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# 缓控释肥侧深施对稻田氨挥发排放的控制效果

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**摘要:**以减少氨挥发损失为目的,以无机化肥分次施用为对照,选用树脂包膜尿素(RCU)、硫包衣尿素(SCU)和掺混控释肥(RBB)3种不同类型缓控释肥料,采用一次性施肥(B)和一基一穗(BF)2种施肥方式,研究了插秧施肥一体化条件下不同类型缓控释肥侧深施及施用方式对稻田田面水氮浓度及氨挥发损失的影响。结果表明,除SCU处理基肥期田面水总氮和铵态氮质量浓度均高于常规分次施肥处理CN,RCU和RBB处理均低于CN处理。不同缓控释肥料稻田氨挥发损失差异较大,损失量占施肥量的3.84%~28.17%。与CN处理相比,不同类型缓控释肥料均有减少稻田氨挥发损失的效应,处理间氨挥发损失量表现为:CN、B-SCU>BF-SCU、BF-RBB、BF-RCU、B-RBB、B-RCU。一次性基施下,B-SCU处理的氨挥发总量显著高于B-RCU和B-RBB处理,一基一穗下3种处理间氨挥发总量差异不显著。不同肥料在2种施肥方式下氨挥发损失量差异不显著,但表现不一致。BF-SCU处理的氨挥发损失量低于B-SCU处理,BF-RCU和BF-RBB处理的氨挥发损失量分别高于B-RCU和B-RBB处理。阶段氨挥发损失来看,施用SCU处理的基肥-蘖肥(7.54%)和蘖肥-穗肥阶段(16.04%)的损失较高,RBB处理的基肥-蘖肥阶段氨挥发损失(2.91%)明显增加,而RCU处理的穗肥后阶段(2.75%)是氨挥发损失的集中时期。追施穗肥尿素增加了穗肥后阶段的氨挥发排放损失,穗肥后阶段氨挥发量与田面水铵态氮质量浓度在不同类型肥料间无明显相关关系。

**关键词:**稻田;侧深施肥;缓控释肥;氨挥发;田面水

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## Control Effect of Side Deep Fertilization with Slow-release Fertilizer on Ammonia Volatilization from Paddy Fields

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**Abstract:** In order to reduce the ammonia volatilization in paddy fields, seven treatments were evaluated. These included three slow-release nitrogen fertilizers [sulfur-coated urea (SCU); resin-coated urea (RCU); release bulk blending fertilizer (RBB)], two fertilization modes [single base fertilization (B) and combined with panicle fertilizer (BF)], and conventional split fertilization (CN). The effects of side deep fertilization for slow-release nitrogen fertilizers on ammonia volatilization and surface water nitrogen dynamics were examined using a rice transplanter with a fertilizer sowing mechanism in the Taihu Lake region. The results showed that total nitrogen and ammonium nitrogen concentration in the surface water of the SCU treatment in the base period were higher, and those for RCU and RBB were lower than in the CN treatment. The cumulative ammonia volatilization during the whole rice season varied among different types of slow-release nitrogen fertilizers from 3.84% to 28.17% of the total N applied. The nitrogen loss from ammonia volatilization using the three slow-release nitrogen fertilizers was decreased when compared with conventional split fertilization. The ammonia volatilization loss exhibited the following relationship for the treatments: CN, B-SCU > BF-SCU, BF-RBB, BF-RCU, B-RBB, and B-RCU. When the slow-release nitrogen fertilizers were applied in single base fertilization, the total ammonia volatilization for the SCU was significantly higher than those for the RCU and RBB, while no significant differences were detected when these three slow-release fertilizers were combined with panicle fertilizer. Moreover, although the ammonia volatilization of BF-SCU was lower than that of B-SCU, those of BF-RCU and BF-RBB were higher than those with the B-RCU and B-RBB treatments, respectively. There are no significant differences for nitrogen volatilization when any of these three different fertilizers are applied as B or BF. The results for the emissions during ammonia volatilization during different stages indicated that the ammonia volatilization of SCU at the basal-tillering fertilization stage (7.54%) and the tillering-panicle fertilization stage (16.04%) were higher than those of the panicle fertilization-mature stage. The N loss from ammonia volatilization for RBB in the base-tillering fertilization stage (2.91%) increased more than in the tillering-panicle fertilization stage and panicle fertilization-mature stage. For RCU treatment, the highest rate for ammonia volatilization was detected at the panicle fertilization-mature stage (2.75%). Compared with the single base fertilization mode, ammonia volatilization during the panicle fertilization-mature stage was increased when combined with panicle fertilizer (BF) for the

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slow-release fertilizer. There was no obvious correlation between the N loss with ammonia volatilization for the three slow-release nitrogen fertilizers and the concentration of ammonium nitrogen in surface water during the panicle fertilization-mature stage.

**Key words:** paddy field; side deep fertilization; slow-release fertilizer; ammonia volatilization; paddy water

水稻是世界上第一大粮食作物, 化肥养分的投入对水稻产量的提高发挥了重要作用<sup>[1, 2]</sup>. 近年来随着化肥研究深入和工艺进步, 缓控释肥料发展取得长足进步<sup>[3-5]</sup>. 作为一类新型肥料, 由于肥料的缓效释放, 缓控释肥料能够控制肥料中养分释放速度, 从而满足水稻生长需肥规律, 提高水稻氮素利用率, 减少氮素环境损失<sup>[6-9]</sup>. 然而缓控释肥料在实际应用中也凸显出了一些问题, 如由于缓控释肥密度相对较轻, 稻田表施容易造成缓控释肥漂浮在水面上从而随水流失; 部分类型缓释肥料包膜易破损, 造成养分在前期快速释放而无法满足不同时期作物养分需求; 部分缓释肥料的养分释放特征与水稻实际养分需求并不完全吻合, 一次性基施难以保证增产效果等<sup>[10]</sup>. 为了保证后期的养分供应, 课题组等在多年的试验基础上, 提出了基于新型缓控释肥的“一基一穗”技术, 能够在增产增效的同时减少氮的环境排放<sup>[10]</sup>. 根据水稻的高产养分需求曲线, 南京农业大学研发了一种与水稻生长需肥规律相吻合的掺混控释肥, 该肥料一次性基施对水稻生长及产量有良好的促进作用<sup>[11-13]</sup>.

肥料深施能够提高利用率, 减少损失<sup>[14, 15]</sup>. 随着经济发展水平的不断提高以及务农劳动力的日益缺乏, 机械化的需求日益旺盛. 近年来, 部分水稻主产区引进了日本井关公司气吹式插秧侧深施肥一体化机器, 取得了良好的省工节本效果<sup>[16]</sup>, 同时有效解决了缓控释肥稻田表施或翻施可能出现的问题. 但侧深施肥下不同类型缓控释肥的环境效应缺乏系统研究.

氨挥发损失是稻田氮素损失的主要途径之一, 约占施氮量的 9% ~ 40%, 氨挥发与田面水氮浓度尤其是氨氮浓度密切相关<sup>[17-19]</sup>. 以往研究表明, 缓控释肥料能够不同程度地减少稻田氨挥发损失<sup>[20-22]</sup>. 但在插秧施肥一体化条件下, 缓控释肥侧深施后其田面水氮动态和氨挥发特征是否会发生变化, 是否对氨挥发的控制效果更佳, 不同类型缓释肥之间是否存在差异, 还不得而知. 为此, 本研究以常规的无机化肥分次施用处理为对照, 采用插秧侧深施肥一体化机器, 重点分析了不同类型缓控释肥在稻田一次性基施和“一基一穗”两种模式下对稻田田面水氮浓度和氨挥发排放的影响, 以期为

稻田面源污染减排提供技术支持.

# 1 材料与方法

## 1.1 试验设计

本试验于 2013 ~ 2014 年在江苏省宜兴市丁蜀镇漳渎村(东经 119°54', 北纬 31°17')进行. 试验田前茬为小麦. 供试水稻品种为武运梗 23 号, 常规粳稻品种, 育苗移栽. 分别于 2013 年 5 月 25 日和 2014 年 5 月 28 号播种, 2013 年 6 月 15 日和 2014 年 6 月 18 日机械移栽, 采用日本井关公司气吹式插秧侧深施肥一体化机器, 缓控释肥侧深施与插秧同步进行, 田间种植密度为 30 cm × 14 cm.

试验设置 3 种类型的缓控释肥: 硫包衣尿素 SCU (N37%)、树脂尿素 RCU (N43%, 3.8% 释放速率, 释放周期 4 个月) 和缓释复混肥 RBB (N: P<sub>2</sub>O<sub>5</sub>: K<sub>2</sub>O = 23: 11: 17, 缓释复混肥由树脂复合肥、树脂二胺、树脂氯化钾和不同释放速率树脂尿素按一定比例掺混而成); 2 种施肥方式: 一次性基施 (B, 全部采用缓控释肥, 与插秧同步一次性深施到田里, 施肥深度 5 cm) 和“一基一穗”方式 (BF, 基肥采用缓控释肥, 与插秧同步深施到田里, 剩余氮采用尿素, 在穗分化期追施), 加上常规化肥分次施肥对照 (CN) 共 7 个处理, 每处理重复 3 次, 具体肥料运筹见表 1. 各处理氮、磷、钾用量均相同, 分别为 270、135 和 216 kg·hm<sup>-2</sup>, 磷用普钙 (12%); 钾用氯化钾 (60%), 磷钾肥全部用作基肥, 一次性施入. 水分管理和病虫草害防治按高产栽培要求进行控制. 为方便插秧机器行走, 试验采用条区顺序排列, 小区面积 120 m<sup>2</sup>, 分 3 次重复进行数据采集.

表 1 肥料类型及运筹方案/kg·hm<sup>-2</sup>

| Table 1 Fertilizer type and fertilization mode/kg·hm <sup>-2</sup> |                      |         |         |
|--------------------------------------------------------------------|----------------------|---------|---------|
| 处理                                                                 | 基肥                   | 分蘖肥     | 穗肥      |
| CN                                                                 | 135 (15: 15: 15 复合肥) | 45 (尿素) | 90 (尿素) |
| B-SCU                                                              | 270 (硫包衣尿素)          | —       | —       |
| B-RCU                                                              | 270 (4 个月树脂尿素)       | —       | —       |
| B-RBB                                                              | 270 (缓释复混肥)          | —       | —       |
| BF-SCU                                                             | 225 (硫包衣尿素)          | —       | 45 (尿素) |
| BF-RCU                                                             | 225 (4 个月树脂尿素)       | —       | 45 (尿素) |
| BF-RBB                                                             | 225 (缓释复混肥)          | —       | 45 (尿素) |

## 1.2 采样及测定方法

水样采集及测定: 2014 年分别于基肥、蘖肥施

用后的第 1~9 d, 穗肥施用后的第 1、2、3、5、7、9、11d, 采集各小区田面水样品, 过滤后用 SKALAR 流动分析仪测定水样的总氮、铵态氮和硝态氮含量。

**氨挥发测定:** 采用密闭室间歇通气法, 分别于每天上午 09:00~11:00 和下午 13:00~15:00 进行两个时间段 2 h 的连续抽气测定, 两次测定值平均后乘以 12 求和计算出每天的总氨挥发量<sup>[23]</sup>, 实时测定稻田氨挥发。由于无机化肥施用后具有集中释放的特征, 因此无机化肥施用后 10 d 内每天采集, 其余时间每隔 3~5 d 采集一次。新型缓释肥料氨挥发采集时间与无机化肥处理采集时间同步。

### 1.3 统计分析方法

不同于无机化肥肥效的集中释放, 缓控释肥具有肥效缓慢释放的特征, 因此氨挥发阶段损失量计算中仅按常规化肥分次施用时间分为 3 个阶段: 基肥-蘖肥阶段, 蘖肥-穗肥阶段, 穗肥后阶段。阶段氨挥发通量计算按照每次测定值进行均值计算, 氨挥发总量计算按照每次氨挥发通量测定值乘以相应天数后求和得出。

常规数据处理和作图在 Excel 2007 中进行, 方差分析在 SPSS 16.0 中进行。采用 LSD 法进行差异显著性分析 ( $P < 0.05$ )。

## 2 结果与分析

### 2.1 田面水氮动态

#### 2.1.1 全氮

田面水总氮质量浓度结果表明 (图 1), 不同肥料处理田面水总氮质量浓度在肥料施用后的第 1~2 d 达到峰值, 此后逐渐降低。基肥期和蘖肥期田面水总氮质量浓度明显高于穗肥期, 3 个肥期质量浓度峰值整体表现为基肥期 > 蘖肥期 > 穗肥期。

与常规化肥分次施肥处理 CN 相比, 一次性基施下, 硫包衣尿素 SCU 在基肥施用后出现明显质量浓度峰值, 且峰值高于常规化肥分次施肥 CN 处理, 蘖肥和穗肥期未出现明显峰值; 树脂尿素 RCU 和掺混控释肥 RBB 均在基施后第 1 d 质量浓度较高, 此后逐渐降低, 未出现明显峰值。“一基一穗”处理下, 不同肥料类型穗肥期追施尿素后第 2 d 达到质量浓度峰值, 且总氮质量浓度高于一次性基施。此外, 常规化肥分次施肥 CN 处理的田面水总氮质量浓度明显高于树脂尿素 RCU 和掺混控释肥 RBB 处理。与树脂尿素 RCU 和掺混控释肥 RBB 相比, 硫包衣尿素 SCU 基施后在整个基肥期和蘖肥期田面

水总氮质量浓度均处于较高水平。

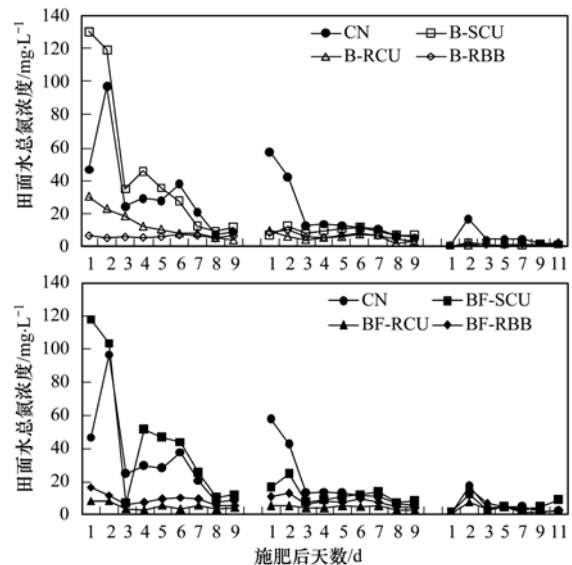


图 1 不同肥料处理的田面水总氮质量浓度

Fig. 1 TN concentration in surface water with different fertilization treatments

#### 2.1.2 铵态氮

施肥后田面水铵态氮质量浓度列于图 2。从中可以看出, 不同肥料处理田面水铵态氮质量浓度在不同肥期的质量浓度变化与总氮一致。3 个肥期质量浓度峰值同样表现为基肥期 > 蘖肥期 > 穗肥期。

与田面水总氮质量浓度相一致, 硫包衣尿素 SCU 基肥期铵态氮质量浓度峰值较高, 并在基肥和蘖肥期均处于较高水平, 穗肥期较低; 树脂尿素 RCU 和掺混控释肥 RBB 基施后短时间内质量浓度升

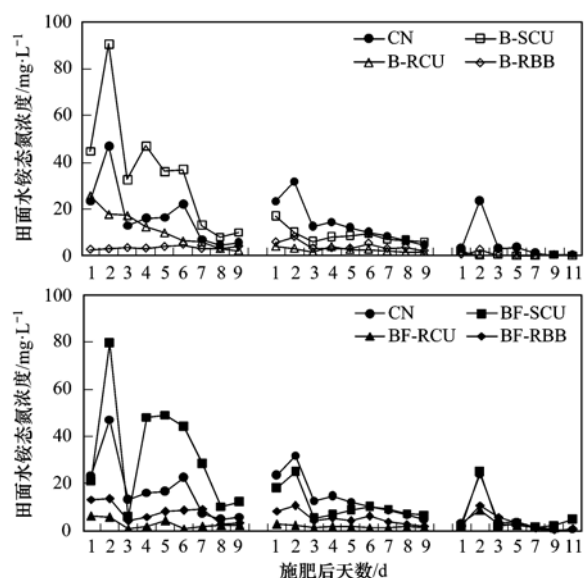


图 2 不同肥料处理的田面水铵态氮质量浓度

Fig. 2  $\text{NH}_4^+-\text{N}$  concentration in surface water with different fertilization treatments

高,此后均较低. 不同类型肥料在穗肥期追施尿素处理的铵态氮质量浓度高于一次性基肥处理. 此外,常规化肥分次施肥 CN 处理的田面水铵态氮质量浓度明显高于树脂尿素 RCU 和掺混控释肥 RBB 处理和硫包衣尿素 SCU 处理的蘖肥和穗肥期质量浓度.

2.2 氨挥发通量

图 3 结果表明,常规化肥分次施肥 CN 处理的氨挥发排在肥料施用后 1~2 d 达到峰值,施肥后短时间内的氨挥发排放通量明显高于缓控释肥处

理. 硫包衣尿素 SCU 在基肥和蘖肥期的氨挥发通量均较高;树脂尿素 RCU 和掺混控释肥 RBB 处理的氨挥发通量相对较低,掺混控释肥 RBB 氨挥发通量略高于树脂尿素 RCU. 与硫包衣尿素 SCU 不同的是,树脂尿素 RCU 和掺混控释肥 RBB“一基一穗”施用方式(BF)较一次性施肥方式(B)降低了基肥和蘖肥期的氨挥发通量. 3 种肥料一基一穗施肥方式(BF)均较一次性施肥方式(B)增加了穗肥期的氨挥发通量.

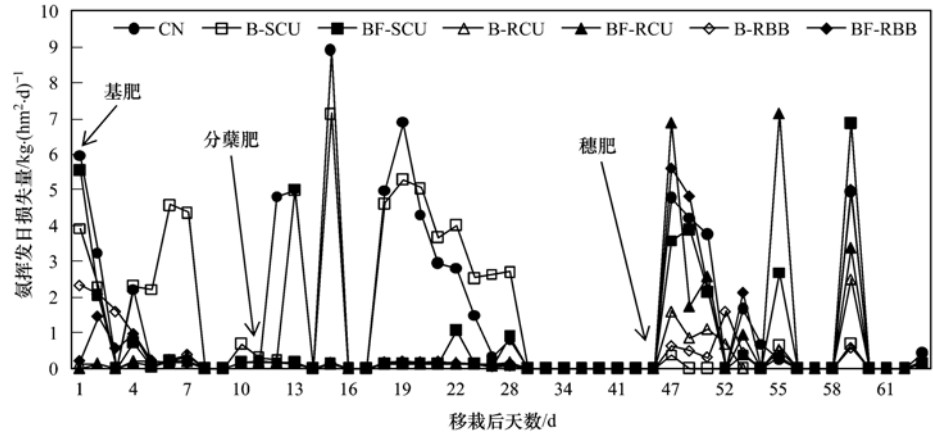


图 3 不同肥料处理的氨挥发损失通量  
Fig. 3 Ammonia volatilization fluxes with different fertilization treatments

2.3 阶段氨挥发损失特征

不同类型肥料和方式下氨挥发通量和阶段损失量结果列于表 2. 从日均氨挥发通量结果来看,基肥-蘖肥阶段,硫包衣尿素 SCU 一次性基肥处理的通量最高,高达  $2.04\text{ kg}\cdot(\text{hm}^2\cdot\text{d})^{-1}$ ,其次是常规化肥分次施肥处理 CN 和硫包衣尿素 SCU 一基一穗处理,分别为  $1.20\text{ kg}\cdot(\text{hm}^2\cdot\text{d})^{-1}$  和  $0.90\text{ kg}\cdot(\text{hm}^2\cdot\text{d})^{-1}$ ;蘖肥-穗肥阶段同样以 CN 处理和硫包衣尿素一次性基肥 B-SCU 处理最高,显著高于其他处理;穗肥后,施穗肥的 4 个处理(包括 CN 和一基一穗施肥模式的 3 个处理)明显高于一次性施肥处理.

不同类型肥料在水稻不同生育阶段的氨挥发损失规律表现不一致(表 3). 一次性基肥条件下,硫包衣尿素 SCU 处理的基肥-蘖肥阶段(7.54%)和蘖肥-穗肥阶段(16.04%)的氨挥发损失比例明显高于穗肥后,其中蘖肥-穗肥阶段氨挥发损失比例显著高于穗肥后阶段的氨挥发损失比例,是氨挥发损失的集中时期;掺混控释肥 RBB 处理的基肥-蘖肥阶段氨挥发损失比例(2.91%)明显高于其它 2 个时期,其中基肥-蘖肥阶段的氨挥发损失比例与穗肥后阶段的损失比例差异显著;而树脂尿素 RCU 处理的穗肥后阶段氨挥发损失比例(2.75%)显著高于基肥-蘖肥和蘖肥-穗肥阶段,是氨挥发损失的集

表 2 不同肥料处理的氨挥发阶段氨挥发通量和阶段损失量<sup>1)</sup>

| 处理     | 基肥-蘖肥                                               |                                    | 蘖肥-穗肥                                               |                                    | 穗肥后                                                 |                                    |
|--------|-----------------------------------------------------|------------------------------------|-----------------------------------------------------|------------------------------------|-----------------------------------------------------|------------------------------------|
|        | 通量/ $\text{kg}\cdot(\text{hm}^2\cdot\text{d})^{-1}$ | 总量/ $\text{kg}\cdot\text{hm}^{-2}$ | 通量/ $\text{kg}\cdot(\text{hm}^2\cdot\text{d})^{-1}$ | 总量/ $\text{kg}\cdot\text{hm}^{-2}$ | 通量/ $\text{kg}\cdot(\text{hm}^2\cdot\text{d})^{-1}$ | 总量/ $\text{kg}\cdot\text{hm}^{-2}$ |
| CN     | 1.20b                                               | 11.99b                             | 1.89a                                               | 43.39a                             | 1.38ab                                              | 20.68ab                            |
| B-SCU  | 2.04a                                               | 20.37a                             | 1.88a                                               | 43.32a                             | 0.12c                                               | 1.87c                              |
| B-RCU  | 0.13d                                               | 1.24d                              | 0.07b                                               | 1.72b                              | 0.49abc                                             | 7.42abc                            |
| B-RBB  | 0.79bcd                                             | 7.86bcd                            | 0.08b                                               | 1.91b                              | 0.30bc                                              | 4.57bc                             |
| BF-SCU | 0.90bc                                              | 8.97bc                             | 0.15b                                               | 3.36b                              | 1.31ab                                              | 19.68ab                            |
| BF-RCU | 0.11d                                               | 1.10d                              | 0.08b                                               | 1.82b                              | 1.52a                                               | 22.78a                             |
| BF-RBB | 0.40cd                                              | 3.94cd                             | 0.07b                                               | 1.66b                              | 1.35ab                                              | 20.26ab                            |

1) 数据后不同字母代表不同处理在  $P<0.05$  水平差异显著(LSD),下同

表 3 不同阶段氨挥发损失量占施氮量的比例/%

| 阶段    | CN     | B-SCU  | B-RCU | B-RBB  | BF-SCU | BF-RCU | BF-RBB |
|-------|--------|--------|-------|--------|--------|--------|--------|
| 基肥-蘖肥 | 4.44a  | 7.54ab | 0.46b | 2.91a  | 3.32ab | 0.41b  | 1.46b  |
| 蘖肥-穗肥 | 16.07a | 16.04a | 0.64b | 0.71b  | 1.24b  | 0.67b  | 0.62b  |
| 穗肥后   | 7.66a  | 0.69a  | 2.75a | 1.69ab | 7.29a  | 8.44a  | 7.50a  |

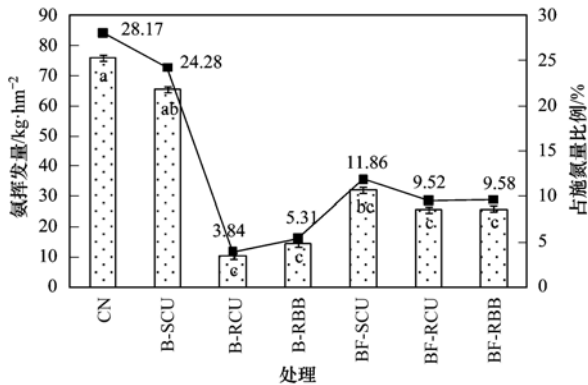
中时期。“一基一穗”模式下,3种肥料追施穗肥后的氨挥发损失比例显著高于基肥-蘖肥和蘖肥-穗肥阶段.3种肥料前期差异也不一致,树脂尿素 RCU 基施后的蘖肥-穗肥阶段的氨挥发排放高于基肥-蘖肥阶段,而硫包衣尿素 SCU 和掺混控释肥 RBB 则相反.

2.4 氨挥发损失总量

不同类型肥料和施用方式下稻季的氨挥发损失总量差异较大,氨挥发损失占施氮量的 3.84%~28.17%(图4).3种新型缓控释肥料的氨挥发总量均低于无机化肥处理 CN.一次性基施下,硫包衣尿素处理(B-SCU)的氨挥发总量显著高于树脂尿素(B-RCU)和掺混控释肥(B-RBB)处理,树脂尿素一次性基施处理(B-RCU)和掺混控释肥一次性基施处理(B-RBB)的氨挥发损失量差异不显著.不同肥料类型下“一基一穗”施肥方式与“一次性基施”施肥下氨挥发损失量差异不显著,但不同类型肥料表现不尽一致.硫包衣尿素“一基一穗”处理 BF-SCU 的氨挥发损失量低于“一次性基施”处理 B-SCU,树脂尿素和掺混控释肥“一基一穗”处理(BF-RCU, BF-RBB)的氨挥发损失量均高于“一次性基施”施肥处理(B-RCU, B-RBB).不同处理下氨挥发总量表现为:CN、B-SCU>BF-SCU、BF-RBB、BF-RCU、B-RBB、B-RCU.

3 讨论

新型缓控释肥料由于密度相对较轻,稻田表施容易漂浮在水面上而随水流失,利用插秧施肥一体化机器可实现缓控释肥料的侧深施,有效避免了此类问题的出现.无机化肥施用后一周内是氨挥发损失的关键时期,氨挥发损失排放峰值一般出现在施肥后的1~2 d内<sup>[17]</sup>.常规化肥分次施用条件下,由于分蘖期时间较长,且此期温度高、光照强,有利于氨挥发的产生,因此蘖肥期是氨挥发损失率最高的时期,而穗肥期稻田郁闭度较高,不利于田面的氨挥发,此期最低<sup>[17,24]</sup>.但对不同类型缓控释肥氨挥发排放特征的研究较少.本研究发现,无机化肥分次施用的氨挥发排放特征与前人研究相同<sup>[17,24]</sup>,但不同类型缓控释肥的氨挥发排放表现出特定的峰值特征.硫包衣尿素 SCU 表现为基肥-蘖肥期和蘖肥-穗肥期排放通量较高,掺混控释肥 RBB 主要集中在基肥-蘖肥阶段,而树脂尿素 RCU 则主要集中在穗肥后阶段.从损失量结果来看,常规化肥分次施用处理 CN 和硫包衣尿素 SCU 处理的基肥-蘖肥及蘖肥-穗肥阶段氨挥发损失量明显高于穗肥后阶段,掺混控释肥 RBB 处理在基肥-蘖肥阶段损失增加,是氨挥发损失的集中时期;而树脂尿素 RCU 处理的穗肥后阶段是氨挥发损失的集中时期.这可能与不同类型肥料的肥效释放特征有关.与树脂膜相比,硫膜易溶解和破碎<sup>[25]</sup>.谷佳林等<sup>[26]</sup>对硫包衣尿素肥料释放特性研究发现,硫包衣尿素养分释放速率受温度和水分影响较大,肥料所处环境温度越高,水分含量越大,养分释放速率越快.稻田温度较高,移栽时土壤水分含量处于饱和状态,这可能加快了硫包衣尿素的释放.而缓释复混肥和树脂尿素采用树脂包膜工艺,受水分影响较小<sup>[27]</sup>.杨铎等<sup>[28]</sup>对树脂包膜尿素在稻田的释放特征研究表明4个月树脂尿素在3a田间试验中分别在152、158和142 d时间内释放了73%、83%、69%,控释效果较好.而本研究中选用的掺混控释肥 RBB 是由不同释放速率的肥料组配而成,因此其前期养分释放高于树脂尿素 RCU.



柱形图中不同字母代表不同处理在  $P < 0.05$  水平差异显著 (LSD)

图 4 不同肥料处理的氨挥发损失总量

Fig. 4 Volume of cumulative ammonia emissions in the paddy season with different fertilization treatments

氮挥发损失是稻田氮素损失的主要途径, 约占施氮量的 9% ~ 40%<sup>[17~19]</sup>. 本研究发现, 不同类型缓控释肥料的氮挥发损失差异较大, 氮挥发损失量占施肥量的 3.84% ~ 28.17%. 孙祥鑫等<sup>[22]</sup>在寒地稻田研究表明, 树脂尿素和硫包衣尿素的氮挥发减排幅度分别为 73.4% 和 72.2%. 本研究表明, 在太湖地区稻麦轮作农田, 3 种新型肥料在 2 种施用方式下的氮挥发损失量均低于无机化肥处理, 减排幅度在 13.80% ~ 86.36% 之间, 其中硫包衣尿素处理 (SCU) 的氮挥发总量相对较高, 树脂尿素 (RCU) 和掺混控释肥 (RBB) 基本相当. 此外, 等施氮量下, “一基一穗”技术模式比一次性施肥明显增加了穗肥后的氮挥发排放通量.

稻田田面水以铵态氮为主, 总氮和铵态氮质量浓度变化较一致<sup>[29]</sup>. 本研究发现, 硫包衣尿素处理 SCU 的田面水总氮和铵态氮质量浓度在基肥和蘖肥期较高, 穗肥期较低; 树脂尿素 RCU 基施后田面水氮质量浓度短期内质量浓度升高, 此后均较低; 而掺混控释肥 RBB 在 3 个肥期均未表现出明显的质量浓度峰值. “一基一穗”技术方式的田面水氮质量浓度高于一次性基施. 俞映惊等的研究指出<sup>[19]</sup>, 施肥后稻季氮挥发量主要受田面水中铵态氮平均含量的影响, 但具体到每日氮挥发通量, 由于受环境因素影响, 两者间并未有很好的相关性. 本研究表明, 3 种新型肥料在基肥和蘖肥期田面水铵态氮质量浓度与阶段氮挥发损失量表现较一致, 但穗肥期表现并不一致. 尤其在一次性施肥下, 树脂尿素 RCU 穗肥期田面水铵态氮质量浓度低于掺混控释肥 RBB 处理, 但氮挥发损失高于掺混控释肥 RBB 处理. 这说明, 穗肥后阶段氮挥发损失量与田面水氮质量浓度在不同肥料类型间并无明显相关关系. 前述结果说明, 新型肥料下, 基肥和蘖肥期田面水铵态氮质量浓度可以在一定程度上反映氮挥发损失风险, 但穗肥期田面水铵态氮质量浓度不能作为氮挥发损失风险的评判指标.

#### 4 结论

(1) 等施氮量下, 与常规化肥分次施用相比, 3 种新型缓控释肥料在 2 种施用模式下均能够不同程度减少稻田的氮挥发排放, 减排程度可达 13.80% ~ 86.36%. 施用树脂尿素和掺混控释肥的减排效果优于硫包衣尿素. 不同类型肥料在 2 种施肥方式下季节氮挥发量差异不显著, “一基一穗”模式明显增加了穗肥后的稻田氮挥发损失.

(2) 不同类型缓控释肥的氮挥发排放表现出特定的阶段损失特征. 一次性施肥下, 硫包衣尿素在基肥-蘖肥和蘖肥-穗肥阶段的损失较大, 掺混控释肥在基肥-蘖肥阶段损失高于其它 2 个阶段, 而穗肥后阶段是施用树脂尿素的氮挥发损失集中时期. 追施穗肥尿素增加了穗肥后阶段的氮挥发排放损失.

(3) 穗肥后阶段氮挥发量与田面水铵氮质量浓度在不同类型肥料间无明显相关关系.

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