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专论与综述

微生物种子包衣的应用与研究进展

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摘　要：种子包衣是一种高效、新兴的种子处理技术。该技术将外源性材料与种子紧密结合，从而提高种子性能，最终提高作物产量和品质。植物有益微生物(plant beneficial microorganisms, PBM)是指能够促进植物养分吸收、增强其对生物和非生物胁迫的耐受力，并促进植物生长或减少农业化学投入的微生物。因此，PBM 可以作为一种微生物种子包衣剂。微生物种子包衣作为一种能够显著提高作物产量、经济效益和农业系统的可持续性发展的革新性技术，因其生态安全性和社会经济效益被认为是传统农业技术有前途的替代品。本文综述了微生物种子包衣技术及其在作物生产中的应用，并对其局限性和不一致性进行讨论。
关键词：种子包衣；微生物种衣剂；有益微生物；种子萌发；生物和非生物胁迫

The microbial seed coating and its application

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Abstract: Seed coating is an efficient seed treatment technology, which combines exogenous materials with seeds to improve seed performance and further crop yield and quality. Plant beneficial microorganisms (PBM) refer to the microorganisms that can promote plant nutrient absorption, enhance its tolerance to biotic and abiotic stresses, promote plant growth or reduce the agricultural chemical input. Therefore, PBM can be used as a microbial seed coating agent. As an innovative technology, microbial seed coating can significantly improve crop yield and its

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economic benefits, and maintain sustainable development of the agricultural system, which was thought to be a promising alternative to conventional agricultural technology. The present paper reviewed the microbial seed coating technology and its application in crop production, and its limitation and inconsistence were also discussed.

Keywords: seed coating; microbial seed coating agent; beneficial microorganism; seed germination; biotic and abiotic stress

化肥、杀虫剂和农用化学品的大量使用严重污染空气、土壤和水资源，破坏生态系统的生物多样性，引起全球广泛关注[1]。为应对这些挑战，我国推出精准农业政策，即以先进技术为基础，在提高粮食产量与品质的同时，减少水和农用化学品投入，以降低经济、环境和健康成本，重视土壤及其居民，保持生态系统健康和谐发展[2-4]。

种子包衣是精准农业政策的一项重要技术，它是指利用杀菌剂、杀虫剂、激素、肥料或有益微生物等有效成分包裹在种子表面，使种子外形成具有一定功能和包覆强度的保护层(种衣剂)，是现代农业保护种子或幼苗初始发育阶段的常见策略[5]。种衣剂不仅可以为种子提供萌发时所需的营养物质，也可以保护作物免受生物和非生物胁迫的侵害，提高产量和品质[6-7]。

根据功能或用途现可将种衣剂分为物理型种衣剂、化学型种衣剂、生物型种衣剂、特异性种衣剂和综合型种衣剂五类[8]。但物理型种衣剂会减少种子对水分的吸收和氧气的利用，从而延迟种子发芽[9]。化学型种衣剂的使用引起的环境污染对非靶标生物和一些有益生物产生不利影响，使有害生物对农药产生抗性，从而影响生态平衡[10-11]。相较而言，微生物种衣剂具有安全、高效、环保和对人畜无毒的特性，其主要成分是植物有益微生物(plant beneficial microorganisms, PBM)或其分泌物；其可以减少接种剂量且能在特定位置有效释放，从而增强种子活力，进而减少农药和化肥的使用量，减小对环境的影响[12]。此外，现代农业设备可以精准地播种包衣种子，有效控制种植密度，从而实现或接近精准农业，使微生物种子包衣技术具有广阔的应用前景[13-14]。

1 微生物种子包衣

植物有益微生物能促进植物生长、提高营养元素的吸收、恢复土壤肥力和增强植物对生物和非生物胁迫的耐受力[15-17]。然而，目前缺乏接种有益微生物的有效方法，在开阔的农田里大面积无针对性地接种此类微生物的成本相对较高[18]，而通过种子包衣的方法可以有效接种 PBM，促进植物生长。例如，de Gregorio 等[19]用纳米纤维固定化细菌包衣大豆种子，提高了大豆的发芽率(98.9%±1.1%)，促进大豆生长。Oliveira 等[20]发现，在加入 100%的 Hoagland 溶液条件下，利用丛枝菌根真菌(arbuscular mycorrhizal fungi, AMF)制作种子包衣，可使植物茎中钾、硫和锌的含量与未接种的对照相比分别增加到(50.1±1.54) g/kg、(3.0±0.20) g/kg 和(72.3±10.43) mg/kg，而且运用种子包衣技术的植物其根系中 AMF 的定殖率与常规接种的植物并无显著差异，表明 AMF 的种子包衣可以有效减少化肥和杀虫剂的使用。因此，有益微生物作为种衣剂在精准农业方面具有良好的应用前景。

1.1 微生物种子包衣配方

种子包衣是促进可持续农业的最佳方法之一。微生物种衣剂的配方一般包括 3 个基本要素：微生物、载体和添加剂[21]。用于微生物种子包衣的载体可以轻松黏附于种子，确保种子萌发和幼苗发育以及其在种子上的存活率和足够的保质期。最常见的微生物包衣载体包括二氧化硅和生物炭[22]。Głodowska 等[23]提出，以生物炭

作为载体，与假单胞菌(*Pseudomonas libanensis*)混合后包衣玉米种子，与对照相比，植物鲜重增加 2−10 g，株高增加 4%−26%。羧甲基纤维素(carboxymethyl cellulose, CMC)和藻酸盐作为常见的微生物种子包衣添加剂，由于成本低和环境安全，常用于商业微生物接种[24]。Zhou 等[24]研发的根瘤菌种子包衣包括根瘤菌和钼酸铵，并使用藻酸盐和脱脂牛奶作为黏合剂，当钼酸铵用量为0.2%时，接种根瘤菌菌株 ACCC 17631 的苜蓿其生长、结瘤和固氮能力达到最大，其中株高最高达 42.01 cm，生物量最高达 3.04 g/株，最大根瘤数为 22.89 个/株，最大根瘤重量 0.057 g/株。植物有益微生物是种子包衣制作中的关键。Ma 等[25]通过种子包衣将 AMF 异形根孢囊霉(*Rhizophagus irregularis*) BEG140 和 BEG140+植物促生菌(plant growth promoting bacteria, PGPB) 假单胞菌(*P. libanensis*) TR1 接种于豇豆种子，其在植株根部的菌根定殖率分别为 21.7%和 24.2%，TR1 能显著增加植物地上部(111%)和总植株干重(101%)，以及地上部与根部干重比(83%)。Zhang 等[26]发现生物复合种衣剂解淀粉芽孢杆菌(*Bacillus amyloliquefaciens*) Ba、枯草芽孢杆菌(*Bacillus subtilis*) Bs wy-1、*Bacillus subtilis* WXCDD105、荧光假单胞菌(*Pseudomonas fluorescens*) WXCDD51 和贝莱斯芽孢杆菌(*Bacillus velezensis*) WZ-37 处理的番茄种子株高(9.95±0.73) cm、茎径(1.88±0.15) mm、根长(6.01±0.28) cm、鲜重(2.71±0.08) g 和干重(0.172 7±0.01) g 均显著高于对照。

1.2 微生物种子包衣贮存期

有效的贮存期是种子包衣商业成功的关键因素之一[27]。虽然微生物在种子包衣上存活的最佳条件尚不明确，但人们对影响微生物生存的几个因素如温度、水分、包衣材料和污染物等进行了研究[28]。Georgakopoulos 等[29]评估了对甜菜和黄瓜进行生物防治的细菌和真菌拮抗剂，发现其中 *Pseudomonas adaceae* 是最有效的生物防治剂，在适宜环境温度下的泥炭配方中可存活 2 年。据报道，生物炭作为载体可以保持有益微生物的生存和丰度[30-31]。以生物炭为微生物种子包衣的载体，加上慢生型大豆根瘤菌(*Bradyrhizobium japonicum*)作为接种剂，可以维持较高丰度的细菌种群超 4 个月，这能确保大豆的高效结瘤[32]。Tripti 等[33]研究了含有伯克霍尔德氏菌(*Burkholderia* sp.)菌株 L2 和生物炭包衣对番茄种子的影响，结果表明，*Burkholderia* sp.菌株 L2 在生物炭中的生存时间延长到 240 d，该生物配方不仅能促进种子萌发和植物生长，而且能够增加番茄产量和改善土壤肥力。因此，探索能够提高微生物存活率的配方是开发高效接种剂的关键步骤。

2 微生物种子包衣对作物的益处

包衣种子在农作物中应用较多，如小麦[34]和玉米[35]等谷物，以及西红柿、黄瓜、和甜菜等蔬菜[26]。已有研究表明，通过种子包衣将有益微生物应用于作物后可促进种子萌发、植物生长、提高产量和营养价值(表 1，图 1)[36-44]。Hoseini 等[36]研究表明，接种哈茨木霉(*Trichoderma harzianum*) T36 的种子包衣后的幼苗出苗率最高(89.44%)，与对照相比增加 37.2%，芽长和根长分别可达 4.17 和 5.75 cm；Coninck 等[38]使用深绿木霉(*Trichoderma atroviride*)的包衣种子可在低温下储存至少 6 个月，并且其显著增强了幼苗抗黄色镰刀菌(*Fusarium culmorum*)病原体感染的能力；Mhada 等[43]使用热带根瘤菌(*Rhizobium tropici*)和海藻糖对种子进行包衣，对照组种子在 50 mmol/L 盐浓度下的光合活性降低了一半，而 *R. tropici* 和海藻糖包衣的种子仍保持其活性，能减轻盐胁迫对植株的负面影响。因此，选择能够赋予植物宿主耐受性的微生物菌株和适当的储存方法以确保微生物的生存、生长和功能来提高作物生产力，可以大大减轻生物与非生物胁迫对植物生态系统功能的负面影响。

表 1 用于可持续农业的微生物种子包衣

Table 1 Microbial seed coating for sustainable agriculture

功能微生物 Functional microbes	宿主植物 Host plant	包衣材料 Coating materials	胁迫类型 Stress	试验 Experiment	作用 Function	参考文献 References
哈茨木霉 *Trichoderma harzianum*	茴香 *Foeniculum vulgare* Mill.	蛭石、高岭土和珍珠岩 Vermiculite, kaolin and perlite	干旱 Drought	盆栽 Potting	促进植物生长(发芽率和组织长度) Promote plant growth (germination rate and tissue length)	[36]
荧光假单胞菌 *Pseudomonas fluorescence*	孜然 *Cuminum cyminum* L.	蛭石、高岭土和珍珠岩 Vermiculite, kaolin and perlite	干旱 Drought	盆栽 Potting	获得高出苗率, 增加植物可溶性蛋白和抗氧化酶活性 Obtain a high emergence rate, increase plant soluble protein and antioxidant enzyme activity	[37]
深绿木霉 *Trichoderma atroviride*	玉米 *Zea mays* L.	滑石粉、小麦糠和碳酸钙 Talc, wheat bran and calcium carbonate	枯萎病 Damping-off	盆栽 Potting	在低温下延长微生物的保质期，减少幼苗病害的出现 Extend microbial shelf life at low temperatures, reduced the occurrence of seedling diseases	[38]
绿僵菌 *Metarhizium*	玉米 *Zea mays* L.	硅藻土和水凝胶 Diatomite and hydrogel	病虫害 Plant diseases and insect pests	盆栽 Potting	改善植物的生长特征，减少病虫害 Improve plant growth characteristics and reduce pests and diseases	[39]
绿僵菌或球孢白僵菌 *Metarhizium* or *Beauveria bassiana*	玉米 *Zea mays* L.	甲基纤维素、黄原胶、菜籽油、膨润土和滑石粉 Methylcellulose, xanthan gum, rapeseed oil, bentonite and talc	病虫害 Plant diseases and insect pests	盆栽 Potting	减少由真菌病原体引起的植物根部腐烂 Reduce plant root decay caused by fungal pathogens	[40]
枯草芽孢杆菌 *Bacillus subtilis*	玉米，油菜 *Zea mays* L., *Brassica napus* L.	玉米淀粉、甲壳素和甘油 Corn starch, chitin and glycerol	–	盆栽 Potting	促进幼苗生长，减少机械磨损期间灰尘颗粒的释放 Promote seedling growth and reduce the release of dust particles during mechanical wear	[41]
哈茨木霉 *Trichoderma harzianum*	番茄 *Solanum lycopersicum* L.	纤维素和木薯糊精 Cellulose and cassava dextrin	病害，盐度和温度 Disease, salinity and temperature	盆栽 Potting	促进种子萌发 Promote seed germination	[42]
热带根瘤菌 *Rhizobium tropici*	菜豆 *Phaseolus vulgaris* L.	海藻糖 Trehalose	盐度 Salinity	盆栽 Potting	增加发芽率，调节形态参数 Increase germination rate and adjust morphological parameters	[43]
假单胞菌 *Pseudomonas*	小麦 *Triticum aestivum* L.	锌和阿拉伯树胶 Zinc and arabic gum	–	盆栽 Potting	提高植物产量，胚乳锌含量和增加生物可利用锌 Increase plant yield, endosperm zinc content and enhance bioavailable zinc	[44]

–：未提及

–: Not mentioned.

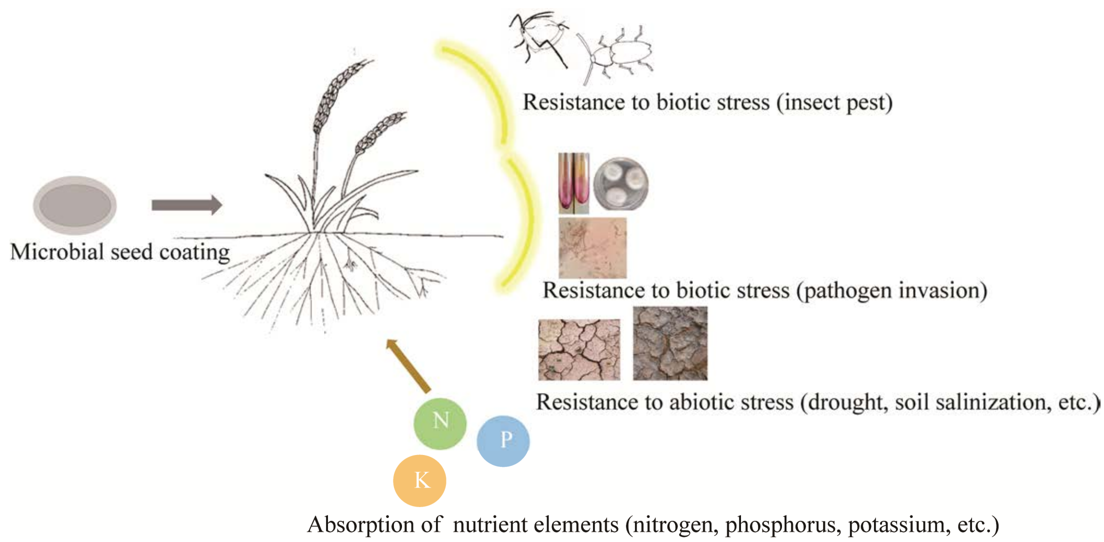

图 1　微生物种子包衣的作用
Figure 1　The function of microbial seed coating.

2.1　改善种子可种植性

种子包衣还可改变种子的形态特性如大小、重量、形状和均匀度，提高小粒种子和外形不规则种子的播种性能，有利于机械化精量播种并减少播种特定地点所需的种子数量，以实现精准农业[45]。Ryu 等[46]研究表明，用多粘芽孢杆菌(*Paenibacillus polymyxa*)包衣种子能够增加种子大小，可以帮助更好地精确播种，并保护植物免受各种植物病原体的侵害。Javed 等[47]通过用根瘤菌、滑石、氧化钙和膨润土的组合进行种子包衣，有利于机械播种，节约成本，同时也提高了番茄种子的发芽率。

2.2　提高种子质量

种子质量是创造最佳作物养分所依赖的重要因素，含有有益微生物的种子包衣可以克服种子萌发的限制，提前开始代谢酶活动和资源调动，从而提高种子质量及作物产量[48]。含有亲水物质的种子包衣通过改善水和空气运动，以及早期和快速完成吸收和活性代谢阶段来提高萌发潜力[49-50]。Wu 等[51]发现利用生防菌株产酸克氏杆菌(*Klebsiella oxytoca*) Rs-5 和芽孢杆菌 BCL-8 (*Bacillus* sp. SL-13、SL-14 和 SL-44)的组合对棉花种子进行包衣，棉花种子在盐碱地中的发芽率提高了 11.3%。Singh 等[52]研究发现，根瘤菌作为豇豆种子包衣剂可以提高种子质量和作物性能，与未包衣种子相比，在贮藏 12 个月后其萌发潜力和幼苗活力均有所改善。微生物包衣种子已被广泛接受作为许多作物的标准产品，如小麦、玉米、豇豆、苜蓿、番茄和西葫芦[53]。

2.3　促进植株生长和营养吸收

含有有益微生物的种子包衣不仅可用于改善种子发芽、幼苗建立和植物生长，还可以提高作物对营养元素的吸收及增加作物的质量和产量[54]。Rouphael 等[55]用 AMF [根内根孢囊霉(*Rhizophagus intraradices*) BEG72 和摩西管柄囊霉(*Funneliformis mosseae*)]以及 *T. atroviride* MUCL 45362 对两种洋蓟品种“Romolo”和“Istar”进行种子包衣并种植，结果发现微生物种子包衣提高了植物产量和营养价值，其抗氧化活性、总酚类、咖啡酰奎宁酸和类黄酮等显著提高。Colla 等[56]研究发现，通过 AMF (*Glomus intraradices*

BEG72 和 *Glomus mossae*)和 *T. atroviride* MUCL 45632 组合包衣种子能显著改善冬小麦的幼苗生长(芽和根部生物量以及叶数分别增加 23%、64%和 29%)、产量(根据生长季节而增加 8.3%−32.1%)和谷物质量(蛋白质浓度增加 6.3%，钾、磷、铁和锌浓度普遍增加)。在盆栽试验中，将 *T. atroviride* 以种衣剂的形式接种到土壤中，生菜、甜瓜、胡椒、西红柿和西葫芦的芽干重分别增加 167%、56%、115%、68%和 58%，在田间条件下生菜芽和根的干重分别增加 61%和 57%；对于西葫芦，接种两种微生物根内球囊霉(*Glomus intraradices*)和 *T. atroviride* 后其早期产量和总产量分别提高 59%和 15%[57]。含有微生物的种子包衣在低投入农业中需求量较大，因为其有可能减少化肥的应用并提高食品营养价值。Rocha 等[58]发现在未施肥的情况下，接种 AMF *R. irregularis* 的种子包衣可使植株的地上部营养浓度如氮、磷、钾和锌的分别增加 110%、93%、88%和 175%。

2.4 增强种子抗生物胁迫的能力

病虫害等生物胁迫严重影响作物生长，降低作物的产量和质量。目前常用的防治方法仍为容易污染环境的化学农药喷施，而通过种子包衣将有益微生物接种到植物中可以有效地拮抗病原菌和害虫，增强作物对病虫害的抵抗能力，从而保护植物的萌发和生长，减少化学农药的使用，从而达到环境友好的目的[59-61]。Kthiri 等[62]发现 *T. harzianum* 种子包衣可保护植物免受枯萎病的侵害，发病率与对照相比降低约 50%；而 Wang 等[63]则发现 *B. amyloliquefaciens* FS6 和噻虫嗪、甲虫灵、氟虫腈的种子包衣对人参灰霉病具有较好的防治作用。Mahmood 等[64]发现，在盆栽试验中，微生物种子包衣和杀真菌剂对鹰嘴豆枯萎病的防治效果几乎相同，且 *T. harzanium* 和杀真菌剂多菌灵处理种子可将疾病减少率提高到 93.75%，比单独施用更有效。Javed 等[65]发现，与无包衣处理的种子相比，用 *Bacillus* sp. KS-54 包衣水稻种子能有效地抑制水稻种植过程杂草的生长。因此，将微生物包衣应用于农作物上具有可行、经济和环境友好的战略[66]。

2.5 增强种子抗非生物胁迫的能力

环境因素，特别是干旱胁迫在萌发阶段可以抑制酶的活性，从而降低作物的萌发和幼苗指数，扰乱植物生命周期[67]。带有微生物制剂的种子包衣可以提高植物的耐旱能力、种子萌发、幼苗指数和生长效率等，是应对干旱胁迫的有效方法之一[68]。Piri 等[37]研究发现，在干旱胁迫下，用 *T. harzianum* 和 *P. adaceae* 对孜然种子进行包衣，不仅可以改善种子的物理特性，还可提高蛋白质含量和抗氧化酶活性，促进其机械化种植。

由不合理灌溉和过量施用农药化肥等引起的土壤盐渍化，也是全球许多农业地区作物生长和生产力的主要限制因素；盐度诱导的应激通常通过非气孔和气孔调节过程降低光合速率，干扰养分摄取，并导致植物的各种代谢紊乱和渗透应激[69-70]。各种研究表明有益微生物的种子包衣在盐胁迫下可以有效地促进植物生长。Shahzad 等[71]发现，利用蜡样芽胞杆菌(*Bacillus cereus*) Y5、*Bacillus* sp. Y14 和 *B. subtilis* Y16 等比例混合对小麦种子进行包衣，能够极大地改善气体交换、离子含量和生理生化，与未接种对照相比，株高、穗长、籽粒产量和秸秆产量分别增加 14.57%、16.75%、23.77%和 22.74%。

此外，炎热和寒冷的极端温度也是作物生产的重要限制因素。Rakesh 等[72]发现聚合物薄膜包衣起到温度开关的作用。AMF 可以缓解植物的温度应激，其与聚合物薄膜相结合的包衣

可以作为减轻植物温度应激的有效工具[73]。重金属胁迫是作物生产的不利因素之一，利用一些可以耐重金属的菌株制成包衣，使作物在重金属胁迫下更好地生长, 并且在保证作物可食用性前提下，或可用来修复重金属污染土壤[74]。Singh 等[75]研究发现 3 种耐汞细菌及其复合菌包衣促进芥菜在汞胁迫条件下的生长，同时增强芥菜对汞的积累。

3 常见微生物种子包衣及其应用

通过种子接种的 PBM 可以提高种子发芽率、植物性能及对生物(如病原体和害虫)和非生物(如盐、干旱和重金属)胁迫的耐受性，同时减少农用化学品的使用[76](表 2)。目前，木霉菌、芽孢杆菌等在种子包衣剂制作方面的应用相对广泛。

表 2 不同种类的微生物种子包衣

Table 2 Different microbial seed coating

功能微生物 Functional microbes	宿主植物 Host plant	作用 Function	参考文献 References
哈茨木霉 *Trichoderma harzianum*	玉米 *Zea mays* L.	提高种子的发芽率、发芽速度及根长 Improve the germination rate, germination speed and root length of seeds	[77]
木霉 *Trichoderma*	蓖麻 *Ricinus communis* L.	增强抗菌活性和种子品质 Enhance antimicrobial activity and seed quality	[78]
拟康宁木霉 *Trichoderma koningiopsis*	水稻 *Oryza sativa* L.	增加叶长和干重 Increase leaf length and dry weight	[79]
枯草芽孢杆菌 *Bacillus subtilis*	棉花 *Gossypium hirsutum* L.	增加种子发芽率并促生长 Increase seed germination rate and promote plant growth	[80]
芽孢杆菌 *Bacillus*	小麦 *Triticum aestivum* L.	促进植物生长 Promote plant growth	[81]
蜡样芽胞杆菌 *Bacillus cereus*	黄瓜，辣椒 *Cucumis sativus* L., *Capsicum annuum* L.	促进植物生长并具有产 IAA 功能 Promote plant growth and exhibit IAA production	[82]
假单胞菌 *Pseudomonas libanensis*	豇豆 *Vigna unguiculata* (L.) Walp.	提高粮食产量和营养含量 Improve grain yield and nutrient content	[83]
荧光假单胞菌 *Pseudomonas fluorescens*	番茄 *Solanum lycopersicum* L.	增加株高、茎径、根长、鲜重和干重 Increase plant height, stem diameter, root length, fresh weight and dry weight	[26]
绿针假单胞菌 *Pseudomonas chlororaphis*	小麦 *Triticum aestivum* L.	促进幼苗生长，提高幼苗中防御相关酶过氧化物酶(peroxidase, POD)、超氧化物歧化酶(superoxide dismutase, SOD)、过氧化氢酶(catalase, CAT)、苯丙氨酸解氨酶(phenylalanine ammonia lyase, PAL)和多酚氧化酶(polyphenol oxidase, PPO)的活性 Promote seedling growth and increase the activity of defense related enzymes peroxidase, superoxide dismutase, catalase, phenylalanine ammonia lyase and polyphenol oxidase in seedlings	[84]
假单胞菌 *Pseudomonas*	鹰嘴豆 *Cicer arietinum* L.	降低植物疾病发病率，增加植物地上部重量 Reduce the incidence rate of plant diseases and increase the aboveground weight of plants	[85]

3.1 木霉属(*Trichoderma*)种子包衣

木霉属(*Trichoderma*)是根际最常见的腐生真菌物种，主要用于生物农药行业[86]。已有研究发现其具有帮助植物抵御病原菌侵害以及促进宿主植物生长等能力[87-88]。Dogaru 等[77]发现加入 *T. harzianum* KUEN 1585 的种子包衣可使玉米种子的发芽速度及根长分别提高 21.3%和 14.9 cm。Chandrika 等[78]利用木霉(*Trichoderma*)与壳聚糖、聚乙二醇制备的共混膜溶液对种子包衣进行优化，增强了抗菌活性和种子品质，但将其应用于生产实践还需要考虑木霉生长条件、包衣制剂等一系列因素。Cortés-Rojas 等[79]发现将拟康宁木霉(*Trichoderma koningiopsis*) Th003 采用转鼓法的涂覆工艺制作种子包衣，可使其在 8 °C 下保质期延长至 15 个月，在 18 °C 下保持 9 个月。Swaminathan 等[28]发现改变制剂辅料和低温环境可以延长 *T. atroviridae* 孢子的存活率，更利于种子包衣储存。因此，从以往研究结果来看，加入木霉菌的种子包衣或许可以大量投入到今后的农业生产中，减少化学农药的使用，降低对土壤及作物污染。

3.2 芽孢杆菌属(*Bacillus*)种子包衣

芽孢杆菌(*Bacillus* sp.)是研究最广泛的植物根际促生细菌之一，在农业方面有广阔的应用前景。目前芽孢杆菌已成为模式生物，在次级代谢产物产生、孢子形成、生物膜形成、植物根部附着等方面发挥作用[89]。Tu 等[80]用 *B. subtilis* SL-13 制成的微胶囊化微生物种衣剂(encapsulated microbial seed coating agent, ESCA)处理棉花种子后发芽率提高 28.74%，棉苗的株高、根长、全株鲜重和全株干重分别增加 52.70%、25.13%、46.47%和 33.21%。Ain 等[81]利用 *Bacillus* sp. AZ6 涂覆尿素制成包衣，与对照相比，小麦株高、根长和分蘖数分别提高 24.6%、17.8%和 23.3%。Jetiyanon 等[82]发现用 *B. cereus* RS87 制成的种子包衣，与对照相比，植株株高和根长分别增加约 25%和 50%，同时菌株 RS87 可产生大量 IAA。因此，从以往研究结果来看，利用芽孢杆菌制作的种子包衣对农作物的生长发育具有促进作用，在农业生产上具有良好的应用价值。

3.3 假单胞菌属(*Pseudomonas*)种子包衣

假单胞菌(*Pseudomonas* sp.)在环境中广泛分布，其中一些具有生物防治活性、植物生长促进活性、诱导植物系统防御反应等能力[90]。Xu 等[84]发现利用 *Pseudomonas chlororaphis* YB-10 制成的小麦种子包衣菌落数在 10^7 CFU/mL 和 10^8 CFU/mL 时，能够显著促进幼苗的生长，同时提高小麦幼苗中防御相关酶过氧化物酶(peroxidase, POD)、超氧化物歧化酶(superoxide dismutase, SOD)、过氧化氢酶(catalase, CAT)、苯丙氨酸解氨酶(phenylalanine ammonia lyase, PAL)和多酚氧化酶(polyphenol oxidase, PPO)的活性，增加植物对病原体的抗性。Hameeda 等[85]通过种子包衣方法对鹰嘴豆施用 *Pseudomonas* sp. CDB 35 和 BWB 21 等细菌后，发现植物生物量(干重)增加(18%−30%)，在施用 CDB 35 处理时植物疾病发生率降低 47%。因此，假单胞菌属微生物或许可以作为新型种衣剂投入到农业生产中。

4 微生物种子包衣局限性和不一致性

大量研究表明微生物种子包衣的接种效率和有效性等同于甚至超过种子浸泡、叶面喷雾、土壤浇灌等其他接种方法[58,91-92]。相反地，也有研究表明微生物种子包衣的接种效率和有效性不如其他接种方法。Amutha[93]比较了包括种子包衣在内的 4 种不同接种方法，发现所有方法都可以将 *Beauveria bassiana* 接种到棉花中，但叶面喷雾和土壤浇灌的定殖率最高(30.5%)。Müller

等[94]在盆栽试验中分别使用 2 种种子包衣技术和种子浸泡对大丽花接种普城沙雷氏菌(*Serratia plymuthica*) HRO-C48，结果表明种子浸泡接种HRO-C48对枯萎病抑制效果最明显。Rehman等[44]使用 4 种不同的方法(土壤浇灌、叶面喷雾、种子浸泡和种子包衣)将 *Pseudomonas* sp. MN12与锌联合使用，以评估对小麦生产力的互作效应，结果表明所有方法均可提高小麦的产量和谷物锌生物强化，但种子浸泡的效果最显著。因此，提高微生物种子包衣的接种效率和有效性也是研究的重点，对微生物种子包衣的应用极其重要。

尽管盆栽试验为微生物接种的益处提供了重要且有用的数据，但还需要在一系列环境中验证田间条件下的微生物效应。现场性能不一致可能是广泛应用有益微生物种子包衣的主要制约因素之一。Shaharoona 等[95]研究发现，在盆栽试验中利用产生 ACC 脱氨酶的假单胞菌 *Pseudomonas* spp.对玉米种子进行包衣可显著提高玉米的生长，然而在田间试验中发现含有ACC 脱氨酶的根瘤菌在低水平的肥料下，能更为有效地改善玉米生长和产量。此外，Shaharoona 等[96]发现在较低的氮、磷和钾水平下，盆栽和田间试验中产生 ACC 脱氨酶的 *P. fluorescens* 对小麦生长、产量和营养利用效率的影响最为显著。微生物接种方法的有效性也可能因试验规模而异。Kazempour[97]在温室和田间条件下使用不同的接种方法(种子包衣、土壤浇灌和叶面喷雾)评估了 *P. fluorescens* 对水稻枯萎病的抑制能力，发现在温室条件下通过种子包衣接种的 *P. fluorescens* 更有效，而在田间试验中，通过 *P. fluorescens* 种子包衣和叶面喷雾的联合应用获得了最佳效果。因此，明确验证试验的有效性和涵盖该过程所有阶段的微生物应用的结果至关重要。

5 结论与展望

种子包衣是推进精准农业的有前途的技术，对作物安全健康的生长具有重要意义，而且满足了日益增长的自动化需求。试验证明，用有益的微生物包衣种子既能提高作物产量和质量，同时降低施用农药的不利影响。此外，种子包衣可以作为杀真菌剂的替代品进行商业应用，因为其对几种根腐病提供了农药同等或更好的生物控制。为更好地了解种子包衣及优化微生物接种剂对作物的应用技术，在农业生产方面大规模地应用，可以从以下几方面进行深入研究：

(1) 关于接种剂配方(例如微生物生存能力、载体成分选择和生产成本)的研究，尽管一些材料(如海藻酸盐)具有提高微生物存活率的能力，但它们也可以阻碍发芽、缩短包衣种子的保质期或增加产品的成本。因此，探索不同包衣材料、作物和微生物的组合配比，以及明确不同微生物种子包衣的作用和配方极为重要。

(2) 微生物种子包衣应用的微生物为植物有益微生物，但有些可能是人畜条件致病菌，因此在投入农业生产前要对其进行一系列风险评估以判断其是否对人畜生存健康造成威胁。

(3) 对更多尚未试验的作物使用微生物种子包衣进行试验，例如中草药、烟草等更多的作物，探究其在种子萌发和植物生长过程中可能发挥的作用，使微生物包衣种子能被更广泛地应用。

(4) 制定微生物种子包衣技术标准，以便于商业化生产和大规模种植。随着研究的深入，有望发现更多的微生物资源，并开发更多的种子包衣新技术，从而为该技术提供更好的前景和潜力。

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