纳米材料在农业上的应用及其对植物生长和发育的影响

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摘要: 随着纳米材料研究的深入, 其在植物上的应用越来越广泛。本文对纳米材料在农业上的应用现状进行了综述, 内容包括纳米肥料、纳米保鲜材料、纳米农药与纳米环境改良等四个方面, 并对纳米材料在植物中的毒性和吸收转运的研究以及其在植物生长与发育上的作用做出了概述。

关键词: 纳米材料; 植物; 应用; 生长; 发育

纳米技术是20世纪80年代末诞生并崛起的高科技, 其对世界经济的发展, 以及工业和人们的生活产生了非常重要的影响, 纳米技术研究尺寸在1~100 nm具有物理、化学和生物特性的物质(Gruère等2011)。纳米材料是纳米科技发展的重要基础, 也是纳米科技最为重要的研究对象。生物医学(Zhang等2008)和农业(Chen和Yada 2011)是纳米材料研究中最为密集的领域。

广义上, 纳米材料是指在三维空间中至少有一维处于纳米尺度范围或由它们作为基本单元构成的材料, 即纳米材料是物质以纳米结构按一定方式组装成的体系, 或纳米结构排列于一定基体中分散形成的体系, 包括纳米超微粒子、纳米块体材料和纳米复合材料等(Arruda等2015)。狭义上, 纳米材料可分为自然和人工合成的纳米颗粒(engineered nanoparticles, ENPs), ENPs又可分为Carbon-based和Metal-based的两种类型。Carbon-based ENPs主要有富勒烯和碳纳米管(carbon nanotubes, CNTs)两种类型; 而Metal-based ENPs分为金属、金属氧化物和量子点(Peralta-Videa等2011)。在生产上使用最多的Metal-based ENPs有nZnO、$nTiO_2$、nAu、nAg、$nCeO_2$、nCu等(Keller等2013)。

目前人们对纳米材料的特性及所形成机理的认识, 主要集中在尺寸效应、表面与界面效应和量子隧道效应等几个方面(Mukherjee等2016)。由于其独特的尺寸效应, 纳米材料会呈现出许多大尺寸材料不具备的特殊性质, 如优良的物理化学性能、加工性能和生态性。依据纳米材料的基本特性, 在农业等各方面获得广泛应用。如: 利用纳米材料开发的纳米填充肥料, 可控制释放调节植物生长和增强靶标活性(Derosa等2010); 使用各种纳米杀虫剂来防治植物病虫害(Moraru等2003); 通过向原有包装材料中加入纳米材料的新型纳米包装材料, 具有纳米材料的表面等离子体性质, 并表现出很好的力学性能、透气性和光催化性等(Li等2016)。

本文综述了纳米材料在农业上的应用现状, 并对纳米材料在植物中的毒性和吸收转运的研究以及其在植物生长与发育上的作用做出了概述。

1 纳米材料在农业上的应用

纳米产品已在催化、光电、能源、生物医药等不同行业得到广泛应用, 在过去十年内, 纳米产品的种类快速增加, 在生物学等新领域中的应用也日益受到重视(Klaine等2008)。在农业中主要应用于纳米肥料、纳米保鲜材料、纳米农药和纳米环境改良等方面。

1.1 纳米肥料

纳米肥料是纳米技术在农业上的一个里程碑式的应用, 它是用纳米材料技术构建、用医药微胶囊技术和化工微乳化技术改性及化学聚合而形成的全新肥料, 包括纳米结构肥料与纳米材料包膜或胶结缓、控释肥料(张夫道等2002)。传统化肥的使用存在许多问题, 而低利用率是突出的问题, 这不仅增加了生产成本, 而且导致环境污染(Wilson等2008)。具有比表面积大等特性的纳米材料可以有效地解决这个问题。硫纳米涂层(≤100 nm)可确保肥料有效控制释放, 并最终提高其利用效率(Santoso等1995)。可生物降解的聚合壳聚糖纳米颗粒(约为78 nm)已经用于氮、磷、钾肥料(如脲、

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磷酸钙和氯化钾)的控制释放(Corradini 2010)。Kottegoda等(2011)基于改性的羟基磷灰石纳米粒吸附尿素而制成的纳米肥料, 能持续缓慢地释放氮素达60 d, 而传统商业肥料释放氮素量不均匀且持续时间短(约30 d)。添加纳米剂的复合肥能促进水稻分蘖的形成, 增加孕穗期叶绿素含量和干物质累积量, 从而增加稻谷产量, 提高氮肥利用率, 同时降低稻田水中总氮含量, 减少氮肥流失造成的水环境污染(武美燕等2010)。施用纳米膨润土和纳米活性炭包膜氮肥可提高早稻产量, 增加氮、磷、钾养分吸收量, 促进氮、磷、钾向籽粒的转运(王小娟等2011)。Millán等(2008)报道了尿素沸石片(urea-fertilized zeolite chips)可缓慢释放氮肥, 并且显著提高磷酸盐矿物的溶解性, 从而改善作物对磷的吸收, 增加作物产量。由蒙脱土(montmorillonite, MMT)制成的纳米肥料具有较强的吸水性, 可形成原纳米MMT颗粒体积的10~15倍的凝胶体, 从而降低水分的释放速度供作物吸收利用, 有很好的抗旱和促进生长作用(刘群等2012)。

1.2 纳米保鲜材料

聚合物基纳米复合材料是按照一定比例将分散均匀的纳米颗粒与高分子聚合物通过合成、添加、改性等方式加工混合而形成复合包装材料(尹国平和陈志周2012), 已应用于果蔬产品贮藏保鲜(张文林等2013)。纳米材料的表面等离子体性质及其良好的力学性能、透气性和光催化性, 能有效阻止微生物的生长, 并且较好地保持果蔬在贮藏过程中感官品质和营养成分, 延长产品储藏期, 具有延缓果蔬的品质劣变及延长冷藏期的作用(马宁等2012; 杨龙平等2015; 尹晓婷等2015)。陈建中等(2016)利用纳米TiO_2壳聚糖中草药复方涂膜保鲜剂配方, 观测其对草莓果实采后的保鲜效果, 结果显示, 处理后的草莓果实失重显著减慢, 且维生素C含量的下降也得到了较好的控制。张蓓等(2016)研究了蜂胶/纳米SiO_2复合涂膜处理对圣女果成熟与衰老过程中相关酶活性的影响, 结果表明, 蜂胶/纳米SiO_2复合涂膜的保鲜效果显著优于蜂胶涂膜和对照。随着果实的后熟, 超氧化物歧化酶(superoxide dismutase, SOD)、过氧化物酶(peroxidase, POD)、多聚半乳糖醛酸酶(polygalacturonase, PG)、果胶酯酶(pectinesterase, PME)以及纤维素酶(cellulase, CE)的活性均先增加后减小, 而多酚氧化酶(polyphenol oxidase, PPO)活性逐渐增加。刘永等(2016)以鲜切苹果为保鲜对象, 研究海藻酸钠/纳米SiO_2涂膜对鲜切苹果的保鲜效果, 结果表明, 海藻酸钠/纳米SiO_2涂膜能有效保持鲜切苹果的鲜度和硬度、延缓鲜切苹果水分的散失、减少可溶性固形物含量和可滴定酸含量的降低、抑制色泽变化和褐变、抑制PPO活性的升高。徐庭巧等(2016)研究了纳米碳酸钙改性聚乙烯膜(nano-$CaCO_3$-modified low-density polyethylene, NCCLDPE)对2°C下杨梅果实贮藏品质和生理的影响, 结果发现, NCCLDPE膜的氧气和二氧化碳的透过率分别为普通LDPE膜的72.39%和81.33%, 从而有利于在包装袋内更快的形成低氧和高二氧化碳的环境, NCCLDPE包装比普通包装杨梅果实的腐烂率低23.74%, 而总酚和花色苷含量分别高7.63%和14.75%。NCCLDPE包装延缓了杨梅果实原果胶的降解和水溶性果胶的增加, 维持了果实的品质和质地。

1.3 纳米农药

传统控制病原体和害虫的方法已经影响了农民的生活环境和经济收入, 因为90%的农药在施用期间会损失于空气与径流中。此外, 滥用农药可增加病原体和害虫的抗性, 减少土壤微生物的多样性, 减少固氮; 导致农药的生物积累, 传粉昆虫减少, 并破坏鸟类的栖息地(Liu等2006; Tarafdar等2013)。Goswami等(2010)报道了疏水型nTiO_2 (金红石)在2 g·kg^{-1}浓度下对水稻象鼻虫的防效效率为93%, 而亲水型nTiO_2 (金红石)和亲水型nTiO_2 (锐钛矿)对水稻象鼻虫的防效效率分别为56%和65%。nSiO_2可将靶基因转移到细胞中(Torney等2007), 并且该技术已成功用于制备杀虫剂和驱虫剂等制剂中(Gajbhiye等2009)。Liu等(2006)研究表明, 含有井冈霉素(validamycin)的多孔中空nSiO_2可用作水溶性农药的有效控释。由于nSiO_2的吸收能力, 其可进入害虫抵抗杀虫剂的屏障——表皮层, 从而表现出优良的杀虫性能(Barik等2008)。阿维菌素, 一种通过抑制氯离子通道来阻断昆虫中的神经递质的农药, 它被紫外线照射6 h即失活, 而以纳米颗粒为载体的阿维菌素缓慢控释时间可达30 d (Ghormade等2011)。Yang等(2009)研究表明含有大蒜精油的纳米聚乙二醇涂层可有效抑制赤拟谷盗虫(*Tribolium castaneum*)等害虫。

1.4 纳米环境改良

农业生产中由于化学药物的不当使用、畜禽排泄物等带来的土壤、水体污染、富营养化、有害气体污染等已经成为制约农业生产可持续发展的因素(孙长娇等2016)。随着环境分子科学的快速发展, 纳米材料在污染环境修复研究中的应用越来越受到重视(王萌2012)。纳米颗粒由于具有巨大的比表面积和微界面特征, 可以强化多种界面反应, 如对重金属离子及有机污染物的表面吸附、专性吸附及增强的氧化还原反应等, 在重金属及有机污染物等污染土壤及污水治理中有望发挥重要作用(王萌等2010)。碳纳米管是一种新型的吸附材料, 其具有独特的多孔和空心结构、较大的比表面积以及与污染物间的多种相互作用, 对水相中多种无机和有机污染物具有良好的吸附性能(于飞2013); 纳米零价铁可以修复多氯联苯、DDT等有机物污染的土壤和地下水(曹梦华2013; 陈曦2014; 汪玉2012); $nTiO_2$的光催化物质在紫外线照射下, 产生的氧和氢氧自由基有很强的化学反应活性, 可以与细菌、有机物等发生反应, 生成CO_2和H_2O, 从而分解水体、土壤环境中的有机化合物和细菌等污染物质(胡学香2003)。

2 纳米材料在植物中的毒性和吸收、转运的研究

植物是高等生物暴露于纳米材料的一条主要途径, 纳米材料可能通过食物链使其在高等生物中积累, 因而了解纳米材料在植物中的毒性及其吸收转运是非常重要的。

2.1 纳米材料的植物毒性

早期对纳米材料与植物之间作用的研究主要集中在纳米材料的植物毒理学上。根据纳米材料和植物种类的不同, 显现出的植物毒性也各不相同。植物毒性测定通常在植物发育的两个阶段进行: (1)在种子萌芽期间, 测量发芽率和根长; (2)在幼苗生长期间, 测定根、茎的伸长情况和干鲜重, 通过这些来评估纳米颗粒对植物的影响。近年来, 植物叶片数(Lee等2010)、叶绿素含量(Parsons等2010)以及纳米颗粒的细胞和基因毒性已被用于判定植物毒性的新指标。到目前为止, 已有多种植物被用来观测对纳米材料的植物毒性、吸收和生物积累的响应研究(Ghosh等2010; López-Moreno等2010; Khodakovskaya等2011; Wang等2011), 如小麦(*Triticum aestivum*)、南瓜(*Cucurbita pepo*)、黄瓜(*Cucumis sativus*)、大豆(*Glycine max*)、番茄(*Lycopersicon esculentum*)、甘蓝(*Brassica oleracea*)等。邹丽莎(2014)通过在营养液中添加不同浓度的nZnO和等剂量的可溶性锌(3 $mg \cdot L^{-1}$)进行室内水培试验。研究玉米(*Zea mays*)对nZnO的吸收积累特性以及nZnO的植物毒性来源。综合萌发率、生物量、叶绿素、根细胞伤害率、MDA、SOD、POD等指标测定结果分析认为, nZnO的毒性部分源于溶出的离子态锌, 更多来自于纳米颗粒态。郭敏(2016)采用水培种植水稻(*Oryza sativa*)实验, 通过研究多壁碳纳米管(multi-walled carbon nanotubes, MWCNTs)、nZnO和nCuO在浓度为10、50和100 $mg \cdot L^{-1}$时对水稻幼苗生长指数、氧化胁迫效应、生理功能、物质合成的影响, 以及纳米材料在植物体内的吸收, 揭示了典型人工纳米材料对水稻的植物毒性以及在植物体内的吸收行为。桂新(2016)研究了纳米氧化铈($nCeO_2$)对生菜(*Lactuca sativa*)毒性的影响, 结果表明, 土壤中添加$nCeO_2$后, 1 000 $mg \cdot kg^{-1}$会抑制生菜的生长, 并且叶片中硝态氮含量和可溶性糖含量都显著下降, 说明$nCeO_2$对生菜有毒性效应。通过测定植物根和茎叶组织中SOD、POD和MDA的活性, 表明$nCeO_2$在生菜根部活化, 发生了价态转化, $nCeO_2$对于生菜根部的毒性可能是由于$nCeO_2$部分转化Ce^{3+}导致。

2.2 纳米材料在植物中的吸收与转运

与纳米材料的植物毒性相比, 对植物系统中纳米材料的吸收与转运的研究较少。与动物细胞不同, 植物细胞具有细胞壁, 几乎没有吞噬作用。在进入植物细胞之前, 纳米材料必须穿透细胞壁和细胞质膜。作为天然筛的植物细胞壁的孔径通常为3~8 nm, 厚度为5~20 nm (Carpita和Gibeaut 1993)。具有小于最大孔尺寸的纳米颗粒能通过并到达质膜, 而较大的颗粒则不能进入植物细胞。例如, 3 nm的$nTiO_2$ (锐钛矿)能够穿过细胞壁, 进入植物细胞并积累在拟南芥根和叶的特定亚细胞位置(Kurepa等2010); 而25 nm的TiO_2不能穿过细胞壁, 从而聚集在了玉米根部表面, 因此阻碍了根系对水的传导性和利用性, 减少了植物蒸腾作用, 并影响植物生长发育(Asli和Neumann 2009)。Saboattwood等(2012)试验结果证明番茄幼苗对nAu具有选择性

吸收, 即3.5 nm的nAu可被植物吸收, 但18 nm的nAu则附聚在根系表面。Birbaum等(2010)提出, 当玉米植株暴露于37 nm的$nCeO_2$气溶胶或悬浮液时, 纳米颗粒没有被植物体吸收转运。但是, 还有一些文献报道指出, 具有较大尺寸的纳米颗粒却可以在植物中被吸收转运。例如, 47 nm的Fe_3O_4可以穿透表皮并在南瓜植物体内转运(Corredor等2009), 45 nm的$NaYF_4$:Yb纳米颗粒可以在拟南芥中被吸收并转运到维管系统、茎和叶中(Hischemöller等2009)。

一些学者认为, 纳米颗粒(ENP)可能诱导形成新的更大尺寸的细胞壁孔径, 通过它们, 更大的ENP可以被吸收。使用光学和荧光显微镜可以监测显示ENP的吸收情况(Liu等2010; Wang等2011)。Wild和Jones (2009)使用双光子激发显微镜(two-photon microscopy, TPE)观察到MWCNTs穿透小麦根的细胞壁并到达细胞质, 但没有完全进入细胞。Zhai等(2014)通过透射电子显微镜(transmission electron microscope, TEM)观察得出, nAu可以直接被杨树的根部吸收, 并且转移到茎和叶。在整个植株中, Au(III)离子被吸收并还原成nAu。Sun等(2014)使用共聚焦激光扫描显微镜(confocal laser scanning microscope, CLSM)和TEM观察了4种植物组织、细胞和亚细胞中20 nm的$nSiO_2$的位置和定量, 结果表明, $nSiO_2$可以通过共质体和质外体途径穿透到根, 然后通过木质部的导管组织转到植物的茎和叶。Wang等(2012)利用TEM和能量色散光谱(energy dispersive spectroscopy, EDS)检测玉米植物的木质部汁液中的nCuO, 结果显示nCuO可以穿透根组织, 到达木质部, 并被转移到地上部分。分根实验和高分辨率TEM观察进一步表明, nCuO可以通过韧皮部从茎转移回根, nCuO从Cu(II)还原为Cu(I)。

3 纳米材料对植物生长和发育的影响

纳米材料处理可以增强种子的活力, 提高植物体内各种酶的活性, 进而促进植物根系生长, 提高植物对水分和肥料吸收, 促进新陈代谢, 在原有品种农艺性状的基础上进一步提高植物的抗虫、抗病以及各种抗逆性能力, 达到增产和品质改善的效果。

3.1 纳米材料对种子萌发的影响

Lahiani等(2013)在无菌琼脂培养基中加入MWCNT的实验结果显示, MWCNT可刺激三种重要作物(大麦、大豆、玉米)的种子发芽, 这是由于MWCNT渗透种皮的能力加强了种子对水分的吸收。此外, 他们还报道了MWCNT调控编码大豆、玉米和大麦种皮上几种类型的水通道蛋白的基因表达情况。Ghodake等(2010)使用MWCNTs处理黑豆(*Phaseolus mungo*)幼苗, 结果显示在10、20和40 $\mu g \cdot mL^{-1}$浓度下, 与对照相比, 根的生长分别提高138%、202%和135%。Mondal等(2011)报道了直径约30 nm的MWCNTs对芥菜(*Brassica juncea*)种子的有益影响。类似的效果也出现在了MWCNTs处理杂交Bt棉(hybrid Bt cotton), 番茄(*Lycopersicum esculentum*)和水稻(*Oryza sativa*)等植物上(Nalwade和Neharkar 2013; Nair等2010)。

nAg可促进濒危的药用树木——乳香(*Boswellia ovalifoliolata*)的种子萌发和幼苗生长(Savithramma等2012)。nPd、Au、Cu可促进莴苣种子萌发(Shah和Belozerova 2009)。在金属氧化物方面, $nSiO_2$在玉米和番茄(Siddiqui和Al-Whaibi 2014; Suriyaprabha等2012a, b)中, $nTiO_2$在菠菜和小麦(Feizi等2012; Hong等2005b; Larue等2012; Yang等2006; Yang和Watts 2005; Zheng等2005, 2008)中, nZnO在花生、大豆、小麦、洋葱和黄瓜(de la Rosa等2013; Prasad等2012; Ramesh等2014; Sedghi等2013; Raskar和Laware等2014)中, nAl_2O_3在拟南芥和浮萍(*Lemna minor*) (Juhel等2011; Lee等2010)中的研究均表明, 纳米材料可在不同程度上促进种子萌发。

3.2 纳米材料对植物生长及元素吸收的影响

Barrena等(2009)在莴苣和黄瓜中, Arora等(2012)在芥菜中, Savithramma等(2012)在乳香和Gopinath等(2014)在嘉兰(*Gloriosa superba*)中报道了nAu可增加叶片数、叶面积、植株高度、叶绿素含量和糖含量, 从而增加作物产量。Lin等(2004)对长白落叶松(*Larix olgensis*)幼苗外源施加$nSiO_2$的结果显示, $nSiO_2$改善了幼苗生长和质量, 包括平均高度、根管直径、主根长度和幼苗侧根数, 并诱导叶绿素的合成。裴福云等(2015)对比喷施相同含硅量的纳米硅藻土和$nSiO_2$后, 发现苋菜(*Amaranthus tricolor*)干物质量分别提高43.4%和14.9%, 吸收氮、磷、钾总量分别提高了36%和20%。$nTiO_2$促进油菜(*Brassica napus*)幼苗的根和胚芽生

长(Mahmoodzadeh等2013)。Jaberzadeh等(2013)研究发现, $nTiO_2$增加了在干旱胁迫下的小麦植株生长与产量。此外, $nTiO_2$调节参与氮代谢的酶活性, 例如硝酸盐还原酶、谷氨酸脱氢酶、谷氨酰胺合酶和谷氨酸-丙酮酸转氨酶, 帮助植物吸收硝酸盐, 也有利于蛋白质和叶绿素形式的无机氮转化为有机氮, 这可以增加植物的鲜重和干重(Yang等2006)。$nTiO_2$/ZnO处理水培生菜试验发现, 其可显著增加生菜根系对氮、磷、钾、锌等元素的吸收以及生菜地上部对氮、磷、钾、钙的吸收(Li等2014; 李贵莲等2015; 苏蔚等2015; Wang等2016)。nZnO可显著提高瓜尔豆(*Cyamopsis tetragonoloba*)的生物量, 促进叶绿素和蛋白质合成, 改善根际微生物群体, 即酸性磷酸酶、碱性磷酸酶和植酸酶的活性(Raliya和Tarafdar 2013)。从光扫描显微镜和电感耦合等离子体/原子发射光谱中可以看出, 绿豆(*Vigna radiata*)和鹰嘴豆(*Cicer arietinum*)的幼苗根吸收了nZnO, 从而促进了根和茎的伸长及其生物量(Mahajan等2011)。Tripathi和Sarkar (2015)利用扫描电子和荧光显微镜证实, 小麦植株内存在水溶性CNTs, 并且CNTs在光照和黑暗条件下均可诱导根茎生长。CNTs诱导水和必需的Ca和Fe营养元素的吸收效率, 从而促进植物生长和发育(Tiwari等2014; Villagarcia等2012)。王佳奇(2013)研究了纳米碳对玉米生长及养分吸收的影响发现, 纳米碳的加入提高了土壤中碱解氮、速效磷、速效钾养分的含量, 并促进了玉米对氮、磷、钾等养分的积累量。刘秀梅(2005)研究得出, 纳米-亚微米级复合材料能提高作物对褐潮土、红壤和风沙土中氮、磷、钾的吸收和利用, 显著增加作物干重及作物体内氮、磷、钾的含量。

3.3 纳米材料对植物光合作用的影响

Krishnaraj等(2012)研究了nAg对水培生长的假马齿苋(*Bacopa monnieri*)生长代谢的影响, 研究发现nAg可诱导植物体内蛋白质和碳水化合物的合成。nAg可增加芥菜、大豆和玉米的植物生长(茎长、根长、叶面积)和生化特性(叶绿素、碳水化合物、蛋白质含量、抗氧化酶) (Salama 2012; Sharma等2012)。$nTiO_2$可充当光催化剂并诱导氧化还原反应(Crabtree 1998), 其提高了植物的光吸收性能以及从光能到电和化学能的转化, 并且诱导二氧化碳的同化。$nTiO_2$显著促进老化种子的活力及叶绿素的形成, 保护叶绿体免于长时间光照老化(Hong等2005a, b), 并刺激核酮糖-1,5-二磷酸羧化酶(Rubisco)活性来增强光合碳同化, 从而增加植物生长和发育(Gao等2006; Yang等2006)。Ma等(2008)研究的$nTiO_2$的分子响应机制表明, $nTiO_2$诱导Rubisco活化酶mRNA的标记基因, 并增强Rubisco活化酶的蛋白水平及其活性, 从而改善了Rubisco羧化和光合碳反应的高效率。此外, Qi等(2013)研究了外源施加$nTiO_2$可提高植物的净光合速率、导水性和蒸腾速率。

3.4 纳米材料对植物抗氧化性的影响

Kumar等(2013)报道了nAu对拟南芥的种子萌发和抗氧化系统有重要作用, 并改变其小RNA的表达水平, 调节植物中的各种形态、生理和代谢过程。Haghighi等(2012)和Siddiqui等(2014)分别在番茄和南瓜中发现, 在NaCl胁迫下, $nSiO_2$可促进种子萌发, 并刺激其抗氧化系统。在MS培养基上施加nZnO, 可促进香蕉(*Mousa sapientum*)体细胞胚胎发生、植株再生以及诱导脯氨酸合成, 还可提高SOD、CAT和POD的活性, 从而提高植株对生物胁迫的抗性(Helaly等2014)。徐立娜等(2015)通过营养液培养实验, 研究nCuO悬浮液对拟南芥叶片生长、叶绿体活性氧产生和保护酶活性的影响。结果表明, nCuO悬浮液处理96 h后,拟南芥叶片生长受到显著抑制, 叶绿体中过氧化氢、羟基自由基和超氧阴离子含量均随着NPs处理浓度的增加和时间的延长而逐渐上升; SOD、POD、CAT及抗坏血酸过氧化物酶(ascorbate peroxidase, APX)的活性和丙二醛(malonaldehyde, MDA)含量增加, 即nCuO能激发植物细胞的防御反应。

4 问题与展望

纳米技术作为一种先进的技术, 在电子、能源、医学和生命科学等众多领域都有应用。前期的研究集中于纳米材料对植物的毒性机理上, 纳米材料对植物的有益效果方面的研究仍不完善。已有的研究已经证实纳米材料对植物的生长发育具有较大的影响, 但尚有许多问题需深入探讨, 例如, 分子水平上, 哪些基因与蛋白质参与纳米材料对植物生长的调控? 植物的哪些生理代谢过程会被纳米材料诱导? 纳米材料处理下光合作用代谢

途径和其他代谢通路之间存在怎样的联系? 如何找出针对某种植物生长最合适的纳米颗粒大小及浓度? 对这些问题的深入研究, 有助于更好地了解纳米材料在植物生长发育中的响应机制, 并将其更好地应用于农业生产中。

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Applications of nanomaterials in agriculture and its effects on the growth and development of plants

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Abstract: With the deep development of nanomaterials, the applications of nanomaterials become more and more popular. The present review addresses four aspects regarding nanomaterials in agriculture, including nano-fertilizers, nano-packing materials, nano-pesticides and environmental improvement. Additionally, contents related to toxicity, uptake and transport between nanomaterials and plants are discussed, as well as the effects of nanomaterials on the growth and development of plants.

Key words: nanomaterials; plants; applications; growth; development

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