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Plant Autotoxicity: Review (Part II). Families: Chlorellaceae to Plantaginaceae

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ABSTRACT

Autotoxicity, one of the major causes of soil sickness in plants, can inhibit plant growth, lead some soil diseases, and result in negative soil environment and economic loss. In this paper, 25 plant species from 17 genera in 12 families were briefly reviewed on their autotoxicity to give some hints to deal with the soil sickness for agricultural crops or medicinal plants, or the regeneration problems for forest plant species. The 12 families reviewed here are as the following: Chlorellaceae, Liliaceae, Malvaceae, Moraceae, Myrtaceae, Nostocaceae, Nyssaceae, Osmundaceae, Paeoniaceae, Pinaceae, Phytolaccaceae and Plantaginaceae.

Key words: Autotoxicity, autotoxins, soil sickness, crops, medicinal plants, forest plants, weeds

1. INTRODUCTION

Autotoxicity is an intraspecific allelopathy that occurs when a plant species releases chemicals that inhibit or delay germination and growth of the same plant species (52). It causes a strong decline in the yield and performance of several crops that grown in monoculture, such as orchards and perennial forages (2), and perennials plants (e.g., coniferous trees, orchards) (52).

Autotoxicity studies cover a wide range of taxonomically distant species (40). The extracts of *Gossypium hirsutum* L., *Eucalyptus globulus* Labill and *Pinus sylvestris* (3,16,17,20,48,50), and root exudates of *Asparagus officinalis* L., *Fritillaria pallidiflora* Schrenk, *Lilium brownii* var. *viridulum* and *Paeonia ostii* T. (4,45,56,61) have been observed for autotoxicity. In addition, the decomposed of cotton stalks is autotoxic to growth (22).

In this paper, autotoxicity of plants from 12 families were briefly reviewed. The 12 families are as following: Chlorellaceae, Liliaceae, Malvaceae, Moraceae, Myrtaceae, Nostocaceae, Nyssaceae, Osmundaceae, Paeoniaceae, Pinaceae, Phytolaccaceae and Plantaginaceae.

2. CHLORELLACEAE

2.1. *Chlorella*

Chlorella vulgaris cells growth was retarded in the medium containing its own filtrate, the inhibition increased with an increase of filtrate percentage (43). *C. vulgaris* cells produced some substances causing its own growth inhibition, and the autotoxin was identified as chlorellin (44).

3. LILIACEAE

Liliaceae plants are widely distributed, mainly in temperate regions of the Northern Hemisphere. Some species of Liliaceae are popular cultivated plants. Lilies (*Lilium brownii* var. *viridulum*) and tulips (*Tulipa gesneriana* L.) in particular have had considerable symbolic and decorative value, and appear frequently in paintings and the decorative arts. Plants from 3 genera in this family, including *Asparagus*, *Fritillaria* and *Lilium*, have autotoxic effects.

3.1. *Asparagus*

Asparagus (*Asparagus officinalis* L.) is a perennial vegetable, but its crop productivity and quality decrease gradually year by year. One possible reason for "asparagus decline" is thought to be the autotoxicity of asparagus (33,59).

Root exudates of asparagus was autotoxic to the growth of asparagus radicle and shoot (60). An aqueous methanol extract of asparagus rhizomes inhibited the growth of asparagus seedlings in a concentration-dependent manner (18). The extracts of root and stem showed autotoxic effect (61). Benson (1) revealed that shoots of cloned asparagus plants in nutrient solutions of the same plant were fewer than with fresh nutrient solutions, which indicated that asparagus plant may contain some phytotoxic compounds.

Asparagus root contained ferulic, isofemlic, malic, citric, fumaric (13), caffeic (34) and *p*-coumaric acids and iso-agatharesinol (18). The IC_{50} values of *p*-coumaric acid on asparagus root and shoot growth were 0.36 and 0.53 mM, respectively. The IC_{50} values of iso-agatharesinol on asparagus root and shoot were 0.62 and 0.72 mM, respectively (18).

3.2. *Fritillaria*

Fritillaria pallidiflora Schrenk is a well-known medicinal plant and belongs to the *Fritillaria* genus of the Liliaceae family, distributed mainly in Xinjiang Province of China. The dry bulb of this plant is widely used as an important drug source as anantiasthmatic, antitussive, and expectorant agent in traditional Chinese medicine (TCM) (23).

Wang (57) demonstrated that the aqueous extract of *F. pallidiflora* bulb, stems and leaves exhibited autotoxicity on the seedling growth and seed germination. At the concentration of 0.1 g/mL, the aqueous extract of *F. pallidiflora* leaves both inhibited germination, radical and hypocotyl growth. The aqueous extract of stem at 0.05 g/mL and 0.1 g/mL caused inhibition rates of 51.9 % and 71.2 % to seed germination, respectively.

Root exudates of *F. pallidiflora* consisted of 1, 3, 5-triallyl-1, 3, 5-triazine-2, 4, 6(1H, 3H, 5H)-trione phenols, which were inhibitory to seed germination, radical and hypocotyl length. Specifically, when the concentration of the compound concentration was 10 mmol/L, the inhibition rates of seed germination, radical and hypocotyl length were 59.7%, 100% and 100%, respectively (56).

3.3. *Lilium*

The bulbs of *Lilium brownii* var. *viridulum* are commonly used as both traditional Chinese medicines in China and popular functional food for many centuries (30).

The root exudates of this species exhibited inhibition on seedling height, leaf fresh weight and bulb fresh weight. At the concentration of 100 % (v/v), the root exudates reduced leaf fresh weight and bulb fresh weight by 60.70 % and 59.00 %, respectively (4). Root exudates of *L. brownii* var. *viridulum* decreased the content of chlorophyll, malondialdehyde and proline in seedling leaf, and increased the activities of SOD, POD and CAT (4).

Lilium davidii var. *unicolor* Salisb was also reported to possess autotoxicity. GC-MS revealed that indane, 2-tert-butylphenol, 2-methoxy-4-vinylphenol, vanillin, naphthalene, dodecanoic acid, 1,4-benzenedicarboxylic acid, bis (2-ethylhexyl) ester,

4-hydroxy-3,5-dimethoxy-benzaldehyde and tetradecanoic acid were present in the aqueous extract of the root and stem of this species (15).

4. MALVACEAE

The Malvaceae family consists of 243 genus and 4,225 species. This family contains some agriculturally important crops such as cotton (*Gossypium hirsutum* L.) and some medicinally important plants such as *Sida* spp. (32).

4.1. *Gossypium*

Cotton is a shrub native to tropical and subtropical regions around the world. Cotton stalk directly returning to cotton field can inhibit cotton growth in Xinjiang province, China (16). Cotton released allelochemicals which accumulated during continuous monocropping. The inhibitory effects became stronger with the increasing of the duration of continuous monocropping (28).

The shoot and root tissue extracts of cotton at 20 to 80 mg/mL inhibited germination and growth of its own seedlings (16). The aqueous extract of cotton leaf was inhibitory to seed germination at 10-50 mg/mL. The inhibition of the aqueous extract of leaf to root growth was more obvious than that of the aqueous extract of root (50).

Li and Zhang (22) found that when the seedlings were treated with the 30-day microbially decomposed cotton stalks, they displayed better growth and physiological characteristics than those treated with the products of 30-day naturally decomposed cotton stalks. When treated with the microbially decomposed cotton stalks at a low concentration of 5 g/kg, the seedling dry weight and plant height even increased significantly compared to the untreated control ($P<0.05$). Gas chromatography-mass spectrometry (GC-MS) analysis showed that two compounds, dibutyl phthalate (DBP) and diisobutyl phthalate (DIBP), were detected with higher concentrations in the naturally decomposed cotton stalk extracts than that in microbially decomposed cotton stalks, which strongly inhibited the cotton seedling growth in bioassay, suggesting the two compounds might be the responsible allelochemicals inducing autotoxicity to cotton growth.

Four more phenolic acids (p-hydroxybenzoic, ferulic, gallic and vanillic acids) were identified in aqueous extract of plant parts and root exudate by HPLC. The amounts of the 4-phenolic compounds in different cotton plant parts followed the order: shoot extract > root extract > root exudate (16). There were significant differences in phenolic acids concentrations among the fields with different cultivation history. Gallic acid concentrations in soil increased with long period of cotton cultivation. In contrast, the concentrations of both ferulic acid and vanillin were the highest in the 5-year continuous cotton cropped treatments. Total phenolic acids concentrations increased during the first 10-year of monocropped cotton but then declined (17).

The shoot and root tissue extracts of cotton at 20 to 80 mg/mL inhibited enzyme activities (SOD, POD, MDA) and root activity of cotton seedling (16). Monocropping of cotton decreased activity of both the root tripheyl tetrazolium chloride (TTC) and superoxide dismutase (SOD). The addition of activated charcoal decreased the harmful effects on TTC and SOD (28). At 0.5 to 2 g/L, the four phenolic acids significantly

inhibited the growth, enzyme activities (SOD and MDA), and root activity of cotton seedlings (17).

5. MORACEAE

Moraceae, the mulberry family, distributed mostly in tropical and subtropical regions. Moraceae are monoecious or dioecious trees, shrubs, lianas, or rarely herbs comprising 40 genera and 1000 species, nearly all with milky sap.

5.1 *Humulus*

Hop (*Humulus lupulus* L.) is a perennial herb that has been widely used in brewing around the world. Autotoxicity has been reported as one of the major problems hindering continuous hop cultivation (63).

The autotoxins 2,4-bis(1,1-dimethylethyl)-phenol in rhizosphere soil of hop was identified by GC-MS. A pot experiment showed that 2,4-bis(1,1-dimethylethyl)-phenol significantly affected the photosynthesis and hop seedling growth in a concentration-dependent manner (63).

6. MYRTACEAE

The Myrtaceae family produces a rich assortment of important secondary metabolites, including many natural β-triketones. The herbicidal chemical, leptospermone, was isolated from the bottlebrush (*Callistemon citrinus* (Curtis) Skeels). Leptospermone and other triketone herbicides exert bleaching and herbicidal action through intricate metabolic interplay by inhibition of p-hydroxyphenylpyruvate dioxygenase (HPPD) (41).

6.1. *Eucalyptus*

It has been observed by Singh (1991) that none of the large number of seeds of Eucalyptus that fall on the ground of monoculture plantation germinates, primarily because of high amount of inhibitors that get accumulated after having released from the trees (51).

Many researches exhibited that Eucalyptus residues can be seen as a source of potentially valuable bioactive extracts (48). What's more, the essential oils from Eucalyptus have also been reported to exhibit toxicity against other plants. Cao (3) investigated the autotoxicity of the volatiles in fresh branches and leaves of *Eucalyptus globulus* Labill on the seed. The volatile concentration was 0.0772 g/cm^3, 0.0257 g/cm^3 and 0.0085 g/cm^3. Branches and leaves volatiles both exhibited inhibition at high concentration. The effect of leaves volatiles was higher than that of branches volatiles at 0.0772 g/cm^3. Except for 0.0257 g/cm^3 treatment, the autotoxicity reached significant level in the leaves volatiles and branches volatiles treatment.

7. NOSTOCACEAE

7.1. *Nostoc*

Harder (12) reported that old cultures of *Nostoc prunctifome* had autotoxic effects.

8. NYSSACEAE

Plants from two genera in this family were reported to have autotoxic effect including *Camptotheca* and *Nyssa*.

8.1. *Camptotheca*

Camptotheca, the happy trees, comprises only two species and is distributed in lowland warm-temperate forests of the Yangtze River Basin and south-western areas of China. The genus is notable for being a major source of the anticancer drug camptothecin (CPT), which is a strong inhibitor of nucleic acid synthesis in mammalian cells and induces the breaking-up of strands in chromosomes (11).

Autotoxicity induced by endogenous compounds in camptotheca (*Camptotheca acuminata* Decne.) was reported by Li in 2010 (21). Fast-growing camptotheca plants can avoid poison by its endogenous camptothecin (DNA topoisomerase I inhibitor) at more than 10 times higher than the fatal concentration of exogenous application to the plant. However, auxin-reducing pruning could induce endogenous autotoxicity in camptotheca: dramatic deviations from normal morphogenesis, including serrated or lobed leaves, disturbed phyllotaxis, and fasciated stems. The abnormal morphogenesis appears correlatively with the elevated camptothecin contents following decapitation pruning (21).

8.2. *Nyssa*

Nyssa yunanenesis W. C. Yin, a critically endangered plant, is an androdioecious species (54). There are only eight wild individuals left in Yunnan Province, southwestern China (62). Autotoxicity is known to regulate density-dependent intraspecific competition in plants, but at the same time due to the effects on regeneration and hence population size, it may have implications for conservation.

N. yunnanensis may negatively affect its natural regeneration through autotoxic effects on seed germination and seedling growth. *In situ* field experiments demonstrated that seed germination of *N. yunnanensis* was significantly inhibited by both litter and seed capsule. Extracts of different organs of *N. yunnanensis* had significant negative effects on its seed germination, and the inhibition rate of root extracts (80.9 %) was significantly higher compared with the leaves and stems. Seedling growth also was suppressed by extracts of different organs, whereas no significant differences were found in the root/shoot ratio. The degree of inhibition of both germination and seedling growth increased with extract concentration. Soil experiments demonstrated also that seed germination and seedling growth were suppressed in soil where *N. yunnanensis* had previously grown (62).

9. OSMUNDACEAE

9.1. *Osmunda*

Two plants of *Osmunda claytoniana* and *Osmunda cinnamomea* from Osmundaceae family were confirmed having autotoxic potential. Munther and Fairbrothers (36) suggested that *O. claytoniana* and *O. cinnamomea* germination were inhibited by itself leaf extract, and leaf leachates of *O. cinnamomea* also restrained spore germination.

10. PAEONIACEAE

Paeoniaceae, the peony family, consisting of only the genus *Paeonia* with about 33 species distributed in Europe, Asia, and western North America. Economically, the group is important for various garden species of peonies, whose showy large blossoms grow in a wide range of forms and colours.

10.1. *Paeonia*

The peony, native to Asia, Europe and Western North America, is a flowering plant in the genus *Paeonia*, the only genus in the family Paeoniaceae. Peonies are among the most popular garden plants in temperate regions.

The aqueous extracts root and rhizosphere soil of *Paeonia ostii* T. showed autotoxic potential on root growth of seedlings (46).

Ferulic acid (3.7 μg/g), cinnamic acid (21.78 μg/g), vanillin, coumarin and paeonol (35.3 μg/g) were detected in rhizosphere soil by HPLC. These compounds and their mixture had significant effect on the plant height, root length and biomass of *P. ostii* seedling (46). Further studies revealed that these autotoxins inhibited its own growth by influencing root enzymes activity and chlorophyll synthesis (46). It was also demonstrated that the free proline content and activities of SOD and POD increased by the *P. ostii* root exudates (45).

11. PINACEAE

The problem of autotoxicity is common in woodlands, and is one of the major reasons for growth reduction under the continuous monoculture practice. In forest ecosystems, many examples of autotoxicity exist in coniferous trees from 3 genera (*Abies*, *Picea abies*, *Picea* and *Pinus*) in Pinaceae family, including *Abies balsamea*, *Picea abies*, *Picea mariana*, *Pinus halepensis*, *Pinus densiflora* and *Pinus laricio*.

11.1. *Abies*

Inhibition of nitrification by allelopathic substances in forest ecosystems was documented (29). The inhibition of nitrification increases during succession in grasslands and often reaches its maximum in climax ecosystems. This inhibition was regarded as important in successional dynamics since NH_4^+ nitrogen is less subject to leaching than the NO_3^- form. Moreover nitrate nutrition is more demanding on the energy of the plant since it must be reduced prior to assimilation and translocation (47).

Foliar leachates of balsam fir (*Abies balsamea*) strongly inhibited nitrification. Balsam fir needle extracts (5 %, w/v) completely prevented the oxidation of ammonium, and 2 %, w/v extracts prevented the oxidation of ammonium to nitrate to a large extent (55).

11.2. *Picea*

11.2.1. *Picea abies*

There are numerous reports of spruce (*Picea abies* L. Karst) regeneration failure in mountain forest.

Phytoxicity of spruce litter, root extracts (19), and soil solutions (58) on spruce growth have been demonstrated. Germination bioassays with natural leachates of spruce showed negative effects on root elongation of spruce seedlings. Growth bioassays on litter and humus demonstrated inhibitory effects of these organic layers. p-Hydroxyacetophenone, a spruce-specific metabolite, was isolated in spruce through fall (10^{-6} M), in water extracts of litter (between 1 and 8 µg/g dry wt) and organic layer (less than 1 µg/g dry wt) in addition to tannins and several common phenolic acids. p-Hydroxyacetophenone and caffeic acid reduced, even at 5×10^{-5} M, spruce seedling growth, especially root development (10).

11.2.2. *Picea mariana*

The water leachates of black spruce (*Picea mariana*) forest soil organic matter inhibit itself seedling growth quite dramatically. The aqueous extract of the organic matter of black spruce showed inhibition to the primary root growth and development of the black spruce seedlings. Field observations also indicate that, 4-6 years after clear-cutting, seedbed conditions improve and some growth from natural regeneration occurs. It is possible that the heat of fire and/or exposure to solar radiation may reduce the level of chemical inhibition by breaking down the allelopathic compounds present in the seedbed (31).

11.2.3. *Picea schrenkiana* Fisch. et Mey.

Schrenk spruce (*Picea schrenkiana* Fisch. et Mey.) is an endemic species in Middle Asia and plays an important role in water conservation. However, natural regeneration has been problematic, which has been widely documented.

Results showed that the original water extract of Schrenk spruce needles and the diethyl ether, ethyl acetate and n-butanol soluble fractions of the original water extract all exhibited strong autotoxic effects on seed germination and seedling growth (26,27). Specifically, the growth of Schrenk spruce seedling was inhibited by the diethyl ether extract at 1.25 mg/mL (24,42). The aqueous extracts of Schrenk spruce at 0.1 g/mL was significantly inhibitory to seed germination, and the inhibition rate reached 31.3%, and when at 0.05 g/mL, the aqueous extract was significantly inhibitory to the radicle length and plantule length, and the inhibition rate reached 44 % and 27.8 %, respectively (14).

Investigation of the chemical composition of Schrenk spruce needles reveals a great number of secondary metabolites that may serve as allelochemicals. Among them, phenolic acids, long-chain fatty acid, tannin, indole and flavonoid were best correlated to the observed autotoxic effects (25). Bioassay-guided fractionation of the diethyl ether fraction of a water extract of Schrenk spruce needles led to the isolation of the phenolic compound 3,4-dihydroxy-acetophenone (DHAP). DHAP significantly inhibited seed germination and seedling growth at concentrations of 2.5 mM and 0.5 mM ($p < 0.05$). Soil analysis revealed that Schrenk spruce forest soils contained exceptionally high DHAP concentrations (mean = 0.51±0.03 mg/g dry soil), sufficient to inhibit natural Schrenk spruce recruitment (42). Additionally, Pan (42) identified a new allelochemical 2-keto-4a-methyl-8-methoxy-2, 3, 4, 4a, 5, 6, 11, 12-ocahydro chrysene in the diethyl ether fraction of Schrenk spruce aqueous extracts.

11.3. *Pinus*

11.3.1. *Pinus halepensis*

Aleppo pines (*Pinus halepensis* Mill.) is one of the major tree species in the western Mediterranean basin, ecological and economical values (53).

Fernandez et al. (9) reported that autotoxicity was a potential functional process that could influence natural regeneration of Aleppo pines. It was demonstrated that young Aleppo pines exhibited a toxic effect on germination whereas old pines showed the most important effect on seedling growth. Moreover, needle extracts presented an important dose effect on germination compared to roots.

GC-MS analysis of aqueous extracts revealed approx. 59 components from needles and roots. The major constituents were divided into different phytochemical groups: phenolics (50 %), fatty acids (44 %), and terpenoids. Roots and needles had two distinct chemical profiles, while needle leachates were composed mainly of oxygenated terpenoids (e.g., α-eudesmol, α-cadinol, and α-terpineol) (8).

11.3.2. *Pinus laricio*

Fifteen phenolic acids were identified in the water-soluble phenolics extracted from litter of forest soil under *Pinus laricio* Poiret trees. Benzoic, protocatechuic, ferulic, salicylic, vanillic and syringic acid were the main allelochemicals present in the surface horizon of soil in autumn and winter. Vanillin was significantly most abundant in the autumn litter. Phenols extracted from litter inhibited seed germination of *P. laricio*. The phenols also had inhibitory effect on glyoxylic enzyme activities. In fact, the phenolic extracts having the inhibitory effect on the glyoxylic enzyme activities, suggested that the inhibition of seed germination was linked to a low utilisation of storage lipids, with consequent deficit in glucose, the main respiratory substrate, necessary to seed germination (37,38,39).

11.3.4. *Pinus radiata*

Chou (6) reported that aqueous extracts of soil-root mixtures caused significant growth reduction of *Pinus radiata* Don seedlings. Particularly, the height of *P. radiata* seedlings grown on soils incorporating different proportions of root tissues (25 % and 50 %) was shown to be reduced by 20-80 %. the aqueous extracts from seedlings soil/root mixtures also showed a significant reduction in growth. This growth-retarding effect was partially overcome by the addition of nutrients or by soil sterilisation. It is postulated that growth retardation was caused not only by nutrient deficiency resulting from the addition of organic matter with a high C/N ratio, but also by phytotoxic substances present in the root tissue.

11.3.5. *Pinus sylvestris*

Chen (5) investigated the autotoxicity of the surface soil, rhizosphere soil, non-rhizosphere soil, ground litter leaching liquor of *Pinus sylvestris*. It was found that the ground litter (1:5, solid and liquid ratio) had extremely significant inhibition effect on seed vigor index, shoot length and the growth of young branches.

11.3.6. *Pinus tabulaeformis*

All (roots, branches and leaves) extracts and the volatile oil of *Pinus tabulaeformis* Carr exhibited autotoxic effect. When the extracts concentration was 30 mg/mL, the ethyl acetate extract of *P. tabulaeformis* leaves decreased the seed germination, the root and shoot growth by 86.95 %, 100 % and 100 %, respectively. While the ethyl acetate extract of *P. tabulaeformis* branches decreased the seed germination, the root growth and shoot growth by 86.95 %, 93.22 % and 90.09 %, respectively. The *P. tabulaeformis* volatile oil significant inhibited seed germination and itself growth, and the inhibition rates of seed germination, the root and shoot growth was 65.52 %, 83.33 % and 77.14 %, respectively (20).

12. PHYTOLACCACEAE

Phytolaccaceae, the pokeweed family of flowering plants, comprising 18 genera and 65 species of herbs, shrubs, and trees, mostly native to tropical and subtropical North America and Africa.

12.1. *Phytolacca*

Edwards (7) reported the autotoxicity of the aqueous extract of pokeweed (*Phytolacca americana* L.). Except for juvenile leaves and the root, most extracts of the pokeweed plant inhibited seed germination with more mature structures exerting more inhibition. Specifically, the presence of extracts from most plant parts correlated with reduced or no germination by seeds of its own species, whereas the presence of distilled water correlated with high percentages of germination by control seeds. Whether diluted with water by 5-fold (20 %, v/v) or undiluted, juice of pokeweed fruits completely inhibited the laboratory germination of pokeweed seeds.

13. PLANTAGINACEAE

The traditional Plantain family was small, consisting of only 3 genera and 270 species, almost all of them plantain (*Plantago*).

13.1. *Plantago*

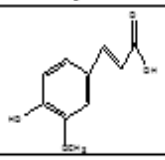
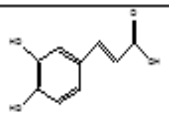
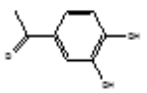
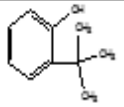
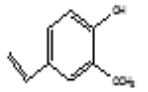
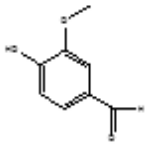
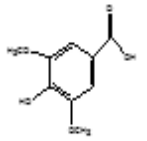
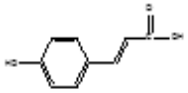
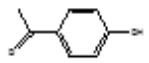
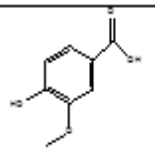
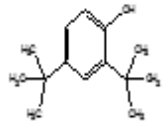
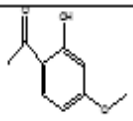
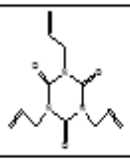
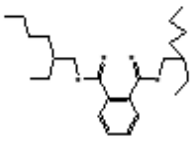
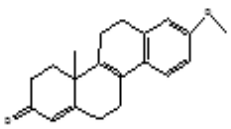
Plantago lanceolata L. appear to be inhibited more by exudates from its own species. The *P. lanceolata* is normally found as isolated individuals, or a few individuals in a group, not as pure stands. This is surprising for the *Plantago*, whose only mechanisms of dispersal are a short, nearly vertical rhizome and a rather heavy seed (40).

Sagar and Harper (45) founded that *P. lanceolata* seedlings close to an established *P. lanceolata* individual had less chance of survival than those further away. So the well spread out distribution is apparently continuously and dynamically maintained. Milton (35) sowed *P. lanceolata* in pure stands outdoors and found high yield in the first year, but a marked decline in the second and third years. This could be due to an autotoxic substance which accumulated in the soil.

Table 1. Autotoxic plants and their autotoxins

Family	Genus	Plant	Autotoxins	Reference
Chlorellaceae	*Chlorella*	*C. vulgaris*	Chlorellin	44
Liliaceae	*Asparagus*	*A. officinalis*	Ferulic, Isofemlic, Malic, Citric, and Fumaric, Caffeic and p-Coumaric acids and Iso-agatharesinol	13,34,18
	Fritillaria	*F. pallidiflora*	1, 3, 5-Triallyl-1, 3, 5-triazine-2, 4, 6(1H, 3H, 5H)-trione	56
	Lilium	*L. davidii*	indane, 2-Tert-butylphenol, 2-Methoxy-4-vinylphenol, Vanillin, Naphthalene, Dodecanoic and Tetradecanoic acids, 1,4-Benzenedicarboxylic acid, bis(2-ethylhexyl)ester, 4-Hydroxy-3,5-dimethoxy-benzaldehyde	15
Malvaceae	*Gossypium*	*G. hirsutum*	Dibutyl phthalate and Diisobutyl phthalate p-Hydroxybenzoic, Ferulic, Gallic and Vanillic acids	16,22
Moraceae	*Humulus*	*H. lupulus*	2,4-Bis(1,1-dimethylethyl)-phenol	63
Nyssaceae	*Camptotheca*	*C. acuminata*	Camptothecin	11,21
Paeoniaceae	*Paeonia*	*P. ostii*	Ferulic Acid, Cinnamic Acid, Vanillin, Coumarin and Paeonol	46
Pinaceae	*Picea*	*P. abies*	p-Hydroxyacetophenone	10
		P. schrenkiana	2-Keto-4a-methyl-8-methoxy-2, 3, 4, 4a, 5, 6, 11,12 -ocahydro chrysene, 3,4-Dihydroxy-acetophenone	42
	Pinus	*P. halepensis*	α-Eudesmol, α-Cadinol, and α-Terpineol	8
		P. laricio	Benzoic, Protocatechuic, Ferulic, Salicylic, Vanillic and Syringic acids	37,38,39

Table 2. Chemical structures of autotoxins

Phenolic compounds			
			
Ferulic acid 46	Caffeic acid 34	3,4-dihydroxy-acetophen-one 42	2-tert-butylphenol 15
			
2-methoxy-4-vinylphenol 15	Vanillin 15,46	Syringic acid 37,38,39	p-coumaric acid 16,18
			
p-Hydroxyacetophenone 10	vanillic acid 16	2,4-bis(1,1-dimethylethyl)-phenol 63	Paeonol 46
Esters			
			
1, 3, 5-triallyl-1, 3,5-triazine-2, 4, 6(1H, 3H, 5H)-trione 56	dibutyl phthalate 22	bis(2-ethylhexyl) phthalate ester 15	diisobutyl phthalate, bis(2-methy-lpropyl)ester 22
Flavonoids			
 2-keto-4a-methyl-8-methoxy-2, 3, 4, 4a, 5, 6, 11, 12-ocahydro chrysene 42			

14. CONCLUSIONS

Autotoxicity is the main reason causing continuous cropping obstacle in the plantation of some important agricultural crops and medicinal plants. In this review, autotoxicity of 25 species from 12 families were summarized. Most of these species were crops (such as *Gossypium hirsutum* and *Asparagus officinalis*, etc.) or tree species (*Eucalyptus globulus*, *Pinus sylvestris*, *Nyssa yunanenesis*, *Picea abies*, *Picea mariana*, *Picea schrenkiana*, *Pinus halepensis* and *Pinus laricio*, etc.) or medicinal plants (*Fritillaria pallidiflora*, *Paeonia ostii* and *Phytolacca americana*, etc.) or algae (*Chlorella vulgaris* and *Nostoc prunctifome*)

In general, the self-toxic effects of crops and medicinal plants can cause great economic losses to farmers, but it is negligible. Some plants are very autotoxic, as they cause intraspecific competition e.g. *Nyssa yunanenesis* and *Picea mariana*, etc. Autotoxicity regulates the density-dependent intraspecific competition in plants, but also affects the regeneration and hence, population size, it may have implications for conservation (62).

The autotoxin isolation and identification studies showed that phenolic acids were the main autotoxins causing the autotoxicity of crops (Table 1). More structure types of autotoxins were found in crops, medicinal plants and tree species (Table 2). The elucidation of autotoxins were not only important in solving the problem of continuous cropping obstacle, but also meaningful in findings of the new herbicidal chemicals. Therefore, the elucidation of autotoxins from more medicinal plants and invasive weed species deserves more attention.

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