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# 稻田氮、磷损失与过程监测方法研究进展

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**摘要**: 水稻是我国主要的粮食作物之一。水稻生产过程中土壤和肥料中的部分氮磷元素以溶质或颗粒形态通过淋溶、径流迁移至周围水体,造成地下水污染和水体富营养化。稻田土壤中氨挥发产生的氨气和反硝化反应产生的氧化亚氮气体进入大气,加剧了温室效应。笔者围绕稻田氮磷的气体挥发、径流和淋溶 3 个流失途径介绍了国内外常用的监测方法,并进一步讨论了针对径流和淋溶这 2 种流失途径的监测指标、监测频率和监测深度等问题,总结了 2 种流失途径的主要氮磷流失形态,根据产流特征和施肥时间确定监测时间节点,综合考虑植物吸收和地下水深度确定淋溶监测深度,以期为稻田氮磷流失监测提供相关技术支持和科学依据。

**关键词**: 稻田; 氮磷; 监测方法
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**Research Advances on Process and Monitoring Methods of Nitrogen and Phosphorus Loss in Paddy Fields.** *HU Bing-tao*[1,2], *ZHANG Long-jiang*[1], *YANG Shi-hong*[2], *CHEN Yu-dong*[1①], *ZHOU Hui-ping*[1②] (1. Nanjing Institute of Environmental Sciences, Ministry of Environmental Protection, Nanjing 210042, China; 2. College of Water Conservancy and Hydropower Engineering, Hohai University, Nanjing 210098, China)

**Abstract**: Rice is one of the major cereal crops in China. During the rice production process, part of the nitrogen and phosphorus in the soil and fertilizer migrates to the surrounding water body through leaching and runoff in the form of solutes or particles, causing groundwater pollution and eutrophication of water bodies. Ammonia produced by ammonium volatilization in paddy soil and nitric oxide produced by denitrification reactions enter the atmosphere, aggravating the greenhouse effect. The commonly used monitoring methods of gas volatilization, runoff, and leaching in paddy fields from domestic and international studies are introduced, and the monitoring indicators, monitoring frequency, and monitoring depth in the pathways are further discussed; the main nitrogen and phosphorus forms in runoff loss and leaching loss are summarized; the monitoring frequency is determined by the characteristics of runoff and the fertilization; plant absorption and depth of groundwater should be considered to determine the depth of leaching monitoring. This study provides a reference for further monitoring of nitrogen and phosphorus losses in paddy fields.

**Key words**: paddy field; nitrogen and phosphorus; monitoring method

农田面源污染是目前发生面最广、影响最大的面源污染,是面源污染的主要形式[1]。农田面源污染是指在农业生产活动中氮和磷等营养物质、农药、重金属以及其他有机和无机污染物质、土壤颗粒等沉积物以降雨为载体并在降雨的冲击和淋溶作用下,通过农田地表径流和地下淋溶过程对大气、土壤和水体等环境形成的污染[2]。从本质上讲,农田面源污染物是来自于农田土壤中的农业化学物质,因此,它的产生、迁移与转化过程实质上是污染物从土壤圈向其他圈层,特别是水圈扩散的过程[3]。

氮、磷是植物生长发育需要量较大的营养元素,过去几十年里施用化肥一直是提高世界粮食产量的重要措施。我国是世界化肥第一消费大国,化肥消费量达到 5 562 万 t 以上,约占世界化肥总消费量的 34%,我国稻田单季氮肥用量平均为 180 kg·

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$hm^{-2}$，比世界平均施氮水平高 75%[4-5]。施入农田的氮肥、磷肥不能完全被作物吸收利用，大部分氮肥、磷肥通过地表径流进入河流、湖泊或通过非饱和区渗透进入地下水，造成水体富营养化和地下水污染[6-8]。我国水稻生产中氮肥平均利用率为 30%~35%，高产地区更低，磷肥利用率低至 15%~25%[9-10]。美国 60%左右的地表水环境问题是由农业生产引起的，农业面源污染被美国环境保护总署列为河流和湖泊的第一污染源。欧洲国家农业生产活动中排放的氮磷量占地表氮磷总负荷的 24%~71%[11]。日本地下水源调查结果显示约 90%的地下水源中 $\rho$(硝酸盐)超过 3 $mg \cdot L^{-1}$[12]。我国北方京、津、唐等地 69 个观测点数据显示 50%以上硝酸盐超标，最高可达 67.7 $mg \cdot L^{-1}$[13]。

长期以来，针对稻田氮磷流失的环境效应问题国内外已开展大量监测工作，根据稻田氮磷流失途径可将监测划分为稻田氮素气态损失、氮磷径流流失和氮磷淋溶流失 3 类。笔者就稻田氮磷流失研究中采用的监测方法和监测内容进行阐述。

## 1　稻田氮素气态损失监测

氮素的挥发损失以氨氮为主，氮肥表施时氨挥发损失占总施氮量的 10%~60%[14]。稻田氨挥发的监测方法可分为直接法和间接法。直接法中较为常用的方法主要有密闭生长箱法、微气象法和风洞法。间接法是根据稻田生态系统氮素平衡，由施肥量、植物吸收量、土壤残留量和淋失量来估算氨挥发量，该方法不考虑反硝化作用，误差较大[15]。

密闭生长箱法是将被测植物放置在密闭装置中，用酸或碱性物质置换气体的方法采集植物释放的氨，然后定量测定。该装置结构简单，能够直接捕获土壤排放的挥发氨，但密闭条件下氨挥发过程不同于自然通风条件下，并且植物蒸腾的水汽在生长室内壁被吸附，氨在置换出生长室前可能被这些水汽吸收，从而影响测定结果[16]。有学者针对密闭箱法的通风问题做出改进。王朝辉等[17]设计了原位测定田间土壤氨挥发的一种通气装置，该方法中氨捕获器由 1 个聚氯乙烯硬质塑料管和 2 片浸过磷酸甘油溶液的海绵构成。土壤表面经海绵与外界环境的空气流通，海绵上层吸收空气中的氨，下层吸收装置内土壤挥发氨，测定结果的准确度和精确度较高，氨回收率达 99.51%，变异系数仅为 0.77%。

微气象法主要发展为涡度相关法、梯度扩散法和质量平衡法 3 种方法。涡度相关法是根据垂直风速脉动和被测气体浓度脉动来获得气体通量的方法，该方法要求被测气体的水平浓度梯度可忽略不计以及观测期间大气条件稳定。但是涡度相关法要求使用快速响应的气体检测器，测量频率要求达 5~10 Hz，且由于氨的易吸附性和易溶性，目前还没有可靠的应用于涡度相关法的高频率测定设备。梯度扩散法首先假设在风速和 $NH_3$ 浓度均一的大面积农田上空存在一个 $NH_3$ 浓度梯度不随时间变化的剖面，通过测定 $NH_3$ 的揣流扩散系数($K$)和垂直方向上 $NH_3$ 浓度梯度来计算 $NH_3$ 的垂直通量，所以该方法需要面积巨大的均匀下垫面。质量平衡法要求必须在几个高度处同时测定风速和大气中氨浓度，设置的最后高度应当在试区半径长度的 1/10 处，一般至少要测 5 个高度层面，试验区外作物的覆盖应与试验区内相同[15]。

风洞法在欧洲国家应用较多，由采样箱、采样系统和控制系统 3 个部分构成[18]，采用流过风洞的风速平均值代表实际田间风速[19]，从而较准确地估计氨挥发量，几种常见风洞法的回收率：Lockyer 风洞回收率为 77%~87%，Moal 风洞回收率为 70%~80%，Braschkat 风洞回收率为 97%~103%[20-22]。然而，风洞法无法解决不能模拟静风和降水条件的问题，当风速低于 0.3 $m \cdot s^{-1}$时误差较大，虽然风洞内外风速能保持高度一致，但是由于风洞边界的影响，会高估氨挥发速率[23-24]。稻田土壤中的硝化和反硝化作用会产生 $N_2O$ 和 $N_2$ 气体，其中，$N_2O$ 约占稻田 $N_2O$ 和 $N_2$ 排放量的 2/3，$N_2$ 约占 1/3。然而，目前水稻田的硝化和反硝化作用尚缺乏合适的田间原位监测方法[25]。

## 2　氮磷径流流失监测

### 2.1　监测方法

降雨事件和分蘖末期的排水晒田是稻田发生径流、产生氮磷径流流失的直接驱动力。目前，稻田氮磷径流流失按照监测尺度分为田间小区监测、农田多点位监测和平方公里网格监测[26-27]。

田间小区监测是构建互相隔离、独立封闭灌溉和排水系统的种植小区，同时监测降雨产生的径流的水质和水量，从而确定氮磷的单位负荷量，通过单位面积氮磷负荷量乘以田间小区面积来估算氮磷流失负荷量[28-30]。利用人工控制的田间小区开展监测是定量研究农田养分流失的常用方法[31-35]。BARTON 等[31]在云南省设置不同坡度田间小区研究传统耕作、免耕、秸秆覆盖、聚乙烯地膜覆盖和间作的水土保持效果。WON 等[36]为研究秸秆覆盖和

土壤改良剂对韩国坡地土壤径流和非点源污染影响开展了多种处理的砂壤土场的田间小区实验。

农田多点位监测指在农田及周边沟渠、河道等关键点位进行水质和水量监测，以研究农田所在的小面积区域氮磷输出特征[37-38]。例如，高超等[33]在太湖何家浜流域 2 次典型降雨事件中以单块封闭水稻田直入河点和汇流沟渠入河点为采样点，探究非点源污染物在降雨过程中初期冲刷效应。SHARPLEY 等[39]监测阿肯色州 Discovery 农场的作物种植区水道水量和水质情况，以评估保护性耕作对农场环境的影响。

平方公里网格监测指在平方公里网格尺度上，考虑降雨、施肥等因素，选取沟渠、河道系统完整的田块作为氮磷污染监测点，研究不同利用类型农田氮磷迁移过程。KUPKANCHANAKUL 等[40]在印度邦帕通盆地采集河流、水产养殖场和稻田水样和底泥样本并结合数学模型分析主要河流污染物来源。陈成龙等[41]选取三峡库区涪陵段封闭性较好的王家沟小流域，采集各点位地表径流样品，探究稻田空间格局对氮磷流失的影响。

### 2.2　监测指标

土壤养分进入地表径流的主要内在驱动力大致可以归纳为对流扩散作用、雨滴击溅搅动和水流冲刷作用等。土壤中氮磷以 2 种形态进入径流：一种是溶解态，养分溶解于土壤溶液中，通过水分交换进入地表径流；另一种是吸附态，部分养分被吸附在土壤颗粒表面，通过解吸或伴随侵蚀泥沙进入地表径流[42]。

部分学者认为氮以溶解态形式流失到径流中的养分占比较高[43-47]。例如，邱卫国等[46]在上海郊区通过测坑和水稻田大田实验发现氮素径流损失以溶解态为主。叶玉适等[48]通过水肥耦合对杭州稻田氮磷迁移影响实验研究发现，溶解性氮（DN）是天然降雨径流流失氮素的主要形态，约占 TN 的 70%～92%；$NO_3^-$-N 约占 40%～80%，$NH_4^+$-N 浓度较低，仅占 3.4%～27%。然而也有学者认为稻田径流中氮素流失形态以颗粒态氮（PN）为主[49-51]。陈颖等[52]对自然降雨条件下海河流域水稻田地表径流的研究发现，PN 是农田径流损失的主要形式，其流失量与径流量呈明显正相关。于兴修等[51]研究西苕溪流域不同土地利用类型土壤氮径流流失过程发现，TN 和 PN 浓度随降雨过程逐渐降低，稻田径流排放中 PN 占 TN 的比例稳定在 66.9%～83.6%。

降雨或灌溉会冲击土壤表层，使表层土壤富集的磷颗粒大量析出而随径流流失，颗粒态磷（PP）是土壤磷径流损失的主要形态。另外，施磷肥会将磷素带入土壤，施肥后因短期内降雨而流失的主要磷形态是可溶性磷（DP）[53]。施入稻田的磷会立即水解，释放出大量无机磷酸盐，使得施磷后短期内以溶解态为主的磷素流失潜能不断增加[54]。根据研究统计，PP 和 DP 在径流流失磷素中的比例分别可达 59.35%～80.04%和 19.96%～40.65%[26,52,55-56]。同一次径流中，早期径流液中磷以 PP 为主，而后期 DP 比例加大[56]。

### 2.3　监测频率

降雨是稻田氮磷流失的重要驱动力[57]。焦少俊等[58]的研究表明，1/3～1/2 的稻田氮素径流损失由施肥后的随机性大雨导致。一次降雨内，由于初期冲刷效应，往往在径流起涨期间径流水质较差，各污染物浓度较高；在径流回落阶段，径流水中各污染物浓度往往有所下降[59-60]。径流产生初期，采取径流水样的时间间隔较短，频次较多。管毓堂等[60]在太湖流域水稻田降雨径流实验中水田径流产生时采集水样 1 次，此后，在 5、10、20、30、60 和 120 min 时采样并同步记录流量；120 min 后每 2 h 采样 1 次。高超等[33]在太湖流域水稻田排污实验中设置采样时间为农田径流形成时，前期采样时间间隔为 10 min，中后期随时间推移采样频率逐渐降低，采样时间间隔逐步延伸至 60 min 以上。径流水样采集频率也可按水样体积计。张继宗等[61]于太湖流域稻田施基肥后第 3 和第 16 天进行模拟降雨实验，在径流产生初期每个样品体积为 10 L，在单位时间产生的径流量稳定后，每个样品体积为 50 L。降雨结束后径流采样频率可降低，一般隔天采集 1 次[62]。梁新强等[45]在太湖流域稻田灌溉、降雨后第 1、3 和 5 天采集稻田径流水样，发现灌溉复水后短期内径流水中 $NO_3^-$-N 浓度出现高峰期，甚至高于穗肥施用后的最高值，发生暴雨事件后稻田排水监测需增加取样频率[63]。

## 3　氮磷淋溶流失监测

### 3.1　监测方法

淋溶是由于降水的天然下渗或人工灌溉使表层土壤中一些矿物盐类或有机物质溶解并转移到下层土壤中的过程[64]。目前，监测农田氮磷淋溶污染的方法主要有土壤溶液提取法、渗漏池实验法和同位素示踪法。

土壤溶液提取法指根据负压原理，用某一类定点溶液提取器收集田间某一深度土壤淋溶液，测定

土壤溶液实际养分浓度[65]。目前,运用最多的主要有排水采集器法[66-68]和吸力杯测渗计法[69]。排水采集器法可以直接测定淋失的养分浓度和体积,但其安装复杂,维护困难,不仅会对原状土壤产生较大扰动,而且可能产生边际优先流,影响淋溶水的形成。吸力杯测渗计法安装操作方便,对原状土壤的破坏性较小,但是只能测定淋溶液养分浓度[70-71],淋溶液体积需要根据气象数据利用水分平衡原理[72]或者根据当地淋溶水淋溶速率[73]进行估算。

渗漏池实验法用于监测超过作物根系利用深度的土壤剖面中的氮磷进入地下水体的情况。实际操作中首先在选定地点挖出一定深度的方形坑,开挖时尽量分层保存挖出的土壤,用水泥等建筑材料建立渗漏池,并留出不同深度的采样孔,分层回填土壤,待土壤性质稳定后开展渗漏监测。渗漏池监测可以研究不同深度渗漏流失情况,但是由于只能监测点位,难以反映区域氮磷流失负荷。

同位素示踪法具有准确、安全和不干扰自然的特性,被广泛运用于监测氮磷的吸收、转化和分配状况[74-76]。张惠[75]采用$^{15}N$示踪法研究黄河上游灌区稻田系统氮肥去向和稻田氮素平衡,发现当季残留在土壤中的大部分肥料氮富集在深度为 0~30 cm 的耕层。谢学俭等[77]运用$^{32}P$标记方法研究稻季施肥后磷的垂直迁移,结果表明磷在施入水田后大部分滞留在 0~5 cm 表层土中,$^{32}P$浓度随土层深度增加而降低。由于 $Br^-$ 化学性质稳定,土壤中微生物不参与 $Br^-$ 转化,应用 $Br^-$ 作为标记物更能反映土壤氮磷淋溶流失潜力[74]。

### 3.2 监测指标

土壤颗粒和土壤胶体带负电,所以对 $NH_4^+$-N 有强吸附作用,这使得大部分可交换态 $NH_4^+$-N 得以保存在土壤中。但在特定条件下,存在 $NH_4^+$-N 通过质流或水分下渗在土壤中迁移的情况;土壤对 $NO_3^-$-N 的吸附甚微,故 $NO_3^-$-N 易遭受雨水或灌溉水淋洗而进入地下水或通过径流、侵蚀等汇入地表水中[78]。

氮素淋溶形态以 $NO_3^-$-N 为主,$NO_2^-$-N 和 $NH_4^+$-N 占小部分[78]。$NH_4^+$-N 分布于土壤上层和中层,$NO_3^-$-N 多分布于土壤下层[79]。叶玉适等[80]在杭州余杭区取 30 cm 深度稻田淋溶水样分析发现,该深度水样中各形态氮以 $NH_4^+$-N 为主,占 TN 的 70.1%,$NO_3^-$-N 占 13.0%,$NO_2^-$-N 占 1.3%。李娟[26]对临安市水稻种植区不同深度淋溶液的分析发现,60 cm 深度处 $NH_4^+$-N 和 $NO_3^-$-N 流失量分别占 TN 的 13.41%~24.34%和 34.11%~75.84%。谢育平[81]通过在南通市开展的稻田养分迁移实验发现,$NO_3^-$-N 为该地 90 cm 深度淋溶液中氮素主要形态。

土壤对磷素的固定能力较强,磷在土壤剖面中向下迁移很少,一般移动速度每年不超过 0.1 mm;土壤施磷 100 a 后磷素仍集中在 40 mm 土层内[82]。除了一些有机土以外,即使在过量施肥的土壤或地下水位较高的砂质土壤中,多数情况下淋溶水中磷浓度仍较低[83]。但是也有学者认为当土壤中磷素达到一定水平时,土壤中较强的磷吸附位就会被占据,从而导致土壤对磷素的吸持能力接近饱和,此时磷素流失量就会随土壤磷素的增加而急剧增加[55,84]。

土壤磷素淋溶形态分为 PP 和 DP。PP 包括含磷矿物、含磷有机质和被吸持在土壤颗粒上的磷,在一定条件下被溶解和吸持[85]。DP 包括钼酸盐反应磷(MRP)和可溶性有机磷(DOP)。按照淋溶时间顺序,最先淋溶出土壤的磷是附着在细小土壤颗粒上的 PP,其次是 DOP。随着水分的增加以及淋溶的延续,更多的 MRP 被溶解而随水流出土壤[86]。所以 PP、DOP 和 MRP 均可能是淋溶磷的主要组成形态[54,87-88]。LÜ 等[89]在洛桑实验站抽取施加过磷酸钙的 12 块稻田小区 65 cm 深度淋溶水,发现淋溶水中 PP 占 TP 的 33.8%~87.3%,是淋溶水中磷的最主要组成形态。王小治等[88]利用太湖地区长江岸边砂质渗育性水稻土进行实验,发现各施肥处理 90 cm 处土壤溶液中的磷均以 DOP 为主,占 DP 的 56%~100%。项大力等[42]利用淋溶池设施研究 3 个灌溉水平对土壤磷素淋失的影响,结果表明土壤中磷淋失形态均以 DP 为主,MRP 约占 DP 的 50%。

### 3.3 监测频率

水稻生产活动中,施肥后一段时期内大量氮磷通过淋溶进入环境。现有研究[42,48,54,89]表明,施肥后在没有发生降雨的情况下,稻田淋溶水中 TN、$NH_4^+$-N 和 $NO_3^-$-N 浓度均在 10 d 内达到高峰,然后逐渐下降,淋溶 TP 和 DP 浓度变化趋势也相同,均在施肥后 7 d 达到最高值,然后逐渐下降。淋溶水中 $NO_3^-$-N 浓度高峰可能出现在施肥后稍迟时间,且浓度变化情况复杂,受硝化条件、水分条件等多种因素影响。施肥后一定时期内淋溶水中各形态氮磷浓度变化幅度较其他时期大。为了解淋溶水中氮磷变化规律,该时期内监测采样频率一般设置为隔天监测,监测时间跨度一般为 7~10 d[90-92]。

然而,有研究者发现海相沉积物发育土 30、60 和 90 cm 深度淋溶液中 $NO_3^-$-N 浓度均在施肥后 10~15 d 前后升高到峰值,然后逐渐下降[93]。杨梢娜[94]在杭嘉湖平原稻田监测到施基肥 14 d 后淋溶水中 $NO_3^-$-N 浓度达到峰值。以上 2 项研究中 $NO_3^-$-N 峰值出现时间滞后,需要延长施肥后氮淋溶流失监测时间。

### 3.4 监测深度

关于农田氮磷的淋溶损失,不同学者的研究结果相差较大。目前,氮磷淋失研究中淋溶量的准确获取仍是一个难点[95],这也是由不同的气候条件、土壤特性、作物类型、耕作制度、灌溉方式和施肥管理[86, 92, 96-98],以及淋溶水采样深度[99]这些关键因素造成的。李卫华等[13]在福建闽侯县将淋溶水收集装置设置于稻田田间正下方 40 cm 处,是考虑到该深度以下的氮磷不会被作物吸收。王德建等[100]考虑到太湖地区地下水水位在 80 cm 左右,故取太湖地区 80 cm 深度土层淋溶液作为稻田氮素淋洗到地下水中的量。鉴于磷素的移动性小,谢育平[81]认为 30 cm 深处土壤淋溶水中 DP 浓度变化情况可以代表进入环境的磷素变化情况。为研究进入环境的氮磷淋溶量,设置取样深度时需要考虑植物吸收、地下水深度和氮磷移动特性等因素。

## 4 展望

水稻是我国最主要的粮食作物,播种面积约占粮食种植总面积的 30%,稻田面源污染具有分散面广、随机性强、不易监测和难以量化等特征,这些因素使得稻田氮磷流失监测工作呈现难度大且紧迫性强的特点。现有的稻田氮磷污染监测方法多服务于科学研究,在实际监测应用中需要根据当地作物、土壤、降水和耕作制度等情况对监测指标、监测频率等监测内容进行调整。另外,将 GIS 和 RS 技术运用于稻田氮磷流失监测工作能够实现点位监测与区域监测的结合,大幅提高区域氮磷流失负荷计算精度,这是今后的研究方向。

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