Arbuscular mycorrhizal symbiosis and active ingredients of medicinal plants: current research status and prospectives

Yan Zeng · Lan-Ping Guo · Bao-Dong Chen ·
Zhi-Peng Hao · Ji-Yong Wang · Lu-Qi Huang ·
Guang Yang · Xiu-Ming Cui · Li Yang ·
Zhao-Xiang Wu · Mei-Lan Chen · Yan Zhang

Received: 23 August 2012 / Accepted: 31 January 2013 / Published online: 17 February 2013
© Springer-Verlag Berlin Heidelberg 2013

Abstract Medicinal plants have been used world-wide for thousands of years and are widely recognized as having high healing but minor toxic side effects. The scarcity and increasing demand for medicinal plants and their products have promoted the development of artificial cultivation of medicinal plants. Currently, one of the prominent issues in

medicinal cultivation systems is the unstable quality of the products. Arbuscular mycorrhiza (AM) affects secondary metabolism and the production of active ingredients of medicinal plants and thus influence the quality of herbal medicines. In this review, we have assembled, analyzed, and summarized the effects of AM symbioses on secondary metabolites of medicinal plants. We conclude that symbiosis of AM is conducive to favorable characteristics of medicinal plants, by improving the production and accumulation of important active ingredients of medicinal plants such as terpenes, phenols, and alkaloids, optimizing the composition of different active ingredients in medicinal plants and ultimately improving the quality of herbal materials. We are convinced that the AM symbiosis will benefit the cultivation of medicinal plants and improve the total yield and quality of herbal materials. Through this review, we hope to draw attention to the status and prospects of, and arouse more interest in, the research field of medicinal plants and mycorrhiza.

Yan Zeng and Lan-Ping Guo contributed equally to this work.

Y. Zeng · L.-P. Guo · L.-Q. Huang (✉) · M.-L. Chen · Y. Zhang
Chinese Materia Medica Resources Center, China Academy
of Chinese Medical Sciences,
No. 16 Nanxiaojie, Dongzhimennei, Dongcheng District,
Beijing 100700, People's Republic of China
e-mail: huangluqi@263.net

B.-D. Chen · Z.-P. Hao · Z.-X. Wu
Soil Ecology and Ecosystem Restoration, State Key Laboratory
of Urban and Regional Ecology, Research Center
for Eco-Environmental Sciences, Chinese Academy of Sciences,
No. 18 Shuangqing Road, Haidian District,
Beijing 100085, People's Republic of China

Y. Zeng · G. Yang
State Key Laboratory of Earth Surface Processes and Resource
Ecology, Beijing Normal University, No. 19 New Street Outside
Street, Haidian District,
Beijing 100875, People's Republic of China

X.-M. Cui · L. Yang
Sanqi (*Panax notoginseng*) Academy of Sciences,
No. 99 Shaba North Road, Kaihua Town, Wenshan County,
Yunnan 663000, People's Republic of China

Y. Zeng · J.-Y. Wang
China National Corp. of Traditional & Herbal Medicine,
No. 15 East Mansion, Xisihuannorth Road, Haidian District,
Beijing 100195, People's Republic of China

Keywords Arbuscular mycorrhizal symbiosis · Medicinal plants · Secondary metabolites · Active ingredients

Introduction

Arbuscular mycorrhizal (AM) fungi contribute greatly to crop productivity and ecosystem sustainability in new plant production strategies (Gianinazzi et al. 2010) and are essential for the sustainable management of agricultural ecosystems (Jeffries et al. 2003; Smith and Read 2008; Barrios 2007). They promote the accumulation of effective ingredients of medicinal plants, which has become a hot area of

research lately. Mandala (*Datura stramonium*) and Schizonepeta (*Schizonepeta tenuifolia*) were the first medicinal plants shown to be affected by AM fungi (Wei and Wang 1989, 1991). A literature research for studies on the relationship between AM fungi and medicinal plants resulted in reports involving 50 species from 19 families (Table 1), including some commonly used medicinal plants such as *Salvia miltiorrhiza*, *Glycyrrhiza inflata*, *Atractylodes macrocephala*, *Bupleurum scorzonrifolium*, *Artemisia annua*, and *Atractylodes lancea*. Some are also endangered herbs, such as *Panax ginseng*, *Panax notoginseng*, and *Paris polyphylla* var. Some medicinal plants are also used for food (or additives), such as *Coriandrum sativum*, *Mentha arvensis*, and *Ocimum basilicum*, oregano etc. Mycorrhiza-orientated research topics have included AM fungal resources, inoculation methods, as well as effects on the growth, development, and secondary metabolism (active ingredients) of medicinal plants. The active ingredients of medicinal plants are mostly plant secondary metabolites, the quality of which directly affects the quality of medicinal materials. These metabolites included terpenes (such as total essential oil, sesquiterpene, diterpenes), phenols (such as flavonoids or coumarin), and alkaloids (such as scopolamine, berberine, camptothecin).

A total of 47 papers have focused on the secondary metabolites of medicinal plants associated with AM fungi. Research objectives have been not only to use AM to increase the yield, but also to improve the quality of medicinal materials. While many studies have shown that mycorrhiza play positive roles in improving the contents of secondary metabolites in medicinal plants (Table 2), in-depth research is still required to understand the mechanisms by which AM fungi affect the accumulation of effective ingredients in medicinal plants (Toussaint 2007). Here, we summarize the current research progress on the relationship between AM and secondary metabolites of medicinal plants. We consider that this research area is very important, and that the application of issuing knowledge can have great potential in improving the quality of medicinal materials.

Impacts of the arbuscular mycorrhizal symbiosis on secondary metabolites contents in medicinal plants

Many different secondary metabolites with different functions are produced during the growth and development of plants. Symbioses between plants and AM fungi can promote the accumulation in medicinal plants of several secondary metabolites which play important roles in treating human diseases (Tables 1 and 2).

Terpenes

Terpenes and terpenoids (or isoprenoids) are the primary constituents of the essential oils of many types of plants and flowers. The contents of some derivatives are high in plants that are associated with AM fungi (Janardhanan and Abdul-Khaliq 1995; Maier et al. 1999; Gupta et al. 2002; Akiyama and Hayashi 2002). In medicinal plants, essential oils are mixtures of some low-molecular weight terpenoids which are often the active ingredients of herbal medicines. Many studies have shown that the contents of essential oils in medicinal plants increase after the plants have been inoculated with AM fungi (Table 2). However, most of these medicinal plants, such as mint, oregano, basil, dill, orchid celery, fennel, and agastache, are not yet considered as medicinal raw materials and food additives (e.g., spices).

Some important and unique active ingredients or aroma components in certain medicinal plants have unique functions, and this has become the focus of many researches on the effects of AM symbiosis in medicinal plants. Contents of these unique ingredients can be used as standards for the quality of medicinal plants, such as levels of limonene and carvone in dill (Kapoor et al. 2002a), thymol in carum (Kapoor et al. 2002a), geraniol and linalool in coriander (Kapoor et al. 2002b), anethol in fennel (Kapoor et al. 2004), sesquiterpene lactones in Arnica (Jurkiewicz et al. 2010), and artemisinin in *A. annua* (Kapoor et al. 2007; Chaudhary et al. 2008; Huang et al. 2011). Previous research has shown that the AM symbiosis can promote the production of specific secondary metabolites in specific medicinal plants. For example, Liu et al. (2007) have found that the content of glycyrrhizic acid, a triterpenoid saponin and an important active ingredient in glycyrrhiza in plants, increases with the AM symbiosis in liquorice plants by 0.38–1.07-fold after 4 months of cultivation and by 1.34–1.43-folds after 30 months of cultivation compared with non-mycorrhizal control plants (Liu et al. 2007). Researchers have also studied the impact of the AM symbiosis on transplanted tissue cultured medicinal plants; AM fungal inoculation increases, for example, the content of essential oil in oregano plants derived from micropropagated seedlings (Morone Fortunato and Avato 2008).

Phenolic compounds

Structurally, phenolic compounds contain an aromatic group, one or more hydroxyl group(s), and other groups. AM fungi can induce defence-related compounds, including the production of phenolics, in plants (Volpin et al. 1994; Harrison 1999). Phenolic compounds, such as flavonoids and coumarin, are the active ingredients in many medicinal plants. Researchers have found that the content of flavonoids in *Bupleurum chinense*, *S. miltiorrhiza*, *Ginkgo biloba*

Table 1 Medicinal plants that have been investigated for AM effects

Family	Species	Medicinal value	Reference
Solanaceae	<i>Datura stramonium</i>	Removing rheumatism, treating cough, alleviating pain	Wei and Wang 1989
Araliaceae	<i>Panax ginseng</i>	Reinforcing vital energy, restoring physiological weakness	Zhang et al. 1990; Xing et al. 2000; Xing et al. 2003; Li 2003a; Cho et al. 2009
	<i>Panax notoginseng</i>	Removing passive congestion, detumescence, treating pain, maintaining hemostasis	Ren et al. 2007; Zhang et al. 2011
Labiatae	<i>Salvia miltiorrhiza</i>	Treating irregular menstruation, cardiovascular diseases, hepatitis and asthma	He et al. 2009a,b; Wang and He 2009; Ma et al. 2009; He et al. 2010; Meng and He 2011
	<i>Schizonepeta tenuifolia</i>	Treating flu, headache, and vomiting	Wei and Wang 1991
	<i>Bupleurum scorzonerifolium</i>	Treating cold, fever, chest pain, irregular menstruation, uterine fall off and rectocele	Teng and He 2005
	<i>Pogostemon cablin</i>	Treating cold and diarrhea	Arpana et al. 2008
	<i>Coleus forskohlii</i>	Treating cardiopathy and glaucoma	Sailo and Bagyaraj 2005
	<i>Salvia officinalis</i>	Against inflammations and infections of the mouth and throat	Nell et al. 2009
Gentianaceae sp.	<i>Gentiana manshurica</i>	Treating acute icterohepatitis, fever, and convulsions	Wang et al. 1998
Liliaceae	<i>Aloe barbadensis</i>	Antibacterial and anti-inflammatory effects, enhancing immunity	Gong et al. 2002
	<i>Ophiopogon japonicus</i>	Treating cough, insomnia and constipation	Pan et al. 2008
	<i>Paris polyphylla</i> var.	Treating malignant boil and swell, sore of the throat, and trauma	Zhou et al. 2009, 2010
	<i>Allium sativum</i>	Against arteriosclerosis and high blood pressure, modulating cardiovascular and immune systems	Borde et al. 2009
Ginkgoales engler	<i>Ginkgo biloba</i>	Furti: treating cough and gasp, wet dream, high frequency of urination, and hypertension	Qi et al. 2002, 2003; Zhang et al. 2004; Wu and Wei 2008
Gramineae	<i>Coix lachrymal-jobi</i> var.	Treating diarrhea, edema, dermatophytosis and pulmonary abscess	Li 2003b
Nyssaceae	<i>Camptotheca acuminata</i>	Treating tumors	Huang et al. 2003; Zhao et al. 2006, 2006; Yu et al. 2010
Asteraceae	<i>Atractylodes macrocephala</i>	Treating abdominal distension, diarrhea, edema, spontaneous perspiration and fetal irritability	Lu and He 2005, 2008; Lu et al. 2008a,b; Wang et al. 2010; Lu et al. 2011
	<i>Atractylodes lancea</i>	Treating abdominal fullness and distention, diarrhea, edema, dermatophytosis, rheumatism, cold and nyctalopia	Guo et al. 2006; Zhang et al. 2010, 2011
	<i>Artemisia annua</i>	Resisting malaria	Kapoor et al. 2007; Rapparini et al. 2008; Chaudhary et al. 2008; Awasthi et al. 2011; Huang et al. 2011
	<i>Echinacea purpurea</i>	Antibacterial and antiviral effects	Araim et al. 2009
	<i>Arnica montana</i>	Treating bruises, swellings and diseases of the mouth	Jurkiewicz et al. 2010
	<i>Inula ensifolia</i>	Diminishing inflammation and antiviral effect	Zubek et al. 2010
	<i>Artemisia umbelliformis</i>	Antibacterial and antiviral effects	Binet et al. 2011
	<i>Tagetes erecta</i>	Diminishing inflammation, treating cold and cough	Asrar and Elhindi 2010
Rutaceae	<i>Phellodendron amurense</i>	Treating dysentery, detoxicating and curing furuncles	Fan et al. 2006; Jie et al. 2007; Cai et al. 2008
	<i>Phellodendron chinense</i>	Treating dysentery, detoxicating and curing furuncles	Zhou and Fan 2007
	<i>Citrus aurantium</i>	Promoting digestion and increasing appetite	Wu et al. 2010
Leguminosae sp.	<i>Pueraria lobata</i>	Treating fever, headache, and diarrhea	Wang et al. 2006
	<i>Astragalus membranaceus</i>	Increasing immunity, treating diabetic mellitus	Lu and He 2008; He et al. 2009b

Table 1 (continued)

Family	Species	Medicinal value	Reference
Lamiaceae	<i>Glycyrrhiza inflata</i>	Clearing away toxic materials, eliminating phlegm and relieving cough	Liu et al. 2007; Liu and He 2009
	<i>Castanospermum australe</i>	Against AIDS, Pompe's disease, diabetes and cancer	Abu-Zeyad et al. 1999
	<i>Prosopis laevigata</i>	Strengthening immune system	Rojas-Andrade et al. 2003
	<i>Mentha arvensis</i>	Treating cough and headache	Gupta et al. 2002; Karagiannidis et al. 2011
	<i>Ocimum basilicum</i>	Treating trauma and snake bite	Copetta et al. 2006; Toussaint et al. 2007; Lee and Seagel 2009; Prasad et al. 2011; Rasouli-Sadaghiani et al. 2010
Oleaceae	<i>Origanum</i> sp.	Appetitanregend, promoting digestion, antibacterial effect	Khaosaad et al. 2006
	<i>Origanum vulgare</i>	Appetitanregend, promoting digestion, antibacterial effect	Morone Fortunato and Avato 2008
	<i>Origanum onites</i>	Appetitanregend, promoting digestion, antibacterial effect	Karagiannidis et al. 2011
	<i>Coleus forskohlii</i>	Anticancer and cardioactive effects, diminishing inflammation	Sailo and Bagyaraj 2005
	<i>Forsythia suspense</i>	Clearing away toxic materials, treating cold, fever, and sore throat	Zhao et al. 2007
Taxaceae	<i>Taxus chinensis</i> var.	Anticancer effect	Ren et al. 2008
Araceae	<i>Pinellia ternate</i>	Treating cough and vomiting	Chen et al. 2009a, b; Guo et al. 2010; Chen et al. 2010; Shen et al. 2011
Umbelliferae	<i>Anethum graveolens</i>	Treating flatulence, anti-spasm effect	Kapoor et al. 2002a
	<i>Trachyspermum ammi</i>	Treating gaseous distention, cholera and diarrhea	Kapoor et al. 2002a
	<i>Coriandrum sativum</i>	Promoting appetite, treating analgesia, detoxifying	Kapoor et al. 2002b; Farahani et al. 2008
	<i>Foeniculum vulgare</i>	Promoting appetite and digestion	Kapoor et al. 2004
	<i>Angelica dahurica</i>	Treating headache, toothache and nasosinusitis	Cao and Zhao 2007; Zhao et al. 2009; Zhao and He 2011
Garcinia	<i>Hypericum perforatum</i>	Antibacterial effect, diminishing inflammation, maintaining hemostasis, detoxicating, detumescence	Zubek et al. 2012)
Apocynaceae	<i>Catharanthus roseus</i>	Anticancer effect	Rosa-Mera et al. 2011
Valerianaceae	<i>Valeriana officinalis</i>	Mild sedatives and tranquilizers, inducing sleep	Nell et al. 2010; Geneva et al. 2010

Table 2 Effects of AM symbiosis on secondary metabolism of medicinal plants under the conditions of artificial inoculation

Secondary metabolite	Medicinal plant	AMF	Change in secondary metabolite	Reference
Terpene	<i>Schizonepeta tenuifolia</i>	<i>Glomus epigae</i> , <i>Glomus mosseae</i>	163.64–209.09 % of the control	Wei and Wang 1991
	<i>Atractylodes macrocephala</i>	<i>Glomus mosseae</i>	136.47–144.12 % of the control	Lu et al. 2011
	<i>Mentha arvensis</i>	<i>Glomus fasciculatum</i> , <i>Glomus etunicatum</i> , <i>Glomus lamellosum</i>	103.33–105.36 % or 190–270 % of the control	Gupta et al. 2002; Karagiannidis et al. 2011
	<i>Origanum</i> sp.	<i>Glomus mosseae</i>	Significant improvement	Khaosaad et al. 2006;
	<i>Origanum vulgare</i>	<i>Glomus viscosum</i> T. H. Nicolson, strain A6	No change	Morone Fortunato and Avato 2008;
	<i>Origanum onites</i>	<i>Glomus etunicatum</i> , <i>Glomus lamellosum</i>	130.43–182.61 % of the control	Karagiannidis et al. 2011
	<i>Ocimum basilicum</i>	<i>Glomus mosseae</i> , <i>Gigaspora rosea</i>	33.33–114.03 % of the control	Copetta et al. 2006; Rasouli-Sadaghiani et al. 2010
	<i>Anethum graveolens</i>	<i>Glomus macrocarpum</i> , <i>Glomus fasciculatum</i>	190 % of the control	Kapoor et al. 2002a
	<i>Trachyspermum ammi</i>	<i>Glomus macrocarpum</i> , <i>Glomus fasciculatum</i>	172 % of the control	Kapoor et al. 2002a
	<i>Coriandrum sativum</i>	<i>Glomus hoi</i>	Significant improvement	Farahani et al. 2008
	<i>Foeniculum vulgare</i>	<i>Glomus macrocarpum</i> , <i>Glomus fasciculatum</i>	Significant improvement, 178 % of the control the highest	Kapoor et al. 2004
	<i>Artemisia Annua</i>	<i>Glomus macrocarpum</i> , <i>Glomus fasciculatum</i>	Significant improvement	Chaudhary et al. 2008
	<i>Pogostemon cablin</i>	<i>Acaulospora laevis</i> , <i>Gigaspora margarita</i> , <i>Glomus bagyarajii</i> , <i>Glomus etunicatum</i> , <i>Glomus fasciculatum</i> , <i>Glomus intradices</i> , <i>Glomus leptotichum</i> , <i>Glomus macrocarpum</i> , <i>Glomus monosporum</i> , <i>Glomus mosseae</i> , <i>Scutellospora calospora</i>	84.25 % of the control (<i>Scutellospora calospora</i>) Others: 106.16–119.86 % of the control	Arpana et al. 2008
	<i>Atractylodes lancea</i>	<i>Glomus mosseae</i> ; <i>Glomus versiforme</i> , <i>Glomus aggregatum</i> , <i>Glomus fasciculatum</i>	No change	Guo et al. 2006; Zhang et al. 2010, 2011
Thymol	<i>Trachyspermum ammi</i>	<i>Glomus fasciculatum</i>	151.21 % of the control	Kapoor et al. 2002a
	<i>Coriandrum sativum</i>	<i>Glomus macrocarpum</i> , <i>Glomus fasciculatum</i>	128 % and 143 % of the control	Kapoor et al. 2002b
	<i>Foeniculum vulgare</i>	<i>Glomus macrocarpum</i> , <i>Glomus fasciculatum</i>	Significant enhancement, Cis-anethol: 138.89–311.11 %, Trans-anethol: 105.88–106.75 % of the control	Kapoor et al. 2004
	<i>Artemisia Annua</i>	<i>Glomus macrocarpum</i> , <i>Glomus fasciculatum</i> ; <i>Glomus mosseae</i> , <i>Glomus versiforme</i>	Significant increase, 115.2–132.8 % of the control	Kapoor et al. 2007; Chaudhary et al. 2008
	<i>Arnica montana</i>	<i>Glomus geosporum</i> , <i>Glomus constrictum</i> , <i>Glomus intradices</i> , <i>Glomus mosseae</i>	Either increase or decrease	Huang et al. 2011; Jurkiewicz et al. 2010
Sesquiterpene lactones	<i>Glycyrrhiza inflata</i>	<i>Glomus mosseae</i>	138–243 % of the control	Liu et al. 2007
	<i>Bornylacetate</i> , 1,8-cineole, α -thujones, β -thujones	<i>Glomus mosseae</i> , <i>Glomus verforme</i>	Relative quantity increases	Geneva et al. 2010
	<i>Valeriana officinalis</i>	<i>Glomus intradices</i>	Significant increase	Toussaint et al. 2007; Lee and Scagel 2009
Phenols	Rosmarinic, Caffeic acids	<i>Glomus caledonium</i> , <i>Glomus mosseae</i>	Significant increase	

Table 2 (continued)

Secondary metabolite	Medicinal plant	AMF	Change in secondary metabolite	Reference
Polyphenol	<i>Ocimum basilicum</i>	<i>Glomus intraradices</i>	No change	Lee and Scagel 2009
Phenolics	<i>Echinacea purpurea</i>	<i>Glomus intraradices</i>	Significant increase in roots	Araim et al. 2009
Phenolic acids	<i>Arnica montana</i>	<i>Glomus geosporum</i> , <i>Glomus constrictum</i> , <i>Glomus intraradices</i> , <i>Glomus intraradices</i> , <i>Glomus mosseae</i>	Significant increase in roots	Jurkiewicz et al. 2010
Phenolic compounds	<i>Catharanthus roseus</i>	<i>Glomus</i> species	Significant increase	Rosa-Mera et al. 2011
Thymol derivative	<i>Inula ensifolia</i>	<i>Glomus intraradices</i> , <i>Glomus clarum</i> , Crude inoculum	Either increase or decrease	Zubek et al. 2010
Flavonoid	<i>Bupleurum</i> <i>scorzonnerifolium</i> <i>Salvia miltiorrhiza</i>	<i>Glomus mosseae</i> , <i>Glomus caledonium</i>	Significant increase: 6.42–12.39 % of the control	Teng and He 2005
		<i>Glomus mosseae</i> ;	Significant increase: 116.67–367.83 % of the control	He et al. 2009b; Meng and He 2011
	<i>Astragalus membranaceus</i>	<i>Glomus mosseae</i> ;	101.32–103.23 % of the control	He et al. 2009c
Imperarorin, total coumains,	<i>Angelica dahurica</i>	<i>Glomus</i> species;	Significant increase: imperarorin: 108.52 %; total coumains: 196.45 % of the control	Zhao et al. 2009; Zhao and he 2011
Total phenolic, rosmarinic acid	<i>Salvia officinalis</i>	<i>Glomus mosseae</i> , <i>Glomus intraradices</i> , inoculum consisted of six different <i>Glomus</i> species (<i>G. mosseae</i> , <i>G. intraradices</i> , <i>G. cladoideum</i> , <i>G. microaggregatum</i> , <i>G. caledonium</i> , and <i>G. etunicatum</i>).	No change in leaves and roots	Nell et al. 2009
Sesquiterpenic acid	<i>Valeriana officinalis</i>	<i>Glomus mosseae</i> , <i>Glomus intraradices</i> , inoculum consisted of six different <i>Glomus</i> species (<i>G. mosseae</i> , <i>G. intraradices</i> , <i>G. cladoideum</i> , <i>G. microaggregatum</i> , <i>G. caledonium</i> and <i>G. etunicatum</i>)	Significant increase: 18–48 % of the control	Nell et al. 2010
Alkaloid	<i>Castanospermum australe</i>	<i>Glomus intraradices</i> , <i>Gigaspora margarita</i>	Significant increase: 166.67–218.75 % of the control	Abu-Zeyad et al. 1999
Trigonelline	<i>Prosopis laevigata</i>	<i>Gigaspora rosea</i>	Significant increase: 180 % of the control	Rojas-Andrade et al. 2003
Vinblastine alkaloid	<i>Catharanthus roseus</i>	<i>Glomus</i> species	Significant increase	Rosa-Mera et al. 2011
Hyosine, hyoscyamine	<i>Datura stramonium</i>	<i>Glomus mosseae</i> , <i>Glomus epigaeum</i>	Significant increase, Hyosine: 103.25–117.21 % Hyoscyamine: 132.26–161.29 % of the control	Wei and Wang 1989
Berberine, jatrorrhizine, palmatine	<i>Phellodendron amurense</i>	<i>Glomus mosseae</i> , <i>Glomus etunicatum</i> , <i>Glomus versiforme</i> , <i>Glomus diaphanum</i>	Significant increase, Berberine: 349.80–765.56 %; Jatrorrhizine: 331.07–554.37 %; Palmatine: 423.98–661.40 % of the control	Fan et al. 2006
Berberine	<i>Phellodendron chinense</i>	<i>Acaulospora laevis</i> , <i>Acaulospora mellea</i> , <i>Glomus ditum</i> , <i>Glomus intraradices</i> , <i>Glomus mosseae</i> , <i>Glomus versiforme</i>	Significant increase in the tree bark	Zhou and Fan 2007

Table 2 (continued)

Secondary metabolite	Medicinal plant	AMF	Change in secondary metabolite	Reference
L-ephedrine, guanosine	<i>Pinellia ternate</i>	<i>Glomus intraradices</i> , <i>Glomus mosseae</i>	Significant increase in the tuber, Maximum amount: L-ephedrine 565.11 % and guanosine 478.00 % of the control	Guo et al. 2010
Camptothecin	<i>Camptotheca acuminata</i>	<i>Acaulospora mellea</i> , <i>Glomus intraradices</i>	Significant increase	Zhao et al. 2006; Yu et al. 2010
Forskolin	<i>Coleus forskohlii</i>	<i>Acaulospora laevis</i> , <i>Gigaspora margarita</i> , <i>Glomus bagyarjii</i> , <i>Glomus monosporum</i> , <i>Glomus fasciculatum</i> , <i>Glomus mosseae</i> , <i>Glomus leptotichum</i> , <i>Glomus macrocarpum</i> , <i>Glomus intraradices</i> , <i>Glomus etunicatum</i> , <i>Scutellospora calospora</i>	Significant increase, 128.07–163.16 % of the control	Sailo and Bagyaraj 2005
Alliin	<i>Allium sativum</i>	<i>Glomus fasciculatum</i>	Significant increase, 4–50 % of the control	Borde et al. 2009
Others	Hypericin, pseudohypericin	<i>Glomus intraradices</i> , <i>Glomus mosseae</i> , <i>Glomus constrictum</i> , <i>Glomus geosporum</i>	Significant increase in some AMF	Zubek et al. 2012

and *Astragalus membranaceus* (Zhang et al. 2004; Teng and He 2005; He et al. 2009a, b; Meng and He 2011), and of total coumarin and imperatorin in *Angelica dahurica* (Zhao et al. 2009; Zhao and He 2011) are significantly higher when the plants are associated with AM fungi. The levels of other active ingredients in medicinal plants, such as phenolics in purple coneflower (*Echinacea purpurea*) (Araim et al. 2009), phenolic acid in *Arnica montana* and *Catharanthus roseus* (Jurkiewicz et al. 2010; Rosa-Mera et al. 2011), sesquiterpenic acid in *Valeriana officinalis* (Nell et al. 2010), and a thymol derivative in *Inula ensifolia* (Zubek et al. 2010), are also promoted by the formation of AM symbiosis.

However, some studies have shown that AM do not have positive effects on the composition of phenolic ingredients. For example, inoculation with AM fungi results in an increase in anthocyanin content, but fails to alter the polyphenolic profile of leaves and stems of basil (*O. basilicum*) (Lee and Scagel 2009). Nell et al. (2009) found that AM symbiosis has no effect on the total concentrations of phenolic and rosmarinic acid in the roots of *Salvia officinalis*, while Geneva et al. (2010) reported an important decrease in total phenols and flavonoids contents of leaves in mycorrhizal *S. officinalis*.

Alkaloids

Alkaloids are cyclic and nitrogen-containing compounds. Plants often produce alkaloids to defend themselves against pests, diseases, and other external biological stimuli. Wei and Wang (1989) found that AM symbiosis can increase the total contents of hyoscyamine and scopolamine in *D. stramonium*. Subsequently, there have been reports that AM symbiosis plays a positive role in the accumulation of alkaloids in some important medicinal plants, such as camptothecin in *Camptotheca acuminata* and vinca alkaloids in vinca (*C. roseus*) which have important anticancer functions (Yu et al. 2010; Rosa-Mera et al. 2011). Some commonly used “heat-clearing” herbs (antifebrile herbs), when associated with AM fungi, have higher contents of alkaloids. For example, levels of berberine, jatrorrhizine, and palmatine increase in *Phellodendron amurense* (Fan et al. 2006) and berberine in *Phellodendron chinense* (Zhou and Fan 2007). Also, the herb *Pinellia ternata*, which is used as an expectorant and cough medicine, produces a higher content of L-ephedrine hydrochloride in AM plants (Guo et al. 2010).

Castanospermum australe, which is a medicinal plant native to northeast Australia, produces castanospermine that can inhibit the AIDS virus (Hadwiger et al. 1986). A positive correlation has been observed between AM fungal colonization and the content of castanospermine in seeds of field-grown trees of *C. austral*, and these results suggesting that AM symbiosis increases the contents of castanospermine have been confirmed for leaves of seedlings grown in the

greenhouse, irrespective of P treatments (Abu-Zeyad et al. 1999). *Coleus* (*Coleus forskohlii*) is an important medicinal plant with alkaloids and forskolin in the root system. It is extensively used to treat heart diseases, glaucoma, asthma, and certain types of cancers (Shah et al. 1980). In greenhouse studies conducted to investigate the effectiveness of 11 AM fungi on coleus production, results showed that AM formation increases the content of forskolin (Sailo and Bagyaraj 2005). In studies of changes in secondary metabolites of the semi-arid legume *Prosopis laevigata*, Johnst in an in vitro system, Rojas-Andrade et al. (2003) found that the root concentration of trigonelline, another medicinal alkaloid, was already 1.8-fold higher in plants during the presymbiotic phase of AM development. Finally, garlic (*Allium sativum*), which is a very popular cooking additive, is also known as a folk medicine commonly used against arteriosclerosis and high blood pressure. One compound in garlic, alliin (converted from alliin by the enzyme allinase), has antioxidative and anticarcinogenic properties, and is capable of modulating the functions of the cardiovascular and immune systems (Harris et al. 2001). Borde et al. (2009) found that garlic plants inoculated with mycorrhizal fungi have higher levels of alliin and allinase activities than non-inoculated garlic plants under field conditions.

Others

Hypericum perforatum is a valuable medicinal plant species which produces the important active ingredients hypericin and pseudohypericin, polycyclic aromatic diones with antiviral activity and inhibitory effects towards AIDS. Zubek et al. (2012) have shown that the contents of hypericin and pseudohypericin increase significantly in plants in the presence of AM symbiosis.

Effect of AM symbiosis on chemical composition of secondary metabolites

While AM symbiosis can significantly increase the contents of some secondary metabolites of medicinal plants, it is not clear whether the composition of the secondary metabolites in medicinal plants also changes. There are contrasting reports that AM symbiosis can change or optimize the chemical composition in medicinal plants. No differences were found in essential oil components between mycorrhizal and non-mycorrhizal plants of *A. lancea* from the region of Maoshan, the production area of Daodi medicinal materials used as a synonym of high-quality Chinese herbal medicine (Huang et al. 2004). Likewise, mycorrhizal oregano (*Origanum vulgare*) showed a chemical profile of essential oils which was comparable to that of control plants, with carvacrol as the main compound (Morone Fortunato and Avato 2008). In contrast, Karagiannidis et al. (2011) found that AM fungal colonization

increases the contents and changes the composition of essential oils in oregano (*Origanum onites*) and mint (*Menta viridis*). Geneva et al. (2010) also observed that AM formation in *S. officinalis* changes the composition of essential oils, and promotes the relative quantities of bornylacetate, 1,8-cineole, α -thujones and β -thujones. Mycorrhizal roots of *Artemisia umbelliformis* are reported to have a significantly increased percentage of E-ocimene and reduced percentages of E-2-decenal and (E, E)-2-4-decadienal (Binet et al. 2011), while AM fungal inoculation increases not only essential oil concentrations in coriander (*C. sativum*) but also geraniol and linalool, which are landmark components for quality evaluation (Kapoor et al. 2002b). Similarly, AM symbiosis significantly increases the concentrations of not only the essential oils but also the important active ingredient anethol in fennel (*Foeniculum vulgare*) (Kapoor et al. 2004).

Differential effects of AM fungi in promoting the accumulation of secondary metabolites of medicinal plants

The degree of influence of different AM fungi on the same medicinal plant or of the same AM fungus on different medicinal plants can vary. Jurkiewicz et al. (2010) reported that inocula composed of different AM fungi differed not only in their effectiveness in establishing symbiosis and promoting growth of *A. montana*, but also in the degree to which they increased plant contents in phenolic acids and sesquiterpene lactones. Similar results have been obtained by several researchers. For example, when *Glomus mosseae* BEG 12, *Gigaspora margarita* BEG 34, and *G. rosea* BEG 9 were inoculated onto basil plants (*O. basilicum* var.), essential oil contents were significantly incremented, but to different extents depending on the AM fungus, with *G. rosea* BEG 9 having the greatest effect (Copetta et al. 2006). AM symbiosis significantly increased the contents of essential oils in dill, carum, and coriander, and *G. fasciculatum* appeared to be more effective than *Glomus macrocarpum* (Kapoor et al. 2002a, b). Rasouli-Sadaghianil et al. (2010) also reported that *G. fasciculatum* may have a higher symbiotic potential in increasing essential oil contents in basil. On the other hand, *G. macrocarpum* was the more effective of the two fungi in enhancing the concentration of artemisinin in *A. annua* (Chaudhary et al. 2008).

Since different AM fungi can promote the accumulation of secondary metabolites to different extents in medicinal plant species, large scale screening of a range of AM fungi is required in order to obtain an ideal strain. When 11 different AM fungal species were evaluated for their symbiotic effects on patchouli (*Pogostemon cablin*) (Arpana et al. 2008) or *C. forskohlii* (Sailo and Bagyaraj 2005) in the greenhouse, it was found that all enhanced essential oil contents in *P. cablin* and forskolin in *C.*

forskohlii. However, *Glomus etunicatum* gave the most promising results with *Pogostemon* (Arpana et al. 2008), and *G. bagyarajii* with *C. forskohlii* (Sailo and Bagyaraj 2005). Other work has shown that the production of secondary metabolites in different parts of a medicinal plant may either be enhanced or reduced depending on which AM fungus is associated. For example, AM fungal species specificity was observed in stimulating the production of thymol derivatives in the roots of *I. ensifolia* inoculated with four different AM fungi. Root content of 7-isobutyryloxythymol methyl ether increased after inoculation with *G. clarum*, but not after inoculation with *G. intraradices* (Zubek et al. 2010). On the contrary, all four AM fungi caused decreases in the shoot content of 7-isobutyryloxythymol methyl ether.

While knowledge about the impact of different AM fungi on active ingredients of medicinal plants is the basis for their screening vis-a-vis a specific medicinal plant, synergistic effects with other microorganisms also need to be considered due to the complexity of the soil environment. Therefore, future screening of AM fungal inocula should be performed in the context of a variety of microorganisms. In a study to determine the effect of four different AM fungi and two free living nitrogen fixing bacteria (NFB) on the content of artemisinin in *A. annua* inoculated alone or in combination, plants co-inoculated with *G. mosseae* and a *Bacillus subtilis* strain produced 25.5–103.2 % more artemisinin than in other treatments, indicating a synergistic effect between *G. mosseae* and *B. subtilis* (Awasthi et al. 2011). Synergy has also been observed between *G. fasciculatum* and a beneficial *Pseudomonas* in improving yield and forskolin content of *C. forskohlii* tubers under field conditions (Singh et al. 2013).

Mechanism by which AM symbiosis promotes secondary metabolism of medicinal plant

The increase in concentrations of several groups of plant metabolites as a result of AM establishment has, in general, been considered as a defense response to fungal colonization. However, it is not clear how AM fungi trigger changes in the concentrations of phytochemicals in plant tissues (Toussaint et al. 2007), and there are only a few reports about the molecular mechanism(s) by which AM symbiosis promotes the accumulation of secondary metabolites.

Effect of interaction of P fertilizer and AM symbiosis on accumulation of secondary metabolites of medicinal plants

AM fungi promote the absorption of P by plants (Smith and Read 2008). *Castanospermum austral* plants treated with P and those inoculated with AM fungi have similar contents of alkaloids (castanospermine) in their leaves. The fact that P

treatment significantly increases alkaloid content of both non-mycorrhizal and mycorrhizal plants indicates that P nutrition may play a direct role in increasing the contents of secondary metabolites (Abu-Zeyad et al. 1999). Kapoor et al. (2004) obtained similar results for the accumulation of essential oil in fennel. Nell et al. (2009) found that full phosphorus treatment leads to a 1.2-fold increase in total phenolic and rosmarinic acid concentrations in the leaves of *S. officinalis*, as compared with a half phosphorus treatment, AM fungal inoculation, or control plants, which suggests that secondary metabolite contents increase only when P is supplemented in a sufficient amount. However, the same authors (Nell et al. 2010) observed either unchanged or significantly decreased contents of sesquiterpenic acid in different genotypes of *V. officinalis* when plants were treated with P. Therefore, the effects of P on secondary metabolites may vary between different medicinal plants.

On the other hand, Toussaint et al. (2007) reported that although high P amendments to non-mycorrhizal plants increase rosmarinic and caffeic acid concentrations in sweet basil (*O. basilicum*), the increased production of rosmarinic and caffeic acids in the shoots of AM plants is not solely due to improved P nutrition. Observations in mycorrhizal *A. annua* suggest that the increase in artemisinin concentration may not be entirely attributed to enhanced P nutrition (Chaudhary et al. 2008; Kapoor et al. 2007). Khaosaad et al. (2006) also found that essential oil concentration significantly increases in two oregano genotypes associated with *G. mosseae*, but the levels of essential oil in plants treated with P are not changed, which indicates that the increase in essential oil concentration in mycorrhizal oregano plants is not due to an improved P nutrition, but directly depends on association with the AM fungus.

Effect of AM symbiosis on characteristics of medicinal plants

Essential oil is synthesized in the glandular trichome of plant leaves and so there is usually a strong positive correlation between the density of glandular trichomes and the levels of accumulated essential oil or other secondary metabolites in plants such as *O. basilicum*, *Origanum* sp, *A. annua*, and *M. arvensis*. Interestingly, AM symbiosis formation increased the density of glandular trichome on the upper leaf epidermis of *O. vulgare*-micropropagated seedlings (Morone Fortunato and Avato 2008), and Copetta et al. (2006) have suggested that significantly increased levels of essential oil in *O. basilicum* colonized by three different AM fungi result from significantly larger numbers of peltate glandular trichomes on the basal and central leaf zones (Copetta et al. 2006). In line with this, Kapoor et al. (2007) found that two AM fungi increased the density of foliar glandular trichomes in *A. annua*, and that a

strong correlation existed between the density of glandular trichomes on leaves and artemisinin concentrations.

Discussion and perspectives

There have been several previous evaluations and summaries about the advantages, prospects, and feasibility of introducing AM fungi into the process of cultivation of medicinal plants (Guo et al. 2006; Zeng et al. 2007; Yang et al. 2008; Xiao et al. 2011). The growing shortage of wild medicinal plant resources may provoke a crisis based on a blind pursuit for total yield without considering the quality of the medicinal plants. The challenge is to increase total yield while maintaining or improving quality assurance. The quality of herbal material in terms of active ingredients is influenced not only by abiotic factors such as light, temperature, humidity, soil fertility, and cultivation techniques, but also biotic factors such as herbivore attack, disease-related stimuli, and mutual symbioses with rhizobium and mycorrhizal fungi (Szakiel et al. 2011a, b). The positive role of AM symbiosis in plant growth, disease resistance, and both yield and quality of medicinal materials makes AM fungi potential alternatives to existing methods for promoting growth of some important medicinal herbs, especially since natural ways of growing such crops are currently highly sought after in the herbal industry (Toussaint et al. 2007).

In this paper, we have tried to provide a comprehensive review of information available about research on AM and secondary metabolites of medicinal plants, in order to set a basis for future work. The mechanisms by which AM fungi trigger changes in the concentration of phytochemicals in plant tissues are not yet well understood (Toussaint 2007). AM symbiosis activity promotes absorption of P, N, and other mineral nutrients, and thus contributes to the accumulation of secondary metabolites in plants. For example, isoprenoid biosynthesis requires acetyl-CoA, ATP, and NADPH and is dependent on the concentration of inorganic phosphorus in the plant, so that terpenoid derivative essential oils are enhanced through better plant absorption of P (Loomis and Croteau 1972). Tyrosine and phenylalanine are important precursors of some secondary metabolites, such as rosmarinic and caffeic acids (Petersen and Simmonds 2003). Consequently, AM symbiosis can enhance the synthesis of certain amino acids and contribute to the accumulation of specific metabolites by promoting N uptake (Smith and Read 1997; Toussaint et al. 2004). Some research has also shown that symbiosis with AM fungi results in the increase of terpenoids and phenolic acids, which may result from increased absorption of mineral nutrients, especially P and N (Kapoor et al. 2002a, b; Toussaint et al. 2007). Finally, changes in the secondary metabolites of mycorrhizal plants may result from changes in levels of

phytohormones like cytokinin or gibberellin (Allen et al. 1980, 1982; Copetta et al. 2006; Kapoor et al. 2007; Toussaint 2007). However, these and other possibilities all remain to be verified (Toussaint 2007).

The AM symbiosis has obvious advantages in alleviating stresses under poor climate and soil conditions (such as fertilizer shortage and water deficiency) like those met in the cultivation area of *G. inflata* where plants face nutrient stress, water stress, and salt stress under desertification conditions and where AM fungi have the potential to significantly improve the yield and quality of licorice (Liu et al. 2007). In this context, it is necessary to perform studies under environmental conditions inherent to those of the cultivation area in order to obtain the ideal conditions under which AM fungi can promote the productivity of medicinal plants. The use of agricultural facilities to control environmental factors and provide favorable conditions for the symbiosis between medicinal plants and AM fungi will favor the yield and quality of medicinal materials, under specific soil and climate conditions.

In conclusion, in order to further knowledge about the organic production of herbal materials, much effort is needed in research on the role of AM fungi and the AM symbiosis and the use of mycorrhizal technology in the cultivation of medicinal plants. To meet these objectives, future research priorities should focus on: (1) selection efficient AM fungal strains adapted to production conditions, (2) procedures for the production of seedlings of medicinal plants with mycorrhiza, (3) intensive cultivation of medicinal plants and the production of organic medicinal materials, and (4) mechanisms by which AM fungi change the contents of active ingredients in medicinal plants.

Acknowledgments This study was supported by the National Natural Science Foundation of China (NSFC) (81130070, 81072989, and 41101245), Special Industry Research Project by State Administration of Traditional Chinese Medicine (201107009), International Technical Cooperation Project (2009DFA31660), Project of Science and Technology Plan of Yunnan Province (2008IF025-4) and Research Project of Academy of Chinese Medical Sciences of China (ZZ20090302).

References

- Abu-Zeyad R, Khan AG, Khoo C (1999) Occurrence of arbuscular mycorrhiza in *Castanospermum australe* A. Cunn. & C. Fraser and effects on growth and production of castanospermine. *Mycorrhiza* 9:111–117
- Akiyama K, Hayashi H (2002) Arbuscular mycorrhizal fungus-promoted accumulation of two new triterpenoids in cucumber roots. *Biosci Biotechnol Biochem* 66(4):762–769
- Allen MF, Moore TS, Christensen M (1980) Phytohormone changes in *Bouteloua gracilis* infected by vesicular-arbuscular mycorrhizae. I. Cytokinin increases in the host plant. *Can J Bot* 58:371–374
- Allen MF, Moore TS, Christensen M (1982) Phytohormone changes in *Bouteloua gracilis* infected by vesicular-arbuscular mycorrhizae.

- II. Altered levels of gibberellin-like substances and abscisic acid in the host plant. *Can J Bot* 60:468–471
- Araim G, Saleem A, Arnason JT, Charest AC (2009) Root colonization by an arbuscular mycorrhizal (AM) fungus increases growth and secondary metabolism of purple coneflower, *Echinacea purpurea* (L.) Moench. *J Agric Food Chem* 57:2255–2258
- Arpana J, Bagyaraj DJ, Prakasa Rao EVS, Parameswaran TN, Abdul Rahiman BA (2008) Symbiotic response of patchouli [*Pogostemon cablin* (Blanco) Benth.] to different arbuscular mycorrhizal fungi. *Adv Environ Biol* 2(1):20–24
- Asrar AWA, Elhindi KM (2010) Elhindi. Alleviation of drought stress of marigold (*Tagetes erecta*) plants by using arbuscular mycorrhizal fungi. *Saudi J of Biol Sci* 18(1):93–98
- Awasthi A, Bharti N, Nair N, Singh R, Shukla AK, Gupta MM, Darokar MP, Kalra A (2011) Synergistic effect of *Glomus mosseae* and nitrogen fixing *Bacillus subtilis* strain Daz26 on artemisinin content in *Artemisia annua* L. *Appl Soil Ecol* 49:125–130
- Barrios E (2007) Soil biota, ecosystem services and land productivity. *Ecol Econ* 64:269–285
- Binet MN, Van Tuinen D, Deprêtre N, Koszela N, Chambon C, Gianinazzi S (2011) Arbuscular mycorrhizal fungi associated with *Artemisia umbelliformis* Lam, an endangered aromatic species in Southern French Alps, influence plant P and essential oil contents. *Mycorrhiza* 21:523–535
- Borde M, Dudhane M, Jite PK (2009) Role bioinoculant (AM fungi) increasing in growth, flavor content and yield in *Allium sativum* L. under field condition. *Not Bot Hort Agrobot Cluj* 37(2):124–128
- Cai BY, Jie WG, Ge JP, Yan XF (2008) Molecular detection of the arbuscular mycorrhizal fungi in the rhizosphere of *Phellodendron amurense*. *Mycosystema* 27(6):884–893
- Cao DX, Zhao JL (2007) The investigation of arbuscular mycorrhizal fungi and soil factors from the rhizosphere of medicinal plant *Angelica dahurica*. *Acta Agr Boreali-Sin* 22:47–50
- Chaudhary V, Kapoor R, Bhatnagar AK (2008) Effectiveness of two arbuscular mycorrhizal fungi on concentrations of essential oil and artemisinin in three accessions of *Artemisia annua* L. *Appl Soil Ecol* 40:174–181
- Chen LT, Guo QS, Liu ZY (2009a) Colonization pattern and dynamic change of arbuscular mycorrhizal fungi in *Pinellia ternate*. *Guizhou Agr Sci* 37(2):37–39
- Chen LT, Liu ZY, Guo QS, Zhu GS (2009b) Advances in studies on arbuscular mycorrhizas in medicinal plants. *Chin Tradit Herb Drugs* 40(1):156–160
- Chen LT, Guo QS, Liu ZY (2010) Arbuscular mycorrhiza of cultivated and wild *Pinellia ternate*. *Chin J Chin Mater Med* 35(4):405–410
- Cho EJ, Lee DJ, Wee CD, Kim HL, Cheong YH, Cho JS, Sohn BK (2009) Effects of AM FUNGI inoculation on growth of *Panax ginseng* C.A. Meyer seedlings and on soil structures in mycorrhizosphere. *Sci Hortic* 122(4):633–637
- Copetta A, Lingua G, Berta G (2006) Effects of three AM fungi on growth, distribution of glandular hairs, and essential oil production in *Ocimum basilicum* L. var. Genovese. *Mycorrhiza* 16:485–494
- Fan JH, Yang GT, Mu LQ, Zhou JH (2006) Effect of AM fungi on the content of berberine, jatrorrhizine and palmatine of *Phellodendron amurense* seedlings. *Prot Forest Sci Technol* 5:24–26
- Farahani HA, Lebaschi MH, Hamidi A (2008) Effects of arbuscular mycorrhizal fungi, phosphorus and water stress on quantity and quality characteristics of coriander. *J Adv Nat Appl Sci* 2(2):55–59
- Geneva MP, Stancheva IV, Boychinova MM, Mincheva NH, Yonova PA (2010) Effects of foliar fertilization and arbuscular mycorrhizal colonization on *Salvia officinalis* L. growth, antioxidant capacity, and essential oil composition. *J Sci Food Agric* 90:696–702
- Gianinazzi S, Gollotte A, Binet MN, Tuinen DV, Redecker D, Wipf D (2010) Agroecology: the key role of arbuscular mycorrhizas in ecosystem services. *Mycorrhiza* 20:519–530
- Gong MQ, Wang FZ, Chen Y (2002) Study on application of arbuscular-mycorrhizas in growing seedling of Aloe vera. *J Chin Med Mater* 25(1):1–3
- Guo LP, Wang HG, Hang LQ (2006) Effects of arbuscular mycorrhizae on growth and essential oil of *Atractylodes lancea*. *Chin J Chin Mater Med* 31(8):1491–1495
- Guo QS, Chen LT, Liu ZY (2010) Study on influence of arbuscular mycorrhizal fungi on *Pinellia ternata* yield and chemical composition. *Chin J Chin Med* 35(3):333–338
- Gupta ML, Prasad A, Ram M, Kumar S (2002) Effect of the vesicular-arbuscular mycorrhizal (VAM) fungus *Glomus fasciculatum* on the essential oil yield related characters and nutrient acquisition in the crops of different cultivars of menthol mint (*Mentha arvensis*) under field conditions. *Bioresour Technol* 81(1):77–79
- Hadwiger A, Neimann H, Kaebisch A, Bauer H, Tamura T (1986) Appropriate glucosylation of the FMS gene product is a prerequisite for its transforming potency. *EMBO J* 5:689–694
- Harris JC, Cottrell S, Plummer S, Lloyd D (2001) Antimicrobial properties of *Allium sativum* (garlic). *Appl Microbiol Biotechnol* 57:282–286
- Harrison M (1999) Molecular and cellular aspects of the arbuscular mycorrhizal symbiosis. *Annu Rev Plant Biol* 50:361–389
- He XL, Li J, Gao AX, Zhao LL, Zao JL (2009a) Effects of different host plants on the development of AM fungi in the rhizosphere of *Salvia miltiorrhiza*. *J Hebei Univers* 29(5):533–537
- He XL, Li J, He C (2009b) Effects of AM fungi on the chemical components of *Salvia miltiorrhiza* Bge. *Chin Agr Sci Bull* 25(14):182–185
- He XL, Liu T, Zhao LL (2009c) Effects of inoculating AM fungi on physiological characters and nutritional components of *Astragalus membranaceus* under different N application levels. *Chin J Appl Ecol* 20(9):2118–2122
- He XL, Wang LY, Ma J, Zhao LL (2010) AM fungal diversity in the rhizosphere of *Salvia miltiorrhiza* in Anguo city of Hebei province. *Biodiv Sci* 18(2):187–194
- Huang YF, Li HH, Chen HY, Li Y (2003) Preliminary study on the mycorrhiza inoculation on the seeding of camptotheca acuminata. *Guangdong ForestSci Technol* 19(1):40–42
- Huang LQ, Chen ML, Xiao PG (2004) The modern biological basis and model hypothesis on the research of genuineness of Chinese herbal medicine. *Chin J Chin Mater Med* 29(6):494–496
- Huang JH, Tan JF, Jie HK, Zeng RS (2011) Effects of inoculating arbuscular mycorrhizal fungi on *Artemisia annua* growth and its official components. *Chin J Appl Ecol* 22(6):1443–1449
- Janardhanan KK, Abdul-Khaliq K (1995) Influence of vesicular arbuscular mycorrhizal fungi on growth and productivity of German chamomile in alkaline usar soil. In: Adholeya A, Singh S (eds) *Mycorrhizae: Biofertilizers for the Future*. Tata Energy Research Institute New, Delhi, pp 410–412
- Jeffries P, Gianinazzi S, Peretto S, Turnau K, Barea JM (2003) The contribution of arbuscular mycorrhizal fungi in sustainable maintenance of plant health and soil fertility. *Biol Fertil Soils* 37:1–16
- Jie WG, Cai BY, Ge JP, Yan XF (2007) Identification of arbuscular mycorrhizal fungi of *Phellodendron amurense* Rupr. *Biotechnology* 17(6):32–35
- Jurkiewicz A, Ryszka P, Anielska T, Waligórski P, Białońska D, Góral ska K, Michael MT, Turnau K (2010) Optimization of culture conditions of *Arnica montana* L.: effects of mycorrhizal fungi and competing plants. *Mycorrhiza* 20:293–306
- Kapoor R, Giri B, Mukerji KG (2002a) *Glomus macrocarpum*: a potential bioinoculant to improve essential oil quality and concentration in Dill (*Anethum graveolens* L.) and Carum (*Trachyspermum ammi* (Linn.) Sprague). *World J Microb Biot* 18:459–463
- Kapoor R, Giri B, Mukerji KG (2002b) Mycorrhization of coriander (*Coriandrum sativum* L.) to enhance the concentration and quality of essential oil. *J Sci Food Agr* 82:339–342

- Kapoor R, Giri B, Mukerji KG (2004) Improved growth and essential oil yield and quality in *Foeniculum vulgare* mill on mycorrhizal inoculation supplemented with P-fertilizer. *Bioresour Technol* 93:307–311
- Kapoor R, Chaudhary V, Bhatnagar AK (2007) Effects of arbuscular mycorrhiza and phosphorus application on artemisinin concentration in *Artemisia annua* L. *Mycorrhiza* 17:581–587
- Karagiannidis N, Thomidis T, Lazari D, Filotheou EP, Karagiannidou C (2011) Effect of three Greek arbuscular mycorrhizal fungi in improving the growth, nutrient concentration, and production of essential oils of oregano and mint plants. *Sci Hortic* 129:329–334
- Khaosaad T, Vierheilig H, Nell M, Zitterl-Eglseer K, Novak J (2006) Arbuscular mycorrhiza alter the concentration of essential oils in oregano (*Origanum sp.*, Lamiaceae). *Mycorrhiza* 16:443–446
- Lee J, Scagel CF (2009) Chicoric acid found in basil (*Ocimum basilicum* L.) leaves. *Food Chem* 115(2):650–656
- Li CX (2003a) Effect of vesicular-arbuscular mycorrhizal fungi on production of *Ginseng*. *J Chin Med Mater* 26(7):475–476
- Li CX (2003b) Effects of infecting vesicular-arbuscular mycorrhiza on growth and development of *Coix Lachryma-jobi* L. *J Shanxi Agr Univers* 23(4):351–353
- Liu T, He XL (2008) Research on the formation course of arbuscular mycorrhizae from *Astragalus membranaceus* (Fisch.) Bunge seedlings. *J Hebei Fores Orc Res* 23(3):311–314
- Liu SL, He XL (2009) Effects of AM fungi on growth of *Glycyrrhiza inflata* Bat under water stress. *J Nuc Agr Sci* 23(4):692–696
- Liu JN, Wu LJ, Wei SL, Xiao X, Su CX, Jiang P, Song ZB, Wang T, Yu ZL (2007) Effects of arbuscular mycorrhizal fungi on the growth, nutrient uptake and glycyrrhizin production of licorice (*Glycyrrhiza uralensis* Fisch.). *Plant Growth Regul* 52(1):29–39
- Loomis WD, Croteau R (1972) Essential oil biosynthesis. *Rec Adv Phytochem* 6:147–185
- Lu YQ, He XL (2005) Effects of AM fungi on the chemical composition and growth amount of *Atractylodes macrocephala* koidz seedling on different N levels. *J Hebei Univers* 25(6):650–653
- Lu YQ, He XL (2008) Effects of AM fungi on photosynthetic pigment of *Atractylodes macrocephala* under different nitrogen levels. *Acta Agr Bor Occi Sin* 17(4):314–316
- Lu YQ, Cui Y, He XL (2008a) Effects of AM fungi on biomass and nitrogen content of *Atractylodes macrocephala* under different nitrogen levels. *J Henan Agr Sci* 4:94–96
- Lu YQ, He XL, Li LZ (2008b) Effects of AM fungi on leaf protective enzymes of *Atractylodes macrocephala* under different nitrogen levels. *Hubei Agr Sci* 47(6):659–660
- Lu YQ, Wang DX, Lu XL, Li LM, Li Y, He XL (2011) Effects of AM fungi on physiological character and nutritional component of *Atractylodes macrocephala* under different N levels. *Acta Bot Bor Occi Sin* 31(2):351–356
- Ma J, He XL, Jiang ZM, Wang LY (2009) Influence of soil factors on arbuscular mycorrhizal fungal colonization of *Salvia miltiorrhiza*. *Acta Agr Bor Occi Sin* 18(5):194–198
- Maier W, Schmidt J, Wray V, Walter MH, Strack D (1999) The arbuscular mycorrhizal fungus, *Glomus intraradices*, induces the accumulation of cyclohexenone derivatives in tobacco roots. *Planta* 207:620–623
- Meng JJ, He XL (2011) Effects of AM fungi on growth and nutritional contents of *Salvia miltiorrhiza* Bge. under drought stress. *J Agr Univ Hebei* 34(1):51–61
- Morone Fortunato I, Avato P (2008) Plant development and synthesis of essential oils in micropropagated and mycorrhiza inoculated plants of *Origanum vulgare* L. ssp. *hirtum* (Link) Ietswaart. *Plant Cell Tiss Org* 93:139–149
- Nell M, Vötsch M, Vierheilig H, Steinkellner S, Zitterl-Eglseer K, Franz C, Novak J (2009) Effect of phosphorus uptake on growth and secondary metabolites of garden (*Salvia officinalis* L.). *J Sci Food Agric* 89:1090–1096
- Nell M, Wawrosh C, Steinkellner S, Vierheilig H, Kopp B, Lössl A, Franz C, Novak J, Zitterl-Eglseer K (2010) Root solonization by symbiotic arbuscular mycorrhizal fungi increases sesquiterpenic acid concentrations in *Valeriana officinalis* L. *Planta Med* 76:393–398
- Pan PL, Chen DQ, Chen YT, Zhou FM (2008) The research on the sift and germinate of AM FUNGI spore of *Ophiopogon japonicas*. *Mod Chin Med* 10(10):13–14
- Petersen M, Simmonds MSJ (2003) Rosmarinic acid. *Phytochemistry* 62:121–125
- Prasad A, Kumar S, Khaliq A, Pandey A (2011) Heavy metals and arbuscular mycorrhizal (AM) fungi can alter the yield and chemical composition of volatile oil of sweet basil (*Ocimum basilicum* L.). *Biol Fert Soils* 47(8):853–861
- Qi GH, Zhang LP, Yang WL, Lu XR, Li CL (2002) Effects of arbuscular mycorrhizal fungi on growth and disease resistance of replanted ginkgo (*Ginkgo biloba* L.) seedlings. *J Hebei Forest Orch Res* 17(1):58–61
- Qi GH, Zhang LP, Yang WL, Lv GY (2003) The effects of arbuscular mycorrhiza fungi on ginkgo (*Ginkgo biloba* L.) in the field. *Hebei Fruits* 19(1):40–42
- Rapparini F, Llusia J, Penuelas J (2008) Effect of arbuscular mycorrhizal (AM) colonization on terpene emission and content of *Artemisia annua* L. *Plant Biol* 10:108–122
- Rasouli-Sadaghiani MH, Hassani A, Barin M, Danesh YR, Sefidkon F (2010) Effects of arbuscular mycorrhizal (AM) fungi on growth, essential oil production and nutrients uptake in basil. *J Med Plants Res* 4(21):2222–2228
- Ren JH, Liu RX, Li YL (2007) Study on arbuscular mycorrhizae of *Panax notoginseng*. *Microbiology* 34(2):224–227
- Ren JH, Zhang JF, Liu RX, Li YQ (2008) Study on arbuscular mycorrhizae in *Taxus chinensis* var. *mairei*. *Acta Bot Bor Occi Sin* 28(7):1468–1473
- Rojas-Andrade R, Cerda-García-Rojas CM, Frías-Hernández JT, Dendooven L, Olalde-Portugal V, Ramos-Valdivia AC (2003) Changes in the concentration of trigonelline in a semi-arid leguminous plant (*Prosopis laevigata*) induced by an arbuscular mycorrhizal fungus during the presymbiotic phase. *Mycorrhiza* 13:49–52
- Rosa-Mera CJD, Ferrera-Cerrato R, Alarcón A, Sánchez-Colín MJ, David OD (2011) Arbuscular mycorrhizal fungi and potassium bicarbonate enhance the foliar content of the vinblastine alkaloid in *Catharanthus roseus*. *Plant Soil* 349:367–376
- Sailo GS, Bagyaraj DJ (2005) Influence of different AM-fungi on the growth, nutrition and forskolin content of *Coleus forskohlii*. *Mycol Res* 109(7):795–798
- Shah V, Bhat SV, Bajwa BS, Domacur H, De SNJ (1980) The occurrence of forskolin in Labiatae. *Planta Med* 39:183–185
- Shen XL, Guo QS, Liu ZY, Zhu GS, Liu YX (2011) Colonization progress of arbuscular mycorrhizae on tissue-cultured plantlets of *Pinellia ternata*. *Chin J Chin Mater Med* 36:93–96
- Singh R, Soni SK, Kalra A (2013) Synergy between *Glomus fasciculatum* and a beneficial *Pseudomonas* in reducing root diseases and improving yield and forskolin content in *Coleus forskohlii* Briq. under organic field conditions. *Mycorrhiza* 23:35–44
- Smith SE, Read DJ (1997) *Mycorrhizal symbiosis*. Academic Press Ltd., London
- Smith SE, Read DJ (2008) *Mycorrhizal symbiosis*, 3rd edn. Academic, London
- Szakiel A, Pączkowski, Henry (2011a) Influence of environmental biotic factors on the content of saponins in plants. *Phytochem Rev* 10:493–502
- Szakiel A, Pączkowski, Henry (2011b) Influence of environmental abiotic factors on the content of saponins in plants. *Phytochem Rev* 10:471–491
- Teng HR, He XL (2005) Effects of different AM fungi and N levels on the flavonoid content of *Bupleurum scorzonnerifolium* Willd. *J Shanxi Agr Sci* 4:53–54

- Toussaint JP (2007) Investigating physiological changes in the aerial parts of AM plants: what do we know and where should we be heading? *Mycorrhiza* 17:349–353
- Toussaint JP, St-Arnaud M, Charest C (2004) Nitrogen transfer and assimilation between the arbuscular mycorrhizal fungus *Glomus intraradices* Schenk & Smith and Ri T-DNA roots of *Daucus carota* L. in an in vitro compartmented system. *Can J Microbiol* 50:251–260
- Toussaint JP, Smith FA, Smith SE (2007) Arbuscular mycorrhizal fungi can induce the production of phytochemicals in *sweet basil* irrespective of phosphorus nutrition. *Mycorrhiza* 17:291–297
- Volpin H, Elkind Y, Okon Y, Kapulnik Y (1994) A vesicular arbuscular mycorrhizal fungus (*Glomus intraradices*) induces a defense response in alfalfa roots. *Plant Physiol* 104:683–689
- Wang LY, He XL (2009) The resource and spatio-temporal distribution of AM fungi from *Salvia miltiorrhiza* in Anguo. *J Agr Univ Hebei* 32(6):73–79
- Wang Q, Li HQ, Du YR, Li Y, Li HW (1998) Isolation and identification of VA mycorrhizal fungi on *Radix gentianae*. *Biotechnology* 8(2):19–22
- Wang Q, He XL, Chen TS, Dou WF (2006) Ecological research of arbuscular mycorrhizal fungi in rhizosphere of *Pueraria lobata*. *J Hebei Univ* 26(4):420–425
- Wang DX, Lu YQ, He XL (2010) Effects of AM fungi on growth and physiological characters of *Atractylodes Macrocephala* under different P-applied levels. *Acta Bot Bor Occi Sin* 30(1):136–142
- Wei GT, Wang HG (1989) Effects of VA mycorrhizal fungi on growth, nutrient uptake and effective compounds in Chinese medicinal herb *Datura stramonium* L. *Sci Agr Sin* 22(5):56–61
- Wei GT, Wang HG (1991) Effect of vesicular-arbuscular mycorrhizal fungi on growth, nutrient uptake and synthesis of volatile oil in *Schizonepeta tenuifolia* Briq. *Chin J Chin Mater Med* 16(3):139–142
- Wu QC, Wei QA (2008) Arbuscular mycorrhizae of *Ginkgo biloba* and its correlation with soil available phosphorus. *J Yangtze Univ* 5(3):49–52
- Wu QS, Liu W, Zhai HF, Ye XF, Zhao LJ (2010) Influences of AM fungi on growth and root antioxidative enzymes of *Trifoliate orange* seedlings under salt stress. *Acta Agr Univ Jiangxiensis* 32(4):759–762
- Xiao WJ, Yang G, Chen ML, Guo LP, Wang M (2011) AM and its application in plant disease prevention of Chinese medicinal herbs cultivation. *Chin J Chin Med* 36(3):252–257
- Xing XK, Li Y, Yolande D (2000) Ten species of vAM fungi in five ginseng fields of Jilin province. *J Jilin Agr Univ* 22(2):41–46
- Xing XK, Li Y, Wang Y, Zhang MP (2003) Foundation of dual cultural system of ginseng VA mycorrhiza fungi. *J Jilin Agr Univ* 25(2):154–157
- Yang G, Guo LP, Huang LQ, Chen M (2008) Inoculation methods of AM fungi in medicinal plant. *Resources Sci* 30(5):778–785
- Yu Y, Yu T, Wang Y, Yan XF (2010) Effect of inoculation time on camptothecin content in arbuscular mycorrhizal *Camptotheca acuminata* seedlings. *Chin J Plant Ecol* 34(6):687–694
- Zeng Y, Guo LP, Hang LQ, Zhou J, Sun YZ (2007) AM and its application in TCM cultivation. *World Sci Technol/Moder TCM Mater Med* 9(6):83–87
- Zhang MC, Jing YJ, Ma J (1990) The changing of microbial ecological types after the improvement of ginseng soil. *J Jilin Agr Univ* 12(4):42–46
- Zhang Y, Xie LY, Xiong BQ, Zeng M, Yu D (2004) Correlation between the growth of arbuscular mycorrhizal fungi in the rhizosphere and the flavonoid content in the root of *Ginkgo biloba*. *Mycosystema* 23(1):133–138
- Zhang J, Liu DH, Guo LP, Jin H, Zhou J, Yang G (2010) Effects of four AM fungi on growth and essential oil composition in rhizome of *Atractylodes lancea*. *World Sci Technol/Moder TCM Mater Med* 12(5):779–782
- Zhang J, Liu DH, Guo LP, Jin H, Yang G, Zhou J (2011) Effects of arbuscular mycorrhizae fungi on biomass and essential oil in rhizome of *Atractylodes lancea* in different temperatures. *Chin Tradi Her Drugs* 42(2):372–375
- Zhao JL, He XL (2011) Effects of AM fungi on drought resistance and content of chemical components in *Angelica dahurica*. *Acta Agr Bor Occi Sin* 20(3):184–189
- Zhao X, Wang BW, Yan XF (2006) Effect of arbuscular mycorrhiza on camptothecin content in *Camptotheca acuminata* seedlings. *Acta Ecol Sin* 26(4):1057–1062
- Zhao PJ, An F, Tang M (2007) Effects of arbuscular mycorrhiza fungi on drought resistance of *Forsythia suspense*. *Acta Bot Bor Occi Sin* 27(2):396–399
- Zhao JL, Deng HY, He XL (2009) Effects of AM fungi on the quality of trueborn *Angelica dahurica* from Hebei province. *Acta Agr Boreali-Sin* 24:299–302
- Zhou JH, Fan JH (2007) Effects of AM fungi on the berberine content in *Phellodendron chinense* seedlings. *North Hortic* 12:25–27
- Zhou N, Xia CL, Jiang B, Bai ZC, Liu GN, Ma XK (2009) Arbuscular mycorrhiza in *Paris polyphylla* var. *yunnanensis*. *Chin J Chin Med* 34(14):1768–1772
- Zhou N, Zou L, Wang GZ, Jiang B (2010) Primary explore to relation of arbuscular mycorrhizae and its secondary metabolite steroidal saponin in *Paris polyphylla*. *Chin J Exper Trad Med Formulae* 16(16):85–88
- Zubek S, Stojakowska A, Anielska T, Turnau K (2010) Arbuscular mycorrhizal fungi alter thymol derivative contents of *Inula ensifolia* L. *Mycorrhiza* 20:497–504
- Zubek S, Mielcarek S, Turnau K (2012) Hypericin and pseudohypericin concentrations of a valuable medicinal plant *Hypericum perforatum* L. are enhanced by arbuscular mycorrhizal fungi. *Mycorrhiza* 22:149–156