

Soil Sickness : Current Status and Future Perspectives

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ABSTRACT

In agriculture soil sickness is a major problem, which reduces the crops yield. It is caused by various factors viz., soil nutrients imbalance, autotoxins production and accumulation, changes in soil microbial community structure (development of harmful microbes). Soil sickness is major problem in Food crops (Rice, wheat, corn, mungbean, soybean etc), Cash crops (Sugarcane, tobacco, peanut), Vegetables (Cucumber, eggplant, asparagus, watermelon, muskmelon, tomato, potato, ginger etc), medicinal plants (*Rehmania*, ginseng, *Angelica* etc), Fruit trees (Apple, *Citrus* spp., peach, tea, coffee etc) and forest trees (Chinese fir, *Casuarina* spp). This review discusses the (i). Problem of soil sickness in various crops, medicinal plants, forestry and horticultural trees in terrestrial cropping and hydroponics, (ii). Role of soil physico-chemical properties, allelopathic autotoxins and rhizosphere microflora, (iii). Mechanism of soil sickness and (iv). Suggest methods to overcome this problem.

Keywords: Allelochemicals, *Angelica*, apple, broad bean, *Casuarina*, Chinese fir, *Citrus*, coffee, com, cowpea, cucumber, eggplant, ginger, ginseng, lettuce, microbes, mungbean, nutrients, peach, parsley, pea, peanut, pepper, plant-soil interactions, potato, *Rehmania*, rice, soil health, soil microbes, soil sickness, soybean, strawberry, sugarcane, taro, tea, tobacco, tomato, watermelon, wheat.

1. INTRODUCTION

Soil is the natural medium for seed germination, growth and development of plants. Soil sickness reduces the growth and yield of crops (22,24,27,49,59,113,141). The soil sickness is mainly caused by monoculture of the same plant species continuously in the same field. It is known since ancient times and many approaches have been used to overcome the problem. For example, Jiminyashu (ca. 540, an ancient Chinese book), gives detailed description of the importance of suitable cropping sequences for high crop productivity (65). However, scientific work on soil sickness was not initiated until the beginning of 20th Century and has been divided into 3- stages: (i) Pioneer stage (1900s-1950s) focus on phytotoxins, (ii). Second stage (1950s-2000s) focus on phytotoxins and soil microbes and (iii). Third stage (2010s- to date) focussing on the plant and soil relations (65).

Soil sickness or replant disease has been reviewed several times (10,37,45,49,58, 65,72). In this article, we focus on the recent advances and developing trends in soil sickness research to further understand the underlying mechanisms involved and to develop technology to overcome this problem for sustainable crop production.

2. SOIL SICKNESS IN CROPS

Autotoxicity is one of the causes involved in soil sickness or replanting disease of many crop species. It is a special intraspecific allelopathy phenomenon, where the compounds released by a crop plant inhibits the growth of other crop plants of the same specie. Autotoxicity can lead to plant dysplasia (serious diseases and significant decline in yield and quality) caused by continuous growing of same plant species in the same land for many years. In modern times, continuous cropping has become a need due to more intensive land use, owing to population pressure leading to decreased land. The Table 1 shows the Current Status of soil sickness research in crops, vegetables, medicinal plants and in hydroponics etc.

2.1 Staple Food Crops

Soil sickness has been studied in monocultures of several staple food crops over the world such as rice (23,25,28,68,131), wheat (73,94,149,164,173), corn (133,139), mungbean (138,145,151) and soybean (63,121,122,123,168).

(i). Rice: In an intensive farming system, the autotoxicity is often ignored. In Taiwan, Chou (25) found that the autotoxicity of rice residues caused 25% reduction in the second crop of rice due to poor water drainage. Usually rice stubbles are left over after harvest of the first season and used in nutrients recycling in the same field. When the rice stubbles are decomposed under anaerobic conditions they release large amounts of autotoxins into the paddy soil, which inhibits rice growth and reduce its grain yield in successive crop (23,28). Various phenolic acids like *p*-coumaric, *p*-hydroxy benzoic, syringic, vanillic, ferulic, *o*- and *p*-hydroxy phenyl acetic, and 2-hydroxyphenylacetic acids have been isolated from the decomposing residues in the soil and root exudates (131).

Table 1. List of crops and fruit plants adversely affected by Soil sickness problem

S.No	English	Name	Botanical	Economic use		Crop duration		Countries	Nature of soil sickness	References
				use		Annual	Perennial			
1.	Rice	<i>Oryza sativa</i> L.	Grains	Grains	Annual	-	Asian Countries	Autotoxins, nutrient and microbial imbalance	23,25,28,30, 68,131	
2.	Wheat	<i>Triticum sativum</i> L.	Grains	Grains	Annual	-	Asian, USA Latin American Countries	Autotoxins, microbial and nutrients imbalance	73,94, 149,16 4,173	
3.	Corn	<i>Zea mays</i> L.	Grains	Grains	Annual	-	-do-	Autotoxicity, Phytopathogenic microorganisms	133,139	
4.	Soybean	<i>Glycine max</i> L.	Seeds	Seeds	Annual	-	China	Autotoxicity, <i>Penicillium</i>	4,63,121,122, 123,168	
5.	Mungbean	<i>Vigna radiata</i> L.	Seeds	Seeds	Annual	-	India, China	<i>Purpureogenum</i> Autotoxicity, Microbial imbalance	138,145,151, 152	
6.	Sugarcane	<i>Saccharum officinarum</i> L.	Stalks	Stalks	-	Perennial	Asia, USA, Brazil, Australia	Imbalance in microbes, Soil physico- chemical properties, autotoxins	26,58,78,125, 126,132,137, 146,147,154, 156,157	
7.	Tobacco	<i>Nicotiana tabacum</i> L.	Leaves	Leaves	Annual	-	China, USA	Autotoxins, Phytopathogenic fungi	18,107,108	
8.	Peanut	<i>Arachis hypogaea</i> L.	Fruits	Fruits	Annual	-	China	Microbial imbalance	76	
9.	Cucumber	<i>Cucumis sativus</i> L.	Fruits	Fruits	Annual	-	China	Autotoxicity, Microbial imbalance	46,113,114, 116,161,162, 177	
10	Eggplant	<i>Solanum melongena</i> L.	Fruits	Fruits	Annual	-	China, Europe	<i>Verticillium dahliae</i> , Autotoxicity	19,20,115,18 4, 191	

Table 1. Contd.

11	Asparagus	<i>Asparagus officinalis</i> L.	Crown buds	-	Perennial	Europe, Japan, and USA	Autotoxicity, root rot (<i>Fusarium oxysporum</i> spp. <i>asparagi</i>)	55,100,174, 175,177	
12	Water melon	<i>Cucumis lanatus</i> L.	Fruits	Annual	-	China	Autotoxicity, Microbial imbalance	54,163,194	
13	Muskmelon	<i>Cucumis melor</i> L.	Fruits	Annual	-	China	Autotoxicity, Microbial imbalance	176,178	
14	Tomato	<i>Lycopersicon esculentum</i> L.	Fruits	Annual	-	China	Autotoxicity	160,190	
15	Potato	<i>Solanum tuberosum</i> L.	Tubers	Annual	-	China, USA, Europe, South america	Soil-borne diseases	42,77	
16	Ginger	<i>Zingiber officinale</i> L.	Rhizomes	-	Perennial	China	Soil-borne diseases	53	
Medicinal Plants									
17	Rehmannia	<i>Rehmannia glutinosa</i> (Gaertn.) Steud.	Tuberous roots	-	Perennial	China	Soil-borne diseases	40,51,52,79, 80,87,88,103, 165,166	
18	Angelica	<i>Angelica sinensis</i> (Oliv.) Diels	Tuberous roots	-	Perennial	China	Soil-borne diseases	187	
19	Ginseng	<i>Panax notoginseng</i> (Burkill) F. H. Chen	Tuberous roots	-	Perennial	China	Autotoxicity	187	
20	Asian Ginseng	<i>Panax ginseng</i> L.	Tuberous roots	-	Perennial	China	Soil-borne diseases, Autotoxicity	187	
Hydroponics									
21	Cucumber	<i>Cucumis sativus</i> L.	Fruits	Annual	-	Japan	Autotoxicity	2	
22	Tomato	<i>Lycopersicon esculentum</i> L.	Fruits	Annual	-	Japan, China	Autotoxicity	2,90	
23	Strawberry	<i>Fragaria x ananassa</i> Duch.	Fruits	Annual	-	Japan	Autotoxicity	2,4	
24	Taro	<i>Colocasia esculenta</i> (L.) Schott	Corms	Annual	-	Japan	Autotoxicity	5,6	

Table 1. Contd.

		Fruit/Forest trees					
		Fruits	-	Perennial	Europe, American Countries	Phytopathogenic fungi and bacteria	12, 14, 60, 69, 92, 110, 6, 132, 140, 142, 143, 158, 159
25	Apple	<i>Malus sativus</i> L.	Fruits	-	Perennial	Europe, American Countries	12, 14, 60, 69, 92, 110, 6, 132, 140, 142, 143, 158, 159
26	Peach	<i>Prunus persica</i> L.	Fruits	-	Perennial	American Countries	98, 105
27	Bitter Orange	<i>Citrus aurantium</i> L.	Fruits	-	Perennial	Middle East, Asiatic and American Countries	31, 56
28	Orange	<i>Citrus sinensis</i> Osbeck	Fruits	-	Perennial	Middle East, Asiatic and American Countries	31, 56
29	Rough Lemon	<i>Citrus jambhiri</i> Lush.	Fruits	-	Perennial	United States	31, 56
30	Tea	<i>Camelia sinensis</i> L.	Leaves	-	Perennial	China, India, Sri Lanka, Pakistan	16, 112, 136
31	Coffee	<i>Coffea arabica</i> L.	Fruits	-	Perennial	Mexico, Brazil	44, 149
32	Chinese fir	<i> Cunninghamia lanceolata</i> (Lamb.) Hook	Timber	-	Perennial	China, India	Nutrient depletion, proliferation of phytopathogens, soil degradation, autotoxicity
33	Horsetail beefwood	<i>Castarina equisetifolia</i> L.	Plantations	-	perennial	China, India	Autotoxicity 33, 61

Some autotoxins, such as *o*-hydroxyphenylacetic acid reached a peak concentration of 10^{-2} M, in the first week of decomposition while radicle growth of rice seeds is inhibited at 25 ppm concentration (23). The autotoxins in soil reached the highest levels in 6-weeks of decomposition of rice residues, gradually declined thereafter and disappeared after 12-weeks (30). It was also found that autotoxins released from the rice residues showed allelopathic effects on other plant species (68).

Rice is major crop in the rice-wheat cropping system, which has been practiced by farmers of South Asia for more than 1000-years. Continuous cropping of the rice-wheat system for several decades has shown that the yield have stagnated below potential level due to a number of factors including the deterioration of the physical, chemical and biological health of the rice-wheat growing soils. The poor stand establishment of wheat following rice is common. Some findings suggest that residues of aquatic rice weeds have a negative influence on subsequent wheat growth (1). Phenolic compounds (Caffeic acid, chlorogenic acid, ferulic acid, 4-hydroxy-3-methoxybenzoic acid, gallic acid, *p*-coumaric acid, *m*-coumaric acid, syringic acid and vanilic acid) were the phytotoxins associated to this effect. Rice allelochemicals might also be involved. Utilization of rice residues in paddy fields has long been recognised as an important source to improve the organic matter status of soil and was also reported to reduce the emergence of weeds. Some experiments, however, indicate that rice straw suppress the germination of oat and wheat (41).

(ii). Wheat: Under reduced or no-tillage farming systems in wheat (*Triticum aestivum* L.), early poor growth and yield performance have been attributed to retention of stubbles and residues (94). The cause of yield reduction is attributed to the phytotoxic chemicals released from the decomposing wheat residues (73,94,149,173). Wu *et. al* (164) evaluated varietal autotoxicity of root exudates and residue extracts in wheat and found that the root exudates and residue extracts inhibited the wheat germination by 2-21%, radicle growth by 15-30%, and coleoptile growth by 5-20%.

(iii). Corn: Corn (*Zea mays* L.) also suffers from serious soil sickness under continuous cropping systems. This is more detrimental in the No-till farming, where corn residues are left on the soil surface. Singh (133) studied the autotoxic effects of maize on some biophysical and biochemical parameters and found that autotoxicity decreased the dry weight, root and shoot length of maize seedlings. There was a significant decrease in total chlorophyll, protein content and nitrate reductase activity, when maize seedlings were treated with the residue extract (133). Corn residues left in the soil for decomposition also alter the rhizospheric microflora, which in turn inhibits the corn growth (139).

(iv) Mungbean (*Vigna radiata* L.): The International Rice Research Institute, Phillipines investigated the effects of 8- years of mungbean monocropping on grain yield of following mungbean crop. It was found that yield usually declined 30-60% and in some cases, the crop failed. The inhibitory effects were particularly apparent at early growth stages for mungbean (145). Microbial involvement was confirmed and the old roots remaining in the soil were the primary source of infection to the new mungbean plants. The presence and quantity of crop residues were also related to the appearance of growth inhibitory effects. The phytotoxic activity was found primarily in the stems and other aerial parts (151). Yield

decline of mungbean was related to the production of a number of saponins like soyasaponin-I that are released into the soil from the mung bean seedlings. Glucosyl-flavonoid allelochemicals were also isolated from the inhibitory zone of germinating mungbean (138).

(v) **Soybean:** Soil subjected to soybean (*Glycine max* L.) monocropping, reduced soybean yields even after sterilization with methyl bromide (121). Mycotoxins released by *Penicillium purpurogenum* Stoll were involved in growth inhibition of soybean plants (63). In hydroponic culture, the addition of activated charcoal decreased the magnitude of mass reduction in continuous soybean (168). These findings suggested that autotoxins were root exudated by soybean plants. Phenolic autotoxins were identified as vanillic, p-coumatic acid, and ferulic acids and *p*-hydroxy phenyl acetic acid, and *m*-hydroxy-phenylacetic acid which are present in decomposed root and soil solutions (122). The application of *m*-hydroxy-phenylacetic acid significantly inhibited the radicle growth and root tips became thicker and brownish. Transmission electron microscopy analysis showed that it affected the soybean root tip, leading to sparse cytoplasm and fewer organelles in root meristematic cell, cell vacuolation and poorly developed irregular amyloplasts in root columella cell. The *m*-hydroxy-phenylacetic acid modified the expression pattern of genes involved in soybean response to several stressing factors (123).

2.2 Main Cash Crops

(i). **Sugarcane :** Sugarcane (*Saccharum officinarum*) is one of the world's major cash crops. Continuous monocropping of sugarcane including ratooning, is common practice in many regions, which often decreased the sugarcane yield (26,78,155,156,157). Autotoxicity is one major reason for the yield reductions in continuous cropping of sugar cane (125). To prevent soil degradation and soil erosion (122,126), about 600 to 2,400 Kg ha⁻¹ of postharvest residues are every year deposited on the field surface and allowed to decompose in the soil (146). The decomposing sugarcane residues release various allelochemicals into the soil (26,58,125,126,132,137,147) and these autotoxins significantly reduces the germination, radical length and seedling dry weight and delay the early leaf development in target plants (125).

(ii). **Tobacco:** Tobacco (*Nicotiana tabacum* L.) can not be monocultured in successive years, as it suffers from serious replant diseases in continuous monoculture system (18,107,108). Patrick and Koch (107,108) found that the tobacco plant residues could inhibit the respiration, germination and growth of tobacco plants in successive growing seasons and the phytotoxic substances from the plant residues, reduces the resistance of tobacco to black root rot (108). Chen *et al.* (18) in pot experiments studied the effects of continuous monocropping treatment for 0, 3 and 10 years on the growth of flue-cured and burley tobacco plants and the activity of protective enzymes in the leaves. The results showed that the inhibitory effects on the continuously monocropped tobacco were significantly enhanced when the continuous monocropping years extended. It was also found that the growth rates of flue-cured and burley tobacco plants were significantly inhibited, which shortened the plant height and decreased the leaf area. Further, the defense response of tobacco was also triggered in this process, and the activities of

superoxidate dismutase (SOD), peroxidase (POD) and catalase (CAT) in the tobacco leaves were changed, with an initial increase and then a decrease. The malondialdehyde (MDA) content was increased, which in turn significantly reduced the yield and quality of tobacco.

(iii). Peanut (*Arachis hypogaea* L.): The intensive peanut production is widespread in the subtropical regions of China and other countries. Yield decline in peanut is connected to an increased susceptibility to diseases promoted by root exudation of peanut allelochemicals (76). The root exudates of peanut promote the proliferation of phytopathogenic species such as *Fusarium oxysporum*, *Bionectria ochroleuca* and *Phoma macrostoma*.

2.3. Vegetables

The problem of soil sickness in vegetable crops is known since ancient times. Many vegetables such as Cucumber (*Cucumis sativus* L.) (46,113,114,116,161,162, 177), Eggplant (*Solanum melongena* L.) (19,20,115,184,191), (*Asparagus officinalis* L.) (55,99,174,177), Watermelon (*Citrullus lanatus* Thunb. Matsum.) (54,163,194), Lettuce (*Lactuca sativa* L.) (5,6), Broad bean (*Vicia faba* L.) (4), Cowpea (*Vigna unguiculata* L. Walp) (66), Ginger (*Zingiber officinale* Roscoe) (53), Parsley (*Pastinaca sativa* L.) (48), Pea (*Pisum sativum* L.) (179), Pepper (*Capsicum annuum* L.) (91), Strawberry (*Fragaria ananassa* Duch.) (152), Taro (*Colocasia esculenta* L. Schott) (5,6), Tomato (*Lycopersicon esculentum* Mill.) (180) and have been reported to suffer from serious replanting problem, resulting in poor growth and declined yields in monoculture system.

(i) Cucurbit crops: they are very sensitive to changes in soil physico-chemical properties (176). Autotoxicity of root exudates or decaying residues has been reported in cucumber (*Cucumis sativus*), muskmelon (*Cucumis melon*) and water melon (*Cucumis lanatus*) (178). *In vitro* assays indicated that root exudates of cucumber affect uptake of nitrates, sulfates, potassium, calcium, magnesium and iron by cucumber plants. Phenolic compounds released by cucumber plants such as *p*-coumaric acid seem to influence soil microbial communities which in turn affect the growth of cucumber plants (190). They predisposed plant roots to the attack of *F. oxysporum* fsp *melonis* (171).

(ii) Eggplant (*Solanum melongena* L.): The organic substrates such as peat, bark and sawdust are repeatedly used in eggplant cultivation. Quick humification leads to deterioration of the physical condition of these substrates, with the release of phytotoxic compounds to the soil. The assay of several substrates indicated that a mixture of bark and peat increased water available for eggplant growth and had a low content of phenolic compounds (115). Eggplant roots exudate phenolic compounds such as cinnamic acid and vanillin which in concentrations of 1 and 4 mmol/L inhibit eggplant growth and promote the proliferation of verticillium wilt, a disease caused by *Verticillium dahliae* (184). Grafting decreased the cinnamic and vanillic acids contents in root exudates by 69% and 100%, respectively (20). Thus grafting changes the phytochemical pattern of root exudates than non-grafted plants and thus confers eggplant resistance to *V. dahliae* (191).

(iii) Asparagus: The decline in yield of asparagus (*Asparagus officinalis* L.) is attributed to autotoxicity of root tissue as well as its infestation with *Fusarium oxysporum* spp. *asparagi* causing root rot. Asparagus root exudates showed toxicity on asparagus cultivars (175). The addition of shoot and roots, or extracts prepared from them, to soil inhibits asparagus seedling emergence and growth. Phenolic autotoxins were identified as ferulic, iso-ferulic, malic, citric, fumaric, and caffeic acid (55). These autotoxins directly effect the physiological and biochemical processes of asparagus plant and showed synergism with *Fusarium oxysporum* spp. *asparagi* causing increasing the incidence of the root rot disease.

(iv) Tomato (*Lycopersicon esculentum* L.): Eight years of monocropping in greenhouse led to a significant reduction in root vitality and fruit quality of tomato plants (160). Leaf leachates of tomato plants are able to inhibit the root growth of other tomato plants (190). Root exudates in hydroponic culture inhibited the tomato shoot height and fresh weight by 17 and 37%, respectively. Root exudates of tomato plants in hydroponics under controlled climatic conditions were autotoxic and soil factors such as humic and fulvic acids intensified the autotoxicity (90).

(v). Potato: In continuous monoculture, commercial production of potato, numerous soil-borne diseases also persists (42). Current control methods are not always practical or effective for their control. Therefore integrated, sustainable disease- control options such as biological amendments with crop rotation in a suitable cropping sequence are needed (77).

(vi) Ginger (*Zingiber officinale*): It has been cultivated as a spice and herbal medicine since thousands of years. Consecutive cultivation on the same land retards the emergence and early growth of ginger (53). Its rhizomes are easily infected by soil-borne pathogens [bacterial wilt (*Pseudomonas solanacearum*), soft rot (*Pythium aphanidermatum*) and nematodes (*Meloidogyne* spp.)], which cause severe yield losses. Some allelochemicals such as phenolic acids (vanillic acid, syringic acid, *p*-hydrobenzoic acid, *p*-coumaric acid and ferulic acid) and coumarins (umbelliferone and herniarin) were found in stems, leaves and rhizomes of ginger. Aqueous extracts of these organs inhibited the major leaf antioxidant enzymes of ginger seedlings. The phytotoxicity of extract followed the decreasing order of inhibition: stem > leaf > rhizome (53). These results suggest that ginger has autotoxic potential and its residues (stems, leaves) should be removed from the fields to reduce the autotoxic effects on next ginger crop seedlings.

2.4 Hydroponics: Currently, more developed countries have adopted to the hydroponics and closed type hydroponic systems to grow vegetable and ornamental plants on a commercial scale (4). The allelochemicals accumulate in the re-used nutrient solution during hydroponic culture (4) and accumulations of these allelochemicals result in serious autotoxicity and reduction in yield of succeeding crops. Root exudation of some vegetables leads to autotoxicity in close hydroponic systems. Some examples are strawberry, tomato, taro and cucumber. Scavenging of autotoxins from the nutrient solution (i.e. with supplementation of activated charcoal, by electrodegradation, or with addition of microbial strains) increased the yields and sometimes the quality of the

harvestable organs (2). Asao *et al.* (7) investigated the autotoxicity of 37 ornamentals in hydroponics with or without the addition of activated charcoal (AC) to the nutrient solution. Of the 37 plants species, the growth of Lily, Prairie gentian, Corn, Poppy, Farewell-to-spring, Rocket larkspur, and Carnation was significantly inhibited in the absence of activated charcoal compared with those in its presence. By GC-MS, some allelochemicals were identified, which were adsorbed on activated charcoal from the root exudates of 10 ornamentals (7).

2.5 Medicinal Plants

The problem of soil sickness is most serious in the cultivation of medicinal herbs. About 70% of tuber root medicinal plant species (*Rehmannia glutinosa*, *Panax notoginseng*, *Angelica sinensis*, *Panax ginseng*) and other medicinal plants suffer from varying degrees of soil sickness in continuous monoculture (187). The high-quality herbal drugs are produced in ideal and authentic production areas. Under specific natural conditions and ecological environment, the same medicinal plants in different regions, synthesize different chemical ingredients, thus forming genuine and high quality medicine with obvious regional characteristics. Soil sickness has seriously affected the production and quality of Chinese herbal drugs (188). The underlying mechanisms of continuous monoculture problems of medicinal plants are not known and has become a focal point in China.

2.6 Fruits/Forest trees: In fruit orchards, the productivity decreased rapidly over time after the initial establishment of the fruit gardens (14,15,105,106). Regeneration of fruit trees is also difficult in old plantation, which makes the problem more serious. The replant problems and yield decline in orchards have been often associated to the release of autotoxins, and the proliferation of pests and phytopathogenic microbes. In several situations, other causes of replant problems are autotoxicity or adverse changes in soil microflora inhibiting the growth of young trees (64). In forest trees, short rotations have become a common practice. It consists in growing closely spaced forest trees for shorter times than in traditional forestry practice. In this way, more biomass can be harvested over the time, but replant problems occur due to nutrients depletion, specially the phosphorous availability (182).

(i). Apple: In apple replant problem, the initial growth of young plants is suppressed in all apple-growing areas of the world. Utkhede and Li (140,143) identified several pathogenic fungi and bacteria viz., [*Penicillium janthinellum*, *Costantinella terrestris*, *Trichoderma* sp., *Bacillus subtilis*], which were closely associated with replant problems in continuous monoculture of apple. It was also found that interactions between fungi, bacteria and nematodes contributed towards the occurrence of replant disease in apple soil in British Columbia, Canada. Pythiaceus fungi, parasitic nematodes and actinomycetes have been reported to be associated with apple replant problems in England, Europe and the United States (14,60,69,92,106,132,158,159). Toxicity was also associated to the presence of phenolic compounds like (Phlorizin, phloretin, p-hydroxy hydrocinnamic acid, p-hydroxy benzoic acid, and phloroglucinol) in root bark and released into the orchard soil after microbial decomposition of fallen root bark (12). In addition, abiotic factors including unbalanced nutrition, high or low soil pH, poor soil structure, poor drainage and excess or

lack of soil moisture in continuous monoculture systems, also contribute to replant problems of fruit trees (142).

(ii). Citrus: Citrus replanting soil sickness problem had been observed in the orchards of *C. aurantium*, *C. sinensis* and *C. jambhiri*. It is a syndrome mainly due to the phytotoxic allelochemicals, nematodes such as *Tylenchulus semipenetrans* and the rhizosphere pathogens including *Phytophthora citrophthora*, *P. nicotianae*, *Thielaviopsis basicola*, *Fusarium solani* (31,57). The release of autotoxins occurs from dead and decaying roots left in the soil. Ether extractable substances like homovanillic acid, seselin and xanthyletin, present in the *C. jambhiri* roots cause severe toxicity to the young plants (57). The inhibitors stopped the root cell elongation and caused root swelling.

(iv). Peach (*Prunus persica* L.): The bark of old peach roots contains cyanogenic glycoside amygdalin which was related to toxicity to young growing peach plants (98), Microbial degradation of amygdalin in the soil leads to the release of cyanide substances that injury young peach seedlings. The intensity of effect was directly correlated to the amount of roots present in soil. The presence of nematodes in the soil plays an important role in amygdalin release and hydrolyzation (98).

(v). Tea (*Camellia sinensis* L.): It is perennial, woody and evergreen plant and is major cash crop in the hilly and mountainous area of southern China, India, Srilanka, Pakistan. Due to soil sickness, premature aging and degradation of tea gardens have been critical issues limiting the development of tea industry. Studies have shown that autotoxicity may be the major cause of reduced yield and quality in the later growth stages of tea plants. Caffeine, theobromine, polyphenols, and catechins, which are abundant in tea plants, may be involved in soil acidulation and allelopathic autotoxicity (16,136). These allelochemicals significantly inhibits the seed germination and growth of tea plants (16). It is also reported that the catechins influence the growth of both inter- and intraspecific plants and may act as allelopathic autotoxins (112).

(vi) Coffee (*Coffea arabica* L.): Caffeine may cause autotoxicity in coffee plantations. Coffee seedlings are highly susceptible to caffeine exposure (44). However, coffee seeds developed a mechanism to avoid autotoxicity which allow them to germinate despite their high amount of endogenous caffeine (149).

(vii) Chinese fir (*Cunninghamia lanceolata*): It is a fast-growing conifer planted in China for timber production. Failure of Chinese fir seedlings to grow normally in replant woodlands is due to several factors including nutrient depletion, soil degradation and biotic factors. Extracts of Chinese fir stump roots showed toxicity on Chinese fir seed germination (64). Soil extracts obtained from newer replant rotations are more toxic to Chinese fir seedlings than older ones (182). Decomposing root residues together with pathogenic fungi caused drastic growth reduction of seedlings than the decomposing root residue alone. Further work showed that soil allelopathy is dominant factor regulating the productivity and nutrient cycling in Chinese fir short rotations (183).

(viii) Horsetail beefwood (*Casuarina equisetifolia* Forst & Forst): It is a fast growing,

evergreen, nitrogen fixing multipurpose tree, which is widely cultivated in India and China. It showed a strong allelopathic effect on its understorey vegetation (33) and the spraying of aqueous extracts from its leaf litter showed a high degree of effectiveness in the control of weeds in wheat fields (61). Its seedling roots are sensitive to branchlet leachates and root water extracts of *C. equisetifolia*. Autotoxins responsible for this effects were identified as kaempferol-3- α -rhamnoside, quercetin-3- α -arabinoside and luteolin-3',4'-dimethoxy-7- β -rhamnoside (33).

3. MECHANISM OF SOIL SICKNESS

Based on worldwide research, the main reasons for continuous monoculture problems or soil sickness are: (i) Abnormal expression of genes in continuously monocultured plants and their disorderly regulation, which result in an adverse physiological response (87,172); (ii) Deterioration of soil physico-chemical properties and nutrients imbalance (65); (iii) Allelopathic autotoxicity of root exudates (35) and (iv) Imbalance in soil micro-ecosystem (decreased microbial diversity, increased pathogens and pests, the fragile biological interaction), and disruption in rhizosphere soil homeostasis (118).

3.1 Gene expression disorder and soil sickness

In continuous monoculture regime, plants often show dysplasia (decrease in growth rate, shortening of growth period and decline in yield and quality), which is believed to be related to particular physiological responses, gene expression and their regulation (52). Soil sickness in continuous monocultured *R. glutinosa* is seen at the early stage of growth and persists throughout the growth period. Further, the accumulation of free radicals in plant cells, the increase in MDA content and the damage to membrane structure caused by the stressful conditions of continuous monocropping, resulted in the decreased chlorophyll content and stomatal closure (172), which reduces the photosynthetic activity (188). The decrease in root ATPase activity as well as the small capacity of sink, are major reasons for poor growth of continuously monocultured *R. glutinosa* (172,188).

The content of endogenous hormones, such as IAA (Indole acetic acid) and ABA in continuously monocultured *R. glutinosa* plants are also significantly altered (103). At the seedling stage, the content of ABA was significantly higher in the continuously monocultured *R. glutinosa* than in the newly-planted crop. This is not favorable for plant growth, since the high content of ABA in leaves at the early stage often results in closed stoma and decreased photosynthetic activity. However at the root elongation stage, the IAA content of continuously monocultured *R. glutinosa* was significantly lower than in newly-planted plants. Previous studies suggested that the lower level of IAA in leaves accelerated the leaf senescence of *R. glutinosa* at root elongation stage, consequently reducing the transport of photosynthates to the roots. Thus, continuous monoculture destroys the balance of endogenous hormones in *R. glutinosa*, leading to physiological metabolic disorders affecting the normal growth and development of plants.

The changes in specific physiological metabolism or/and endogenous hormones, are a response to environmental stress by regulating the expression of related genes. To

determine the autotoxicity mechanism of rice residues to rice seedlings in rice-rice cropping sequence, Chi *et al.* (21) used microarray assay to analyze the rice root response to ferulic acid (FA), an autotoxin in the rice straw. They found that FA modulates ethylene and jasmonic acid hormone homeostasis, inhibits rice root elongation and the expression of amino acid/auxin permease genes (AAP) induced by FA. This may play an important role in detoxification of autotoxin (21). Fang *et al.* (40) used the suppression subtractive hybridization (SSH) technique to construct the forward and reverse subtractive cDNA libraries of *R. glutinosa* and found that the key genes which regulate essential metabolic pathways were restrained or shut down, disrupting their normal expressions in continuously monocultured *R. glutinosa*. The calcium signaling system (such as calcium-dependent protein kinase, calcium channel protein and calmodulin) and ethylene biosynthesis-related genes (such as ACC oxidase and S-adenosylmethionine synthetase) have specific expression resulting in disturbed metabolic process. Li *et al.* (77) applied high throughput Solexa/Illumina sequencing to generate a transcript library of *R. glutinosa* transcriptome and degradome to identify the key miRNAs and their target genes implicated in replanting disease. Their results showed that these miRNAs involved in the regulation of signal transduction, ion transport and cell division (such as miR2931, miR1861, miR7811) were up-regulated in continuously monocultured *R. glutinosa*, which repressed the normal expressions of these target genes and their protein functions. These miRNAs associated with regulating the formation of fibrous roots and early flowering (such as miR165, miR408, miR156/157) were down-regulated leading to up-regulated target genes promoting the formation of fibrous roots, early flowering, shortening the growth period, resulting in typical symptoms of continuous monoculture problems. It is thus obvious that *R. glutinosa* possesses a unique set of perception, transduction and response systems against environmental stress, especially such as the calcium signaling system. A previous study (51) found that two calcium channels away from the cytoplasm [plasma membrane calcium-transporting ATPase 13 and sarcoplasmic reticulum calcium-transporting ATPase 3] were expressed in a down regulated manner in continuously monocultured *R. glutinosa*, while the calcium channels toward the cytoplasm (such as calcium-dependent protein kinase, calcium-binding protein, calcineurin B-Like, calcium ion binding protein, phospholipase C) were expressed in a up-regulated manner (46). Therefore, continuous monoculture of *R. glutinosa* leads to a great increase in cytoplasmic calcium concentration. It was confirmed that calcium signal blockers could inhibit the gene expression of calcium signaling pathway and thus relieve the continuous monoculture problems to some extent, when continuously monocultured *R. glutinosa* plants were treated with different levels of calcium signal blockers such as CBP (CaM-binding protein), CBL (calcineurin B-like protein), CIBP (Calcium- and integrin-binding protein) and PLC (phospholipase C). However, why continuous monoculture induces a disorder in gene expression in crop plants still remains unknown. This however encourages us to further investigate the underlying mechanism of soil sickness from the soil ecosystem point of view.

3.2 Soil physico-chemical properties and soil sickness

The soil physico-chemical properties [soil texture, structure, water content, air, temperature, pH, organic matter, inorganic elements, etc.] have close relationship with plant growth and development. The soil acidification caused by fertilizer application or

allelochemicals released from continuously monocultured crop plants, is also a result of deterioration in soil physico-chemical properties. This is a continuing process in many farming systems and is one of the reasons for soil sickness (109). Usually, plant roots absorb nutrients from soil solutions to satisfy their growth requirements. The uptake of cations and anions is associated with H^+ extrusion and OH^-/HCO_3^- release respectively. If plants absorb more cations than anions, then more H^+ are released around the roots. Inappropriate fertilizer application or accumulated phytotoxins in soil causes serious soil acidification. Excessive application of ammonium fertilizers or accumulated catechins, lead to Aluminum toxicity. Unfortunately, many acidified soils are uneconomic to be treated with lime (95). Integrated methods should be used to ameliorate soil acidification, such as application of ground limestone, gypsum, plant residues, animal manure and coal-derived organic materials, combined with biological amelioration through managing cation-anion uptake by crops (139). Continuous monoculture also changes the soil physicochemical properties. Wang *et al.* (153) found that continuous monoculture of cotton significantly affect the composition of soil aggregates and the distribution of organic carbon. Long-term continuous monoculture reduced the mechanical stability of soil aggregates. However reasonable rotation with soybean or corn, could effectively promote the formation of aggregates, improve soil texture, enhance soil fertility and thus promote better growth of cotton.

Plants have certain selectivity and preferences in absorbing soil nutrients and hence, differ in the quantity and type of nutrients taken up especially certain trace elements. In long-term monoculture, due to selective absorption of mineral elements by crops, improper fertilization, water management and other agronomic practices, depletes some nutrients and accumulation of other nutrients leading to occurrence of imbalance in soil nutrients, reducing the plant growth (91). The long-term monoculture of lily caused serious deficiency of soil available potassium, organic matter and soil acidification, which became the major limiting factors in high-yield (181). The decline in soil fertility due to continuous monoculture, cannot be alleviated by increasing fertilizer application. For example in continuously monocultured wheat, despite the adequate level of fertilizer, the yields continued to decrease (185). In capsicum, Zhao *et al.* (189) also found that adding potassium fertilizer did not solve the problem of continuous monoculture.

3.3 Allelopathic autotoxins and soil sickness

Schreiner and Reed proposed in 1907 that some crop secretions contained substances which inhibits the growth of their own seedlings (65). Later many studies have indicated that some metabolites (terpenoids, phenolics, steroids, alkaloids and cyanogenic glycosides) secreted by plant roots cause the crop autotoxicity. This has been now reported in many crops [*Oryza sativa* L., *Triticum aestivum* L., *Fragaria ananassa* Duch., *Solanum tuberosum* L., *Arachis hypogaea* L., *Glycine max* L.Merr., *Medicago sativa* L., *Lolium rigidum* Gaud., *Pyrus malus* Mill., *Rehmanniae* Libosch., *Salvia miltiorrhiza* Bge., *Radix Notoginseng* Burk. and *Angelica sinensis* Oliv (65).

To understand the autotoxicity mechanism in tobacco, Jia *et al.* (71) analysed the allelochemicals in the root exudates of tobacco seedlings using gas chromatography and mass spectrometry (GC/MS). Eighteen compounds were identified in the root exudates of tobacco in continuous monocropping and 20 compounds in rotation cropping systems. Of which 14 compounds were in higher amounts in root exudates of tobacco in continuous

monocropping than in rotation cropping. Among the 14-compounds, phytotoxic effects of phthalate esters (dibutyl phthalate, diisooctyl phthalate and diisobutyl phthalate) were evaluated using tobacco seeds as targets. The inhibitory effect of diisobutyl phthalate was much higher than dibutyl phthalate and diisooctyl phthalate at low concentrations, but there were no differences between them at higher concentrations. These results indicated that the phthalate esters from tobacco root exudates may be the major factor in tobacco autotoxicity in tobacco continuous monocropping.

Recent research on continuous monoculture problems have focussed on isolation, identification, quantification of phytotoxic substances and evaluation of their biological activity on many crops under continuous monoculture regimes. Researchers have isolated and identified several autotoxic allelochemicals [*o*-hydroxyphenylacetic, *p*-hydroxybenzoic acid, coumaric acid, benzoic acid, vanillic acid, vanillin, ferulic acid, cinnamic acid, *p*-hydroxybenzoic acid, benzoic acid, homovanillic acid, seselin, xanthyletin, terpenes, abscisic acid-beta-D-glucopyranosyl ester (ABA-GE), 2,4-dihydroxy-1, 4-benzoxazin-3-one, caffeine, polyphenols and catechins etc], from the tissues, organs and root exudates of rice, *R. glutinosa*, cucumber, watermelon, peanut, tomato, ratoon sugarcane, citrus, tea plants etc. (13,16,21,23,28,31,43,56,125,126,135,147,177,179,187). These allelochemicals may affect water use, nutrients uptake, photosynthesis, gene expressions etc and inhibits the normal plant growth and development.

The root exudates of cucumber contain 11- phenolic acids [2,5-dihydroxy benzoic acid, *p*-hydroxybenzoic acid, benzoic acid, cinnamic acid, etc.(177)]. Of these, all except 2-hydroxybenzothiazole were toxic to the growth of receiver plants (177). Liu *et al.* (88) found that the root exudates and the extracts of leaves and tuberous roots of *R. glutinosa* could inhibit the tuberous root growth of the same plant in continuous monoculture system. The most significant inhibitory effect on the tuberous root expansion was by the root exudates. The phytotoxic substances have been separated from *R. glutinosa* fibrous roots using different polar organic solvents. The ethyl acetate extracts, which had the highest inhibition effect on the receiver plant, were subjected to GC/MS analysis and several phenolic compounds [ferulic acid, vanillin, *p*-hydroxybenzoic acid, benzoic acid, protocatechuic acid and gallic acid] were identified (79). The content of coumaric acid, *p*-hydroxybenzoic acid, syringic acid and ferulic acid in the soil was negatively correlated with tuberous root growth of *R. glutinosa* under continuous monoculture conditions (35).

However some believe, that when toxic substances were secreted by plant roots into the soil, they undergo a series of physical, chemical and biological changes [soil adsorption, microbial decomposition, transformation, etc. (67)]. In other words, the direct phytotoxic effects of root exudates on plants might not happen in continuous monoculture regime but the root exudates might be just the inducing factors to indirectly influence the plant performance by changing soil microbial communities. Many believe that the indirect ecological effects of root exudates and soil micro-ecological imbalance are major factors in continuous monoculture problems (86,166).

3.4 Rhizosphere Microflora and Soil Sickness

Yang *et al.* (169) applied the Biolog and T-RFLP methods to analyze the changes in rhizosphere microbial community in the rhizosphere soil of continuously cropped Tobacco. The analysis showed that whether the soil was sterilized or not, the diversity

level of bacterial community in the rhizosphere soil of tobacco decreased as the continuous monocropping years increased and the bacterial community in sterilized soil was highly similar to non-sterilized soil in the same period. These results suggested that the enrichment of exudates and residues from the tobacco had a negative impact on soil bacterial community in continuous monocropping. In addition, it was also found that the monoculture imposed a strong selective pressure on soil microbial flora as the years of continuously monocropped tobacco increased. The pathogens also gradually became a dominant population suggesting that the original balance of soil microbial communities was disrupted and the soil environment was prone to deterioration in continuous monoculture system.

(i). **PLFA:** Lin *et al.* (84,85) used the methods of soil enzyme, Biolog and phospholipid fatty acid biomarkers (PLFAs) to study the microbial diversity in the rhizosphere soils of 1-, 6- and 20-year-old tea plants. Biolog analysis showed that the ability of microbial flora to use six kinds of carbon sources was highest in 6-year-old tea soil and lowest in the 20-year-old tea soil. Microbial utilization of six kinds of carbon sources was moderate in 1-year-old tea soil. Community diversity analysis showed that the Shannon index, Brillouin index, homogeneity index and richness index of the 6-year-old tea soil were the highest and lowest in the 20-year-old tea soil. In the rhizosphere soil of 6-year-old tea plants, the total amount of PLFAs was the highest and the PLFAs contents of bacteria, actinomycetes, and protozoa were higher than in other rhizosphere soils. The rhizosphere soil of 20-year-old tea plants had a higher content of fungi PLFAs, but lower contents of actinomycetes and protozoa PLFAs than the other rhizosphere soils, whereas the content of bacterial PLFAs was close to rhizosphere soil of 1-year-old tea plants. In the rhizosphere soil of 20-year-old tea plants, the abundance of several microbial groups participating in soil nutrients cycling declined, while the abundance of several microbial groups with low metabolic capacity increased. As compared with those in the rhizosphere soil of 6-year-old tea plants, the activities of urease, phosphomonoesterase and peroxidase in the rhizosphere soil of 20-year-old tea plants were lower, while the activities of invertase and polyphenol oxidase were higher. In the rhizosphere soils of different tea plants of different ages, the PLFAs of different microbial groups were closely correlated with the soil enzyme activities and fertility factors. With increasing years of tea monocropping, the microbial community structure in rhizosphere soils changed greatly, reflecting the decline in microbial diversity and an increase in microbial groups with low metabolic capacity, adapting to poor soil conditions. The activities of some key enzymes had also largely decreased.

Qu *et al.* (119) used the approach of using denaturing gradient gel electrophoresis (DGGE) to detect the effects of different phenolic acids of soybean root exudates on soil microbial populations. The results revealed that two phenolic acids (vanillic acid and 2,4-di-tert-butyl phenol) had great effect on specific microbial communities, particularly vanillic acid (i.e., *Hymenagaricus* sp., *Cyathus striatus*, etc.), making them dominant population. Similarly, Zhou *et al.* (192) reported that *p*-coumaric acid, an autotoxin in the root exudates of cucumber, played a role in the allelopathic autotoxicity of cucumber by influencing the soil microbial communities. *p*-Coumaric acid could change the structure and composition of bacterial and fungal communities in the rhizosphere, with increases in the relative abundances of Beta proteobacteria, Firmicutes and a decrease in relative

abundances of Deltaproteobacteria, Bacteroidetes and Planctomycetes. In addition, *p*-coumaric acid increased the *Fusarium oxysporum* population densities in the soil.

Increasing number of studies have found various positive and negative plant-plant interactions within or among plant populations, such as amensalism, autotoxicity, stimulation and interspecific facilitation, all being the results of the integrative effect of plant-microbe interactions mediated by root exudates (152) It is therefore felt that root exudates can significantly influence the components and the structure of microbial flora in rhizosphere soil, especially in different cropping sequences.

(ii). Root Exudates: The root exudates have specialized roles in nutrients cycling and signal transduction between a root system and soil, as well as in plant response to environmental stresses (152). They are the key regulators in rhizosphere communication and can modify the biological and physical interactions between the roots and soil organisms. Organic carbon fixed by plants through photosynthesis can be released into the soil by root secretion, which provides the material and energy for the surrounding microorganisms. Soil microorganisms accumulate in the rhizosphere and rhizoplane with abundant rhizodeposition by chemotaxis or quorum sensing (152). Recently, group specificity in microbial use of root-exudate compounds and rhizodeposition has been reported and found that the different components and proportions of root exudates of different plants make the soil microbial community structure to become specific and representative (104). Gschwendtner *et al.* (50) reported that the quality and quantity of root exudates were dependent on the plant genotype and thus influenced the microbial community structure in rhizosphere. Chaparro *et al.* (17) also found that there was significant change in the components and content of root exudates of *Arabidopsis* at different stages of development. Further, meta transcriptome analysis revealed significant correlations between the microbial functional genes involved in the metabolism of root exudates and the corresponding compounds released by the roots at particular stages of plant development (17)

(iii). Soil Microbial Community: Conversely, the structure and functional diversity of soil microbial community also affects the plant growth and development [root secretion, nutrients absorption, utilization, stress /defense response, etc (39)]. As assessed by GC-MS analysis, soil microbial communities affect the biosynthesis of leaf metabolites of host plant, which impacts the feeding behavior of insects (8). Lakshmanan *et al.* (74) demonstrated that foliar infection by pathogens induced malic acid transporter expression, leading to increased malic acid titers in the rhizosphere of *Arabidopsis*. Malic acid secretion in the rhizosphere increased the beneficial rhizobacteria titers causing an induced systemic resistance response in plants against pathogens. Zolla *et al.* (193) found that under drought conditions, a sympatric microbiome (i.e., having a history of exposure to *Arabidopsis* at a natural site) significantly increased the *Arabidopsis* biomass, while the non-sympatric soils did not affected the plant biomass. This was related to the plant growth promoting rhizobacteria (PGPR) in the soil (such as *Bacillus*, *Burkholderia*, *Acinetobacter*, etc.), which could modify the plant's ability to sense abiotic stress and increase plant biomass.

(iv). Rhizosphere: It is the most active region of microbial activity, is a platform for the

frequent material exchanges and signal transmissions between plants and soil microcosms, which are closely related to underground and aboveground plant growth. The collective genomes of rhizosphere microbial communities can be seen as a second genome of the plant (13). Marasco *et al.* (93) suggest that the plant should not just be seen as single organism, but as a meta-organism, referring to the plant and the surrounding soil microbiome as a whole. Mendes *et al.* (96) used the PhyloChip-based metagenomics to analyze the microbial community structure in disease-conducive soil and disease-suppressive soil. β -Proteobacteria γ -Proteobacteria and Actinobacteria were consistently associated with disease suppression. In particular, the number of *Pseudomonas* sp. was significantly higher in disease-suppressive soil than in disease-conducive soil.

In-depth rhizosphere ecology research in continuous monoculture problem has focussed on rhizospheric biological processes. The cross-talk between plants and microbes is the key factor for allelopathic autotoxicity or soil sickness. Wu *et al.* (165) found that *R. glutinosa* continuous monoculture changed the rhizospheric microbial community composition and activity, with distinct separation between the control, newly planted plots and the second, third year continuously monocultured plot soils. Under continuous monoculture, the number of bacteria in the rhizosphere of *R. glutinosa* were reduced but the fungal and actinomycetes populations increased (80). Further, the genetic diversity analysis of soil microbial populations showed that *R. glutinosa* continuous monoculture decreased the Shannon diversity index and Margalef index and simplified the bacterial community structure. The dominant group in the newly-planted soil were Bacilli, while the dominant group in the 2-years monocultured soil were class ϵ -proteobacteria (186). Lin *et al.* (82,83) found that *Pseudostellaria heterophylla* continuous monoculture significantly decreased the number of bacteria and aerobic nitrogen-fixing bacteria in rhizosphere but significantly increased the amounts of anaerobic cellulose-decomposing bacteria, actinomycetes and fungi. Other research on medicinal plants has also shown that continuous monoculture increase the soil-borne pathogens [*F. solani*, *F. tricinctum*, *Aspergillus calidoustus*, *Phytophthora cactorum*, *Pythium irregulare*, etc. (36,100)]. These findings encourage us to develop Technology to effectively solve the problem of soil sickness in continuous monoculture.

4. CHALLENGES AND PERSPECTIVES IN SOIL SICKNESS RESEARCH

The causes of soil sickness vary among plant species. Within the same plant species, the reasons of soil sickness expression can also vary from one geographical area to another one. This situation is expected due to the diversity of cultural practices, climatic conditions, crop cultivars, soil conditions and microbial populations faced by a crop plant. Several methods have been proposed or are currently used to minimize or partially overcome the soil sickness problem. They are breeding for resistant cultivars, crop rotations and intercropping, soil admendments, appropriate management of crop residues, chemical control, microbial biocontrol and phytotoxin removal.

4.1. Breeding for resistant cultivars: Decades of research showed that many crops have

intraspecific variations in autotoxic potential and in the resistance to pests and diseases. For example, autotoxic potential seems to be a genetic character that vary among the alfalfa and rice cultivars (48,125). High accumulation of phenylpropanoids in the outer layers of the grains and in the stem piths is a genetic character that can be used to improve the resistance of maize inbreds to *Fusarium* spp. and borer pests (129). Hence, crop breeding based on this genetic variability is an attractive strategy to overcome soil sickness. Crop genotypes resistant to pathogens and autotoxins also can be developed as rootstocks for many horticultural crops. This is the case of lemon resistance to *Phytophthora* and the citrus nematode (*Tylenchulus semipenetrans*), due to use of rootstocks of some *Citrus* species or its relatives (i.e. *Poncirus trifoliata*) (135). Nevertheless, crop improvement for resistance to insects and diseases has received more attention than for alleviation of autotoxic feature, probably due to the polygenic nature of autotoxic trait and problems to follow it in laboratory, greenhouse or field experiments (12). Besides the autotoxins are multipurpose compounds that protect the producer plants against many natural enemies. For example, hydroxamic acids in the residues and root exudates of wheat are known allelopathic and autotoxic compounds, but, they are antimicrobials to wheat pathogens and antifeedants to aphids (130). Hence, breeding to decrease the autotoxin production, requires good knowledge of biologically active forms, breakdown products of such compounds and their actual impact at several trophic levels in the agroecosystems.

4.2. Crop rotations and intercropping: They are the oldest and most important methods used to avoid soil sickness. Crop rotations are often restricted by equipment requirements, climatic conditions and the market price of crops (102). They change the contribution of allelochemicals to the soil, avoiding autotoxicity and increase the population of microbial antagonists towards noxious soil borne pathogens and pests. In sugarcane cropping cycle with crops such as soybean or pastures improves the soil fertility and reduces the population of harmful soil microbiota (124). The intercropping increases the soil organic matter and mineral nutrients available for crop growth. For example, green garlic-cucumber intercropping increases the biomass production and improves the mineral nutritional status of the cucumber plants (168). It also can activate microbial disease-suppressive mechanisms such as host dilution and enhanced populations of antagonistic microorganisms. For example, spread of *Rhizoctonia* damping-off in radish-mustard mixture decreases with increasing densities of non-host mustard plants (103). Wheat root infection by *Gaeummanomyces graminis* var. *tritici* was reduced by 25% in wheat-trefoil (*Medicago lupulina*) mixture (33). Many crops exude nematicidal and antimicrobial substances e.g. intercropping of garlic with cowpea or tomato, reduces the occurrence of nematode *Rotylenchulus reniformis* and *Meloidogyne incognita* (39).

4.3. Soil amendments: Continuous monocropping depletes the mineral nutrients in soil and lead to proliferation of noxious microorganisms. In this context, soil amendments with inorganic matter, organic matter or formulated compounds can be used both to control soil born plant pathogens (63). Sometimes biofertilization is better than addition of synthetic fertilizers. An appropriate soil amendment should inhibit the soil borne-pathogens, maintains soil fertility and avoid the detrimental effects in agroecosystems, e.g. the growing and incorporating the *Brassica* green manures to the soil in short breaks between vegetable crops viz., potato and carrot (130). This practice suppress the soil borne pathogens

due to the release of biocidal thiocyanates, nitriles and thiocyanates after hydrolysis of glucosinolates contained in the tissues of the *Brassica* species. Some organic materials carry microbial antibiotic-producing antagonists able to suppress the growth of phytopathogenic fungi, e.g. Finnish peat is made of *Sphagnum* mosses, which suppresses the *Fusarium* spp., *Rhizoctonia solani* and *Alternaria brassicola* in horticultural crops (145). It also contains several species of *Streptomyces* (i. e. *Streptomyces griseoviridis*) which produce complex heptaene antibiotics.

4.4. Chemical control: Synthetic pesticides are often used to deal with soil sickness (63). Some examples are the soil treatments with the nematocide nemacur, and the fungicides benomyl or thiram for control of mungbean soil sickness, the fumigation of soil apple orchards with Basamid (dazomet), the seed treatments with metalaxyl that protects germinating pearl millet seedlings from downy mildew infection or the use of methyl bromide as a preplant soil fumigant to control soil born pests and diseases in horticultural crops (102). Nevertheless, the agricultural use of several of these products is currently forbidden due to the increasing public concerns from their harmful effects on the environment and human health.

4.5. Plant Residues Management: Crop residues often release autotoxins and provide appropriate conditions for proliferation of soil borne pathogens, hence, these residues sometimes are partially or totally removed from soil. Methods of removal vary, burning or use of microbes to hasten the degradation of crop residues (9). Solar sterilization is increasingly used to control many soilborne diseases, however, it also kills all soil microflora. Deep ploughing to turn over the soil, summer ploughing and flooding are used to eliminate noxious microorganisms or autotoxins from the soil profile (124).

4.6. Microbial biocontrol: The use of disease-suppressive microorganisms to improve plant health is an efficient way to improve the soil microenvironment and control the soil-borne pathogens. Many types of antagonistic bacteria (*Pseudomonas* sp., *Burkholderia* sp., *Bacillus subtilis*, etc) and fungi (*Trichoderma*, *Gliocladium*, etc) have been isolated from soil and used to control phytopathogens (58). The antagonistic effects of beneficial microbes on pathogens is significant in the laboratory but many of them can not successfully colonize the rhizosphere soil, suppress soil-borne diseases and improve plant growth.

4.7. Removal of Phytotoxins: Adsorption by activated charcoal (6), degradation by microbial strains (7), electrodegradation and TiO₂ photocatalysis can be used to eliminate the autotoxins from root exudates and other plant sources in horticultural crops (6).

Future Areas of Research

Further research on soil sickness is needed on the following Aspects:

- (i). To better understand the dynamics of microbial populations in the rhizosphere of crop plants.
- (ii). Collective chemical communication between the soil microbial community and the crop plants.
- (iii). Real impact of autotoxins on crop plants and microbial communities on whole

- cocktail of plant and microbial metabolites exuded into the soil.
- (iv). Characterization of new biological agents and organic disease or pest suppressive materials useful for soil sickness control.

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5. REFERENCES

1. Abbas, T., Tanveer, A., Khaliq, A., Sfdahlur, M.E. and Nadeem, M.A. (2014). Allelopathic effects of aquatic weeds on germination and seedling growth of wheat. *Herbologia* **14**: 11-25.
2. Asaduzzaman, M., Kobayashi, Y., Isogami, K., Tokura, M., Tokumasa, K. and Asao, T. (2012). Growth and yield recovery in strawberry plants under autotoxicity through electrodegradation. *European Journal of Horticultural Science* **6**: 58-67.
3. Asaduzzaman, M. and Asao, T. (2012). Autotoxicity in beans and their allelochemicals. *Scientia horticulturae* **134**: 26-31.
4. Asao, T. and Asaduzzaman, M. (2012). *Autotoxicity in Vegetables and Ornamentals and Its Control, Hydroponics - A Standard Methodology for Plant Biological Researches* (Ed., Toshiki Asao). ISBN: 978-953-51-0386-8. In Tech, <http://www.intechopen.com/books/hydroponics-a-standard-methodology-for-plant-biological-researches/autotoxicity-in-vegetables-and-ornamentals-and-its-control>.
5. Asao, T., Kitazawa, H., Ban, T., Pramanik, M.H.R., Matsui, Y. and Hosoki, T. (2004). Search of autotoxic substances in some leaf vegetables. *Journal of the Japanese Society for Horticultural Science* **73**: 247-249.
6. Asao, T., Kitazawa, H., Tomita, K., Suyama, K., Yamamoto, H., Hosoki, T. and Pramanik, M.H.R. (2004). Mitigation of cucumber autotoxicity in hydroponic culture using microbial strain. *Scientia Horticulturae* **99**: 207-214.
7. Asao, T., Kitazawa, H., Ushio, K., Sueda, Y. and Pramanik, M.H.R. (2007). Autotoxicity in some ornamentals with the means to overcome it. *Hortscience* **42**: 1346-1350.
8. Badri, D.V., Zolla, G., Bakker, M.G., Manter, D.K. and Vivanco, J.M. (2013). Potential impact of soil microbiomes on the leaf metabolome and on herbivore feeding behavior. *New Phytologist* **198**: 264-273.
9. Beary, T.P., Boopathy, R. and Templet, P. (2002). Accelerated decomposition of sugarcane crop residue using a fungal-bacterial consortium. *International Biodeterioration and Biodegradation* **50**: 41-46.
10. Berendsen, R.L., Pieterse, C.M. and Bakker, P.A. (2012). The rhizosphere microbiome and plant health. *Trends in Plant Science* **17**: 478-486.
11. Berestetsky, O. A. (1972). Formation of phytotoxic substances by soil microorganisms on root residues of fruit trees. In: *Physiological-Biochemical Basis of Plant Interactions in Phytocenoses*. Vol. **3**: 121-124. (Ed., A.M. Grodzinsky). Naukova Dumka, Kiev. (Russian with English summary).
12. Bertin, C., Yang, X. and Weston, L.A. (2003). The role of root exudates and allelochemicals in the rhizosphere. *Plant and Soil* **256**: 67-83.
13. Blum, U., Shafer, R. and Lehmen, M.E. (1999). Evidence for inhibitory allelopathic interactions involving phenolic acids in field soils: Concepts vs. An experimental model. *Critical Reviews in Plant Sciences* **18**: 673-693.
14. Boener, H. (1959). The apple replant problem. I. The excretion of phlorizin from apple root residues. *Contributions of the Boyce Thompson Institute* **20**: 39-56.
15. Burger, W.P. and Small, J.G.C. (1983). Allelopathy in citrus orchards. *Scientia Horticulturae* **20**: 361-375.
16. Cao, P.R., Liu, C.Y. and Li, D. (2011). Autointoxication of tea (*Camellia sinensis*) and identification of its autotoxins. *Allelopathy Journal* **28**: 155-165.

17. Chaparro, J.M., Badri, D.V., Bakker, M.G., Sugiyama, A., Manter, D.K. and Vivanco, J.M. (2013). Root exudation of phytochemicals in *Arabidopsis* follows specific patterns that are developmentally programmed and correlate with soil microbial functions. *PLoS ONE* **8**: e55731.
18. Chen, D.M., Yang, Y.H., Jing, Y., Wang, H.B., Duan, Y.Q., You, C.H., Tian, W.X. and Lin, W.X. (2011). Constituents of autotoxic chemical from rhizosphere soil under flue-cured tobacco continuous cropping. *Pratacultural Science* **28**: 1766-1769.
19. Chen, S.L., Zhou, B.L., Lin, S.S., Li, X. and Ye, X.L. (2011). Accumulation of cinnamic acid and vanillin in eggplant root exudates and relationship with continuous cropping obstacle. *African Journal of Biotechnology* **10**: 2659-2665.
20. Chen, S.L., Zhou, B.L., Wang, R.H. and Fu, Y.W. (2008). Regulation effects of grafting on cinnamic acid and vanillin in eggplant root exudates. *Chinese Journal of Applied Ecology* **19**: 2394-2399.
21. Chi, W.C., Chen, Y.A., Hsiung, Y.C., Fu, S.F., Chou, C.H., Trinh, N.N., Chen, Y.C. and Huang, H.J. (2013). Autotoxicity mechanism of *Oryza sativa*: Transcriptome response in rice roots exposed to ferulic acid. *BMC Genomics*, **14**: doi 10.1186/1471-2164-14-351.
22. Chou, C.H. (1983). Allelopathy in agroecosystems in Taiwan. In: *Allelochemicals and pheromones*. (Eds., C.H. Chou and G.R. Waller). Institute of Botany, Academia Sinica. *Monograph Series No. 5*: 27-64. Taipei, Taiwan.
23. Chou, C.H. (1986). The role of allelopathy in subtropical agroecosystems in Taiwan. In: *The Science of Allelopathy*. (Eds., A.R. Putnam and C.S. Tang). John Wiley and Sons Inc., New York, pp. 57-73.
24. Chou, C.H. (1989). The role of allelopathy in phytochemical ecology. In: *Phytochemical Ecology: Allelochemicals, Mycotoxins and Insect Pheromones and Allomones*, (Eds., C.H. Chou and G.R. Waller). Institute of Botany, Academia Sinica. *Monograph Series No. 9*: 19-38. Taipei, Taiwan.
25. Chou, C.H. (1990). The role of allelopathy in agroecosystems: studies from tropical Taiwan. In: *Agroecology: Researching the Ecological Basis for Sustainable Agriculture. Ecological Studies*, (Ed., S.R. Gliessman), Vol. **78**: 105-121. Springer-Verlag, Berlin.
26. Chou, C.H. (1995). Allelopathy and sustainable agriculture. In: *Allelopathy, Organisms, Processes and Applications*. (Eds., Inderjit, K.M.M. Dakshini and F.A. Einhellig). *ACS Symposium Series No. 582*: 211-223. American Chemical Society, Washington, DC.
27. Chou, C.H. (1999). Roles of allelopathy in plant biodiversity and sustainable agriculture. *Critical Reviews in Plant Sciences* **18**: 609-636.
28. Chou, C.H. and Lin, H.J. (1976). Autointoxication mechanisms of *Oryza sativa*. I. Phytotoxic effects of decomposing rice residues in soil. *Journal of Chemical Ecology* **2**: 353-367.
29. Chou, C.H. and Patrick, Z.A. (1976). Identification and phytotoxic activity of compounds produced during decomposition of corn and rye residues in soil. *Journal of Chemical Ecology* **2**: 369-387.
30. Chou, C.H., Chiang, Y.C. and Chang, H.H. (1981). Autointoxication mechanism of *Oryza sativa* III. Effects of temperature on phytotoxin production during rice straw decomposition in soil. *Journal of Chemical Ecology* **7**: 741-752.
31. Dalal, R.P., Anirudh, T., Sidhu, A.S., Sangwan, A.K. and Rattanpal, H.S. (2008). Replanting problem in citrus - a review. *Environment and Ecology* **26**: 1279-1283.
32. Deng, L., Kong, C. and Luo, S. (1996). Isolation and identification of extract from *Casuarina equisetifolia* branchlet and its allelopathy on seedling growth. *Chinese Journal of Applied Ecology* **7**: 145-149.
33. Devasahayam H.L. and Henry, L. (2009). *Illustrated Plant Pathology: Basic Concepts*. New India Publishing Agency 433 p., New Delhi, India.
34. Dilday, R.H., Yan, W.G., Moldenhauer, K.A.K. and Gravois, K.A. (1998). Allelopathic activity in rice for controlling major aquatic weeds. In: *Allelopathy in Rice* (Ed., M. Olofsdotter), pp. 7-26. Los Banos, IRRI, Philippines.
35. Du, J.F., Yin, W.J., Li, J. and Zhang, Z.Y. (2009). Dynamic change of phenolic acids in soils around rhizosphere of replanted *Rehmannia glutinosa*. *China Journal of Chinese Material Medica* **34**: 948-952.
36. Dr. Duan, J.L. (2013). *Studies on Microecological Mechanism of Salvia miltiorrhiza Bge. Root Diseases and Growth-Promoting Effects of Antimicrobial Actinomycetes*. Northwest Agriculture and Forestry University, Yangling.
37. East, R. (2013). Microbiome: soil science comes to life. *Nature* **501**: S18-S19.
38. Eisenhauer, N., Scheu, S. and Jousset, A. (2012). A bacterial diversity stabilizes community productivity. *PLoS ONE* **7**: e34517.

39. El Nagdi, W. M., Youssef, M. (2013). Comparative efficacy of garlic clove and castor seed aqueous extracts against the root-knot nematode *Meloidogyne incognita* infecting tomato plants. *Journal of Plant Protection Research* **53**: 285-288.
40. Fang, H.M., Li, M.J., Zheng, H.Y., Yang, Y.H. and Gu, L. (2012). Spatiotemporal expression and analysis of responding consecutive monoculture genes in *Rehmannia glutinosa*. *China Journal of Chinese Materia Medica* **37**: 3029-3035.
41. Farooq, M., Jabran, K., Rehm, H., and Hussain, M. (2008). Allelopathic effects of rice on seedling development in wheat, oat, barley and berseem. *Allelopathy Journal* **22**: 385-390.
42. Fiers, M., Edel-Hermann, V., Chatot, C., Hingrat, L.Y., Alabouvette, C. and Steinberg C. (2012). Potato soil-borne diseases, A review. *Agronomy for Sustainable Development* **32**: 93-132.
43. Friebe, A., Roth, U., Kuek, P., Schnabl, H. and Schulz M. (1997). Effects of 2,4-dihydroxy- 1,4-benzoxazin-3-ones on the activity of plasma memberane H⁺-ATPase. *Phytochemistry* **44**: 979-983.
44. Friedman, J. and Waller, G.R. (1983). Caffeine hazards and their prevention in germinating seeds of coffee (*Coffea arabica* L.). *Journal of Chemical Ecology* **9**: 1099-1106.
45. Friedman, J. and Waller, G.R. (1985). Allelopathy and autotoxicity. *Trends in Biochemical Sciences* **10**: 47-50.
46. Fujiyoshi, P.T., Gliessman, S.R. and Langenheim, J.H. (2002). Inhibitory potential of compounds released from squash (*Cucurbita* spp.) under natural conditions. *Allelopathy Journal* **9**: 1-8.
47. Gog, L., Berenbaum, M.R., Delucia, E.H. and Zangerl, A.R. (2005). Autotoxic effects of essential oils on photosynthesis in parsley, parsnip, and rough lemon. *Chemoecology* **15**: 115-119.
48. Grahari, S. and Miransari, M. (2009). Allelopathic Effects of Rice Cultivars on the Growth Parameters of Different Rice Cultivars. *International Journal of Biological Chemistry* **3**: 56-70.
49. Grodzinsky, A.M., Narwal, S.S. and Polyticka, B. (2006). Allelopathy in soil sickness. Scientific Publishers (India), Jodhpur, India.
50. Gschwendtner, S., Esperschütz, J., Buegger, F., Reichmann, M., Müller, M., Munch, J.C. and Schloter, M. (2011). Effects of genetically modified starch metabolism in potato plants on photosynthate fluxes into the rhizosphere and on microbial degraders of root exudates. *FEMS Microbiology Ecology* **76**: 564-575.
51. Guo, G.Y., Li, M.J., Wang, P.F., Wang, F.Q. He, H.Q., Li, J., Zheng, H.Y., Chen, X.J. and Zhang, Z.Y. (2013). Abnormal change of calcium signal system on consecutive monoculture problem of *Rehmannia glutinosa*. *China Journal of Chinese Materia Medica* **38**: 1471-1478.
52. Guo, G.Y., Wang, F.Q., Fan, H.M., Li, M.J., Zheng, H.Y., Li, J., Chen, X.J. and Zhang, Z.Y. (2012). Advances in allelopathic autotoxicity and monoculture cropping problem of *Rehmannia glutinosa* Libosch. *Modern Chinese Medicine* **14**: 35-39.
53. Han, C.M., Li, C.L. and Zhang, S.L. (2012). Aqueous extracts of ginger decreased levels of antioxidant enzymes, increased levels of membrane and lipid peroxidation in leaves, and inhibited growth of ginger seedling. *Allelopathy Journal* **30**: 259-270.
54. Hao, Z.P., Wang, Q., Christie, P. and Li, X.L. (2006). Autotoxicity potential of soils cropped continuously with watermelon. *Allelopathy Journal* **18**: 111-120.
55. Hartung, A.C., Nair, M.G. and Putnam, A.R. (1990). Isolation and characterization of phytotoxic compounds from asparagus (*Asparagus officinalis* L) roots. *Journal of Chemical Ecology* **16**: 1707-1718.
56. Hase, C.P. and Dhupal, K.N. (2009). Impact of soil sickness and sugarcane trash allelopathy on cane metabolism and yield during monoculturing. *Allelopathy Journal* **23**: 255-268
57. Hassan, M.S., AlSaadawi, I.S. and El-Behadli, A. (1989). Citrus replant problem in Iraq. II. Possible role of allelopathy. *Plant and Soil* **116**: 157-160.
58. Hayat, R., Safdar, A.S., Amara, U., Khalid, R. and Ahmed, I. (2010). Soil beneficial bacteria and their role in plant growth promotion: a review. *Annual Microbiology* **60**: 579-598.
59. Hegab, M.M., Khodary, S.E.A., Hammouda, O. and Ghareib, H.R. (2008). Autotoxicity of chard and its allelopathic potentiality on germination and some metabolic activities associated with growth of wheat seedlings. *African Journal of Biotechnology* **7**: 884-892.
60. Hoestra, H. (1968). Replant disease of apple in the Netherlands. *Meded. Landbouwhoges. Wageningen* **68**: 1-105.
61. Hozayn, M., El-Shahawy, T., Abd El-Monen, A., El-Saady, A. and Darwish, A. (2015). Allelopathic effects of *Casuarina equisetifolia* L. on wheat, associated weeds and nutrient content in the soil. *African Journal of Agricultural Research* **10**: 1675-1683.

62. Hu, J.C. and Wang, S.J. (1996). Study on soil sickness by soybean continuous monocropping: I. Effect of mycotoxin produced by *Penicillium purpurogenum*. *Chinese Journal of Applied Ecology* (China) **7**: 396-400. (Chinese).
63. Huang, H.C., Chou, C.H. and Erickson, R.S. (2006). Soil sickness and its control. *Allelopathy Journal* **18**: 1-22.
64. Huang, Z., Liao, L., Wang, S., and Cao, G. (2000). Allelopathy of phenolics from decomposing stump-roots in replant Chinese fir Woodland. *Journal of Chemical Ecology* **26**: 2211-2219.
65. Huang, L.F., Song, L.X., Xia, X.J., Mao, W.H., Shi, K., Zhou, Y.H. and Yu, J.Q. (2013). Plant-Soil Feedbacks and Soil Sickness: From Mechanisms to Application in Agriculture. *Journal of Chemical Ecology* **39**: 232-242.
66. Huang, X.X., Bie, Z.L. and Huang, Y. (2010). Identification of autotoxins in rhizosphere soils under the continuous cropping of cowpea. *Allelopathy Journal* **25**: 383-392
67. Inderjit, Bajpai, D. and Rajeswari, M.S. (2010). Interaction of 8-hydroxyquinoline with soil environment mediates its ecological function. *PLoS ONE* **5**: e12852.
68. Inderjit, Rawat, D.S. and Foy, C.L. (2004). Multifaceted approach to determine rice straw phytotoxicity. *Canadian journal of botany-revue canadienne de botanique* **82**: 168-176.
69. Jaffee, B.A., Abawi, G.S. and Mai, W.F. (1982). Role of soil microflora and *Pratylenchus penetrans* in an apple replant disease. *Phytopathology* **72**: 247-251.
70. Jennings, J.A. and Nelson, C.J. (1998). Influence of soil texture on alfalfa autotoxicity. *Agronomy Journal* **90**: 54-58.
71. Jia, Z.H., Yi, J.H., Su Y.R. and Shen H. (2011). Autotoxic substances in the root exudates from continuous tobacco cropping. *Allelopathy Journal* **27**: 87-96.
72. Kibblewhite, M.G., Ritz, K. and Swift, M.J. (2008). Soil health in agricultural systems. *Philosophical Transactions of the Royal Society A* **363**: 685-701.
73. Kimber, R.W.L. (1967). Phytotoxicity from plant residues. I. The influence of rotted wheat straw on seedling growth. *Australian journal of agricultural research* **18**: 361-374.
74. Lakshmanan, V., Kitto, S.L., Caplan, J.L., Hsueh, Y.H., Kearns, D.B., Wu, Y.S. and Bais, H.P. (2012). Microbe-associated molecular patterns-triggered root responses mediate beneficial rhizobacterial recruitment in *Arabidopsis*. *Plant Physiology* **160**: 1642-1661.
75. Larkin, R.P. (2008). Relative effects of biological amendments and crop rotations on soil microbial communities and soilborne diseases of potato. *Soil Biology & Biochemistry*, **40**: 1341-1351.
76. Li, X., Ding C., Hua, K., Zhang, T., Zhang, Y., Zhao, L., Yang, Y., Liu, J., and Wang, X. (2014). Soil sickness of peanuts is attributable to modifications in soil microbes induced by peanut root exudates rather than to direct allelopathy. *Soil Biology and Biochemistry* **78**: 149-159.
77. Li, M.J., Yang, Y.H., Chen, X.J., Wang, F.Q., Lin, W.X., Yi, Y.J., Zeng, L., Yang, S.Y. and Zhang, Z.Y. (2013). Transcriptome/degradome-wide identification of *R. glutinosa* miRNAs and their targets: the role of miRNA activity in the replanting disease. *PLoS ONE* **8**: e68531.
78. Li, S.W., Kao, M.M., Shine, J.J., Liu, W.C. and Wang, T.S.C. (1982). Pre-submergence in relation to soil microbial balance and sugarcane production. *Tai Tang Hui Bao* **98**: 25-35.
79. Li, Z.F., Yang, Y.Q., Xie, D.F., Zhu, L.F., Zhang, Z.G. and Lin, W.X. (2012a). Identification of autotoxic compounds in fibrous roots of *Rehmannia* (*Rehmannia glutinosa* Libosch.). *PLoS ONE* **7**: e28806.
80. Li, Z.F., Yang, Y.Q., Xie, D.F., Zhu, L.F., Zhang, Z.G., Huang, M.J., Liu, Z.Q., Zhang Z.Y. and Lin, W.X. (2012b). Effects of continuous cropping on the quality of *Rehmannia glutinosa* L. and soil micro-ecology. *Chinese Journal of Eco-Agriculture* **20**: 217-224.
81. Liang, Y.L., Chen, Z.J., Xu, F.L., Zhang, C.G., Du, S.N. and Yan, Y.G. (2004). Soil continuous cropping obstacles in facility agriculture on Loess Plateau. *Journal of Soil and Water Conservation* **18**: 134-136.
82. Lin, M.Z., Hua, S.H., Chen, Q.Q. and Cai, Y.F. (2012). Studies on continuous cropping obstacle of *Pseudostellariae heterophylla* and the change of *Fusarium oxysporum* numbers in its rhizosphere. *Journal of Yunnan Agricultural University* **27**: 716-721.
83. Lin, M.Z., Wang, H.B. and Lin, H.F. (2012). Effects of *Pseudostellariae heterophylla* continuous cropping on rhizosphere soil microorganisms. *Chinese Journal of Ecology* **31**: 106-111.
84. Lin, S., Huangpu, J.J., Chen, T., Zhang, Z.Y. and Lin, W.X. (2014). Evaluation of allelopathic potential and identification of allelochemicals in *Pseudostellariae heterophylla* rhizosphere soil of different cropping patterns. *Allelopathy Journal* **33**: 151-162.

85. Lin, S., Zhuang, J.Q., Chen, T., Zhang A.J., Zhou, M.M. and Lin, W.X. (2012). Analysis of nutrient and microbial Biolog function diversity in tea soils with different planting years in Fujian Anxi. *Chinese Journal of Eco-Agriculture*, **20**: 1471-1477.
86. Lin, W.X., Chen, T. and Zhou, M.M. (2012). New dimensions in agroecology. *Chinese Journal of Eco-Agriculture* **20**: 253-264.
87. Lin, W.X., Fang, C.X., Wu, L.K., Li, G.L. and Zhang, Z.Y. (2011). Proteomic approach for molecular physiological mechanism on consecutive monoculture problems of *Rehmannia glutinosa*. *Journal of integrated Genomics* **1**: 287-296.
88. Liu, H.Y., Wang, F., Wang, Y.P. and Lu, C.T. (2006). The causes and control of continuous cropping barrier in dihuang (*Rehmannia glutinosa* Libosch.). *Acta Agriculturae Boreali Sinica* **21**: 131-132.
89. Liu, L., Sun, J., Guo, S.R., Huang, B.J., Guo, H.W. and Li, L.Q. (2013). Relationship between changes of nutrients, ions and soil acidification in different continuous cropping years of hot pepper greenhouse soils. *Chinese Agricultural Science Bulletin* **29**: 100-105.
90. Loffredo, E., and Senesi, N. (2006). Allelochemical activity of root exudates from horticultural plants hydroponically grown and the regulation role of humic substrates. *18th World Congress of Soil Science*, July 9-15, Philadelphia, PA.
91. Ma, Y.X., Zhang, G.B., Xie, J.M. and Yu, J.H. (2009). Effects of glutathione on active oxygen scavenging system in leaves of pepper seedlings under autotoxicity. *Acta Botanica Boreali-Occidentalia Sinica* **29**: 1380-1386.
92. Mai, W.F. and Abawi, G.W. (1981). Controlling replant diseases of pome and stone fruits in northeastern United States by preplant fumigation. *Plant Disease* **65**: 859-864.
93. Marasco, R., Rolli, E., Ettoumi, B., Vigani, G., Mapelli, F., Borin, S., Abou-Hadid, F., El-Behairy, U., Sorlini, C., Cherif, A., Zocchi, G., Daffonchio, D. (2012). A drought resistance-promoting microbiome is selected by root system under desert farming. *PLoS ONE* **7**(10): e48479.
94. McCalla, T.M. and Army, T.J. (1961). Stubble mulch farming. *Advances in Agronomy* **13**: 125-196.
95. McLay, C.D.A., Ritchie, G.S.P. and Porter, W.M. (1994). Amelioration of subsurface acidity in sandy soils in low rainfall regions. I. Responses of wheat and lupins to surface-applied gypsum and lime. *Australian Journal of Soil Research* **32**: 835-846.
96. Mendes, R., Kruijt, M., de Bruijn, I., Dekkers, E., van der Voort, M., Schneider, J.H., Piceno, Y.M., DeSantis, T.Z., Andersen, G.L., Bakker, P.A. and Raaijmakers, J.M. (2011). Deciphering the rhizosphere microbiome for disease-suppressive bacteria. *Science* **332**: 1097-1100.
97. Miller, H.G., Ikawa, M. and Peirce, L.C. (1991). Caffeic acid identified as an inhibitory compound in asparagus root filtrate. *HortScience* **26**: 1525-1527.
98. Mountain, W. B., and Boyce, H. R. (1958). The peach replant problem in Ontario. VI. The relation of *Pratylenchus penetrans* to the growth of young peach trees. *Canadian Journal of Botany* **36**: 135-151.
99. Narwal, S.S., Sarmah, M.K. and Nandal, D.P. (1997). Allelopathic effects of wheat residues on growth and yield of fodder crops. *Allelopathy Journal* **4**: 111-120.
100. Nicol, R.W., Yousef, L., Traquair, J.A. and Bernards, M.A. (2003). Ginsenosides stimulate the growth of soilborne pathogens of American ginseng. *Phytochemistry* **64**: 257-264.
101. Niu, M.M., Li, J., Du, J.F., Yin, W.J., Yang, Y.H., Chen, X.J. and Zhang, Z.Y. (2011). Changes in source-sink relationship of photosynthate in *Rehmannia glutinosa* L. and their relations with continuous cropping obstacle. *Chinese Journal of Ecology* **30**: 248-254.
102. Ogwen, J.O. and Yu, J. (2006). Autotoxic potential in soil sickness: a re-examination. *Allelopathy Journal* **18**: 93-102.
103. Otten, W., Filipe, J.A.N. and Gilligan, C.A.N. (2005). Damping off epidemics, contact structure, and disease transmission in mixed species populations. *Ecology* **86**: 1948-1957.
104. Paterson, E., Gebbing, T., Abel, C., Sim, A. and Telfer, G. (2007). Rhizodeposition shapes rhizosphere microbial community structure in organic soil. *New Phytologist* **173**: 600-610.
105. Patrick, Z.A. (1955). The peach replant problem in Ontario. II. Toxic substances from microbial decomposition products of peach root residues. *Canadian journal of botany-revue canadienne de botanique* **33**: 481-486.
106. Patrick, Z.A. (1971). Phytotoxic substances associated with the decomposition in soil of plant residues. *Soil Science* **111**: 13-18.
107. Patrick, Z.A. and Koch L.W. (1958). Inhibition of respiration, germination, and growth by substances arising during the decomposition of certain plant residues in the soil. *Canadian Journal of Botany* **36**: 621-647.

108. Patrick, Z.A. and Koch, L.W. (1963). The adverse effect of phytotoxic substances from decomposing plant residues on resistance of tobacco to black root rot. *Canadian Journal of Botany* **41**: 747-758.
109. Paul, K.I., Black, A.S. and Conyers, M.K. (2003). Development of acidic subsurface layers of soil under various management systems. *Advances in Agronomy* **78**: 187-214.
110. Pei, G.P. (2010). *Physiological and Rhizosphere Soil Nutrients Changes of Continuous Cropping in Potato*. Gansu Agricultural University. Thesis. 85 pp.
111. Peng, Y.C., Liu, T., Zhao, J.J., Sun, S.G., Gao, J., Wang, F.R., Liu, G.S. and Ye, F. (2009). Research advances in effect of continuous cropping on soil characteristics. *Acta Agriculturae Jiangxi* **21**: 100-103.
112. Perry, L.G., Thelen, G.C., Ridenour, W.M., Weir, T.L., Callaway, R.M., Paschke, M.W. and Vivanco, J.M. (2005). Dual role for an allelochemical, (\pm)-catechin from *Centaurea maculosa* root exudates regulates conspecific seedling establishment. *Journal of Ecology* **93**: 1126-1135.
113. Politycka, B. (2005). Soil sickness and allelopathy. *Allelopathy Journal* **16**: 77-84.
114. Politycka, B. and Gmerek, J. (2007). Effect of ferulic and *p*-coumaric acids on the activity of hydrolytic enzymes and the growth of radicles in germinating seeds of cucumber and pea. *Allelopathy Journal* **21**: 227-238.
115. Politycka, B. and Golcz, A. (2006). Soil sickness syndrome in organic substrates repeatedly used in eggplant (*Solanum melongena* L.) growing. *Allelopathy Journal* **18**: 39-46.
116. Politycka, B., Kozłowska, M. and Mielcarz, B. (2004). Cell wall peroxidases in cucumber roots induced by phenolic allelochemicals. *Allelopathy Journal* **13**: 29-36.
117. Protic, R. (1977). Allelopathic activity of harvest remains of wheat and sugar beet on soyabean. *Biološki Vestnik* **25**: 192.
118. Qi, J.J., Yao, H.Y., Ma, X.J., Zhou, L.L. and Li, X.N. (2009). Soil microbial community composition and diversity in the rhizosphere of a Chinese medicinal plant. *Communications in Soil Science and Plant Analysis* **40**: 1462-1482.
119. Qu, X.H. and Wang, J.G. (2008). Effect of amendments with different phenolic acids on soil microbial biomass, activity, and community diversity. *Applied Soil Ecology* **39**: 172-179.
120. Richard, C., Jackson, W. and Waguespack, Jr.H. (2001) Harvester trials and extraneous matter in the Louisiana sugar industry. *Proceedings of International Social Sugarcane Technology* **24**: 263- 268.
121. Ruan, W.B., Wang, J.G. and Zhang, F.S. (2001). The effect of sterilization with CH3Br on root growth of soybean seedling. *Acta Ecologica Sinica* **21**: 759-764. (Chinese).
122. Ruan, W.B., Liu, M.H., Huang, B., Yan, F., Wang, J.G. and Gao, Y.B. (2003). The allelopathic potential of phydroxy-phenylacetic acid and m-hydroxy-phenylacetic acid on soybean (*Glycine max* L.) germination. *Journal of applied Ecology* **14**: 785-788. (Chinese).
123. Ruan, W.B., Zhu, X.H., Li, H.B., Zhang, X., Guo, S.Y., Wang, J.G., Zhang, F.S. and Gao, Y.B. (2009). Soybean Autotoxicity: Effects of m-hydroxy-phenylacetic acid on cell ultrastructural changes and gene expression in soybean roots. *Allelopathy Journal* **24**: 271-282
124. Sampietro, D.A. (2006). Sugarcane soil sickness and Autotoxicity. *Allelopathy Journal* **17**: 33-42.
125. Sampietro, D.A., Sgariglia, M.A. and Soberón, J.R. (2006). Alfalfa soil sickness and autotoxicity. *Allelopathy Journal* **18**: 81-92.
126. Sampietro, D.A. and Vattuone, M.A. (2006). Sugarcane straw and its phytochemicals as growth regulators of weed and crop plants. *Plant Growth and Regulation* **48**: 21-27.
127. Sampietro, D.A., and Vattuone, M.A. (2006). Nature of the interference mechanism of sugarcane (*Saccharum officinarum* L.) straw. *Plant and Soil* **280**: 157-169.
128. Sampietro, D.A., Vattuone, M.A. and Isla, M.I. (2005). Plant growth inhibitors isolated from sugarcane (*Saccharum officinarum* L.) straw. *Journal of Plant Physiology* **163**: 837-846.
129. Sampietro, D.A., Fauguel, C.M., Vattuone, M.A., Presello, D.A. and Catalán, C.A.N. (2013). Phenylpropanoids from maize pericarp: resistance factors to kernel infection and fumonisin accumulation by *Fusarium verticillioides*. *European Journal of Plant Pathology* **135**: 105-113.
130. Sampietro, D.A., Vattuone, M.A. and Catalán, C.A.N. (2013). Exploiting allelopathy in sustainable agriculture: from concept to applied aspects. *Proceedings of Fourth International Seminar of Chinese Agricultural-Sage Culture*, pp. 46-59.
131. Seal, A.N., Pratley, J.E., Haig, T. and An, M. (2004). Identification and quantization of compounds in a series of allelopathic and non-allelopathic rice root exudates. *Journal of Chemical Ecology* **30**: 1647-1662.
132. Sewell, G.W.F. (1981). Effects of *Pythium* species on the growth of apple and possible causal role in apple replant disease. *Annals of Applied Biology* **97**: 31-42.

133. Singh, N.B., Singh, A. and Singh, D. (2010). Autotoxicity of maize and its mitigation by plant growth promoting rhizobacterium *Paenibacillus polymyxa*. *Allelopathy Journal* **25**: 195-204.
134. Singh, P., Suman, A. and Shrivastava, K. (2003) Isolation and identification of allelochemicals from sugarcane leaves. *Allelopathy Journal* **12**: 71-80.
135. Siviero, A., Cristofani, M., Furtado, E.L., Garcia, A.A., Coelho, A.S. and Machado, M.A. (2006). Identification of QTLs associated with citrus resistance to *Phytophthora* gummosis. *Journal of Applied Genetics* **47**: 23-28.
136. Suzuki, T. and Waller, G. R. (1987). Purine alkaloids in tea seeds during germination. In: Waller, G. R. (Ed.), *Allelochemicals: Role in Agriculture and Forestry*. ACS Symposium Series No. **330**: 289-294. American Chemical Society, Washington, DC.
137. Tang, C.X., Weligama, C. and Sale, P. (2013). Subsurface Soil Acidification in Farming Systems: Its Possible Causes and Management Options. *Molecular Environmental Soil Science* **3**: 389-412.
138. Tang, C.S. and Zhang, B. (1986). Qualitative and quantitative determination of the allelochemical sphere of germinating mung bean. In: *The Science of Allelopathy* (Eds., A.R. Putnam and C.S. Tang). pp. 229-242., John Wiley & Sons, New York.
139. Turco, R.F., Bischoff, M., Breakwell, D.P., and Griffith, D.R. (1990). Contribution of soil-borne bacteria to the rotation effect in corn. *Plant and Soil* **122**: 115-120.
140. Utkhede, R.S. and Li, T.S.C. (1988). The role of fungi, bacteria and their interactions in apple replant disease complex in soils of British Columbia. *Acta Horticulturae* **233**: 75-78.
141. Utkhede, R.S. (2006). Soil sickness, replant problem, or replant disease and its integrated control. *Allelopathy Journal* **18**: 23-38.
142. Utkhede, R.S. and Smith, E.M. (1994). Biotic and abiotic causes of replant problems of fruit trees. *Acta Horticulturae* **363**: 25-32.
143. Utkhede, R.S., Vrain, T.C. and Yorston, J.M. (1992). Effects of nematodes, fungi and bacteria on the growth of young apple trees grown in apple replant disease soil. *Plant and Soil* **139**: 1-6.
144. Ventura, W., and Watanabe, L. (1978). Growth inhibition due soil sickness. Proc., International Seminar on Soil to continuous cropping of dryland rice and other crops. Environment and Fertility Management in Intensive. *Soil Science and Plant Nutrition* **24**:375-389.
145. Vestberg, M., Kukkonen, S., Parikka, P., Yu, D. and Romantschuk, M. (2014). Reproducibility of suppression of Pythium wilt of cucumber by compost. *Agricultural Food Science* **23**: 236-245.
146. Viator, R.P., Johnson, R. and Richard, Jr. E.P. (2005). Challenges of post-harvest residue management in the Louisiana sugarcane industry. *Proceedings of International Social Sugarcane Technology* **25**: 238-244.
147. Viator, R.P., Johnson, R.M., Grimm, C.C. and Richard, E.P.J. (2006). Allelopathic, autotoxic, and hormetic effects of postharvest sugarcane residue. *Agronomy Journal* **98**: 1526-1531.
148. Walker, T.S., Bais, H.P., Grotewold, E. and Vivanco, J.M. (2003). Root Exudation and Rhizosphere Biology. *Plant Physiology* **132**: 144-151.
149. Waller, G.R. (1989). Allelochemical action of some natural products. In: *Phytochemical Ecology: Allelochemicals, Mycotoxins, and Insect Pheromones and Allomones* (Eds., C.H. Chou and G.R. Waller). Institute of Botany, *Academia Sinica Monograph* No. **9**: 129-154. Academia Sinica, Taipei.
150. Waller, G.R., Cheng, C.S., Chou, C.H., Kim, D., Yang, C.F., Huang, S.C. and Lin, Y.F. (1995). Naturally occurring allelochemicals from mungbean and their surrounding soil. *Allelopathy Journal* **2**: 147-168.
151. Waller, G., Yang, C., Chen, L., Su, C., Liou, R., Wu, S., Young, C., Lee, J., Cheng, C., Chou, C., and Kim, D. (1999) Saponins produced during the life cycle of mungbeans and their role as allelochemicals. *Studies in Plant Science* **6**: 105-130.
152. Wang, J.H., Chen, T. and Lin W.X. (2013). Plant allelopathy types and their application in agriculture. *Chinese Journal of Eco-Agriculture* **21**: 1173-1183.
153. Wang, J.J., Zhang, F.H., Kang, M.D., Zhang, A.X. and Gong, X. (2013). Long-term continuous cropping soil aggregate composition and distribution of organic carbon under different planting patterns. *Agricultural Engineering Technology* **4**: 15-18.
154. Wang, S.C. (1967). Soil Organic compounds as plant growth promoters and inhibitor. *Soil and fertilizer in Taiwan* **14**: 1-13.
155. Wang, S.C., Cheng, S.Y. and Tung, H. (1967). Extraction and analysis of soil organic acids. *Soil Science* **103**: 360-366.

156. Wang, S.C., Lai, T.M. and Yang, C.C. (1959). Liming as a means to increase sugarcane yield in Taiwan. *Proceedings of the International Society of Sugarcane Technologists* **10**: 556-564.
157. Wang, S.C., Yang, T.K. and Chung, T.T. (1967). Soil phenolic acids as plant growth inhibitors. *Soil Science* **103**: 239-246.
158. Westcott, S.W., Beer, S.V. and Stiles, W.C. (1986). Infection of apple roots by actinomycetes associated with soils conducive to apple replant disease. *Plant Disease* **70**: 1125-1128.
159. Westcott, S.W., Beer, S.V. and Israel, H.W. (1987). Interactions between actinomycetes-like organisms and young apple roots grown in soil conducive to apple replant disease. *Phytopathology* **77**: 1071-1077.
160. Wu, F., Liu, D., Wang, D., Luan, F., Wang, W. and Kong, X. (1997). The effects of different years of continuous cropping on the vitality of root systems and their qualities in the plastic house tomatoes. *Journal of the Northeast Agricultural University* **28**: 33-38.
161. Wu, F. and Wang, X. (2006). Effect of allelochemical on *Fusarium* f. Sp. *Cucumerinum* of cucumber and soil microbes. *Allelopathy Journal* **18**: 129-140.
162. Wu, F., Xue, H. and Zheng, W.X. (2006). Allelopathic effect of root exudates from cucumber cultivars with different resistance on *Fusarium* wilt pathogen. *Allelopathy Journal* **18**: 163-172.
163. Wu, F.Z., Liu, B. and Zhou, X.G. (2010). Effects of root exudates from watermelon cultivars differing in resistance to *Fusarium* wilt on *Fusarium oxysporum* f. sp. *niveum* growth and development. *Allelopathy Journal* **25**: 403-414.
164. Wu, H.W., Pratley, J., Lemerle, D., An, M. and Liu, D.L. (2007). Autotoxicity of wheat (*Triticum aestivum* L.) as determined by laboratory bioassays. *Plant and Soil* **296**: 85-93.
165. Wu, L.K., Li, Z.F., Li, J., Khan, M.A., Huang, W.M., Zhang, Z.Y. and Lin, W.X. (2013). Assessment of shifts in microbial community structure and catabolic diversity in response to *Rehmannia glutinosa* monoculture. *Applied Soil Ecology* **67**: 1-9.
166. Wu, Z.W., Wang, M.D., Liu, X.Y., Chen, H.G. and Jia, X.C. (2009). Phenolic compounds accumulation in continuously cropped *Rehmannia glutinosa* soil and their effects on *R. glutinosa* growth. *Chinese Journal of Ecology* **28**: 660-664.
167. Xiao, C.L., Zheng, J.H., Zou, L.Y., Sun, Y., Zhou, Y.H. and Yu, J.Q. (2006). Autotoxic potential of root exudates of soybean. *Allelopathy Journal* **18**: 121-128.
168. Xiao, X., Cheng, Z., Meng, H., Liu, L., Li, H. and Dong, Y. (2013). Intercropping of green garlic (*Allium sativum* L.) induces nutrient concentration changes in the soil and plants in continuously cropped cucumber (*Cucumis sativus* L.) in a plastic tunnel. *PLoS One* **8**: e62173.
169. Yang, Y.H., Chen, D.M., Jin, Y., Wang, H.B., Duan, Y.Q., Guo, X.K., He, H.B. and Lin W.X. (2011). Effect of different fertilizers on functional diversity of microbial flora in rhizospheric soil of monoculture tobacco. *Acta Agronomica Sinica* **37**: 105-111.
170. Yang, Y.H., Chen, X.J., Chen, J.Y., Xu, H., Li, J. and Zhang, Z. (2011). Differential miRNA expression in *Rehmannia glutinosa* plants subjected to continuous cropping. *BMC Plant Biology* **11**: 53.
171. Ye, S. F., Yu, J.Q., Peng, Y.H., Zheng, J.H., and Zou, L.Y. (2004). Incidence of *Fusarium* wilt in *Cucumis sativus* L. is promoted by cinnamic acid, an autotoxin in root exudates. *Plant and Soil* **263**: 143-150.
172. Yin, W.J., Du, J.F., Li, J. and Zhang, Z.Y. (2009). Effects of continuous cropping obstacle on growth of *Rehmannia glutinosa*. *China Journal of Chinese Materia Medica* **34**: 18-21.
173. Yoneyama, K. and Natsume, M. (2010). Allelochemicals for Plant-Plant and Plant-Microbe Interactions. *Comprehensive Natural Products II* **4**: 539-561.
174. Young, C.C. and Chen, S.H. (1989). Continuous cultivation of asparagus and the allelopathic effect. *Food and Fertilizer Technology Center, Technical Bulletin* **116**: 1-9.
175. Young, C.C. and Chou, T.C. (1985). Autointoxication in residues of *Asparagus officinalis* L. *Plant and Soil* **85**: 385-393.
176. Yu, J.Q. (2001). Autotoxic potential of cucurbit crops: phenomenon, chemicals, mechanisms and means to overcome. *Journal of Crop Production* **4**: 335-348.
177. Yu, J.Q. and Matsui, Y. (1994). Phytotoxic substances in root exudates of cucumber (*Cucumis sativus* L.). *Journal of Chemical Ecology* **20**: 21-31.
178. Yu, J.Q. and Matsui, Y. (1999). Autointoxication of Root Exudates in *Pisum sativus*. *Acta Horticulturae Sinica* **26**: 175-179.
179. Yu, J.Q. and Matsui, Y. (1997). Effect of root exudates of cucumber (*Cucumis sativus*) and allelochemicals on ion uptake by cucumber seedlings. *Journal of Chemistry Ecology* **23**: 817-827.

180. Yu, J.Q., Lee, K.S. and Matsui, Y. (1993). Effect of the addition of activated-charcoal to the nutrient solution on the growth of tomato in hydroponic culture. *Soil science and plant nutrition* **39**: 13-22.
181. Yu, M., Yu, J.Y., Cao, P.G., Liang, H.D., Xiao, H.D., Wang, Y.B. and Cui, Z.X. (2004). Agrochemical characteristics of soil for continuous cropping Lily. *Chinese Journal of Soil Science* **35**: 377-379.
182. Zhang, Q. (1993). Potential role of allelopathy in the soil and the decomposing root of Chinese-fir replant woodland. *Plant and Soil* **151**: 205-210.
183. Zhang, Q., and Yu X. (2001). Allelopathy in replant problem in forest soil. *Allelopathy Journal* **8**: 51-64.
184. Zhang, S.H., Zhou, B.L. and Zhang, L. (2006). Allelopathic effects of *Fructus cnicidii* (*Cnidium monnieri*) and microbial population in rhizosphere of eggplant. *Allelopathy Journal* **18**: 153-162.
185. Zhang, X.L., Pan, Z.G., Zhou, X.F. and Ni, W.Z. (2007). Autotoxicity and consecutive monoculture problems. *Chinese Journal of Soil Science* **38**: 781-784.
186. Zhang, Z.Y., Chen, H., Yang, Y.Q., Chen, T., Lin, R.Y., Chen, X.J. and Lin, W.X. (2010). Effects of continuous cropping on bacterial community diversity in rhizosphere soil of *Rehmannia glutinosa*. *Chinese Journal of Applied Ecology* **21**: 2843-2848.
187. Zhang, Z.Y., Fan, H.M., Yang, Y.H., Li, M.J., Li, J., Xu, H.X., Chen, J.Y. and Chen, X.J. (2011). Construction and analysis of suppression subtractive cDNA libraries of continuous monoculture *Rehmannia glutinosa*. *China Journal of Chinese Materia Medica* **36**: 276-280.
188. Zhang, Z.Y., Yin, W.J., Li, J., Du, J.F., Yang, Y.H. Chen, X.J. and Lin, W.X. (2010). Physio-ecological properties of continuous cropping *Rehmannia glutinosa*. *Chinese Journal of Plant Ecology* **34**: 547-554.
189. Zhao, Z.L., Shi, L.L., Yan, Y.R., Gong, Z.H., Wu, Q.Q. and Guo, J.W. (2006). Effects of fertilization on continuous cropping obstacle in pepper. *Agricultural Research in the Arid Areas* **24**: 77-80.
190. Zhou, Z., Luo, S., and Mou, Z. (1997). Allelopathic effect of tomato. *Chinese Journal of Applied Ecology* **8**: 445-449.
191. Zhou, B.L., Yin, Y.L., Zhang, F.L. and Ye, X.L. (2010). Allelopathic effects of root extracts of grafted eggplants on *Verticillium dahliae* and their ingredients identification. *Allelopathy Journal* **25**: 393-402.
192. Zhou, X. and Wu, F. (2012). *p*-Coumaric acid influenced cucumber rhizosphere soil microbial communities and the growth of *Fusarium oxysporum* f. sp. *cucumerinum* Owen. *PLoS ONE* **7**: e48288.
193. Zolla, G., Badri, D.V., Bakker, M.G., Manter, D.K. and Vivanco, J.M. (2013). Soil microbiomes vary in their ability to confer drought tolerance to *Arabidopsis*. *Applied Soil Ecology* **68**: 1-9.
194. Zou, L.Y., Ogwen, J.O., Sun, Y., Shi, K., Zhou, Y.H. and Yu, J.Q. (2006). Autotoxic potential of root exudates and associated phenolic metabolism in watermelon. *Allelopathy Journal* **18**: 103-110.