第42卷 第6期　　华 中 农 业 大 学 学 报　　Vol.42 No.6
2023年 11月　　Journal of Huazhong Agricultural University　　Nov. 2023,205～212

李綎瑄,解环环,叶超,等.1种植物源次生代谢物在农作物上的应用效果[J].华中农业大学学报,2023,42(6):205-212.
DOI:10.13300/j.cnki.hnlkxb.2023.06.024

1种植物源次生代谢物在农作物上的应用效果

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摘要　为探究植物源次生代谢物对不同作物增产的效果,将甜菜和甘蔗的代谢物提取分离后,通过优化配比,然后与腐殖酸螯合,按照含腐殖酸水溶肥料国家标准形成产品,通过田间试验和水培试验研究该产品在小麦等15种作物上的增产效果及其作用机制。试验设置2个处理:①常规施肥;②常规施肥+含植物源次生代谢物产品,该产品根据不同作物类型分别采用叶面喷施、拌肥和灌根3种方式施用。结果显示:与对照相比,施用含植物源次生代谢物产品,15种作物产量均得到提高,增幅为5.2%～21.1%;水稻、玉米和棉花种子的发芽势分别提高了6.6%、11.5%和15.2%,发芽率分别提高了2.6%、3.5%和6.1%;小麦根系总根长、总表面积和根尖数分别提高了54.44%、60.57%和30.43%;马铃薯、大白菜、包菜和小麦叶片的SPAD值分别提高了4.8%、8.7%、6.6%和9.7%;小麦叶片净光合速率提高了7.9%;马铃薯、大白菜和辣椒中Vc含量分别提高了40.8%、22.9%和28.51%,硝酸盐含量分别下降了28.8%、23.9%和20.27%;葡萄和甜菜的含糖率分别提高了21.81%和15.75%。以上结果表明,植物源次生代谢物能通过提高根系活力、促进养分的吸收,提高叶绿素含量、促进光合产物的累积,从而提高作物产量,改善作物品质,具有良好的提质增效作用。

关键词　植物源次生代谢物; 农作物; 产量; 叶绿素; 根系生长

中图分类号　S147.5　　**文献标识码**　A　　**文章编号**　1000-2421(2023)06-0205-08

随着我国化肥产业的发展,肥料企业为了提高产品的市场竞争力,通常采用改良肥料加工技术来提高产品的影响力。如通过测土施肥技术生产专用配方肥满足作物对养分的需求、通过缓控释肥技术生产满足作物不同生育期对养分的需求,从而实现提高肥料利用效率的目标;或通过添加硝化抑制剂[1]、脲酶抑制剂[2],减少肥料在转化过程中的损失,提高肥料利用效率。然而,这些技术的主要作用是调节土壤对作物所需养分供应的数量和强度,但对作物主动适应环境、吸收养分的能力影响不大。《国家肥料登记管理办法》中明确鼓励通过新物质、新技术研发新型肥料,并将肥料的定义由传统的矿质养分发展为能促进作物生长发育、提高作物抗性、提高作物品质的产品。由此,植物源次生代谢物类物质与肥料产品的复合应用成为新的研究热点。

植物次生代谢物是特种植物在特定条件下生长或诱导,通过代谢合成的一类物质,兼有植物激素类物质的性能[3],能够提高植物对特异环境的适应性,又不会对作物产生激素危害,而且能促进作物代谢能力[4-5]、增加作物干物质积累[6],还能调节植物渗透势、减少果实冻害[7]。如茉莉酸甲酯类[8-9]、苦参碱[10]、生物碱[11]、油菜素内酯[12-13]等都是植物代谢过程中产生的物质,可提高作物抗性、改善植物代谢过程、促进作物生长;褪黑素[14-15]、水杨酸[16-17]等可有效促进作物发芽、生长,提高产量与品质;植物花青素等黄酮类次生代谢物,可提高植物抗氧化能力,是很好的自由基清除剂,可提高植物对逆境胁迫的抗性[18]。

为了高效利用植物源次生代谢物,1999年以来,笔者所在研究团队在王运华教授的带领下,对从甜菜和甘蔗中提取的次生代谢物开展不同配比研究,1999—2014年围绕次生代谢物有效提取与分离、2种提取物的配比以及与腐殖酸的螯合技术与工艺开展系统研究,明确次生代谢物对作物产量的提升效果后,2014年,开发出符合含腐殖酸水溶肥料国家标准的产品,2015年开始,对产品开展试验示范研究,本文就该产品在不同作物上的应用效果进行了总结,分析了次生代谢物对作物生长发育及养分吸收的影

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响,旨在为新型次生代谢物的研发与推广应用提供技术支撑。

1 材料与方法

1.1 试验材料

选择甜菜和甘蔗作为提取植物源次生代谢物的原料,提取分离后,按照一定比例与腐殖酸螯合,形成备用品,其中植物源次生代谢物的含量为0.4%,由武汉皓达农业科技有限公司生产加工为含腐殖酸水溶肥料,供试验示范。

1.2 试验设计

田间试验设2个处理:①常规施肥(CK);②常规施肥+含植物源次生代谢物产品(plant secondary metabolites, PSM),植物源次生代谢物的用量依据作物种类和施用方法有所调整。

含植物源次生代谢物产品的使用方法及用量:(1)叶面喷施(foliar spraying, S):在作物生育期内叶面喷施3次含植物源次生代谢物产品,用量为1 500~2 000 g/hm^2,不同作物由于叶面积指数不同,含植物源次生代谢物产品稀释倍数有所差异;(2)灌根(irrigation root, IR):作物生育期内灌根1~2次,每次用量为3 000 g/hm^2;(3)拌肥(mixed with fertilizer, MF):含植物源次生代谢物产品与基肥搅拌均匀后基施,二者质量比例为0.4:100,不同作物根据种植条件选择合适的施用方法及用量。

水培试验在华中农业大学玻璃温室内进行,光照强度5 000 lx,光照周期16 h/d,温度为白天25 ℃,晚上20 ℃。试验设2个处理:①全量营养液;②全量营养液+含植物源次生代谢物产品。营养液配方:0.24 g/L $Ca(NO_3)_2·4H_2O$,0.5 g/L KNO_3,0.15 g/L $MgSO_4·7H_2O$,0.1 g/L KH_2PO_4,0.1 g/L 酒石酸铁,2.86 g/L H_3BO_3,1.81 g/L $MnCl_2·4H_2O$,0.22 g/L $ZnSO_4·7H_2O$,0.08 g/L $CuSO_4·5H_2O$,0.02 g/L H_2MoO_4,含植物源次生代谢物产品的添加量为1/1 000,每3 d更换1次营养液,培养28 d后采集样品。

1.3 样品采集

田间试验在华中农业大学实习基地进行。土壤样品为黄棕壤,2018年种植油菜前后分批采集土壤样品,风干后过筛备用。

1.4 样品测定项目及方法

土壤基础理化性质参照鲍士旦[19]的方法检测:pH值采用电位法(水土质量比2.5:1)测定;土壤有机质采用重铬酸钾容量法测定;土壤碱解氮采用碱解扩散法测定;土壤速效磷采用0.5 mol/L $NaHCO_3$浸提-钼锑抗比色法测定;土壤速效钾采用1 mol/L NH_4OAc浸提-火焰光度法测定。

植物氮、磷、钾含量测定:H_2SO_4-H_2O_2消煮,氮采用凯氏定氮法测定,磷采用钼锑抗比色法测定,钾采用火焰光度计测定;根系指标采用EPSON1680根系扫描仪进行测定;叶片SPAD值用SPAD-502仪进行测定;叶片光合参数采用便携式光合测定系统Li-6400(American Li-COR)进行测定;作物品质指标参照文献[20]的方法进行测定;维生素C含量采用2,6-二氯靛酚滴定法测定;硝酸盐采用紫外分光光度法测定;含糖率采用蒽酮比色法测定。

1.5 数据处理和统计分析

试验数据采用SPSS 25.0软件进行统计分析,t检验法检验处理间差异的显著性,显著性水平α=0.05,用Origin 2019软件作图。

2 结果与分析

2.1 植物源次生代谢物对作物产量的影响

2015—2021年,田间试验及全国各地试验示范研究结果显示,与单独施用复合肥相比,植物源次生代谢物与复合肥配施能有效提高作物产量(表1)。虽然不同作物植物源次生代谢物的用量不同,但植物源次生代谢物对15种作物都有不同程度的增产作用,其中甜玉米增产率仅5.2%,增产效果不显著,主要原因是植物源次生代谢物施用方式为复合肥与植物源次生代谢物拌肥基施,玉米基肥用量占全生育期总施肥量比例较少,多次追肥稀释了植物源次生代谢物的增产效果。油菜增产达21.1%,主要原因是植物源次生代谢物提高了油菜的抗寒性。关口葡萄施用方式为每株30 g、稀释200倍灌根,叶菜类通过叶面喷施施用。总体而言,增产幅度在7%~20%,表明该植物源次生代谢物与复合肥拌肥基施、灌根、叶面喷施均能有效提高作物产量,且对作物、肥料品种没有选择性。

2.2 植物源次生代谢物对作物生长发育的影响

1)植物源次生代谢物对种子发芽的影响。植物源次生代谢物可提高种子的发芽势和发芽率。由表2可知,与对照相比,添加植物源次生代谢物后水稻种子的发芽势和发芽率分别提高了6.6%和2.6%、玉米种子的发芽势和发芽率分别提高了11.5%和3.5%、棉花种子的发芽势和发芽率分别提高了15.2%和6.1%,均达到显著性差异。

表 1　植物源次生代谢物对不同作物的增产效果

Table 1　The effect of plant secondary metabolites on yield increase of different crops

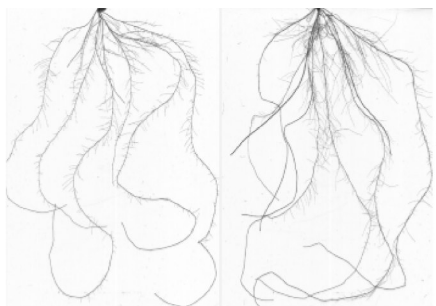
试验作物 Crops	施用方式 Application	产量/(kg/hm²) Yield CK	PSM	增产率/% Rate	试验年份 Year	试验地点 Place
小麦 Wheat	MF	4 140±270b	4 665±300a	12.7	2015－2016	内蒙古呼伦贝尔市新巴尔虎左旗
甜玉米 Sweet corn	MF	12 855±315a	13 530±525a	5.2	2022	华中农业大学
早稻 Rice	MF	7 650±285b	8 250±300a	7.8	2021	浙江省衢州市江山市大桥镇新桥村
马铃薯 Potato	MF	19 305±870b	21 570±990a	11.7	2015－2016	内蒙古呼伦贝尔市牙克石市莫拐农场
红薯 Sweet potato	MF	38 970±1335b	44 820±1620a	15.0	2022	华中农业大学
油菜 Rape	MF	2 820±165b	3 420±270a	21.1	2014－2015	华中农业大学
大豆 Soybean	MF	2 250±225b	2 550±240a	13.3	2022	黑龙江省哈尔滨市宾县宾州镇
紫苜蓿 Alfalfa	MF	15 315±765b	19 080±795a	24.5	2018－2019	内蒙古赤峰市阿鲁科尔沁旗绍根镇
大蒜 Garlic	MF	7 245±285b	7 830±345a	8.1	2016－2017	云南省大理州上关镇大排村
大白菜 Chinese cabbage	S	91 365±1 575b	101 385±2 835a	10.9	2016	华中农业大学
生菜 Lettuce	S	23 310±1 240b	26 070±1 335a	11.8	2016－2017	华中农业大学
辣椒 Pepper	MF	64 680±2 590b	72 345±1 855a	11.9	2020	华中农业大学
茄子 Eggplant	MF	109 800±1 800b	117 780±2 085a	7.3	2022	华中农业大学
萝卜 Turnip	MF	83 805±3 840b	96 270±4 815a	14.9	2021	华中农业大学
关口葡萄 Guankou grape	IR	19 200±1 290b	22 470±1 650a	17.0	2016－2018	湖北省恩施市建始县花坪镇关口乡

注：试验结果采用 t 检验法检验分析，不同字母表示差异达到5%显著水平。下同。Note: The experimental results was analyzed using t-test, with different letters indicating a significant difference of 5%.The same as below.

表 2　不同处理下作物种子的发芽率和发芽势

Table 2　Germination rate and germination potential of crop seeds under different treatments　%

作物 Crop	处理 Treatment	平均发芽势(3 d) Germinative energy	平均发芽率(7 d) Germinative rate
水稻 Rice	CK	85.6±1.1b	92.2±0.6b
	PSM	91.3±0.5a	94.6±0.4a
玉米 Corn	CK	80.3±1.3b	88.5±0.7b
	PSM	89.6±1.8a	91.6±0.5a
棉花 Cotton	CK	70.6±1.5b	85.6±1.2b
	PSM	81.3±1.8a	91.5±0.8a



左边为对照，右边为处理 CK on the left and PSM treatment on the right.

图 1　小麦根系扫描图

Fig.1　Scanning image of wheat root

2)植物源次生代谢物对作物根系发育的影响。如图1和表3所示，施用植物源次生代谢物后小麦的根系较对照更为发达，最大根长、总根长、根系总表面积、根系总体积、根系平均直径和根尖数均得到显著提高，其中总根长较对照提高了54.44%，根系总表面积提高了60.57%，根系总体积提高了73.68%，根尖数提高了30.43%。植物源次生代谢物还能提高作物的根冠比，在促进大白菜和包菜根系生长的同时协调地上部的生长，提高地上部的生物量(表4)。以上结果表明，植物源次生代谢物能促进作物根系的发育。

表 3　不同处理下小麦根系指标的变化

Table 3　Changes in wheat root system indicators under different treatments

处理 Treatment	最大根长/cm Max length	总根长/cm Length	总表面积/cm² Surface area	总体积/cm³ Volume	平均直径/mm Average diameter	根尖数/个 Tips number
CK	31.62±1.23b	512.21±112.35b	59.62±18.69b	0.57±0.15b	0.37±0.07a	815±56b
PSM	35.65±1.56a	785.61±158.56a	95.71±18.32a	0.99±0.21a	0.39±0.06a	1 063±102a

表4 不同处理下大白菜和包菜的干质量和根冠比

Table 4 Dry matter and root to shoot ratio of Chinese cabbage and cabbage under different treatments

作物 Crop	处理 Treatment	根长/cm Length	根系单株干质量/g Root dry weight per plant	地上部单株干质量/g Aboveground dry weight per plant	根冠比 Root/Shoot ratio
大白菜 Chinese cabbage	CK	20.37±0.53a	0.10±0.03b	1.31±0.13b	0.078±0.01b
	PSM	21.93±0.64a	0.17±0.04a	1.83±0.25a	0.094±0.01a
包菜 Cabbage	CK	24.11±0.67b	0.17±0.03b	1.33±0.15b	0.13±0.01a
	PSM	26.23±1.08a	0.23±0.04a	1.72±0.34a	0.13±0.02a

3)植物源次生代谢物对不同作物叶片SPAD值的影响。由表5可知,与对照相比,施用植物源次生代谢物提高了马铃薯、大白菜、包菜和小麦叶片的SPAD值,其增幅在不同作物之间略有不同。与对照相比,施用植物源次生代谢物后马铃薯叶片的SPAD值在整个生育期均得到了提高,其中块茎形成期的增幅最大,达到4.8%;大白菜叶片SPAD值在水培环境和大田试验下均得到了提高,增幅均为8.7%;包菜叶片SPAD值在水培环境下提高了2.3%,大田试验下提高了6.6%;小麦叶片SPAD值在水培环境下得到显著提高,且增幅随着小麦生育期的延长越来越大,在出苗后28 d增幅高达9.7%。以上结果表明,植物源次生代谢物能提高作物叶片的SPAD值。

表5 不同处理下作物叶片SPAD的变化

Table 5 Changes in SPAD of crop leaves under different treatments

作物 Crop	时期 Period	处理 Treatment	SPAD	增幅/% Amplification
马铃薯 Potato	块茎形成期 Tuber formation growth	CK	51.10±1.26a	4.8
		PSM	53.60±1.04a	
	块茎膨大期 Tuber bulking growth	CK	45.70±1.58a	0.8
		PSM	46.10±2.03a	
	块茎成熟期 Tuber maturation growth	CK	43.80±0.95a	2.1
		PSM	44.70±0.46a	
大白菜 Chinese cabbage	苗期(水培) Seedling stage(nutrient solution)	CK	28.60±0.76a	8.7
		PSM	31.10±1.23a	
	成熟期(大田) Maturation stage(field)	CK	38.70±0.95b	8.7
		PSM	42.10±0.53a	
包菜 Cabbage	苗期(水培) Seedling stage(nutrient solution)	CK	38.20±0.35a	2.3
		PSM	39.10±0.48a	
	成熟期(大田) Maturation stage(field)	CK	55.60±1.23b	6.6
		PSM	59.30±1.42a	
小麦 Wheat	(水培)出苗后14 d 14 days after emergence(nutrient solution)	CK	30.52±1.35b	8.1
		PSM	33.00±1.12a	
	(水培)出苗后21 d 21 days after emergence(nutrient solution)	CK	42.73±0.98b	7.9
		PSM	46.13±1.56a	
	(水培)出苗后28 d 28 days after emergence(nutrient solution)	CK	53.36±1.11b	9.7
		PSM	58.52±1.95a	

4)植物源次生代谢物对作物光合能力的影响。由表6可知,施用植物源次生代谢物显著提高了小麦叶片的净光合速率、气孔导度、胞间CO_2浓度和蒸腾速率,增幅分别为7.9%、66.6%、12.9%和56.3%,降低了气孔限制值,降幅为31.7%,从而提高了小麦叶片的光合能力,促进小麦生长。

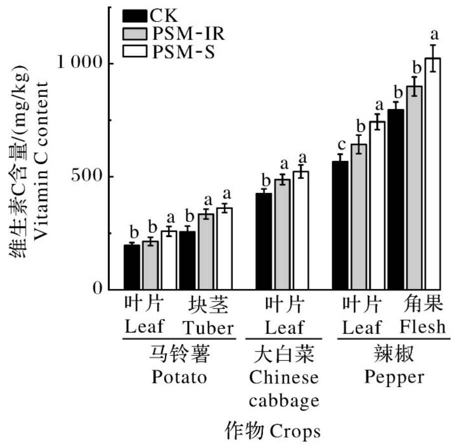
2.3 植物源次生代谢物对作物品质的影响

与对照相比,施用植物源次生代谢物显著提高了马铃薯、大白菜和辣椒Vc的含量(图2),显著降低了其硝酸盐的含量(图3),且植物源次生代谢物灌根(PSM-IR)的效果要优于喷施(PSM-S)。与对照相比,喷施植物源次生代谢物后马铃薯叶片及块茎、大白菜和辣椒叶片及角果中Vc的含量分别提高了

表6　不同处理下小麦叶片光合作用参数的变化

Table 6　Changes in photosynthetic parameters of wheat leaves under different treatments

处理 Treatment	净光合速率/[μmol/(m·s)] Net photosynthetic rate	气孔导度/[mmol/(m·s)] Stomatal conductivity	胞间CO_2浓度/(μmol/mol) Intercellular CO_2 concentration	蒸腾速率/[mmol/(m·s)] Transpiration rate	气孔限制值 Pore limit value
CK	14.08±0.41b	0.21±0.07b	275.97±8.97b	4.19±0.68b	0.315±0.06a
PSM	15.20±0.25a	0.35±0.05a	311.61±15.62a	6.55±0.95a	0.215±0.03b



试验结果采用t检验法检验分析，不同字母表示不同组间差异达到5%显著水平。下同。The experimental results was analyzed using t-test, with different letters indicating a significant difference of 5%. The same as below.

图2　不同处理下作物维生素C含量的变化

Fig.2　Changes in vitamin C content of crops under different treatments

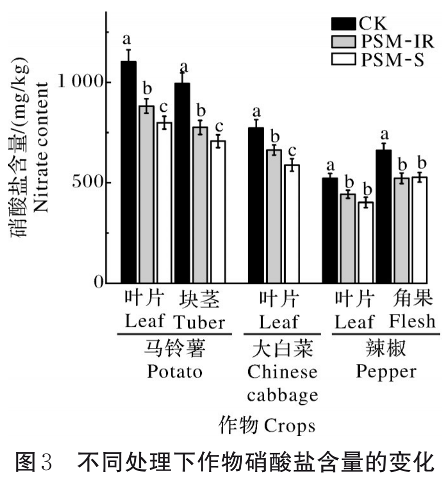


图3　不同处理下作物硝酸盐含量的变化

Fig.3　Changes in nitrate content of crops under different treatments

8.90%、30.58%、14.70%、13.40%和12.90%，灌施分别提高了31.70%、40.80%、22.90%、30.95%和28.51%；喷施植物源次生代谢物后马铃薯叶片及块茎、大白菜和辣椒叶片及块茎中硝酸盐的含量分别下降了20%、22%、14.23%、15.13%和21%，灌施分

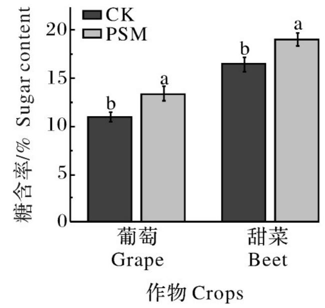


图4　不同处理下作物糖含量的变化

Fig.4　Changes in crop sugar content under different treatments

别降低了27.6%、28.8%、23.9%、22.98%和20.27%；施用植物源次生代谢物还能提高作物糖含量，与对照相比，植物源次生代谢物灌根后葡萄的糖含量提高了21.81%，甜菜糖含量提高了15.75%，均达到了显著性水平（图4，$P<0.05$）。以上结果表明，植物源次生代谢物可提高作物品质。

3　讨　论

本研究结果表明植物源次生代谢物能提高作物产量，对15种作物均具有增产效果。其增产效果可能是由于植物源次生代谢物提高了植物的抗逆能力、促进了根系生长、提高了叶片SPAD值和光合作用能力，从而引起的干物质积累量增加造成的。植物源次生代谢物可能会促进光合作用同化产物向种子中的转运，提高小麦籽粒淀粉合成和干物质积累量[21]，促进生殖枝结实数和种子产量[22]，缓解甘薯淹水胁迫，提高甘薯产量[23]。战帅等[24]研究的植物源次生代谢物能促进生菜对矿质养分的吸收，提高生菜氮、磷、钾的吸收量，从而提高肥料的养分效力系数、促进作物生长、提高作物产量和品质，说明植物源次生代谢物能提高作物对矿质养分吸收的效率，提高肥料的利用率，对化肥具有增效作用。

种子发芽是农业生产的第一步，直接关系着作物的产量和品质。本研究结果表明植物源次生代谢物能显著提高种子的发芽势和发芽率，与刘长乐等[25]报道的植物源次生代谢物提高种子发芽的抗逆

性、提高种子发芽率的结果相似。根系在植物生长过程中不仅是吸收水分和养分的重要器官,还对植物地上部的支撑起着重要作用。本研究结果表明植物源次生代谢物对作物根系的生长发育起着重要作用,与对照相比,植物源次生代谢物对小麦根系的最大根长、总根长、根系总表面积、根系总体积、根系平均直径和根尖数均有促进效果,同时还能提高地上部的生物量,提高作物的根冠比,协调作物地上部和地下部的共同生长发育。这与李田甜等[26]施用胺鲜酯DA-6和缩节胺(DPC)等植物源次生代谢物提高了棉花苗期的主根粗、根体积和根冠比,促进了棉花幼苗根系形态的构成结果相一致。SPAD值能直接反映叶绿素的含量。叶片是植物进行光合作用的主要器官,叶绿素含量与叶片光合作用强度息息相关。与对照相比,施用植物源次生代谢物显著提高了马铃薯、小麦、大白菜和包菜叶片叶绿素含量(SPAD值),增强了小麦叶片的光合作用,提高了气孔导度、胞间CO_2浓度和蒸腾速率,降低了气孔限制值,该结果与他人施用植物源次生代谢物促进作物幼苗生长、提高叶片SPAD值、增强光合作用等[27-30],从而促进产量和品质的提升的研究结果一致。本文中施用植物源次生代谢物能改善作物品质,提高了马铃薯、大白菜和辣椒中Vc的含量,降低了其硝酸盐的含量,提高了甜菜和葡萄中糖的含量,与李海燕等[31]报道的植物源次生代谢物提高阳光玫瑰葡萄的可溶性固形物结果相一致。综合研究结果分析,植物源次生代谢物能促进作物根系的生长发育,增强根系对养分的吸收,同时还能提高地上部的生物量,提高叶片SPAD值和光合作用强度,进而提高叶片的光同化产物,最终达到提高作物产量、改善作物品质的效果。

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Application effect of plant-derived secondary metabolite on agricultural crops

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Abstract To investigate the effect of plant secondary metabolites on the yield increase of different crops,the metabolites of sugar beet and sugarcane were extracted and separated,optimized in proportion,and then chelated with humic acid to form a product according to the national standard of water-soluble fertilizers containing humic acid.Field and hydroponic experiments were conducted to study the yield increase effect and mechanism of this product on 15 crops such as wheat.Two treatments were set up in the experiment:(1) conventional fertilization;(2) conventional fertilization + plant-derived secondary metabolites products,which were applied by foliar spraying,fertilizer mixing,and root irrigation according to different crop types.The results showed that compared with the control,the yield of 15 crops were increased by 5.2% to 21.1% by applying plant-derived secondary metabolites.The germination potential of rice,corn,and cotton seeds increased by 6.6%,11.5%,and 15.2%,respectively,and the germination rate increased by 2.6%,3.5%,and 6.1%,respectively.The total root length,total surface area,and root tip number of wheat roots increased by 54.44%,60.57%,and 30.43%,respectively.The SPAD values of potato,Chinese cabbage,cabbage,and wheat leaves increased by 4.8%,8.7%,6.6%,and 9.7%,respectively.The net photosynthetic rate of wheat leaves increased by 7.9%,and the Vc content of potatoes,Chinese cabbage,and chili increased by 40.8%,22.9%,and 28.51%,respectively.However,the nitrate content decreased by 28.8%,23.9%,and 20.27%,respectively.The sugar content of grapes and beets increased by 21.81% and 15.75%,respectively.The above results indicate that plant secondary metabolites could increase the yield and improve the quality of crop by enhancing the root vitality,promoting nutrient absorption,increasing chlorophyll content,and promoting the accumulation of photosynthetic products,and have good effects of improving fertilizer quality and efficiency.

Keywords plant secondary metabolites;crops;yield;chlorophyll;root growth

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