专论与综述
Reviews

作物从土壤中吸收、传递和累积农药的研究进展

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摘要　农药是保障粮食安全的重要农业投入品，施用后部分农药会沉积在土壤中，甚至会被作物根部吸收，进入作物体内并累积于可食部位，从而导致潜在农产品质量安全问题。研究表明，土壤中的有机质含量、农药的辛醇-水分配系数和作物脂质含量是影响作物吸收非离子型农药的关键因素，作物各部位的脂质含量是影响该类农药累积的关键因素，借助蒸腾作用向上传递是作物根部吸收传导农药的主要动力。本文重点综述了农药被作物的根部吸收、传递和累积及其主要影响因素，结合植物吸收模型的发展及运用，展望了该领域未来发展方向，为农药归趋及应用风险研究提供参考。

关键词　农药；　吸收；　传递；　累积

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Advances in the uptake，translocation and accumulation of pesticides in food crops

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Abstract　Pesticides are important to ensure the agricultural food production. After application，pesticides enter soils，and are then further accumulated in crops via root uptake，leading to potential food safety issues. Studies showed that soil organic matter，octanol-water partition coefficient and the crop lipid content are the key factors that affect the uptake of nonionic pesticides by crops. Plant transpiration is the main driving force for pesticide translocation. In this article，the uptake，translocation and accumulation of pesticides from soil by crops and the main influencing factors were reviewed. Based on the development and application of plant uptake models，future research directions in this area are recommended，which will be helpful for improving the pesticide risk assessment and ensuring the food safety.

Key words　pesticides；　uptake；　translocation；　accumulation

农药是保证农业生产和粮食安全不可或缺的重要农业化学品。根据2018年我国发布的数据显示，农药有效利用率仅为38.8%[1]，这就意味着农药施用后会大部分进入土壤，作物会通过根部吸收土壤中残留的农药，并在作物体内或可食农产品部位进行累积[2]，从而带来潜在的食品安全问题。在20世纪50年代有学者研究了萝卜、马铃薯、豌豆、黄瓜、番茄、甘蓝6种蔬菜对林丹、滴滴涕和艾氏剂的吸收累积[3]，并发现胡萝卜中的农药残留量会随着土壤中的农药浓度升高而增加，农药污染问题开始引起研究者的关注。近年来，关于植物吸收多环芳烃、多氯联苯和卤代有机污染物等热点环境持久污染物已经有较多报道[4]，而农药在农田土壤环境中的污染问题相对研究较少。因此研究作物对农药的吸收，

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揭示其在植物-土壤体系中的环境行为归趋，有利于农药的合理使用，保证农产品质量安全。本文从作物根部吸收农药、农药在作物内的累积、农药在作物中的传输和植物吸收农药模型4个方面进行了综述，并展望了植物吸收农药的未来研究方向，为农药合理使用和农产品质量安全提供参考。

1 作物根部吸收农药行为的研究

多数研究人员认为作物根部吸收农药的过程是农药在各个介质之间经过长时间分配过程最终进入作物体内[5-6]。研究表明，影响作物根部吸收农药的主要因素包括土壤理化性质、农药理化性质和作物种类等[7-8]。

土壤中有机质含量是决定作物暴露于土壤中农药量的关键因子[9]，通常土壤有机质含量高会减弱作物对土壤中农药的吸收，主要是因为土壤中农药会被有机质吸附固定而降低其实际可利用浓度[10-11]。Lichtenstein 等发现根茎类蔬菜萝卜和土豆在有机质含量低的土壤中吸收和累积的林丹更多[3]。Harris 等研究3种有机质含量对植物吸收农药的影响，结果发现作物吸收农药和土壤有机质含量成负相关[2]。Wang 等研究发现无土培养下黄瓜对杀虫剂天名精酮的吸收量是土壤培养的7倍[12]，说明土壤对农药的吸附作用影响了作物对农药的吸收。

农药本身理化性质也决定了其被作物吸收的行为，尤其是农药的水溶性和脂溶性是影响作物吸收的主要因素[13-18]。土壤间隙水（土壤空隙中不受土粒吸附能移动的水分）中的农药随水进入作物体内后，在水和作物组织脂肪之间进行分配。多数研究表明，非离子型化合物在植株体内的传递累积与其自身的辛醇-水分配系数（K_{ow}）密切相关[19]，K_{ow}值小的农药容易通过作物根系吸收累积，随着蒸腾作用向作物地上部分迁移[13,16-17,19-21]，而K_{ow}值大的农药被作物根系吸收后，分配吸附到根部的脂肪中，限制了其从根组织内部向作物地上部分迁移[16-17,19,22-24]。Briggs 等研究了杀线威等18种农药在大麦中的累积，发现在化合物结构和分子量大小相似的情况下，农药的辛醇-水分配系数（K_{ow}）与其在大麦根部累积量呈正相关[25]。Gonzalez 等研究了生菜和甜菜对7种有机氯农药的累积量与农药自身的辛醇-水分配系数相关关系，结果表明亲脂性的农药在作物根和茎部有较多的累积[26]。Gonzalez 等通过研究番茄根系对滴滴涕和硫丹的吸收，发现$\log K_{ow}=6.91$的滴滴涕主要在根部积累，而$\log K_{ow}=4.75$的硫丹则可以向作物上部迁移[27]。Ge 等发现K_{ow}值较高的苯醚甲环唑（$\log K_{ow}=4.36$）在水稻根部累积不向上传输，而K_{ow}值较低的吡虫啉（$\log K_{ow}=0.57$）和噻虫嗪（$\log K_{ow}=-0.13$）则更多地向水稻地上部分传输[28]。

作物种类也是影响根部吸收农药的重要因素，对非离子型农药的吸收与作物本身的脂质含量密切相关。研究表明不同作物种类对农药的吸收累积差异很大[29-31]。Gonzalez 等对比生菜和甜菜在相同栽培条件下对滴滴涕、艾氏剂、狄氏剂、二萘酚等有机氯农药的吸收，发现脂质含量较高的生菜对有机氯农药的吸收高于甜菜[26]。魏峰等研究了3种油料作物对滴滴涕的吸收累积，发现含油量高的花生果仁（含油量46%～52%）和芝麻果仁（含油量52%～54%）中滴滴涕的浓度都明显高于大豆果仁（含油量18%～20%）[32]。Chiou 等研究报道了萝卜、马铃薯、甜菜对艾氏剂、狄氏剂、七氯的累积差异，结果表明高脂肪含量的萝卜（脂肪含量0.24%）富集农药的量要高于低脂肪含量的马铃薯（脂肪含量0.1%）和甜菜（脂肪含量0.17%）[5]。

农药通过分配作用被作物根部吸收后，首先吸附在根部的表皮组织上[33-34]，之后通过作物根部水溶液和组织成分之间的分配作用，累积在作物根部的有机组分里[15,35-39]。影响作物根部累积农药的主要因素是根部组分及其含量。作物根部主要由脂质、水分和碳水化合物组成，脂质是存储农药的主要场所[5,13]，也有报道指出作物的碳水化合物成分会影响作物对农药的累积[39]，只使用作物脂肪含量推测作物对农药的累积量往往低于实际累积量。K_{ow}较高的农药更容易被作物根部富集[40-43]，K_{ow}较低的农药进入作物根部后，多分配在水溶液中[24]。Miglioranza 等研究了番茄不同部位中滴滴涕的累积量，各部位的累积量和部位脂肪的含量呈正相关[44]。Zohair 等研究了艾氏剂、七氯、狄氏剂、滴滴涕、甲氧氯等有机氯农药在马铃薯和胡萝卜果实中的累积量，其中脂质含量最高的果皮中累积农药量占全部果实累积量的57.5%～100%[45]。Florence 等对芋头、甘薯、马铃薯、山药4种根茎类作物吸收农药十氯酮进行研究，发现基于作物的脂质含量难以判断其对十氯酮的吸收累积量，而作物纤维素含量和吸收累积十氯酮的量呈正相关[46]。

2　作物对农药传输行为的研究

农药穿过根表皮进入木质部后,随蒸腾作用主导的上行传输过程沿木质部在作物体内迁移,分配累积于作物茎叶组织中[30,47-50]。研究表明,农药根部吸收和转移农药主要通过共质体和质外体途径运输,在作物蒸腾作用下通过共生细胞传输占主导地位[51-52](图 1),而农药很难通过筛管系统向下输送。

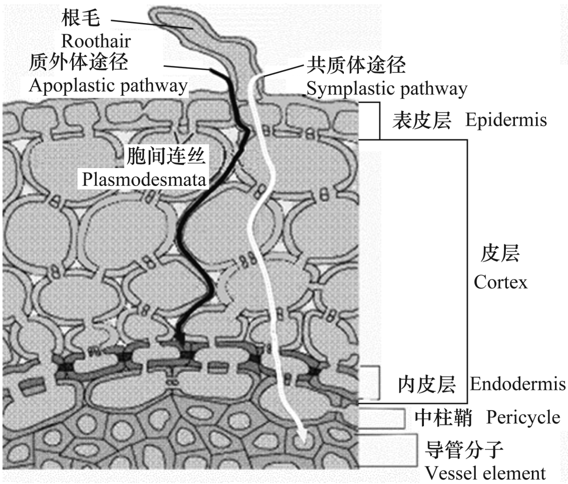

图 1　作物根系组织结构示意图[53]

Fig. 1　Schematic diagram of crop root tissue structure[53]

当农药从根部进入维管束中时,会随着蒸腾流向上移动,通常会累积到发生蒸腾作用强的成熟叶片[47,51]。Wang 等研究表明,通过叶面喷雾方式在黄瓜上施用呋喃丹时,呋喃丹没有向根部迁移的现象,而使用灌根处理时,呋喃丹会呈现向叶部传递的现象[12]。Alsayeda 等将番茄移栽在使用^{14}C标记的吡虫啉污染的土壤中,85%的放射量转移到了番茄茎叶部位,放射量从底部叶到顶部叶逐渐减少[54]。可见,土壤中的农药残留可能通过作物根部吸收和蒸腾作用传递至作物各部位。

3　植物吸收模型的发展

目前利用数学模型预测农药在土壤-作物体系的迁移、累积行为较多[55-56]。模型包括平衡模型、动力学模型以及稳态模型等[57-58]。Briggs 等在 20 世纪 80 年代建立了根系富集系数(RCF)、茎富集系数(SCF)、蒸腾流富集系数(TSCF)与非离子型有机污染 K_{ow} 的经验关系式,表明了不同部位富集系数与 K_{ow} 之间密切相关[25,59-60]。这是较早建立的关于作物吸收非离子型有机污染物的预测模型。模型建立的基础是假设分配过程中每个介质都是均质的。

$$\log RCF = 0.77 \times \log K_{ow} - 1.52^{[25]};$$

$$\log SCF = 0.95 \times \log K_{ow} - 2.05^{[59]};$$

$$TSCF = 0.784 \times e^{-\left[\frac{(\log K_{ow} - 1.78)^2}{2.44}\right]}{}^{[60]}。$$

多隔室模型(detailed compartmental model)是 Lindstrom 和 Boersma 等在 20 世纪 90 年代建立,将有机物在植物体内的传输设定为一级动力学过程,将土壤-植物系统分为 24 个隔室,用不同隔室代表植物的相应部位和土壤;根据质量守恒定律建立了各隔室的数学公式体系[61-62]。该模型考虑因素全面,能较好地模拟植物对土壤中污染物的吸收传递累积,但该模型中引入了大量数学参数,诸如化合物的空气-水分配系数、植物生长速率、植物蒸腾作用速率等,使得实际模拟计算时难度较大。Trapp 等将植物分为根、茎、叶和果实四相,提出了植物吸收有机污染物的四隔室模型(four-compartment model)[63-64],后期将该模型简化为一室模型(one-compartment model)[22],将过去繁琐的计算过程用单一方程表示,但该模型仅限于呈指数级生长的植物,且方程中仍包含多参数的计算,参数测定的准确性直接影响模型预测的准确性。隔室模型都是基于质量守恒定律建立,模型能较好地预测植物体内污染物的浓度,但模型中使用的大量参数都需要实际测定后再通过运算才能使用,运算的复杂程度过高致使隔室模型的实用性受到限制。

分配限制模型(partition limited model)是 Chiou 等基于有机污染物在植物不同组分中的分配提出的[5]。

$$C_{pt} = \alpha_{pt} C_w [f_{pom} K_{pom} + f_{pw}]。$$

其中:C_{pt} 为植物中污染物浓度;C_w 为水溶液污染物浓度;f_{pom} 为植物中脂质的质量分数;f_{pw} 为植物中水的质量分数;K_{pom} 为污染物在植物脂质和水相的分配系数;α_{pt} 为分配平衡系数,表示污染物在植物体与水之间浓度达到平衡的程度,$\alpha_{pt}=1$ 表示分配平衡状态。

该模型将土壤吸附有机物的分配理论应用于土壤有机污染的植物吸收过程。假设植物对有机污染物的吸收为被动吸收,且吸收过程可看作有机污染物在植物体水相-有机相间一系列连续分配过程的组合,土壤及植物体中污染物的代谢不影响植物被动吸收,污染物在植物体(各部位)水相-有机相间处于平衡状态。分配限制模型能够较好地预测农药等

污染物的累积行为[65-66]，但模拟的准确性及适用范围仍有待验证和推广。Li 等通过小麦的根和茎对林丹、六氯苯的吸附研究发现，用分配限制模型所得的预测值小于实测值[39]。

4 展望

作物对农药的吸收累积和传递行为，对优化作物累积农药预测模型和食品安全有重要意义。而作物对农药的吸收、传递和累积一直是农业化学污染领域的研究热点和难点工作。基于对当前主要报道文献的认识，提出今后的研究重点并预测未来研究趋势如下：

1)关于作物根部吸收农药的影响因素已经取得一些基础性结论，但多数研究结果多基于实验室栽培作物的数据，需到田间真实生产环境进行验证，并进一步优化参数。

2)农药在作物体内的传递累积研究还局限于根、茎、叶、果各部位累积浓度对比，尚缺乏深入研究农药分子在各组织细胞间传递的机理。

3)现有的数学模型预测结果多数准确度不高，仍需对模型进行升级和完善，提高预测的准确度。

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