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菌根真菌处理下滇重楼对营养元素的吸收和积累*

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摘 要 通过室温盆栽接种实验,研究在灭菌土壤中,不同丛枝菌根(arbuscular mycorrhizal,AM)真菌处理对滇重楼不同采收期的根际土壤和药材中 N、P、K、Mg、Na、Ca 等 10 种营养元素吸收积累的影响.结果表明,接种不同 AM 真菌可增加果熟期重楼药材中 Mg、Na、Zn、Ni 等营养元素的含量,并能降低重金属离子 Cu 的含量,而衰老期无明显差异;还可对滇重楼根际土壤中 N、P、K、Mn、Ni 等营养元素浓度产生一定影响,增强滇重楼对 Mg、Zn、Ni 的富集能力.在滇重楼的生长过程中,根际土壤和药材中的营养元素含量间存在相关性:成熟期根际土壤中 Na 含量与药材中 N 含量呈正相关,衰老期根际土壤 P 含量与药材中 N、Mg 含量呈负相关.土壤与药材中的营养元素含量相互影响,并对药材的品质形成有较大影响.故可通过接种 AM 真菌增加根际土壤和滇重楼药材中相关营养元素的含量,从而起到提高重楼品质的作用.

关键词 滇重楼, 土壤, AM 真菌, 营养元素, 富集特性.

Absorption and accumulation of mineral elements by *Paris polyphylla* var. *yunnanensis* with different arbuscular mycorrhizal fungi

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Abstract: A potted inoculation experiment was used to study the cumulative effects of 10 nutrient elements in rhizosphere soil and medicinal herbs treated with different AM fungi, such as N、P、K、Mg、Na、Ca, etc. The results showed that inoculation with different AM fungi increased the contents of Mg、Na 、Zn、Ni and decrease the contents of heavy metal ion Cu at the Paris at the fruit maturing stage, but there was no significant difference at the senescence stage. It also influenced the concentrations of nutrient elements in the rhizosphere soil, such as N、P、K、Mn、Ni, and enhance the enrichment ability to Mg、Zn、Ni.There was a correlation between the contents of nutrient elements in rhizosphere soil and medicinal materials during the growth process of *Paris polyphylla* var. *yunnanensis*, and there was a positive correlation between the content of Na in rhizosphere soil and the content of N in *Paris polyphylla* var.*yunnanensis* at the maturity. The contents of P in rhizosphere

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soil was negatively correlated with the contents of N、Mg in Pairs during senescence stage.The content of nutrient elements in soil directly affects the content of nutrient elements in medicinal materials, and had a great effect on the yield and quality of medicinal materials. Therefore, in actual production, AM fungi inoculation can increase the content of related nutrient elements in the rhizosphere soil and medicinal herbs, so as to play a role in improving the quality of *Paris polyphylla* var.*yunnanensis*.

Keywords: *Paris polyphylla* var.*Yunnanensis*, soil, arbuscular mycorrhizal fungi, mineral element, enrichment factors.

滇重楼(*Paris polyphylla* var. *yunnanensis*)为百合科重楼属植物,具有清热解毒、消肿止痛、凉肝定惊之功效,为临床常用清热解毒药[1].近年来,云南、贵州、重庆等地滇重楼栽培面积不断增加以供应市场需求,缓解市场的供需矛盾,然而不规范种植技术及含重金属的农药化肥的不合理使用,使得滇重楼生长地的土壤环境日益恶化,造成滇重楼产量和品质下降[2-5].因此,通过农业生物技术途径来提高滇重楼产量和品质已成为国内研究滇重楼规范化栽培体系的热点领域.

丛枝菌根真菌(arbuscular mycorrhizal fungi),简称 AMF 或 AM 真菌,是一类广泛分布于陆地生态系统中的土壤微生物,能与绝大部分植物根系形成互惠共生体[6],已成为一类新型的微生物肥料.前期研究表明,滇重楼是典型的丛枝菌根植物,AM 真菌能改善滇重楼植株的光合特性与生理生化指标、提高其根茎的化学品质[7-9],并且丛枝菌根菌丝可协助宿主植物吸收营养元素和水分,从而增强植物对营养物质的吸收能力,促进植物生长发育并提高抗逆性[10-12].

矿质营养在生物体内参与激素、酶、维生素等相关的众多生理活性反应,对机体代谢有着十分重要的作用.何忠俊等[13-16]采用盆栽实验,研究比较钙、镁、锌、钼等无机元素水平对滇重楼生长的影响,结果显示,钙可增加滇重楼株高;镁能降低滇重楼株高,使叶变大;锌可提高滇重楼株高,但对根茎增加不显著;钼显著提高了滇重楼株高和根茎产量.说明矿质营养对重楼的生长发育有一定的作用,其作用方式与矿质营养元素种类和含量密切相关.李秀珍等[17]采用等离子体发射光谱法对北重楼根及根茎中的微量元素进行检测分析,发现 Ca、Zn 含量可能与重楼的消炎、止血、生肌作用有关;高含量的 Mg 能促进抗毒素的合成,提高机体免疫力.说明重楼药材的多种药理活性与矿质营养元素含量有一定的关系.接种 AM 真菌能够增加矿质营养元素在土壤中的含量,促进滇重楼根系对微量元素的吸收利用,还可部分提高滇重楼植株中甾体皂苷的含量,提高滇重楼的品质[7,18-19].

本实验在室温盆栽条件下研究了接种不同种 AM 真菌对滇重楼根茎及其根际土壤中营养元素含量的影响,为充分利用 AM 真菌资源提高滇重楼的品质提供理论和技术支持.

1 材料与方法(Materials and methods)

1.1 供试材料与培养

本实验所用 AM 真菌为通过美国国际丛枝菌根真菌种质资源保藏中心(INVAM)所购得的相应 AM 真菌纯净菌剂,接种菌剂为带有菌丝、孢子及侵染后根段的栽培基质[20],见表 1.

栽培基质取自重庆三峡学院百安校区附近农田,风干后过 2 mm 筛,与河沙 3∶1(*V*/*V*)混匀,121 ℃高压灭菌 2 h,晾干备用.采用室温盆栽方法,设 AM(接种 28 种 AM 真菌)组和 CK(对照)组共 29 个处理.每处理 6 盆,每盆栽种 15 株滇重楼.将栽培袋用 10%次氯酸钠溶液消毒 15 min 后,并用流水清洗干净.

2013 年 2 月 24 日,选择大小一致的滇重楼根茎,接种方法为层施,接种剂量为每盆 15 mL(接种菌剂为带有 AM 真菌孢子、根外菌丝及侵染后根段的栽培土壤混合样品,每 1 mL 约含 60 个孢子[21].对照组加入等量的灭菌接种剂,接种后于室温中培养,给予自然光照.生长发育期间定期浇 Hoagland 营养液以满足植物对养分的需求.

供试滇重楼新鲜根茎选自云南省大理州农业科学推广研究院种植基地同一批次、大小一致、生长良好

的样品,经大理大学张海珠副教授鉴定为百合科植物滇重楼(*Paris polyphylla* var. *yunnanensis*)的新鲜根茎.

表 1　不同处理组及其接种 AM 真菌

Table 1　Different treatment groups and inoculated AM fungi

处理组 Group	AM 真菌 AM fungus	处理组 Group	AM 真菌 AM fungus
Ga	*Gigaspora albida*	Rcl	*Rhizophagus clarus*
Gd	*Gigaspora decipiens*	Rin	*Rhizophagus intraradices*
Gg	*Gigaspora gigantea*	Afo	*Acaulospora foreata*
Gm	*Gigaspora margarita*	Ako	*Acaulospora koskei*
Gr	*Gigaspora rosea*	Asc	*Acaulospora scrobiculata*
Sca	*Scutellospora calospora*	Asp	*Acaulospora spinosa*
Sdi	*Scutellospora dipurpurascens*	De	*Diversispora eburnea*
Spe	*Scutellospora pellucida*	Ds	*Diversispora spurca*
Dh	*Dentiscutata heterogama*	Ec	*Entrophospora colombiana*
Rco	*Racocetra coralloidea*	Pb	*Paraglomus brasilianum*
Rfu	*Racocetra fulgida*	Po	*Paraglomus occultum*
Sde	*Septoglomus deserticola*	Ale	*Ambispora leptoticha*
Svi	*Septoglomus viscosum*	Atr	*Archaeospora trappei*
Fm	*Funneliformis mosseae*	CK	CK groups
Cc	*Claroideoglomus claroideum*		

1.2　滇重楼根际土壤及药用部分的采集与处理

分别于 2013 年 8 月 10 日(果熟期)和 2013 年 11 月 12 日(衰老期)[22]采集滇重楼根际土壤及新鲜根茎.抖动根系去掉黏附在根系上的较大颗粒土,余下的土壤即为根际土,实验室自然风干,按分析要求分别研磨后过筛(40 目),备用.滇重楼根茎清洗后,45 ℃条件下烘干,按分析要求分别磨细过筛(40 目),备用[23].

1.3　仪器与试剂

TAS-990AFG 型原子吸收分光光度计(北京普析通用仪器有限责任公司);C-MAG HP10 型数显加热板(德国 IKA 集团);DZF-6050MBE 型电热恒温真空干燥箱(上海博讯实业有限公司);磷(P)、钾(K)、钙(Ca)、镁(Mg)、钠(Na)、猛(Mn)、锌(Zn)、铜(Cu)、镍(Ni)空心阴极灯(北京曙光明电子光源仪器有限公司);AE-240 型分析天平(梅特勒-托利多仪器上海有限公司).试剂均为优级纯,水为去离子水.

1.4　分析方法

采用原子吸收光谱法测定不同 AM 真菌处理下滇重楼药用部分及根际土壤中 磷(P)、钾(K)、钙(Ca)、镁(Mg)、钠(Na)、猛(Mn)、锌(Zn)、铜(Cu)、镍(Ni)的含量[24],氮(N)采用凯氏定氮法测定[25].

1.5　滇重楼中营养元素富集系数评价

富集系数(C)= 营养元素在植物体中的量/营养元素在其植物所生长土壤中的量[26].

1.6　数据处理

采用 Excel 软件以及 SPSS 19.0 统计软件对所测数据进行处理,并进行 LSD 检验和 DUNCAN 多重比较及相关性分析.

2　结果与讨论(Results and discussion)

2.1　栽培土壤中的营养元素含量分析

土壤中营养元素参与植物生长发育过程,调节植物体各项生理功能,是植物产量和品质形成的重要物质基础[27].通过原子吸收光谱法及凯氏定氮法,系统检测了不同采收期接种不同 AM 真菌后栽培土壤中营养元素的含量,结果显示,与对照组相比,接种不同 AM 真菌后滇重楼根际土壤中营养元素含量存在显著差异,其中 N、P、K、Ca、Na、Mn、Ni 等营养元素在果熟期的根际土壤中含量相对较高,而 Cu、Ni 等营养元素在衰老期的根际土壤中含量相对较高,并且不同 AM 真菌对根际土壤中营养元素作用能力不一.这说明土壤中营养元素含量不仅与 AM 真菌菌株有关,与植株所处的生长发育时期也有很大关系.结果见表 2.

表 2 土壤中营养元素含量的比较(mg·kg^{-1})

Table 2 Comparison of nutrient contents in the soil (mg·kg^{-1})

处理组	N		P		K		Ca		Mg		Na		Mn		Zn		Cu		Ni	
Group	果熟期	衰老期	果熟期	衰老期	果熟期	衰老期	果熟期	衰老期	果熟期	衰老期	果熟期	衰老期	果熟期	衰老期	果熟期	衰老期	果熟期	衰老期	果熟期	衰老期
Ga	31.502m	55.983f	242.494h	244.177abcdefg	8.728abcdef	8.328a	40.676no	39.708n	15.843c	8.550k	0.926g	0.779cd	161.790r	182.148o	69.860fg	47.429lmno	12.725a	11.420a	21.083ab	16.413bc
Gd	41.962k	27.986j	271.994efg	252.836abcdefg	7.588hij	7.613a	42.029lm	38.486o	11.625k	10.810ij	0.868gh	0.675cdefg	158.052s	210.799jk	73.750de	56.236ghi	12.438a	11.622a	22.188a	17.933abc
Gg	56.006i	41.996h	264.958fg	218.419cdefg	9.398a	7.283a	45.398h	40.404m	14.180fg	10.563ij	1.559a	0.665cdefg	170.151p	196.636m	84.958b	68.750c	12.681a	10.750a	20.740abc	17.625abc
Gm	195.961c	83.924c	223.396i	284.291abcd	8.449abcdefgh	7.608a	47.492f	43.855hi	13.237hi	13.497de	0.837ghijk	0.650cdefg	180.210m	231.101e	74.925d	54.986hij	13.174a	10.497a	20.230abcd	16.933bc
Gr	38.494k	13.985k	228.683hi	270.046abcdef	9.048abcd	6.845a	45.245h	38.567o	10.929klm	9.000k	1.044f	0.510g	178.226mn	223.036gh	76.193d	56.250ghi	12.990a	12.063a	20.859abc	17.313abc
Sca	69.965h	56.000f	301.566cd	247.022abcdefg	8.362bcdefgh	7.071a	46.351g	38.274o	10.362m	8.810k	1.141e	0.742cde	159.883rs	208.768kl	67.416ghi	64.984d	14.170a	10.122a	18.789bcd	16.871bc
Sdi	139.930d	41.971h	306.582c	255.281abcdefg	7.669ghij	8.803a	46.598g	44.833ef	14.930de	14.805c	0.775hijklm	0.832c	157.973s	226.984f	74.963d	61.219ef	13.181a	11.369a	17.616bcd	18.116ab
Spe	24.500o	69.930e	216.426i	248.507abcdefg	8.708abcdef	8.430a	41.796lm	39.920mn	11.682k	10.172ij	0.867gh	0.562efg	245.251d	206.480l	58.721lmn	49.925klm	12.556a	9.174b	17.866bcd	17.287abc
Dh	83.983g	27.997j	239.077hi	120.357h	9.086abc	8.441a	47.363f	48.422c	12.366j	13.927cd	0.822ghijk	0.724cde	190.401k	226.927f	78.691c	47.464lmno	12.803a	11.242a	18.486bcd	18.049ab
Rco	230.977b	14.000k	238.982hi	309.180ab	7.819fghij	9.333a	59.507a	44.892ef	16.800b	9.868j	1.474b	1.380a	245.190d	226.927f	61.204kl	48.713lmn	13.990a	13.552a	14.364e	16.613bc
Rfu	27.986n	27.987j	353.207a	323.036a	8.080defghij	8.482a	42.866jk	56.358a	10.997klm	15.539b	1.250d	0.751cde	202.678i	261.228a	71.232ef	42.436p	13.059a	11.233a	13.497e	17.599abc
Sde	41.987k	27.975j	258.134g	186.201g	5.363k	8.409a	51.214d	41.150l	12.875ij	8.181k	0.390o	0.727cde	164.144q	216.781i	65.000ij	51.212jkl	11.563a	12.303a	16.875d	17.424abc
Svi	83.924g	27.986j	302.996c	202.656efg	7.824fghij	7.691a	56.330b	45.197e	19.985a	6.248l	1.346c	0.565efg	206.635h	196.587m	64.951ij	43.739op	12.366a	10.997a	18.049bcd	17.371abc
Fm	41.929k	14.000k	297.802cd	233.787bcdefg	8.816abcde	8.143a	42.220kl	39.970mn	14.805def	8.560k	0.747hijklm	0.632defg	176.240n	208.768kl	57.471mn	44.989nop	11.494a	11.185a	19.053abcd	17.308abc
Cc	55.961i	41.975h	308.252c	271.940abcdef	7.368ij	8.251a	41.817lm	39.618n	9.375n	8.857k	0.625n	0.529fg	212.882g	234.751d	67.500ghi	51.148jkl	11.875a	11.415a	17.125cd	18.089ab
Rcl	55.978i	27.990j	273.562efg	277.357abcde	9.030abcd	9.718a	44.360i	44.175ghi	14.313efg	17.045a	0.643n	0.764cd	253.497c	255.272b	68.750fgh	54.945hij	12.563a	12.113a	17.688bcd	17.358abc
Rin	41.987k	73.504de	214.609i	290.301abcd	9.216ab	8.660a	42.057lm	41.733k	8.991n	12.288fg	0.657mn	0.619defg	279.617a	220.564h	67.433ghi	57.385fghi	11.801a	10.978a	18.294bcd	16.904bc
Afo	56.000i	27.986j	323.708b	265.117abcdef	8.767abcdef	8.643a	40.484no	39.900mn	12.481j	14.658c	0.724jklmn	0.644cdefg	180.120m	210.430jk	68.647fgh	46.158mnop	12.169a	11.914a	17.411bcd	20.958a
Ako	35.005l	48.980g	311.529bc	215.517defg	8.631abcdef	8.065a	41.221mn	39.708n	10.367m	10.359ij	0.684lmn	0.786cd	174.167o	192.286n	66.200hi	74.888b	12.178a	11.420a	12.491ef	17.162ab
Asc	41.975k	27.996j	363.668a	291.859abcd	7.941efghij	6.789a	48.658e	44.201ghi	13.934g	11.727gh	0.805ghijkl	0.679cdefg	202.678i	224.617fg	71.232ef	51.148jkl	12.559a	11.352a	10.622fg	17.340abc
Asp	27.992n	41.987h	306.520cd	296.130abc	7.194j	6.799a	51.895c	46.246d	13.743gh	11.103hi	0.737hijklmn	0.778cd	194.508j	220.564h	41.229p	53.643ijk	12.181a	12.849a	9.745g	16.592bc
De	55.833i	48.995g	284.178de	196.436fg	9.260ab	8.433a	43.420j	49.788b	11.244kl	14.309cd	0.825ghijk	0.700cdef	178.270mn	245.313c	51.224o	44.989nop	12.869a	11.622a	19.053abcd	16.496bc
Ds	125.975e	41.987h	287.586ef	188.686g	8.216cdefghi	9.540a	43.154j	42.562j	10.544lm	16.488a	0.826ghijk	0.650cdefg	186.156l	235.044d	62.391jk	47.464lmno	12.853a	11.242a	18.530bcd	17.549abc
Ec	41.992k	41.983h	289.087ef	308.067ab	8.604abcdef	8.261a	42.894jk	44.071ghi	11.486k	12.603f	0.844ghij	0.636cdefg	265.350b	210.483jk	73.658de	58.647efgh	11.486a	11.355a	17.104cd	13.851c
Pb	31.502m	76.965d	155.796k	262.413abcdef	8.555abcdefg	9.431a	40.828n	44.598fg	15.063d	13.487de	0.728ijklmn	0.752cede	216.944f	232.957de	52.500o	62.438de	12.188a	10.677a	19.438abcd	17.358abc
Po	34.998l	55.983f	159.258k	268.422abcdef	9.015abcd	8.575a	41.675lm	41.895k	12.563j	14.353cd	0.860ghi	0.629defg	227.097e	206.480l	52.500o	59.910efg	12.313a	2.808c	18.813bcd	17.661abc
Ale	272.986a	34.995i	192.148j	277.080abcde	8.606abcdef	8.939a	39.375p	46.117d	14.048g	14.350cd	0.659mn	0.799cd	216.727f	230.755e	59.940klm	121.038a	12.737a	13.040a	18.419bcd	17.719abc
Atr	111.955f	118.988b	123.102l	272.697abcdef	8.340bcdefgh	8.373a	39.930op	44.413fgh	11.423k	11.165hi	0.709klmn	0.504g	226.814e	234.751d	56.180n	57.385fghi	12.734a	9.481b	18.290bcd	16.779bc
CK	52.482j	349.965a	218.201i	278.002abcde	0.027l	9.333a	39.930op	43.714i	11.423k	12.809ef	0.406o	0.942b	6.250t	212.829j	108.125a	69.983c	12.188a	10.622a	4.688h	15.996bc

注:每组同列不同的小写字母代表0.05水平上显著性差异;果熟期 Ripening pereid; 衰老期 Aging period

2.2　药材中营养元素含量分析

植物体营养元素含量水平是植株在生长发育过程中吸收累积的土壤营养元素经植株代谢利用后剩余的部分,它与栽培土壤的营养水平有密切关系,但主要还是由植株的自身特异性所决定[28].从表 3 可知,在果实成熟期,接种 AM 真菌条件下的滇重楼药材中 Mg、Na、Zn、Ni 含量普遍高于 CK 组,最高与 CK 组相差 21 倍;重金属 Cu 的含量在接种 AM 真菌后显著低于 CK 组.但衰老期无显著性差异.有研究表明滇重楼中重要的药效成分重楼皂苷 I 与植株中 Mg 的含量呈正相关;重楼皂苷 II 与无机元素 Ni 呈正相关;重楼皂苷 VII 与无机元素 Na 呈正相关[29].所以接种 AM 真菌可通过增加相关无机元素在植株内的富集来提高滇重楼有效成分含量,降低对人体有害的重金属元素含量,提高其品质.

2.3　药材对营养元素富集系数

富集系数(C)表示植物体对某种营养元素的吸收特征,反映了植物中某营养元素含量与其生长基质中同种元素含量对比相对贫化或富集的程度[30].其中 $C<0.1$ 时表示强烈贫化,$C<0.5$ 时表示相对贫化,$0.5<C<1.5$ 时表示二者属同一水平,$1.5\leqslant C\leqslant 3$ 时表示相对富集,$C>3$ 时表示强烈富集[31].表 4 中富集系数的均数分析表明,滇重楼对部分 AM 真菌处理组 Na、Cu、K、Mn、Ni 的富集能力较强,而应用 AM 菌后可明显增大滇重楼对 Mg、Zn、Ni 的富集能力.

2.4　土壤中营养元素间相关性分析

由表 5 可知,果熟期滇重楼种植基地土壤中的营养元素间存在不同程度的相关性.Mg 与 Ca 存在显著性正相关,Mn 与 K 存在显著性正相关,Zn 与 K、Mn 存在显著性负相关,Cu 与 N、Na 存在显著性正相关,Ni 与 K 存在显著性正相关,表明种植基地土壤中以上两种营养元素之间存在相互促进或抑制吸收的关系.其余营养元素两两之间亦存在不同程度的相关性,但均未达到显著水平.衰老期 Mg 与 K、Ca 存在显著性正相关,Mn 与 Ca、Mg 存在显著性正相关,其他元素间呈负相关或正相关但均未达到显著性.

2.5　药材中营养元素间相关性分析

表 6 中结果显示果熟期滇重楼根茎中的营养元素间存在不同程度的相关性:Mg 与 Ca 有显著正相关性,Mn、Zn、Cu 分别与 Mg、Ca 呈明显正相关,Mn 与 Zn、Cu、Ni 以及 Cu 与 Ni 之间均呈显著性正相关.由此说明以上两种营养元素之间存在协同作用.其余元素间存在正相关或负相关但未达到显著性.衰老期时 Mn 与 Ca、Mg 呈显著性正相关,Cu 与 Zn 呈显著性正相关.其余元素之间呈正相关或负相关,均未达到显著性水平.由此推测,多种营养元素在滇重楼生长过程中的积累可能存在竞争或协同两种效应,不同生长时期表现出不同的变化规律.

2.6　药材与土壤间营养元素相关性分析

对接种不同 AM 真菌滇重楼种植土壤与根茎间的 10 种矿质营养元素的量变化的相关性分析(表 7),结果表明:成熟期根际土壤 Na 与药材中 N 元素的量呈正相关,土壤 Mn 与药材中 Zn 元素的量呈正相关;衰老期根际土壤 P 与药材中 N、Mg 元素的量呈显著负相关,土壤 Na 和药材 P 元素的量呈显著负相关.说明滇重楼药材中这些营养元素与土壤环境背景值密切相关,土壤营养元素含量影响药材中营养元素含量[32].

3　结论(Conclusion)

不同 AM 真菌处理对滇重楼种植土壤及药材中营养元素的含量有较大影响.与 CK(空白)组相比,接种 AM 真菌可增加滇重楼药材中 Mg、Na、Zn、Ni 元素的含量,降低重金属元素 Cu 的含量,即提高药材品质的同时减少对人体有害的重金属元素 Cu 的含量;还可增加果熟期根际土壤中 N、P、K、Ca、Na、Mn、Ni 等营养元素含量,促进营养物质的形成积累.而不同生长期的滇重楼各营养元素含量有显著性差异,即滇重楼对各元素的富集能力受生长期的影响较大.其中果熟期较衰老期含有更为丰富的营养元素种类及数量,且重金属含量较少,药用价值相对较高,是药材采集的最佳时期.AM 真菌处理能够促进营养元素进入到植物体内,可明显增大滇重楼对 Mg、Zn、Ni 的富集能力,但不同菌株对增加植物内营养元素含量的能力有所不同,这也说明优良菌株的筛选十分必要.通过药材与土壤间营养元素相关性分析,重楼中营养元素含量多少的顺序与根际土壤中存在相似性,表明重楼对营养元素的吸收与根际土壤营养元素之间有一定关联性.

表 3 药材中营养元素含量的比较(mg·kg^{-1})

Table 3 Comparison of nutrient contents in the herbs (mg·kg^{-1})

处理组 Group	N		P		N/P		K		Ca		Mg		Na		Mn		Zn		Cu		Ni	
	果熟期	衰老期	果熟期	衰老期	果熟期	衰老期	果熟期	衰老期	果熟期	衰老期	果熟期	衰老期	果熟期	衰老期	果熟期	衰老期	果熟期	衰老期	果熟期	衰老期	果熟期	衰老期
Ga	1.815k	1.143q	0.160b	0.401k	11.358hijk	2.850m	7.372efgh	28.854a	1.212n	3.542b	57.577b	10.415a	7.340i	9.242a	11.341jk	24.071a	41.999r	10.865a	0.532op	3.659a	17.822o	4.971b
Gd	1.790k	2.705d	0.140b	0.143w	12.814ghijk	18.955b	9.581bcde	20.418a	3.107j	7.832b	15.384kl	8.191a	20.316a	8.990a	18.311gh	29.744a	47.957q	6.118a	0.980no	2.596a	37.494j	5.869ab
Gg	3.606a	2.219i	0.381b	0.377l	9.467kl	5.891gh	10.260bcd	28.565a	2.535jkl	3.998b	20.490ij	10.518a	19.365ab	13.942a	11.494jk	26.510a	57.346op	6.646a	1.723lm	3.068a	7.496r	4.172b
Gm	1.275o	1.800n	0.161b	0.341q	7.916l	5.286ij	4.921hijk	25.709a	1.022n	4.701b	5.196o	7.393a	4.247j	12.238a	4.446m	19.201a	8.044u	4.272a	0.112p	1.577a	13.040p	9.037ab
Gr	2.965d	2.445f	0.107b	0.316t	27.764c	7.736d	6.873fghi	25.369a	2.033lm	8.821b	8.470no	6.068a	14.649de	11.437a	13.079j	21.630a	17.688t	2.772a	0.233p	0.960a	12.706p	4.944b
Sca	1.472n	2.442f	0.100b	0.363mn	14.81fgh	6.729f	10.679bc	18.331a	1.708mn	7.469b	19.576ij	7.570a	20.499a	11.043a	14.713hij	21.642a	55.237p	7.873a	2.284jkl	0.150a	38.404j	3.547b
Sdi	2.462g	2.441f	0.228b	0.353p	10.82ijkl	6.922ef	4.213jkl	26.973a	2.419jkl	5.353b	20.885i	8.723a	7.431i	13.847a	15.087hij	35.458a	78.928l	5.898a	2.695ij	0.612a	48.628h	4.924b
Spe	2.546f	2.224i	0.082b	0.447e	31.119b	4.970jk	5.286hijk	22.261a	1.531mn	5.885b	9.783n	5.795a	8.824h	10.890a	13.833ij	31.375a	74.402m	3.496a	3.077i	0.783a	32.777k	6.719ab
Dh	1.832k	2.957c	0.140b	0.358o	13.088ghij	8.249c	7.914efg	24.477a	2.103klm	8.676b	21.644i	10.510a	13.386e	14.179a	20.459g	26.492a	39.920r	5.917a	1.808klm	0.479a	155.813d	5.167b
Rco	2.302h	2.161j	0.170b	0.064x	13.537fghij	33.836a	4.196jkl	6.230a	6.791f	5.944b	51.445c	5.497a	9.218gh	9.245a	35.999e	15.146a	338.191f	6.370a	5.838f	1.832a	51.943g	5.048b
Rfu	3.124c	1.924m	0.201b	0.333r	15.577fg	5.786ghi	6.065ghij	17.884a	11.658a	9.106b	51.247c	5.171a	9.476gh	11.692a	108.479a	21.638a	469.202a	2.499a	14.304a	0.428a	391.147a	10.244ab
Sde	2.485g	2.944c	0.820a	0.551a	11.207hijk	5.342ij	6.495fghij	32.425a	2.504jkl	8.398b	9.606n	9.141a	10.504fg	13.839a	18.338gh	30.561a	53.643p	6.272a	2.162jkl	0.217a	25.948l	6.043ab
Svi	2.289h	2.014kl	0.115b	0.431g	19.993e	4.670kl	11.577b	23.797a	4.671h	7.262b	11.273mn	7.087a	13.615e	17.868a	13.577ij	15.959a	75.859m	2.895a	2.484ijk	0.296a	44.968i	5.839ab
Fm	2.249h	2.021kl	0.132b	0.412i	17.038f	4.912jk	4.569ijkl	16.032a	7.303ef	2.745b	43.329d	8.634a	14.426de	14.616a	9.227kl	23.719a	67.955n	2.362a	2.170jkl	1.129a	23.067m	6.304ab
Cc	1.715l	1.821n	0.077b	0.408j	22.391d	4.459kl	3.449kl	14.209a	9.566b	10.857b	15.087kl	8.220a	4.364j	12.243a	16.958hi	35.443a	56.733op	3.998a	4.353h	1.005a	17.082o	20.411a
Rcl	1.637m	2.026k	0.041b	0.325s	39.819a	6.227g	13.498a	20.920a	5.781g	4.131b	36.908e	7.514a	9.352gh	12.531a	46.259c	20.001a	417.332b	3.820a	10.195b	1.095a	31.172k	7.189ab
Rin	1.984j	1.549p	0.201b	0.275p	9.892jkl	5.638hi	11.196b	21.686a	2.883jk	7.010b	5.354o	7.613a	4.607j	11.433a	7.844l	28.107a	79.930l	4.568a	1.017no	1.350a	1.245s	9.860ab
Afo	1.779k	2.176j	0.148b	0.503c	12.065ghijk	4.328l	2.431l	14.704a	4.819h	1.679b	29.800n	9.096a	6.983i	15.442a	42.145d	28.951a	253.616j	3.099a	3.995h	0.878a	63.591f	10.795ab
Ako	1.973j	2.918c	0.115b	0.521b	17.198f	5.604hi	5.956ghijk	13.957a	4.722h	2.412b	13.542lm	8.719a	15.639cd	11.493a	12.356jk	19.204a	261.358i	2.798a	1.326mn	0.707a	20.344n	7.046ab
Asc	3.513b	1.897m	0.207b	0.359o	16.98f	5.290ij	6.598fghij	13.731a	3.704i	12.494b	17.582jk	7.818a	2.697k	19.237a	14.835hij	17.583a	55.145p	2.698a	0.453op	0.673a	3.297s	11.241ab
Asp	2.624c	2.307h	0.168b	0.419h	15.65fg	5.502hi	4.149jkl	4.980a	8.251cd	8.032b	32.793f	8.993a	8.105hi	8.693a	31.671f	27.321a	378.429d	5.521a	8.137d	1.835a	24.439lm	4.921b
De	2.057i	3.249b	0.137b	0.520b	15.008fgh	6.244g	8.922cdef	21.410a	5.110h	50.066b	28.449g	12.607a	16.360c	14.995a	34.487e	51.656a	84.661k	5.724a	2.629ij	0.212a	186.255c	6.523ab
Ds	2.499fg	3.517a	0.168b	0.414i	14.889fgh	8.490c	5.360hijk	17.057a	2.819jk	9.044a	24.351h	8.715a	11.151f	11.883a	17.982gh	19.196a	59.066o	6.018a	1.456mn	0.348a	21.229n	7.114ab
Ec	2.066i	1.973l	0.077b	0.438f	26.884c	4.501kl	6.679fghij	21.220a	7.724de	8.292b	45.704d	8.224a	9.241gh	15.499a	42.458d	24.089a	313.561h	3.425a	5.157g	0.859a	90.659e	7.974ab
Pb	2.057i	1.991kl	0.079b	0.418h	26.022c	4.767kl	11.196b	21.177a	2.883jk	8.935b	5.354o	10.369a	4.607j	15.539a	7.844l	35.441a	79.930l	3.223a	1.017no	0.866a	1.245s	11.993ab
Po	1.662m	2.376g	0.130b	0.493d	12.82ghij	4.823jkl	8.653cdef	17.236a	8.403cd	7.098b	56.801b	5.094a	14.200e	12.585a	47.833c	15.953a	387.643c	2.498a	7.468e	0.208a	31.141k	12.262ab
Ale	2.241h	1.579p	0.153b	0.284u	14.685fgh	5.566hi	11.474b	18.851a	8.192cd	6.308b	76.347a	7.467a	18.962b	12.835a	40.669d	13.520a	357.535e	3.246a	6.144f	0.771a	24.077lm	8.615ab
Atr	2.008ij	1.718o	0.152b	0.366m	13.178ghij	4.697kl	8.411defg	25.431a	6.835f	8.259b	44.843n	5.571a	10.962f	12.642a	83.333b	11.898a	322.372g	3.448a	5.990f	1.170a	198.430b	5.171b
CK	1.982j	2.589e	0.140b	0.362no	14.187fghi	7.159e	4.611ijkl	17.908a	8.711c	7.637b	8.412no	8.094a	7.104i	12.691a	12.463jk	28.945a	21.560s	6.171a	9.646c	2.443a	9.347q	6.545ab

表 4　药材对营养元素的富集系数

Table 4　Enrichment factors of nutrients by the herbs

处理组	N		P		K		Ca		Mg		Na		Mn		Zn		Cu		Ni	
Group	果熟期	衰老期	果熟期	衰老期	果熟期	衰老期	果熟期	衰老期	果熟期	衰老期	果熟期	衰老期	果熟期	衰老期	果熟期	衰老期	果熟期	衰老期	果熟期	衰老期
Ga	0.058de	0.020lm	0.001cdefg	0.002ab	0.845ij	3.465ab	0.030no	0.089lm	3.634e	1.218a	7.930p	11.866r	0.070kl	0.132bcd	0.601op	0.229a	0.288a	21.598b	0.845t	0.303ijk
Gd	0.043fg	0.097e	0.001defgh	0.001ab	1.263d	2.682cde	0.074hi	0.204cde	1.323no	0.758g	23.419c	13.322q	0.116i	0.141bc	0.650op	0.109b	0.209c	11.167e	1.690m	0.327ijk
Gg	0.064d	0.053i	0.001b	0.002ab	1.092f	3.922a	0.056jkl	0.099lm	1.445m	0.996c	12.420m	20.965g	0.068kl	0.135bcd	0.675nop	0.097b	0.242b	14.271d	0.361v	0.237m
Gm	0.007mn	0.021lm	0.001cdef	0.001ab	0.582no	3.379ab	0.022o	0.107kl	0.393r	0.548jkl	5.076s	18.832jkl	0.025n	0.083bcde	0.107q	0.078b	0.120def	7.510gh	0.645n	0.534e
Gr	0.077c	0.175a	0.000defgh	0.001ab	0.760k	3.706a	0.045lmn	0.229c	0.775p	0.674h	14.028k	22.425f	0.073kl	0.097bcde	0.232q	0.049b	0.074hij	3.978ij	0.609n	0.286kl
Sca	0.021ijk	0.044j	0.000fgh	0.001ab	1.277d	2.593cdef	0.037mno	0.195cdef	1.889j	0.859e	17.964g	14.876op	0.092j	0.104bcde	0.819mno	0.121b	0.011m	16.461c	2.044i	0.210m
Sdi	0.018jklm	0.058i	0.001cdef	0.001ab	0.549op	3.064bc	0.052klm	0.119jkl	1.399mn	0.589ij	9.594o	16.641m	0.096j	0.156b	1.053klm	0.096b	0.046jklm	8.982fg	2.760g	0.272l
Spe	0.104jklm	0.032k	0.000efgh	0.002ab	0.607n	2.641cdef	0.037mno	0.147ghij	0.837p	0.570jk	10.176o	19.389ijk	0.056lm	0.152b	1.267k	0.070b	0.062hijk	4.268i	1.835k	0.389gh
Dh	0.022a	0.106d	0.001cdefg	0.003a	0.871i	2.900bcd	0.044lmn	0.179defg	1.750k	0.755g	16.287h	19.572ij	0.107ij	0.117bcde	0.507p	0.125b	0.037jklm	13.671d	8.429d	0.286kl
Rco	0.010ijk	0.154b	0.001cdef	0.000a	0.537p	0.668h	0.114g	0.132ijk	3.062f	0.557jk	6.254r	6.698s	0.147h	0.067cde	5.526f	0.131b	0.131de	9.667ef	3.616f	0.304jkl
Rfu	0.112klmn	0.069h	0.001cdefgh	0.001ab	0.751k	2.108efg	0.272a	0.162fghi	4.660b	0.333n	7.583p	15.561no	0.535b	0.083bcde	6.587c	0.059b	0.033klm	1.907jk	28.981a	0.582d
Sde	0.059de	0.105d	0.003a	0.003a	1.211e	3.856a	0.049lm	0.204cde	0.746p	1.117b	26.933b	19.037ijkl	0.112i	0.141bc	0.825mno	0.122b	0.019klm	9.924ef	1.538o	0.347ij
Svi	0.027hij	0.072gh	0.000efgh	0.002ab	1.480b	3.094bc	0.083h	0.161fghi	0.564q	1.134b	10.111o	31.633a	0.066kl	0.081bcde	1.168kl	0.066b	0.024klm	1.348k	2.491h	0.336ijk
Fm	0.054def	0.144c	0.000defgh	0.002ab	0.518p	1.969efg	0.173e	0.069mn	2.927g	1.009c	19.309f	23.114ef	0.052m	0.114bcde	1.182kl	0.053b	0.098fgh	13.645d	1.211q	0.364hi
Cc	0.031hij	0.043j	0.000gh	0.002ab	0.468q	1.722g	0.229b	0.274b	1.609l	0.928d	6.983q	23.146ef	0.080k	0.151b	0.840mno	0.078b	0.085ghij	4.402i	0.998s	1.128a
Rcl	0.029hij	0.072gh	0.000h	0.001ab	1.495b	2.153efg	0.130g	0.094lm	2.579h	0.441m	14.555j	16.397mn	0.182f	0.078bcde	6.070d	0.070b	0.087fghi	4.521i	1.762l	0.414g
Rin	0.047efg	0.021lm	0.001c	0.001ab	1.215e	2.504cdef	0.069hij	0.168efgh	0.595q	0.620hi	7.013q	18.477kl	0.028n	0.127bcd	1.185kl	0.080b	0.114efgh	6.147h	0.068x	0.583d
Afo	0.032hi	0.078g	0.000defgh	0.002ab	0.277r	1.701g	0.119g	0.042n	2.388i	0.621hi	9.646o	23.989de	0.234d	0.138bc	3.694i	0.067b	0.072hij	3.685ij	3.652f	0.515ef
Ako	0.056de	0.060i	0.000efgh	0.002ab	0.690l	1.730g	0.115g	0.061n	1.306no	0.842ef	22.848d	14.616p	0.071kl	0.100bcde	3.948h	0.037b	0.058hijklm	3.096ijk	1.629n	0.411gh
Asc	0.084c	0.068h	0.001cdefgh	0.001ab	0.831j	2.023efg	0.076hi	0.283b	1.262o	0.667h	3.352t	28.346b	0.073kl	0.078bcde	0.774mnop	0.053b	0.054ijkl	2.964ijk	0.310w	0.648c
Asp	0.094b	0.055i	0.001cdefgh	0.001ab	0.577no	0.732h	0.159f	0.174defg	2.386i	0.810f	10.995n	11.167r	0.163g	0.124bcde	9.179a	0.103b	0.151d	8.791fg	2.508h	0.297kl
De	0.037gh	0.066h	0.000defgh	0.003ab	0.963h	2.539cdef	0.118g	1.006a	2.530h	0.881e	19.840e	21.427g	0.193f	0.211a	1.653j	0.127b	0.016lm	29.097a	9.776c	0.395gh
Ds	0.020ijkl	0.084f	0.001cdefg	0.002ab	0.652m	1.788g	0.065ijk	0.212cd	2.309i	0.529kl	13.500l	18.295l	0.097j	0.082bcde	0.947lmn	0.127b	0.027klm	10.979e	1.146r	0.405gh
Ec	0.049efg	0.047j	0.000gh	0.001ab	0.776k	2.569cdef	0.180e	0.188def	3.979d	0.653h	10.949n	24.355cd	0.160g	0.114bcde	4.257g	0.058b	0.075ghij	3.785ij	5.301e	0.576d
Pb	0.065d	0.026l	0.001defgh	0.002ab	1.309c	2.246defg	0.071hij	0.200cdef	0.355r	0.769g	6.332r	20.670gh	0.036n	0.152b	1.522j	0.052b	0.071hijk	4.055i	0.064x	0.691b
Po	0.047efg	0.042j	0.001cd	0.002ab	0.960h	2.010efg	0.202d	0.169efgh	4.521c	0.355n	16.512h	20.006hi	0.211e	0.077bcde	7.384b	0.042b	0.017lm	3.708ij	1.655mn	0.694b
Ale	0.008lmn	0.045j	0.001cde	0.001ab	1.333c	2.109efg	0.208cd	0.137hijk	5.435a	0.520kl	28.759a	16.072mn	0.188f	0.059de	5.965d	0.027b	0.061hijkl	2.958ijk	1.307p	0.486f
Atr	0.018jklm	0.014k	0.001b	0.001ab	1.009g	3.037bc	0.171e	0.186def	3.926d	0.499l	15.458i	25.084c	0.367c	0.051e	5.738e	0.060b	0.092fghi	6.171h	10.849b	0.308jkl
CK	0.002n	0.007n	0.001cdefg	0.001ab	170.390a	1.919fg	0.218bc	0.175defg	0.736p	0.632hi	17.491g	13.469q	1.994a	0.136bc	0.199q	0.088b	0.200c	11.497e	1.994j	0.409gh

表 5 土壤中营养元素间相关分析

Table 5 Correlation analysis between soil nutrients

月份 Month	元素 Nutrients	N	P	K	Ca	Mg	Na	Mn	Zn	Cu	Ni
8 月 August	N	−									
	P	−0.237	−								
	K	0.038	0.011	−							
	Ca	0.264	0.267	−0.044	−						
	Mg	0.283	0.007	0.041	0.555**	−					
	Na	0.145	0.174	0.384*	0.466*	0.376*	−				
	Mn	0.092	−0.127	0.721**	0.120	0.038	0.189	−			
	Zn	−0.019	0.118	−0.518**	−0.114	−0.128	0.016	−0.587**	−		
	Cu	0.493**	−0.012	0.162	0.318	0.111	0.562**	−0.068	0.052	−	
	Ni	0.099	−0.276	0.690**	−0.153	0.064	0.259	0.364	−0.227	0.118	−
11 月 November	N	−									
	P	0.260	−								
	K	0.258	0.013	−							
	Ca	0.008	0.107	0.235	−						
	Mg	0.094	0.133	0.535**	0.497**	−					
	Na	0.137	0.222	0.375*	0.239	0.098	−				
	Mn	−0.070	0.221	0.347	0.646**	0.616**	0.069	−			
	Zn	0.199	0.165	0.089	−0.081	0.142	0.141	−0.075	−		
	Cu	−0.201	0.007	−0.011	0.133	−0.106	0.348	0.209	0.051	−	
	Ni	−0.289	−0.250	0.055	−0.133	0.174	−0.157	0.070	−0.060	−0.010	−

** $P<0.01$, * $P<0.05$, 表 6、表 7 同.

表 6 药材中营养元素间相关分析

Table 6 Correlation between nutrients in herbs

月份 Month	元素 Nutrients	N	P	K	Ca	Mg	Na	Mn	Zn	Cu	Ni
8 月 August	N	−									
	P	0.350	−								
	K	−0.096	−0.081	−							
	Ca	0.033	−0.196	−0.181	−						
	Mg	−0.027	−0.142	0.052	0.532**	−					
	Na	0.019	0.027	0.409*	−0.051	0.215	−				
	Mn	0.091	−0.062	0.019	0.645**	0.608**	0.040	−			
	Zn	−0.008	−0.169	0.060	0.681**	0.690**	0.034	0.794**	−		
	Cu	0.027	−0.125	−0.046	0.813**	0.493**	−0.077	0.763**	0.765**	−	
	Ni	0.125	−0.033	−0.036	0.414*	0.335	0.086	0.818**	0.425*	0.521**	−
11 月 November	N	−									
	P	0.257	−								
	K	−0.044	0.201	−							
	Ca	0.379*	0.212	0.015	−						
	Mg	0.304	0.365	0.211	0.412*	−					
	Na	0.002	0.406*	0.189	0.210	0.240	−				
	Mn	0.324	0.304	0.156	0.597**	0.654**	0.074	−			
	Zn	0.116	−0.173	0.242	0.067	0.442*	−0.440*	0.236	−		
	Cu	−0.365	−0.396*	0.070	−0.276	0.180	−0.438*	−0.006	0.531**	−	
	Ni	−0.275	0.167	−0.269	0.039	−0.108	0.228	0.136	−0.452*	−0.227	−

表 7　药材与土壤间营养元素相关性分析

Table 7　Correlation analysis between herbnutients and soil nutrients

月份 Month	营养元素 Nutrients		药材 Herbs									
			N	P	K	Ca	Mg	Na	Mn	Zn	Cu	Ni
8 月 August	土壤 Soil	N	−0.139	−0.019	−0.009	0.021	0.338	0.084	0.053	0.138	0.007	−0.053
		P	0.309	0.053	−0.325	0.102	−0.106	−0.030	−0.020	−0.022	0.033	0.140
		K	0.018	−0.248	0.306	−0.268	0.241	0.217	0.104	0.173	−0.317	0.120
		Ca	0.236	0.294	−0.074	−0.121	−0.131	−0.047	−0.137	−0.015	−0.065	−0.075
		Mg	0.143	0.059	0.159	−0.082	0.214	−0.036	−0.132	0.040	−0.045	−0.185
		Na	0.376*	−0.108	0.154	−0.089	0.146	0.341	0.116	0.064	−0.028	0.215
		Mn	−0.001	−0.185	0.290	0.056	0.264	−0.147	0.278	0.436*	0.015	0.108
		Zn	0.069	0.081	−0.089	−0.120	−0.310	−0.043	−0.207	−0.377*	0.010	−0.067
		Cu	0.009	−0.186	0.078	−0.244	0.126	0.238	0.129	0.020	0.018	0.213
		Ni	−0.223	−0.021	0.395	−0.494	0.054	0.361	−0.134	−0.250	−0.502	−0.057
11 月 November	土壤 Soil	N	0.015	0.036	0.039	0.001	−0.027	−0.065	0.086	0.149	0.289	−0.024
		P	−0.579**	−0.389*	−0.403*	−0.206	−0.543**	−0.210	−0.226	−0.251	0.245	0.294
		K	0.069	−0.057	−0.004	−0.019	0.005	−0.034	0.081	0.010	−0.098	0.175
		Ca	0.014	−0.064	−0.107	0.393*	−0.016	0.195	0.044	−0.178	−0.280	0.028
		Mg	0.184	−0.014	−0.090	0.158	0.062	0.078	0.078	−0.173	−0.220	0.186
		Na	0.071	−0.477**	−0.398*	−0.062	−0.007	−0.292	−0.081	0.375*	0.243	−0.259
		Mn	0.078	−0.226	−0.132	0.374*	−0.137	0.044	0.118	−0.278	−0.381*	0.283
		Zn	−0.151	−0.136	0.004	−0.179	−0.044	−0.074	−0.246	−0.078	0.055	−0.016
		Cu	−0.003	−0.317	−0.125	0.045	0.323	−0.062	0.140	0.210	0.193	−0.224
		Ni	0.101	0.073	−0.039	−0.198	0.036	0.116	0.069	−0.178	−0.168	0.258

本研究表明,AM 真菌处理能够提高根际土壤中营养元素含量,改善滇重楼的生长发育过程,增加药材中营养物质积累,从而提高滇重楼的品质和产量,促进滇重楼种植业的可持续健康发展.

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