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# 农田生态系统中新污染物的生态环境效应与去除技术研究

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**摘要**:在梳理国内外关于农药、抗生素及抗性基因、微塑料、全氟化合物等典型新污染物在农田生态系统的来源分布特征、迁移转化机制、生态环境风险和主要去除方法等相关研究进展的基础上,探讨了农田灌排水条件变化对新污染物输移的影响效应;提出未来应加强农田生态系统中新污染物全生命周期的观测,精准把握典型新污染物来源、种类及其在农田生态系统中的分布和含量水平,特别是在作物不同生长期及随农田灌排水系统输移转化和生物累积效应;进一步理解其在水-土-作物系统的富集转化过程与生态风险,建立结合农田沟渠灌排工程的新污染物去除的适用性方法技术体系,为我国农田新污染物防控治理提供技术支撑,保障区域生态安全与高质量绿色发展。

**关键词**:新污染物;农田生态系统;迁移转化;生态效应;灌排系统;去除技术

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**Research on ecological and environmental effects and removal technologies of emerging contaminants in agricultural ecosystems**//LU Bianhe[1,2], WANG Peifang[1,2], QIAN Jin[1,2], ZHU Ningyuan[1,2], WANG Yimin[1,2], ZHEN Ruoxi[1,2], ZHOU Gang[1,2] (1. *College of Environment*, *Hohai University*, *Nanjing* 210098, *China*; 2. *Key Laboratory of Integrated Regulation and Resource Development on Shallow Lakes*, *Ministry of Education*, *Hohai University*, *Nanjing* 210098, *China*)

**Abstract**: Based on a comprehensive review of domestic and international research progress regarding the source distribution characteristics, migration and transformation mechanisms, ecological and environmental risks, and main removal methods of typical emerging contaminants (including pesticides, antibiotics and antibiotic resistance genes, microplastics, and per- and polyfluoroalkyl compounds) in agricultural ecosystems, this study investigates the impact of changes in farmland irrigation and drainage conditions on the transport of emerging contaminants. The study proposes that future research should strengthen the whole-life cycle monitoring of emerging contaminants in agricultural ecosystems to accurately identify the sources, types, distribution patterns, and concentration levels of typical emerging contaminants. Particular attention should be paid to their transport, transformation, and bioaccumulation effects during different crop growth stages and through farmland irrigation and drainage systems. Further understanding should be developed regarding their accumulation and transformation processes in the water-soil-crop system and associated ecological risks. Additionally, an applicable technical system for emerging contaminant removal should be established by integrating with farmland ditch and drainage engineering. These advancements will provide technical support for the prevention and control of emerging contaminants in China's agricultural systems, ensuring regional ecological security and promoting high-quality green development.

**Key words**: emerging contaminants; agricultural ecosystem; transport and transformation; ecological effects; irrigation and drainage system; removal technologies

为保障粮食的高产稳产,农业生产中大量使用化肥、农药、杀虫剂和农膜等投入品,导致农田环境中积累了包括农药、抗生素及抗性基因(ARGs)、全氟化合物(PFASs)和微塑料(MPs)在内的多种新型污染物。这些污染物通过农田灌溉和排水进行水分运移,在农田、土壤、微生物及作物间迁移转化,部分

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累积在作物叶片甚至籽粒中,给粮食品质、人群健康和生态安全带来了严重威胁。国家高度重视新污染物的治理。2022 年发布的《新污染物治理行动方案》及 2024 年《中共中央、国务院关于推进美丽中国建设的意见》等政策文件,明确提出加强新污染物的环境风险管理。然而,目前农田生态系统新污染物存在污染程度不清、危害风险不明、防控技术不足等问题,特别是其迁移转化规律及影响机制解析未能与农田灌排有机结合。为此,本文在综述农田生态系统新污染物的主要来源及污染特征,梳理典型新污染物的迁移、转化、影响机制及生物毒性与生态风险的基础上,解析了灌排水过程中新污染物的环境行为影响及去除机制,提出了未来应进一步加强的研究方向,为农田生态系统新污染物的风险管理与控制治理提供依据。

## 1 新污染物来源及污染特征

### 1.1 主要来源

农田生态系统中新污染物的主要来源按照其用途可归纳为:①农药施用。包括用于控制病虫害的杀虫剂、杀菌剂和除草剂等[1]。②田间施肥,尤其是使用农家肥。畜禽养殖使用的抗生素通过农家肥进入土壤,导致抗生素残留及 ARGs 累积[2];同时,农家肥也是 MPs 污染的重要传递途径,会破坏土壤结构并阻碍作物正常生长[3-4]。③灌溉水。当前河湖水体受新污染物的影响,且缺少中水作为灌溉水源,使得多种新污染物随着灌溉水进入农田[5-6]。④农业设施施用。如农用薄膜、农业器械等现代农业用品的使用带来了 MPs 和 PFASs 等新污染物的农田输入和累积[7]。

### 1.2 农田土壤中新污染物赋存水平

研究表明,全球农田土壤已受到新污染物的广泛污染。美国阿拉巴马州农田 PFASs 质量比达 166 μg/kg[8],墨西哥农田中多种抗生素质量比均处于 μg/kg 水平[9]。全球生物地理学研究指出,印度、东亚、西欧和美国的农田是 ARGs 热点分布区域[10]。据估算,欧洲和北美农田每年分别输入高达 43 万 t 和 30 万 t 的 MPs[11]。我国的相关研究发现,有机氯农药、有机磷农药等污染物已在稻田等生态系统中大量积累[12],长江三角洲地区磺胺类抗生素质量比高达 235 μg/kg[13],同时 ARGs 种类繁多,常见的包括 *sul*2 和 *tetG* 等,其目标基因相对丰度可达 $6.7\times10^{-3}$ 和 $5.2\times10^{-3}$(以 16S rRNA 基因为参比)[14]。相关研究表明,我国稻田土壤中 PFASs 质量比达 17.12 μg/kg[15],农田土壤中的 MPs 丰度达 503 ng/kg[16]。

### 1.3 作物中新污染物富集量

农作物中的新污染物检出率同样令人关注。Donkor 等[17]在加纳蔬菜和水果中检出大量的有机磷和拟除虫菊酯类农药;Malchi 等[18]在以色列农田番薯中检出抗生素磺胺甲恶唑质量比(干重)达 0.25 μg/kg;Larrañaga 等[19]在西班牙的生菜、菠菜和黄瓜中检测到了大量的 ARGs;Piva 等[20]研究发现,加拿大即食蔬菜中的 PFASs 含量超过欧盟限值。

在我国,北方某有机蔬菜基地的蔬菜中检测出 10 种抗生素,最高质量比(干重)达 76.8 μg/kg[21];李喆[22]检测发现青菜中杀虫剂含量最高,质量比(鲜重)达 140.5 μg/kg;Gao 等[23]在田间的小麦和黄瓜中发现了 ARGs,且黄瓜中的 ARGs 丰度更高;而南方某市农田中 PFASs 的赋存量调查显示, PFASs 总的质量比(干重)范围在 6.19~143.13 μg/kg[24]。

## 2 新污染物多介质多界面迁移转化机制及影响因素

各类新污染物进入农田生态系统,在水分流动和作物生长驱动下进行多介质、多界面的迁移转化,并与土壤中微生物和生物系统产生交互影响,进而可能对作物品质与生态健康造成危害。

### 2.1 新污染物在农田土壤中的迁移机制及影响因素

#### 2.1.1 土壤物理特征对新污染物迁移的影响

农田生态系统土壤中新污染物的迁移受到多种土壤理化性质的影响[25]。孔隙度、含水率和孔隙水流速等决定了污染物的迁移过程,其中对流作用是关键的影响因素[26]。当 MPs 粒径小于土壤孔隙时,MPs 会在重力作用下向深层迁移,因此在干旱条件下,土壤裂缝的增加将促使其垂直迁移[27]。水分含量的变化显著影响 PFASs 和农药的迁移速率,水分越少,PFASs 的迁移能力越弱;降水或灌溉则会增加农药在高渗透性土壤中的浸出[26]。

土壤组成也是影响新污染物迁移的重要影响因素。研究表明,高黏土含量的土壤能减少农药和抗生素的迁移,且 ARGs 在黏土中的相对丰度高于壤土和砂土[28-29]。质地细腻的土壤由于孔隙更小、表面积更大,对新污染物的滞留能力更强[30]。

#### 2.1.2 土壤化学性质对新污染物迁移的影响

农田生态系统新污染物的迁移还受土壤化学性质的显著影响,包括土壤有机质、矿物质含量、盐度和 pH 值等。土壤有机质(如黑碳、腐殖质等)是抗生素迁移的重要影响因素,如黑碳等不溶性组分可抑制抗生素迁移,而腐殖质等溶解性有机质则可能

促进其迁移[31];天然有机质可增强 MPs 的迁移[32];ARGs 通过移动遗传元素在微生物间传播,其丰度与土壤有机质和抗生素残留浓度密切相关[33];而有机质含量和阳离子交换容量决定了 PFASs 的迁移能力[34]。

MPs 与土壤矿物质的团聚作用可增加其密度,促进其下行迁移[35];铁/铝氧化物与负电 MPs 的相互作用可能使 MPs 滞留[36]。

土壤盐度和 pH 值会影响微生物的活性和选择压力,从而影响 ARGs 的迁移和丰度[37]。降低土壤 pH 值会减少土壤表面负电荷,进而削弱阴离子型 PFASs 如全氟辛烷磺酰基化合物(PFOS)的迁移[38]。营养盐水平增加(如施用有机肥)会显著提高 ARGs 的分布[39]。

#### 2.1.3　新污染物自身特性对迁移行为的影响

新污染物的物理化学特性也影响其在农田环境中的行为。例如,农药的分子大小决定其是否易于进入土壤孔隙,疏水性则影响其与土壤有机质的亲和力,而电荷特性和氢键能力会调控其与土壤矿物质表面或有机质的相互作用,这些特性共同影响其在土壤中的迁移行为[40]。

MPs 的形状、类型和表面特性显著影响其迁移。细长纤维型 MPs 易与土壤颗粒纠缠,迁移能力较弱[41];表面带羧基的 MPs 在砂质土壤中具有更高的迁移性[42];此外,亲水性较强的聚苯乙烯 MPs 在土壤中表现出更大的迁移潜力[43]。

PFASs 的迁移受其碳链长度和亲水基团的影响,碳链越长,疏水性和吸附能力越强[44],而功能性基团如磺酸基比羧酸基具有更强的疏水性[45]。

### 2.2　新污染物在农田土壤中的转化过程与机制

#### 2.2.1　农田新污染物的转化机制

新污染物在农田土壤中的转化主要包括微生物转化、光解、水解和氧化还原等过程[46]。微生物群落在新污染物降解中起重要作用,分配系数较高的新污染物更易被微生物直接利用或协同代谢[47]。MPs 在机械磨损和生物作用下老化,最终在微生物矿化下分解[48]。抗生素的消散与微生物密切相关,如放线菌可降解磺胺类抗生素[49]。部分 PFASs 可在微生物作用下转化为更稳定的形态,如乙基全氟辛基磺酰胺乙醇逐步转化为 PFOS[50]。携带 ARGs 的细菌在环境变化、种间竞争、噬菌体裂解等过程中死亡;游离的胞外 ARGs 在紫外光和氧化剂作用下被降解[51-52]。

#### 2.2.2　土壤理化性质对新污染物转化的影响

新污染物的转化受土壤 pH 值、温度、含水率等理化性质的影响,这些因素显著影响微生物的多样性和功能,从而影响新污染物的转化及 ARGs 的演化和传播[53]。适宜的 pH 值可加速化学水解和微生物降解[54],而较高的温度将提升反应和代谢速率,提高转化效率[38]。土壤水分为微生物提供介质,但过多或过少都会抑制转化[54]。土壤盐度会增加渗透压,从而限制细菌活性,影响转化效率[47]。有机质可吸附污染物,降低其流动性和生物利用度[48],其丰度与微生物的降解能力密切相关[55]。相比稳定的腐殖质,新鲜植物残留为微生物提供了易获取的能源,促进了新污染物的转化[56]。

### 2.3　新污染物在作物中的吸收累积机制

#### 2.3.1　作物对新污染物的吸收与转运机制

作物对新污染物的吸收受生物因素(如基因型、生理状态)和非生物因素(如污染物特性、环境波动)的影响[57]。Christou 等[58]研究指出,不同作物对新污染的吸收能力一般为:叶菜类大于根菜类大于谷物类大于果菜类。一些作物的特定生理特性使其能够更有效地吸收污染物,例如,东方泽泻(*Alisma orientale*)可通过与 PFASs 结构匹配的根膜通道吸收这些物质[59]。MPs 由于其粗糙多孔结构,易在根际富集,并通过质外体和共质体途径进入植物[60]。同样,进入稻田的抗生素将随着水稻(*Oryza sativa* L.)生长被吸收并在不同器官中累积[61]。

#### 2.3.2　新污染物在作物体内的传输与积累

作物吸收新污染物后,其通过木质部和韧皮部传输,迁移效率受新污染物亲脂性、电荷性和蒸腾速率的共同影响。Miller 等[62]研究表明,$-\lg K_a$($K_a$ 为酸解离常数)>7 且 $\lg K_{ow}$($K_{ow}$ 为辛醇-水分配系数)<0 的新污染物倾向于在木质部和蒸腾器官中积累;$-\lg K_a<7$ 且 $\lg K_{ow}<3$ 的离子型污染物更易在韧皮部中迁移,通常累积于果实而非叶片。PFASs 的代谢过程影响其在植物组织间的转运效率[63]。研究发现,植物如生菜(*Lactuca sativa* L.)能将小粒径(<0.2 μm)的 MPs 转运至地上部分,较大粒径(10 μm)的 MPs 也能从玉米(*Zea mays* L.)幼苗根部迁移到地上部分[64],在油菜(*Brassica campestris* L.)幼苗的根部还观察到了团聚后的 MPs[65],说明 MPs 在植物体内的富集和转运机制复杂,需进一步研究。抗生素在作物体内通过蒸腾拉力向上迁移,亲水性越强,迁移能力越大[66]。关于 ARGs 在植物中的迁移研究较少,但已证实抗性细菌可进入植物根部并传播至叶和茎,加速其在植物中的传播[67]。

## 3　新污染物的生物毒性与生态风险

农田生态系统典型新污染物因为其特殊的结构形式与特性,直接或间接地危害了农作物品质和人

群健康,也给农田生态系统带来了长期的潜在风险。

### 3.1 对植物的生理毒性

新污染物显著影响作物的生长和代谢。例如,磺胺类抗生素(20 mg/kg)会抑制水稻生长,导致叶绿素含量降低,并诱导氧化应激反应[68]。100 μg/L PFASs 暴露便可显著改变植物代谢并影响光合作用[69]。MPs 则会破坏作物幼苗叶片的叶绿体超微结构,干扰植物体的正常代谢[70],引起作物氧化应激反应[71],影响营养元素的吸收[72],造成作物产量和品质的下降。

### 3.2 对土壤动物的生态危害

线虫(*Dorylaimus stagnalis*)、跳虫(*Folsomia candida*)等土壤动物摄入 MPs 后,可诱发肠道组织损伤、氧化应激反应及生长发育抑制[73]。农药残留和 PFASs 抑制了动物的生长发育,降低了动物的存活率和生物多样性[74]。抗生素污染会显著抑制土壤动物丰度,削弱微生物群落多样性,影响土壤养分的有效性和作物产量[75]。ARGs 可借助线虫(*Dorylaimus stagnalis*)等土壤动物在农田中迁移,通过食物链传播,对生态环境和人类健康造成威胁[76]。

### 3.3 对农田土壤微生物的生态扰动

新污染物通过改变土壤理化性质影响微生物群落,扰乱其结构和功能[77]。MPs 为土壤微生物提供定植栖息地,引发微生物争夺,导致微生物活性、群落多样性及组成失衡[78]。质量浓度为 16.33 μg/L 的 PFASs 便可显著增强金黄色葡萄球菌(*Staphylococcusaureus*)的毒力基因表达,进而降低土壤动物免疫力[79]。MPs 暴露将增加病原微生物的相对丰度,进一步影响作物生长[80]。

### 3.4 新污染物的联合生态效应

多种新污染物的组合效应通常强于单一新污染物[81]。例如,MPs 可作为载体增强其他污染物的生态毒性[82]。研究发现,MPs 与抗生素或农药的复合污染使作物遭受更大的氧化胁迫,抑制了作物的光合作用和对营养物的吸收,降低了生物量和产量[83]。新污染物之间也存在拮抗作用,例如 MPs 的吸附可减弱 PFOS 对植物的毒性,某些抗生素与 PFASs 联合使用时也会表现出拮抗作用[84-85]。

## 4 新污染物去除方法与技术研究

### 4.1 功能材料吸附去除法

用于土壤新污染物吸附的材料包括碳基、黏土基材料和离子交换树脂等。碳基材料如活性炭、多壁碳纳米管和生物炭等对疏水性 PFASs 吸附效果优异[86]。小麦生物炭可吸附 80%~86%的敌草隆和溴苯腈[87];在土壤表面施用 1%的生物炭,对磺胺嘧啶和磺胺二甲嗪的去除效率最高[88]。改性生物炭可使土壤以及蔬菜叶、根组织中 ARGs 的丰度分别降低 44.1%、51.8%和 43.4%[89];磁改性生物炭对聚苯乙烯 MPs 的吸附率达 94.6%[90]。然而,吸附剂可能引发二次污染,限制了其规模化应用[91]。

### 4.2 高级氧化法

高级氧化法在难降解有机污染物去除方面进展显著。如过硫酸盐活化的类 Fenton 效应可在 30 min 降解 77%的卡马西平[92];通过光-Fenton 反应,90%以上的三氯杀螟醇被降解,并回收 85.1%的磷酸亚铁[93]。光催化材料如纳米 $TiO_2$,可将 PFOA(全氟辛酸)降解效率从 19%提升至 89%[94];双金属有机框架光催化可降解 99.1%的氟喹诺酮抗生素[95]。纳米材料在 ARGs 去除中发挥着重要作用,如金属氧化物纳米颗粒通过氧化破坏 DNA,抑制细菌生长,减少了 ARGs 的丰度[96]。尽管这些技术在实验室中表现出良好的去除效果,但其在农田土壤或排水沟渠中的实际应用仍面临反应性不足、土壤环境复杂性以及潜在环境风险等问题[97]。

### 4.3 靶向生物降解

微生物降解新污染物被视为生态友好方法。假单胞菌(*Pseudomonas sp.* strain Imbl 5.1)对阿特拉津的降解率超过 96%[98];曲霉真菌(*Aspergillus* spp.)可降解聚乙烯和聚氨酯 MPs 颗粒[99-100]。部分微生物可破坏 PFASs 中的 C-F 键,将其作为能量和碳源[101]。好氧堆肥试验显示,抗生素降解菌群可促进抗生素降解,改变 ARGs 丰度[102]。噬菌体可减少抗性细菌,维持土壤微生物的生态功能[103-104]。

### 4.4 优势植物吸收

利用植物直接吸收和稳定农田生态系统新污染物是一种常见的新污染物去除方法[105]。Zhang 等[106]试验证明灯芯草(*Juncus effusus*)可吸收超 83%的 PFASs,根系发达的植物可修复 MPs 污染土壤[107]。伴矿景天(*Sedum plumbizincicola*)和黑麦草(*Lolium perenne*)对抗生素的去除率分别达 36%~76%和 3.4%~28.8%[108-109]。西葫芦(*Cucurbita pepo*)和蓖麻(*Ricinus communis*)对多种农药具有较强的吸收和转运能力[110-111]。植物根系对不同新污染物的亲和力存在显著差异,这将导致其在植物体内的累积水平呈现显著分化[112],因此筛选高效吸收植物并进行合理配置是利用植物修复农田生态系统面临的巨大挑战。

### 4.5 生化-物化联用技术

生化-物化联用技术是近年来为提高新污染物去除效率而在实践中不断形成的新方法和新技术,

常用的模式包括吸附与微生物降解相结合、高级氧化与植物吸收联用等。例如,侯俊等[113]总结了微生物耦合植物、光催化氧化等技术对毒死蜱的去除效果,阐明了微生物-物化耦合法具有降解效率高、作用时间短等优势。Ye 等[114]结合生物炭与多价噬菌体,协同增强了 ARGs 的消散,有效灭活了抗生素耐药病原菌。He 等[115]利用 $MoS_2$ 纳米颗粒与芦苇(*Phragmites communis*)-根际微生物系统联用,将左氧氟沙星的去除率提高至 88.1%。然而,生化-物化联用技术在农田生态系统新污染物去除中的应用研究尚不广泛,作用机制与实际应用效果仍有待深入探讨,这为未来的研究指明了重要方向。

## 5 农田灌溉排水的新污染物输移影响及去除

### 5.1 灌溉排水对新污染物迁移转化的影响与作用机制

新污染物随灌溉水进入农田,通过作物吸收、土壤渗滤和蒸发等过程,在农田系统中迁移、转化和累积。频繁的灌溉排水和淹水泡田导致土壤特性频繁变化,形成复杂的氧化还原体系,决定了新污染物在土壤中的形态转化[116]。尤其是水稻田,频繁的干湿交替使好氧与厌氧条件反复转换,显著影响了土壤氧化还原状态和微生物群落结构[117]。在水-土界面,有机磷农药等新污染物可在好氧条件下被微生物分泌的加氧酶降解,或在厌氧条件下通过异化铁还原过程降解[118]。淹水的厌氧环境则促进携带 ARGs 的厌氧微生物(如异化铁还原菌)聚集,使水稻土的 ARGs 水平高于旱地土壤[119]。在根-土界面,淹水条件下铁矿物与根际微生物相互作用,在根表形成铁膜,这层铁膜在污染物的生物和非生物转化过程中显著影响了新污染物在根-土界面的迁移、富集和转化[120]。

### 5.2 耦合农田排水系统的新污染物去除技术

新污染物在农田排水系统中随水分和径流进行输移,因此,王沛芳等[121]借助农田沟道系统的微生物、植物及功能材料等,构建了排水沟道带状湿地综合截留系统、水塘洼地湿地净化系统,以及骨干排水沟道与河道滨水带净化系统,实现了对抗生素等难降解污染物高效净化去除。同时借助循环湿地强化净化作用,将部分资源循环回用。近年来,随着对新污染物产生、输送和去除过程研究的不断深入,Jia 等[122]发现,合理的田间利用和排水调控可有效减少新污染物的环境负荷;田间管理中的干湿交替改变了土壤孔隙结构,影响了水分和溶质的传输路径,减少了作物对新污染物的吸收及其在土壤中的累积[123]。另外,在隔离带、坡面体和滨水带等生态缓冲区,适当控制干湿交替的频率和周期,不仅能调节土壤氧化还原电位,影响好氧和厌氧微生物的活性,促进新污染物的生物降解[124-125],还能影响根际铁膜的形成,增强对新污染物的吸附[120]。同时,吸附和高级氧化等新污染物强化去除方法也逐渐加强了与农田排水速度的适应性[126]。可见,合理调整灌溉排水管理不仅有助于在排水工程中有效去除新污染物,还能减少循环用水中新污染物累积及向周围环境的扩散风险。

## 6 结 语

**a.** 建议加快开展系统的污染源头调研与过程管理的全生命周期典型污染物检测工作,结合区域污染源特征及灌溉模式,比较不同灌溉水源对农田系统新污染物输入的特征差异;观测农田灌溉水-田面水-土壤水以及各级排水沟道的新污染物变化动态,揭示新污染物在农田水体中的输移变化规律;分析不同的土层、特征点、作物生育阶段土壤典型新污染物赋存含量,明晰农田生态系统中新污染物的时空分布特征;探究受污染农田作物中典型新污染物累积浓度,刻画不同作物生育阶段作物根系、茎秆及籽实中新污染物的分布和动态迁移过程,评判农田系统典型新污染物的污染水平。

**b.** 建议开展跨学科的系统综合研究,重点关注不同灌溉排水模式、灌溉水源等水分管理模式下,新污染物水-土-根-作物多介质间的迁移过程以及在作物不同组织中的富集规律,阐明新污染物随水分管理在农田中的多界面互馈机制以及作用机理;研究各类新污染物进入作物的吸收路径、转运机制、富集机理及生态效应;筛选出能够反映农田中不同新污染物生物影响的响应敏感因子,建立相应的生态风险评估指标体系;给出新污染物在作物籽粒或蔬菜叶片中的含量水平与健康风险程度。

**c.** 建议加强耦合农田灌溉排水路径,开展新污染物逐级防控净化治理,形成多技术联合的新污染物治理技术体系。针对农田排水毛沟-农沟-斗沟系统的水位、水动力条件和污染物特征差异,筛选和发挥优势水生植物对新污染物吸收富集的去除能力;研发靶向微生物-生物-催化氧化的适用性新污染物去除技术;同时,借助农田退水循环湿地,构建新污染物强化去除的关键技术,建立耦合于农田排水系统的能量自给、组合自由、运维灵便的新污染物逐级净化截留和循环利用技术体系。

**d.** 建议开发农田新污染物迁移转化模型,精确反映新污染物在农田土壤不同深度的赋存特征、根际土壤中的累积含量、农作物不同器官中的分布比

例以及不同生育阶段的累积速率等关键参数；模拟多元水分管理模式(不同水源水质、不同灌溉方式、不同排水形式、循环回用等)情境下新污染物的迁移转化、作物产量品质及区域生态风险，识别各情景下农田生态系统新污染物调控效应；建立多情景水分管理模式优化方法，获取减污-控险-稳产-高质-节约最优情景下的农田灌排模式和水循环利用风险调控策略，为保障粮食安全、区域水生态安全及人群健康提供技术支撑。

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