plants and invasive weed species deserves more attention.

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