

缓释氮肥减量配施和株距对机插杂交籼稻氮素利用的影响

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Effects of Reduced Slow-released Urea Combined with Conventional Urea Under Different Plant Spacing on Characteristics of Nitrogen Utilization in Mechanically-transplanted *indica* Rice

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Abstract: 【Objective】To further study the effects of reduced slow-released urea combined with conventional urea under various row spacing on N accumulation at the main growth stages, N translocation (NT), N apparent use efficiency (NAUE), grain yield, and the correlations among these indexes of mechanically-transplanted rice. 【Method】Based on the previous research of high-yielding nitrogen application rate of 180 kg/hm² (the ratio of slow-released urea and conventional urea was 7:3), three plant spacing (16, 18 and 20 cm, the row spacing was 30 cm) and four treatments of reduced slow-release urea (36, 66, 96 and 126 kg/hm²) combined with conventional urea rate of 54 kg/hm² were conducted. 【Result】There were significant influences on the total nitrogen accumulation amount of the main growth stages, the nitrogen absorption amount of leaves and panicles at maturity stage, N translocation of filling stage, NAUE and grain yield of reduced slow-released urea combined with conventional urea and row spacing. The effects of reduced slow-released urea combined with conventional urea on grain yield and nitrogen absorption and translocation were significantly larger than that of row spacing. When the combined application rate was 150 kg/hm² (slow-released urea and conventional urea application rates were 96 kg/hm² and 54 kg/hm², respectively) and the plant spacing was 18 cm that could facilitate N accumulation of main growth stage, enhance N accumulation amount of different organs at grain filling stage, and promote N translocation of stem sheath and leaves, which further improve N increment of panicle(107.58 kg/hm²), NAUE(66.19%) and grain yield(11463.85 kg/hm²). Meanwhile, it could accelerate the N accumulation at main growth stages when the combined application rate was 180 kg/hm² (slow-released urea and conventional urea were 126 kg/hm² and 54 kg/hm², respectively) and plant spacing was 16 cm, but it might cause the risk of N retention at grain filling stage which decrease the nitrogen translocation rate and finally reduce the nitrogen harvest index (NHI) and NAUE. It is better when the combined application rate was 150 kg/hm² with slow-released N fertilizer was 96 kg/hm² and conventional urea was 54 kg/hm² in terms of high yield and high efficiency. However, when the plant spacing was increased to 20 cm, the absolute value of N absorption at main growth stage was decreased, the N translocation amount from stem sheath and leaves to panicle was increased as well as N accumulation amount of panicle. The grain yield and NAUE were increased with the rising slow-released urea application rate. In this conditions, the combined application rate was 180 kg/hm² (slow-release urea and conventional urea were 126 kg/hm² and 54 kg/hm², respectively) was superior to any other treatments. Correlation analysis indicated that the highest correlation ($r=0.54^{**}\sim 0.85^{**}$) between the total N accumulation amount, N translocation amount of leaves from full heading stage to maturity stage and grain yield and NAUE was obtained which might play an important role in improving NAUE and grain yield. 【Conclusion】The plant spacing was 18 cm, the N for 150 kg/hm² (slow-released urea and conventional urea were 96 kg/hm² and 54 kg/hm²) could maximize N increment of panicle, NAUE and grain yield.

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Key words: mechanically-transplanted rice; plant spacing; slow-released urea; reduced combined application; N utilization characteristics

摘 要: 【目的】进一步研究缓释氮肥减量配施和株距对机插杂交籼稻主要生育时期氮素积累、转运、氮肥利用率及产量的影响,并探讨机插密度和缓释氮肥配施耦合下,氮素吸收、转运及利用率与产量间的关系。【方法】在前期研究确定高产施氮量 180 kg/hm^2 ,机插稻缓释氮肥与常规氮肥适宜配比为 7:3 基础上,设 3 种株距(行距均为 30 cm): 16、18 和 20 cm,以及 4 种缓释氮肥(36、66、96 和 126 kg/hm^2)与常规氮肥(54 kg/hm^2)配施处理。

【结果】缓释氮肥减量配施和株距对机插稻主要生育时期氮素积累总量、成熟期叶片及穗部氮素吸收量、氮素转运量、氮肥利用率及产量均存在显著或极显著的互作效应;缓释氮肥减量配施对机插稻产量及氮素吸收利用与转运特性的影响显著大于株距。株距为 18 cm,缓释氮肥(96 kg/hm^2)与常规氮肥(54 kg/hm^2)配施量为 150 kg/hm^2 能促进水稻主要生育时期及各生育阶段氮素的累积,提高结实期各器官氮素积累量,并促进叶片和茎鞘中氮素的转运,进而显著提高穗部氮素增加量(107.58 kg/hm^2)、氮肥利用率(66.19%)及产量(11463.85 kg/hm^2);株距为 16 cm,缓释氮肥(126 kg/hm^2)与常规氮肥(54 kg/hm^2)配施量为 180 kg/hm^2 虽能促进主要生育时期氮素的累积,但易造成结实期茎鞘及叶片中氮滞留量的增加,降低氮素转运率,导致氮素收获指数和氮肥利用率降低。从高产高效的角度考虑,以缓释氮肥(96 kg/hm^2)与常规氮肥(54 kg/hm^2)配施量 150 kg/hm^2 为宜;当株距增加到 20 cm 时,主要生育时期水稻吸收氮素的绝对量少,茎鞘叶片中的氮素向穗部转运及穗部氮素积累量增加,产量及氮素利用率随缓释氮肥配施量的增加而增加,以缓释氮肥与常规氮肥配施量为 180 kg/hm^2 为宜。相关性分析表明,缓释氮肥减量配施与株距耦合下,机插杂交稻以齐穗至成熟期氮素积累量、叶片氮素转运量与产量及氮肥利用率的相关性($r=0.54^{**} \sim 0.85^{**}$)最高,对提高氮肥利用率及产量更为重要。【结论】株距为 18 cm,缓释氮肥与常规氮肥配施量为 150 kg/hm^2 能协同提高穗部氮素增加量、氮肥利用率及产量,为本研究氮肥减量配施的最佳处理。

关键词: 机插稻;株距;缓释氮肥;减量配施;氮素利用特征

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氮肥管理和种植密度是水稻生产的两个关键栽培技术,它们影响水稻产量和养分吸收利用。合理的栽插密度和氮肥运筹可缓解个体与群体、足穗与大穗的矛盾^[1],是调控机插稻高产优质栽培的重要措施。研究在提高水稻产量的同时,结合缓释氮肥的优势,如何选用机插密度,能同步提高氮素吸收利用效率^[2-3],发挥肥密耦合调控效应,对机插稻的高产栽培和氮肥高效利用具有重要的生产价值。对此,前人进行了大量研究^[4-8]。樊红柱等^[6]研究表明在同一施氮量下,随栽插密度的增大,单位面积有效穗数、氮肥农学利用率、氮肥表观利用率及氮肥偏生产力呈增加的趋势;林洪鑫等^[7]研究表明,超级早稻在 $24 \times 10^4 \sim 30 \times 10^4$ 穴/ hm^2 的栽插密度范围内,产量与生物量及氮素积累总量呈抛物线的关系;陈佳娜等^[8]研究认为,氮肥利用率随氮肥施用量的增加而降低,随栽插密度增加而提高,适当增加机插密度和减少氮肥施用量,既可实现高产又能显著提高氮肥利用率。随着研究的深入,众多学者认为,缓释氮肥一次性基施基本能满足作物生长发育的需求,能有效提高肥料利用率、减轻环境污染,但成本较高,因此为提高肥料利用率和减少经济投入,缓释氮肥的研制与应用已成为研究热点^[9-11]。目前,缓释氮肥在水稻上的研究主要集中于施用量与栽培模式^[12]、施用量与密度^[13]、肥料对比试验^[14],以及缓释肥配施运筹^[15]等方面。而对于缓释氮肥和

常规氮肥配施与品种、施氮量、机插密度等互作效应在机插稻上的研究报道较少;尤其机插密度和缓释氮肥减量与常规氮肥配施优化对中迟熟杂交籼稻氮素吸收利用、转运特征及产量的影响,以及两因素是否存在互作效应均未见报道。我们在前期研究^[14,16]的基础上,对缓释氮肥筛选^[14]及 2015 年缓释氮肥配施^[16]试验进一步研究表明,不同施氮水平和缓释氮肥与常规氮肥配施互作对机插稻氮素利用特征及产量存在显著或极显著的影响,且氮素的吸收及结实期茎鞘氮素的转运与干物质质量、每穗实粒数及产量间存在显著或极显著的正相关性。但确定高产施氮量下合理的缓释氮肥与常规氮肥配施比例后,如何进一步结合不同的机插密度进行适量缓释氮肥与常规氮肥配施,调控机插稻主要生育时期氮素积累、茎鞘及叶片中氮素向穗部转运、氮素吸收利用及产量间的关系,尚不明确。为此,本研究通过机插密度的调控减氮效应,结合缓释氮肥的优势,充分发挥肥密耦合效应,在提高氮肥利用率的同时合理降低氮肥施用量,以期进一步阐明机插密度和缓释氮肥减量与常规氮肥配施对机插稻氮素吸收、利用及转运特征的影响,并探讨缓释氮肥配施和机插密度耦合下,氮素吸收、转运及利用效率与产量间的关系,从而进一步丰富和补充机插稻肥密调控机理,达到既高产高效又环保的目的,为我国西南稻区中迟熟机插杂交籼稻肥密耦合的

高产高效栽培技术提供理论和实践依据。

1 材料与方法

1.1 试验设计

在 2015 年不同施氮水平和缓释氮肥与常规氮肥配施试验研究的基础^[16]上, 于 2016 年在四川成都市温江区水稻所试验农场开展试验以进一步深入和完善。试验田前茬为小麦, 耕层土壤(0—20 cm)质地为砂壤土, 有机质 24.38 g/kg, 全氮 1.76 g/kg, 碱解氮 113.75 mg/kg, 速效磷 65.34 mg/kg, 速效钾 109.58 mg/kg。供试品种为适宜西南稻区栽植且具有代表性的杂交籼稻品种川谷优 7329(生育期 156~165 d), 4 月 15 日播种, 钵体毯状秧盘(中国水稻研究所)早育秧, 每盘播量 75 g, 5 月 21 日用东洋 PF455S 插秧机进行机插, 秧龄 36 d。进行株距(D)×缓释氮肥减量配施(N)二因素裂区试验, 主区为机插株距, 行距均为 30 cm, 设 3 种株距, 即 D₁, 16 cm; D₂, 18 cm; D₃, 20 cm, 基本苗分别为 58.35、51.86、46.68 万株/hm²。副区为缓释氮肥减量配施处理, 在前期研究确定的 180 kg/hm²施氮量、缓释氮肥(金正大树脂包膜缓释氮肥, 含氮量 44%)与常规氮肥(尿素, 含氮量 46%)比例为 7:3(126 kg/hm²:54 kg/hm²)的基础上, 设置 4 种缓释氮肥减量与常规氮肥配施处理和不施氮处理(表 1)。

氮肥均作基肥于机插后 1 d 一次性施用, 磷肥(过磷酸钙)施用量折合 P₂O₅ 75 kg/hm², 钾肥(氯化钾)施用量折合 K₂O 150 kg/hm², 磷钾肥均作底肥基施。每个小区计产面积为 19.6 m², 3 次重复, 各小区间筑土埂并用塑料薄膜包裹, 防止肥水互串, 其他田间管理严格按照当地大面积生产田进行。因本

表 1 缓释氮肥减量与常规氮肥配施设置

Table 1. Reduced slow-released urea combined with conventional urea.

处理 Treatment	施氮量 N application rate	kg/hm ²	
		缓释氮肥 Slow-released urea	常规氮肥 Conventional urea
N ₀	0	0	0
N ₁	90	36	54
N ₂	120	66	54
N ₃	150	96	54
N ₄	180	126	54

N₀—不施氮肥; N₁、N₂、N₃、N₄ 分别代表在常规尿素 54 kg/hm² 的基础上, 缓释氮肥配施量为 36、66、96、126 kg/hm²。

N₀, No nitrogen fertilization; N₁, N₂, N₃ and N₄ represent slow released N addition of 36, 66, 96 and 126 kg/hm² at the base of urea of 54 kg/hm².

研究为 2015 年研究的延续, 两年试验未完全重复, 但相同的氮肥配施处理下, 产量及氮素累积及利用年份间差异均不显著, 为此, 本研究就 2016 年试验结果进行分析。

1.2 测定项目与方法

分别于水稻分蘖盛期(机插后 30 d)、拔节期、齐穗期及成熟期, 根据各小区的平均茎蘖数各取代表性稻株 5 株, 分茎鞘、叶片和穗 3 部分, 于 105℃ 下杀青 30 min, 80℃ 下烘干至恒重, 测定各器官干物质质量, 之后粉碎过 80 目筛, 用浓 H₂SO₄ 加凯氏定氮片消煮, FOSS-8400 凯氏定氮仪测定氮含量。并按照前期试验报道^[12,14]的方法, 计算主要生育时期氮素累积量, 各生育阶段氮素累积速率, 氮素收获指数, 结实期营养器官氮输出量、转运率, 以及氮素干物质生产效率、氮素稻谷生产效率、氮肥农学利用率、氮肥偏生产力和氮肥表观利用率。成熟期各小区除边行全部收获, 按实收株数计产。

某生育时期某器官单位面积氮素累积量(kg/hm²)=某生育时期某器官单位面积干物质累积量×含氮量;

氮素阶段累积量(kg/hm²)=后一生育时期单位面积氮素累积量—前一生育时期单位面积氮素累积量;

氮素阶段累积速率(kg hm⁻² d⁻¹)=某生育阶段单位面积单位时间内氮素累积量;

氮素收获指数(%)=(穗氮素累积量/地上部氮素累积量)×100%;

地上部分(茎鞘、叶片)氮素转运量(kg)=齐穗期地上部分(茎鞘、叶片)氮素累积量—成熟期地上部分(茎鞘、叶片)氮素累积量;

地上部分(茎鞘、叶片)氮素转运率(%)=[地上部分(茎鞘、叶片)氮素转运量/齐穗期地上部分(茎鞘、叶片)氮素累积量]×100%;

氮素干物质生产效率(kg/kg)=成熟期单位面积植株干物质/地上部分氮素累积量;

氮素稻谷生产效率(kg/kg)=实际产量/地上部分氮素累积量;

氮肥农学利用率(%)=[(施氮区产量—空白区产量)/施氮量]×100%;

氮肥偏生产力(kg/kg)=施氮区产量/施氮量;

氮肥表观利用率(%)=[(施氮区植株氮素累积量—空白区植株氮素累积量)/施氮量]×100%。

1.3 数据分析

用 Microsoft Excel、DPS 6.5 处理系统分析数据, Origin 9.0 制图。

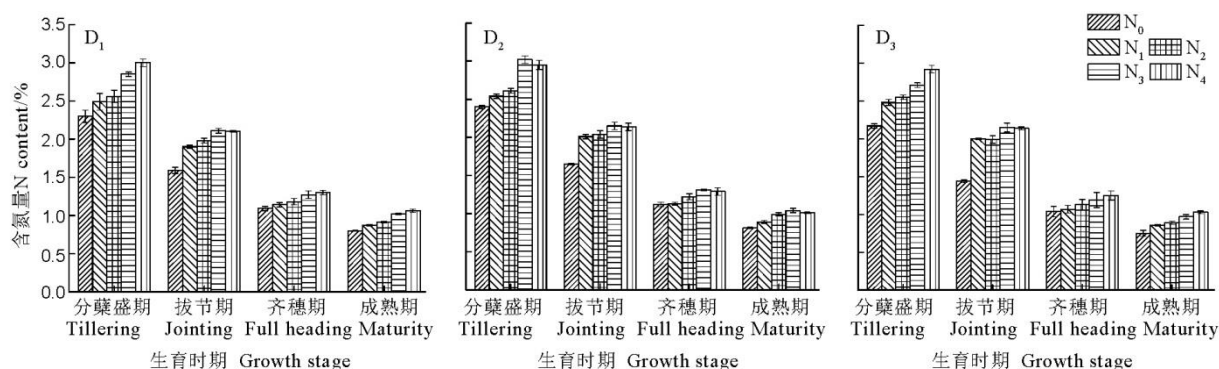


图1 不同处理机插稻主要生育时期群体氮含量

Fig. 1. N contents in plants at main growth stages of mechanically-transplanted rice under treatments of reduced slow-released urea combined with conventional urea.

2 结果与分析

2.1 缓释氮肥减量配施和株距下机插稻主要生育时期稻株氮含量

不同株距和缓释氮肥配施量下机插稻群体主要生育时期植株氮含量存在明显差异(图1), 氮含量均在分蘖盛期最高, 成熟期最低。株距对同时期植株氮含量的影响趋势基本一致, 表现为 $D_2 > D_1 > D_3$ 。就缓释氮肥减量效应来看, 当株距为 D_1 和 D_3 时, 主要生育时期稻株氮含量随缓释氮肥配施量的增加均呈增加的趋势; 而在株距 D_2 下, 主要生育时期稻株氮含量则表现为 $N_3 > N_4 > N_2 > N_1 > N_0$, 且主要生育时期氮含量 N_3 较 N_4 、 N_2 、 N_1 、 N_0 分别增加了3.39%、15.71%、18.90%、25.83%(分蘖盛期), 0.47%、5.39%、6.97%、30.30%(拔节期), 1.55%、7.38%、15.93%、16.96%(齐穗期), 2.97%、5.05%、16.85%、28.40%(成熟期)。

2.2 缓释氮肥减量配施和株距对机插稻各生育时期氮素积累量和收获指数的影响

由表2可看出, 除分蘖盛期氮素积累量和氮素收获指数外, 缓释氮肥减量配施和株距及其交互效应对机插杂交稻主要生育时期氮素积累量与产量的影响均达显著或极显著水平。随生育进程的推进, 植株氮素积累量增加, 随株距的增加氮素积累量、产量及氮素收获指数均呈先增后降的趋势。在株距为 D_1 和 D_3 时, 主要生育时期机插稻氮素积累量和产量与缓释氮肥配施量正相关; 在株距为 D_2 时, 主要生育时期氮素积累量和产量则在 N_3 时最大, 表现为 $N_3 > N_4 > N_2 > N_1 > N_0$ 。

2.3 缓释氮肥减量配施和株距对机插稻主要生育阶段氮素积累量及积累速率的影响

株距仅对分蘖盛期至拔节期氮素积累量及积

累速率的影响达极显著水平; 而缓释氮肥减量配施对分蘖盛期至拔节期及齐穗至成熟期氮素积累量及积累速率的影响达极显著水平(表3)。各生育阶段氮素积累量随生育进程的推进呈先增加后减小的趋势, 而氮素积累速率则不断减小, 随株距的增加, 阶段氮素积累量及积累速率均表现为 $D_2 > D_1 > D_3$ 。在株距为 D_1 、 D_3 下, 各阶段氮素积累量均随缓释氮肥与常规氮肥配施量的减小递减, 而阶段氮素积累速率均在 N_4 时最快; 株距为 D_2 时, 阶段氮素积累量及积累速率均在 N_3 时最大, 且 N_3 与 N_4 处理差异未达显著水平。

2.4 缓释氮肥减量配施和株距对机插稻齐穗期各器官氮素积累量及分配的影响

由表4可见, 缓释氮肥减量配施对机插稻齐穗期各器官氮素积累量的影响均达极显著水平。从机插株距来看, 各器官氮素积累量及叶片氮素积累比例均随株距的增加先增大后减小, 茎鞘氮素积累比例与株距正相关, 而穗部氮素积累比例则相反。从相同株距下缓释氮肥减量配施来看, 当株距为 D_1 和 D_3 时, 各器官氮素积累量随缓释氮肥与常规氮肥配施量的增加而增大; 当株距为 D_2 时, 则表现为 $N_3 > N_4 > N_2 > N_1 > N_0$, 且 N_3 与 N_4 差异不显著。

2.5 缓释氮肥减量配施和株距对机插稻成熟期各器官群体氮素积累量及其分配的影响

由表5可知, 缓释氮肥减量配施和株距对成熟期机插稻叶片、穗氮素积累量的影响达极显著水平, 交互效应显著。各器官氮素积累量均表现为 $D_2 > D_1 > D_3$, 且茎鞘、叶片、穗部氮素积累量 D_2 较 D_1 和 D_3 分别增加了2.60%和15.99%、4.88%和17.60%、8.70%和16.73%; 穗部氮素积累比例在 D_2 时最大, 茎鞘、叶片氮素积累比例则在 D_1 时最佳。 D_1 和 D_3 机插株距下, 各器官氮素积累量随缓释氮肥与常规氮肥配施量的增加而增大, 且叶片、穗的氮

表 2 缓释氮肥减量配施和株距对机插稻各生育时期氮素积累量、产量和收获指数的影响
Table 2. Effects of reduced slow-released urea combined with conventional urea on N accumulation, yield and N harvest index in mechanically-transplanted rice under different plant spacing.

处理 Treatment		氮素累积 N accumulation/(kg hm ⁻²)				稻谷产量	氮素收获指数
		分蘖盛期 Tillering	拔节期 Jointing	齐穗期 Full heading	成熟期 Maturity	Grain yield /(kg hm ⁻²)	N harvest index /%
D ₁	N ₀	12.21±1.11 e	31.21±2.30 e	81.04±3.19 e	99.96±1.77 e	8 141.23±57.93 d	75.16±0.19 a
	N ₁	23.63±4.07 d	60.26±2.28 d	110.57±5.89 d	138.09±5.16 d	9 089.70±57.21 c	68.75±0.40 b
	N ₂	27.91±5.31 c	67.09±1.43 c	119.75±6.95 c	149.88±1.99 c	9 377.61±19.61 b	67.42±0.95 c
	N ₃	34.24±2.91 b	88.66±5.51 b	144.21±9.75 b	180.63±1.60 b	10 003.44±58.44 a	68.99±1.41 b
	N ₄	39.34±2.14 a	96.88±0.69 a	153.86±5.37 a	193.95±2.76 a	10 057.76±17.78 a	67.85±1.08 bc
平均	Average	27.47±3.11	68.82±6.44	121.89±6.23	152.50±2.66	9 333.95±82.19	69.63±0.80
D ₂	N ₀	12.68±0.52 d	33.41±0.94 d	84.48±3.68 e	104.65±4.37 e	8 540.47±31.32 e	75.40±1.50 a
	N ₁	23.64±1.23 c	60.48±1.51 c	112.11±3.02 d	145.68±5.81 d	9 697.88±33.90 d	70.23±1.97 b
	N ₂	29.24±3.30 b	77.64±6.47 b	130.71±1.65 c	170.60±3.17 c	10 187.12±42.58 c	70.40±0.81 b
	N ₃	40.52±3.37 a	104.67±6.00 a	162.20±9.94 a	203.94±5.48 a	11 463.85±49.39 a	68.24±1.40 c
	N ₄	37.42±6.09 a	96.05±6.32 a	152.34±9.55 b	192.32±4.35 b	11 210.84±74.55 b	69.05±2.90 bc
平均	Average	28.70±2.90	74.45±4.25	128.37±5.56	163.44±4.64	10 220.03±46.35	70.66±1.72
D ₃	N ₀	8.39±0.25 d	26.09±3.28 d	73.12±8.19 e	90.46±5.72 e	8 005.77±11.92 e	74.88±1.52 a
	N ₁	19.64±0.51 c	50.79±4.55 c	99.36±4.82 d	127.75±0.64 d	8 427.55±43.30 d	69.79±1.61 b
	N ₂	25.74±2.86 b	57.70±6.16 c	109.54±4.46 c	139.22±7.02 c	9 002.07±48.45 c	69.36±0.95 b
	N ₃	29.22±1.13 b	71.60±6.17 b	125.35±7.64 b	162.37±6.73 b	9 989.09±67.52 b	69.42±1.65 b
	N ₄	36.47±2.47 a	86.62±6.62 a	140.98±4.19 a	180.14±7.26 a	10 732.01±61.01 a	69.33±2.36 b
平均	Average	23.89±1.44	58.56±5.36	109.67±5.86	139.99±5.48	9 231.30±46.44	70.56±1.62
F 值 F value	D	8.51**	89.27**	11.07*	94.75**	486.78**	0.78
	N	129.10**	172.30**	249.42**	515.65**	2165.51**	37.45**
	D×N	1.63	2.79*	3.44**	6.09**	74.82**	0.96

D₁、D₂、D₃代表株距16、18、20 cm; D—株距; N—缓释氮肥配施量; D×N—缓释氮肥减量配施和株距交互。同栏数据(平均数±标准差)后相同字母表示在5%水平上差异不显著(n=3, 最小显著差法)。*, **分别表示在0.05和0.01水平上差异显著。下同。

D₁, D₂ and D₃ represent plant spacing of 16, 18 and 20 cm; D, Plant spacing; N, Treatments of slow-released urea combined with conventional urea; D×N, Interaction of plant spacing and treatments of slow-released urea combined with conventional urea. Values (mean±SD) within a column followed by common letters are not significantly different at P<0.05 (n=3, LSD). * Significant at P<0.05, ** Significant at P<0.01. The same as below.

表 3 缓释氮肥减量配施和株距对机插稻主要生育阶段氮素积累量及积累速率的影响
Table 3. Effects of reduced slow-released urea combined with conventional urea on N accumulation amount and accumulation rate at main growth stage in mechanically-transplanted rice under different plant spacing.

处理 Treatment		氮素积累量			氮素积累速率		
		N accumulation amount/(kg hm ⁻²)			N accumulation rate/(kg hm ⁻² d ⁻¹)		
		分蘖-拔节期 TS-JS	拔节-齐穗期 JS-FHS	齐穗-成熟期 FHS-MS	分蘖-拔节期 TS-JS	拔节-齐穗期 JS-FHS	齐穗-成熟期 FHS-MS
D ₁	N ₀	19.00±1.35 c	49.83±5.29 a	18.92±4.26 c	1.36±0.10 c	1.55±0.17 a	0.43±0.10 c
	N ₁	36.63±5.54 b	50.31±8.16 a	27.52±2.91 b	2.62±0.40 b	1.48±0.24 a	0.62±0.07 b
	N ₂	39.18±5.21 b	52.66±8.15 a	30.13±5.08 b	2.80±0.37 b	1.55±0.24 a	0.68±0.12 b
	N ₃	54.43±13.84 a	55.55±12.60 a	36.41±11.28 a	3.89±0.99 a	1.54±0.35 a	0.83±0.26 a
	N ₄	57.54±9.15 a	56.98±13.71 a	40.09±6.71 a	4.11±0.65 a	1.58±0.38 a	0.91±0.15 a
平均	Average	41.36±7.02	53.06±9.58	30.61±6.05	2.96±0.50	1.54±0.28	0.70±0.14
D ₂	N ₀	20.73±1.15 d	51.07±3.55 a	20.17±5.40 c	1.48±0.08 d	1.60±0.11 a	0.46±0.12 c
	N ₁	36.84±2.72 c	51.62±1.72 a	33.57±3.84 ab	2.63±0.19 c	1.52±0.05 a	0.76±0.09 ab
	N ₂	48.41±3.46 b	53.06±5.09 a	39.89±4.06 a	3.46±0.25 b	1.56±0.15 a	0.91±0.09 a
	N ₃	64.15±4.96 a	57.54±13.76 a	41.74±4.52 a	4.58±0.35 a	1.60±0.38 a	0.95±0.10 a
	N ₄	58.64±2.62 a	56.28±8.68 a	39.98±8.01 a	4.19±0.19 a	1.57±0.24 a	0.91±0.18 a
平均	Average	45.75±2.98	53.92±6.56	35.07±5.17	3.27±0.21	1.57±0.19	0.80±0.12
D ₃	N ₀	17.70±3.31 c	47.03±9.93 a	17.33±3.99 c	1.26±0.24 c	1.47±0.31 a	0.40±0.09 c
	N ₁	31.15±4.04 b	48.57±0.29 a	28.39±5.46 b	2.23±0.29 b	1.43±0.01 a	0.65±0.12 b
	N ₂	31.96±4.78 b	51.84±9.20 a	29.68±3.14 ab	2.28±0.34 b	1.52±0.27 a	0.67±0.07 ab
	N ₃	42.38±5.76 a	53.76±8.26 a	37.02±3.56 a	3.03±0.41 a	1.49±0.23 a	0.84±0.08 a
	N ₄	50.15±8.47 a	54.37±10.58 a	39.16±9.56 a	3.58±0.60 a	1.51±0.29 a	0.89±0.22 a
平均	Average	34.67±5.27	51.11±7.65	30.32±5.14	2.48±0.38	1.49±0.22	0.69±0.12
F 值	D	44.11 ^{**}	0.23	2.53	45.47 ^{**}	0.25	2.56
	N	57.92 ^{**}	1.54	17.89 ^{**}	57.74 ^{**}	0.20	17.76 ^{**}
F value	D×N	1.42	0.03	0.41	1.42	0.03	0.42

TS, Tillering stage; JS, Jointing stage; FHS, Full heading stage; MS, Maturity stage. The same as below.

表 4 缓释氮肥减量配施和株距对机插稻齐穗期各器官群体氮素积累量及其分配的影响
Table 4. Effects of reduced slow-released urea combined with conventional urea on N accumulation amount and its distribution to different organs at full heading stage in mechanically-transplanted rice under different plant spacing.

		茎鞘 Stem-sheath		叶片 Leaf		穗 Panicle	
处理 Treatment		氮积累量 N accumulation /(kg hm ⁻²)	比例 Ratio to total /%	氮积累量 N accumulation /(kg hm ⁻²)	比例 Ratio to total /%	氮积累量 N accumulation /(kg hm ⁻²)	比例 Ratio to total /%
D ₁	N ₀	20.19±0.09 e	24.95±0.52 b	43.65±3.69 c	53.81±2.50 a	17.20±0.18 d	21.24±0.61 a
	N ₁	28.91±2.31 d	26.13±0.53 ab	58.21±3.02 b	52.67±1.79 abc	23.45±1.65 c	21.20±0.54 ab
	N ₂	32.61±1.91 c	27.23±0.43 a	62.19±4.75 b	51.90±1.31 ac	24.95±0.93 c	20.86±0.93 abc
	N ₃	38.22±2.23 b	26.52±0.63 a	77.20±7.21 a	53.49±2.60 ab	28.80±4.59 b	19.99±2.93 ac
	N ₄	40.40±2.23 a	26.31±1.33 a	81.96±6.37 a	53.22±2.54 abc	31.50±1.37 a	20.47±0.52 abc
平均	Average	32.06±1.95	26.23±0.69	64.64±5.01	53.02±2.15	25.18±1.74	20.75±1.11
D ₂	N ₀	21.24±1.07 d	25.14±0.93 bd	44.91±2.24 d	53.16±1.41 a	18.34±1.09 d	21.70±0.60 a
	N ₁	30.78±2.28 c	27.43±1.40 a	57.42±0.74 c	51.24±1.04 b	23.90±0.79 c	21.33±0.76 a
	N ₂	34.68±1.23 b	26.54±0.41 ab	68.93±1.62 b	52.73±0.99 ab	27.10±1.58 b	20.72±0.96 a
	N ₃	42.77±2.06 a	26.38±0.84 abc	87.88±7.68 a	54.12±1.43 a	31.55±1.03 a	19.50±1.17 b
	N ₄	40.30±3.27 a	26.45±2.30 abc	82.49±3.42 a	54.20±1.36 a	29.54±3.55 ab	19.35±1.21 b
平均	Average	33.95±1.98	26.39±1.18	68.33±3.14	53.09±1.24	26.09±1.61	20.52±0.94
D ₃	N ₀	20.69±1.03 d	28.47±0.74 b	37.19±5.62 d	50.72±2.06 a	15.25±2.10 d	20.82±0.57 a
	N ₁	27.85±0.92 c	28.05±0.44 b	51.01±3.60 c	51.30±1.34 a	20.50±0.79 c	20.65±0.80 a
	N ₂	32.44±1.40 b	29.68±1.86 ab	54.61±4.33 c	49.80±1.92 a	22.50±1.60 bc	20.52±0.67 a
	N ₃	37.88±1.14 a	30.32±2.01 a	62.71±5.30 b	49.99±1.61 a	24.76±3.60 ab	19.69±1.69 a
	N ₄	40.33±2.65 a	28.58±1.13 ab	73.04±2.07 a	51.81±0.16 a	27.62±0.51 a	19.61±0.93 a
平均	Average	31.84±1.43	29.02±1.24	55.71±4.18	50.72±1.42	22.12±1.72	20.26±0.93
F 值	D	1.61	5.55	14.65*	4.23	7.96*	1.50
	N	263.55**	2.55	117.14**	1.52	71.18**	3.30*
F value	D×N	1.59	0.96	2.58*	0.87	1.18	0.25

表 5 缓释氮肥减量配施和株距对机插稻成熟期各器官群体氮素积累量及其分配的影响
Table 5. Effects of reduced slow-released urea combined with conventional urea on N accumulation amount and its distribution to different organs at maturity in mechanically-transplanted rice under different plant spacing.

		茎鞘 Stem-sheath		叶片 Leaf		穗 Panicle	
处理 Treatment		氮积累量 N accumulation /(kg hm ⁻²)	比例 Ratio to total /%	氮积累量 N accumulation /(kg hm ⁻²)	比例 Ratio to total /%	氮积累量 N accumulation /(kg hm ⁻²)	比例 Ratio to total /%
D ₁	N ₀	13.64±0.56 d	13.64±0.52 b	11.19±0.68 e	11.20±0.59 c	75.12±1.14 e	75.16±0.19 a
	N ₁	21.67±0.95 c	15.70±0.53 a	21.46±0.66 d	15.55±0.33 b	94.95±4.00 d	68.75±0.40 b
	N ₂	24.58±0.57 b	16.40±0.43 a	24.25±0.88 c	16.19±0.79 ab	101.06±2.76 c	67.42±0.95 c
	N ₃	27.82±1.03 a	15.41±0.63 a	28.21±2.57 b	15.61±1.29 b	124.60±2.06 b	68.99±1.41 b
	N ₄	29.62±2.82 a	15.27±1.33 a	32.74±0.31 a	16.89±0.36 a	131.58±2.34 a	67.85±1.08 bc
平均	Average	23.47±1.19	15.28±0.69	23.57±1.02	15.09±0.67	105.46±2.46	69.63±1.50
D ₂	N ₀	14.18±1.48 d	13.53±0.93 b	11.60±1.22 e	11.07±0.69 c	78.86±1.85 e	75.40±1.97 a
	N ₁	21.86±2.91 c	14.97±1.40 a	21.56±1.59 d	14.80±0.85 b	102.26±2.78 d	70.23±0.81 b
	N ₂	24.75±1.12 b	14.51±0.41 ab	25.75±1.32 c	15.09±0.51 b	120.09±0.86 c	70.40±1.40 b
	N ₃	30.63±2.32 a	15.00±0.84 a	34.18±1.85 a	16.75±0.56 a	139.14±2.88 a	68.24±2.90 c
	N ₄	28.98±4.05 a	15.09±2.30 a	30.51±0.77 b	15.87±0.62 ab	132.84±7.79 b	69.05±1.52 bc
平均	Average	24.08±2.38	14.62±1.18	24.72±1.35	14.72±0.65	114.64±3.23	70.66±1.61
D ₃	N ₀	12.67±1.00 c	14.01±0.74 a	10.03±0.59 e	11.11±0.85 b	67.76±4.96 e	74.88±0.95 a
	N ₁	19.41±0.59 b	15.20±0.44 a	19.17±1.59 d	15.01±1.20 a	89.16±1.90 d	69.79±1.65 b
	N ₂	20.95±2.44 b	15.07±1.86 a	21.71±2.52 c	15.57±1.14 a	96.55±4.86 c	69.36±2.36 b
	N ₃	24.34±2.52 a	15.04±2.01 a	25.24±1.58 b	15.54±0.56 a	112.79±7.30 b	69.42±0.00 b
	N ₄	26.43±2.81 a	14.65±1.13 a	28.93±3.92 a	16.02±1.54 a	124.77±1.48 a	69.33±0.00 b
平均	Average	20.76±1.87	14.80±1.24	21.02±2.04	14.65±1.06	98.21±4.10	70.56±0.00
F 值	D	4.28	0.47	22.76**	0.78	29.08**	0.78
	N	97.05**	3.80*	167.77**	56.17**	416.61**	37.45**
F value	D×N	0.95	0.50	2.93*	1.00	5.67**	0.96

表 6 缓释氮肥减量配施和株距对机插稻齐穗至成熟期氮素转运的影响
Table 6. Effects of reduced slow-released urea combined with conventional urea on N translocation in stem-sheath and leaf from full-heading to maturity stage in mechanically-transplanted rice under different plant spacing.

处理 Treatment		茎鞘 Stem-sheath		叶片 Leaf		地上部分 Above-ground		穗部氮素增加量 N increased in panicle/(kg hm ⁻²)
		氮素转运量 NT/(kg hm ⁻²)	氮素转运率 NTE/%	氮素转运量 NT/(kg hm ⁻²)	氮素转运率 NTE/%	氮素转运量 NT/(kg hm ⁻²)	氮素转运率 NTE/%	
D ₁	N ₀	6.55±0.97 b	32.36±3.33 a	32.46±3.60 c	74.26±2.34 a	39.01±3.30 c	61.03±2.34 a	57.92±1.25 d
	N ₁	7.23±1.75 b	24.83±4.14 b	36.75±2.49 bc	63.09±1.18 b	43.98±3.74 bc	50.43±1.98 b	71.50±2.38 c
	N ₂	8.03±1.63 b	24.49±3.72 b	37.95±5.56 b	60.80±4.31 b	45.98±7.16 b	48.31±4.28 b	76.11±2.64 b
	N ₃	10.40±2.72 a	27.00±5.64 ab	48.99±9.58 a	63.06±6.76 b	59.39±12.25 a	51.10±6.53 b	95.80±6.12 a
	N ₄	10.78±3.45 a	26.56±7.68 ab	49.22±6.46 a	59.87±3.40 b	60.00±3.99 a	49.01±2.08 b	100.08±3.38 a
平均 Average		8.60±2.10	27.05±4.90	41.07±5.54	64.22±3.60	49.67±6.09	51.97±3.44	80.28±3.15
D ₂	N ₀	7.06±0.57 c	33.35±3.90 a	33.30±3.05 c	74.08±3.57 a	40.36±3.55 c	60.99±4.10 a	60.53±1.87 d
	N ₁	8.92±2.11 b	29.03±6.74 a	35.87±1.14 c	62.47±2.43 b	44.78±3.24 c	50.81±3.97 b	78.36±2.55 c
	N ₂	9.92±0.90 ab	28.61±2.25 a	43.18±2.94 b	62.60±2.76 b	53.11±2.74 b	51.25±2.44 b	92.99±1.97 b
	N ₃	12.14±1.87 a	28.40±4.23 a	53.70±6.34 a	61.02±2.10 b	65.85±7.27 a	50.34±2.50 b	107.58±3.48 a
	N ₄	11.32±2.02 ab	28.24±5.50 a	51.99±3.19 a	62.98±1.42 b	63.31±4.92 a	51.56±2.97 b	103.29±7.66 a
平均 Average		9.87±1.49	29.53±4.53	43.61±3.33	64.63±2.45	53.48±4.34	52.99±3.20	88.55±3.51
D ₃	N ₀	8.02±0.79 b	38.78±3.39 a	27.16±5.30 ce	72.74±3.29 a	35.18±4.75 d	60.67±1.98 a	52.51±3.46 e
	N ₁	8.43±1.38 b	30.20±4.11 b	31.83±4.47 bcd	62.22±4.96 b	40.26±5.67 c	50.91±4.75 b	68.65±1.20 d
	N ₂	11.48±2.52 a	35.37±7.23 ab	32.90±1.99 bc	60.30±1.71 b	44.38±1.94 bc	51.00±2.13 b	74.05±3.36 c
	N ₃	13.54±2.01 a	35.79±5.73 ab	37.48±3.90 ab	59.69±1.55 b	51.01±5.01 ab	50.64±2.82 b	88.03±4.83 b
	N ₄	13.89±3.15 a	34.35±7.07 ab	44.11±5.32 a	60.31±6.13 b	58.00±8.45 a	51.08±6.37 b	97.16±1.11 a
平均 Average		11.07±1.97	34.90±5.51	34.70±4.20	63.05±3.53	45.77±5.16	52.86±3.61	76.08±2.79
F 值	D	2.49	5.09	7.45*	0.57	2.67	0.16	22.41**
	N	11.85**	2.29	24.67**	21.07**	31.73**	16.30**	246.56**
F value		D×N	0.39	0.25	0.89	0.64	0.2	3.54**

NT, Nitrogen translocation; NTE, Nitrogen translocation efficiency.

素积累量各缓释氮肥配施处理间差异显著;株距为D₂时,则随缓释氮肥与常规氮肥配施量的增加先增加后减小,在N₃时最大,且叶片、穗氮素积累量在N₃与N₄时差异显著;在3种株距下,各缓释氮肥配施处理间茎鞘氮素积累量比例差异不显著,穗氮素积累比例在N₀时最大。

2.6 缓释氮肥减量配施和株距对机插稻齐穗至成熟期氮素转运的影响

如表6所示,除茎鞘氮素转运率外,缓释氮肥配施量对齐穗至成熟期氮素转运特征的影响均达极显著水平。茎鞘氮素转运量及转运率随株距的增加而增大,叶片氮素转运量及转运率、地上部分氮素转运量和穗部氮素增加量均随株距的增大呈先增加后减小的趋势。株距为D₁和D₃时,氮素转运量和穗部氮素增加量随缓释氮肥与常规氮肥配施量的增加而增大,且氮素转运量整体在N₃与N₄时未达显著水平;株距为D₂时,则在N₃最大。在3种株距下,叶片及地上部分氮素转运率均在N₀时最佳,且各缓释氮肥配施处理间未达显著水平。

2.7 缓释氮肥减量配施和株距对机插稻氮素利用率的影响

除株距对氮素干物质生产效率和氮肥表观利用率的影响未达显著水平外,缓释氮肥减量配施和株距及其互作效应对机插稻氮素利用率的影响均达显著或极显著水平(表7)。氮肥偏生产力、农学利用率及表观利用率均在D₂时表现最佳,且氮肥偏生产力、农学利用率及表观利用率D₂较D₁和D₃分别增加了9.82%和12.37%、38.71%和47.29%及13.39%和19.80%,氮素干物质生产效率随株距的增加先减小后增大,且D₃显著高于D₁,而氮素稻谷生产效率与株距正相关。除株距在D₂时氮素干物质生产效率及稻谷生产效率外,3种株距下氮素干物质生产效率、稻谷生产效率及氮肥偏生产力均随缓释氮肥与常规氮肥配施量的增加而减小;株距为D₁和D₂时,氮肥农学利用率和氮肥表观利用率均在N₃表现最佳;当株距增加到D₃时,氮肥农学利用率随缓释氮肥与常规氮肥配施量的增加而增加,氮肥表观利用率表现为N₄>N₃>N₁>N₂。

表 7 缓释氮肥减量配施和株距对机插稻氮肥利用率的影响
Table 7. Effects of reduced slow-released urea combined with conventional urea on N use efficiency in mechanically-transplanted rice under different plant spacing.

处理 Treatment		氮素干物质生产效率 NMPE/(kg kg ⁻¹)	氮素稻谷生产效率 NGPE/(kg kg ⁻¹)	氮肥偏生产力 NPP/(kg kg ⁻¹)	氮肥农学利用率 NAE/(kg kg ⁻¹)	氮肥表观利用率 NAUE/%
D ₁	N ₀	125.00±1.40 a	81.46±0.86 a			
	N ₁	115.37±1.09 b	65.86±1.32 b	100.99±1.75 a	10.54±1.11 b	42.37±3.82 b
	N ₂	109.85±1.40 c	62.57±0.61 c	78.15±1.00 b	10.30±0.65 b	41.61±2.04 b
	N ₃	98.02±1.26 d	55.38±0.37 d	66.69±0.39 c	12.41±0.75 a	53.78±2.19 a
	N ₄	94.21±1.67 e	51.86±0.73 e	55.88±0.10 d	10.65±0.24 b	52.22±1.16 a
	平均 Average	108.49±1.36	63.43±0.78	75.43±0.81	10.98±0.69	47.50±2.30
D ₂	N ₀	123.41±1.67 a	81.70±3.39 a			
	N ₁	112.42±1.98 b	66.64±2.68 b	107.76±0.38 a	12.86±0.69 d	45.59±10.42 c
	N ₂	101.03±2.46 c	59.73±1.36 c	84.89±0.35 b	13.72±0.55 c	54.96±6.16 b
	N ₃	96.34±2.62 d	56.24±1.48 d	76.43±0.33 c	19.49±0.54 a	66.19±6.32 a
	N ₄	99.13±0.84 c	58.31±1.21 cd	62.28±0.41 d	14.83±0.44 b	48.71±3.92 c
	平均 Average	106.47±1.91	64.52±2.02	82.84±0.37	15.23±0.55	53.86±6.70
D ₃	N ₀	133.84±6.65 a	88.73±5.41 a			
	N ₁	115.63±1.97 b	65.97±0.18 b	93.64±0.48 a	4.69±0.57 d	41.44±7.06 bc
	N ₂	112.60±3.12 b	64.77±3.15 bc	75.02±0.40 b	8.30±0.44 c	40.64±4.35 c
	N ₃	103.09±2.72 c	61.60±2.94 cd	66.59±0.45 c	13.22±0.53 b	47.94±1.09 ab
	N ₄	97.22±2.37 d	59.65±2.66 d	59.62±0.34 d	15.15±0.28 a	49.83±6.75 a
	平均 Average	112.48±3.37	68.14±2.87	73.72±0.42	10.34±0.45	44.96±4.81
F 值 F value	D	6.70	21.32**	316.56**	152.27**	5.98
	N	310.00**	196.25**	7060.91**	178.61**	18.04**
D×N		7.23**	2.91*	59.17**	54.70**	4.73*

NMPE—氮素干物质生产效率；NGPE—氮素稻谷生产效率；NPP—氮肥偏生产力；NAE—氮肥农学利用率；NAUE—氮肥表观利用率。

NMPE, N dry matter production efficiency; NGPE, N grain production efficiency; NPP, Partial factor productivity of applied N; NAE, N agronomy efficiency; NAUE, N apparent use efficiency.

2.8 缓释氮肥减量配施和株距下主要生育阶段氮素积累、转运与氮素利用及产量的关系

本研究条件下氮素积累量及利用率与主要生育阶段氮素积累量及转运量的关系来看(表8),缓释氮肥减量配施和株距处理下机插杂交稻主要生育阶段氮素积累量、结实期茎鞘及叶片氮素转运量与稻谷产量、氮素积累总量及结实期穗部氮素增加量存在显著或极显著的正相关($r=0.35^*\sim 0.94^{**}$)。除拔节至齐穗期氮素积累量与氮肥农学利用率及齐穗至成熟期茎鞘氮素转运量与氮肥表观利用率正相关性未达显著外,主要生育阶段的氮素积累及转运量与氮肥农学利用率及表观利用率均呈显著或极显著正相关性。

3 讨论

氮肥管理和栽插密度是栽培技术的核心因素。氮素是影响水稻生长发育和产量形成的重要因子,近年来为了提高水稻产量,氮肥施用量大幅增加,

从而导致氮肥利用率低、农业生产成本高及环境污染等一系列问题^[17-19]。栽插方式、栽培密度、氮肥运筹、氮肥种类及品种本身特性等都与水稻氮肥利用率的提高密切相关,大量研究^[13,20-24]表明适当增加栽插密度及减少氮肥施用量,可有效提高水稻产量和氮肥利用率。兰艳等^[20]研究发现,在保证水稻高产稳产的前提下,适度增加栽插密度,可提高水稻植株体内氮素积累量,减少氮素损失,进而提高氮肥利用率;徐新朋等^[22]研究表明,适宜的栽插密度下施氮增加了水稻氮素累积,但过量的氮肥促使水稻营养生长,贪青晚熟,过多的氮素在茎鞘叶片中累积,无法转移到籽粒中去,产量反而降低。本研究从机插密度和缓释氮肥减量配施耦合来看,中密度(18 cm)下,缓释氮肥(96 kg/hm²)与常规氮肥(54 kg/hm²)配施量为 150 kg/hm² 可有效提高机插杂交稻主要生育时期及生育阶段氮素含量和积累总量、齐穗期及成熟期茎鞘叶片氮素吸收转运量、氮肥农学利用率及氮肥吸收利用率,最终获得高产,这与前人研究结果基本一致。但以往的氮效率研究主要

表 8 缓释氮肥减量配施和株距下氮素积累利用及产量与主要生育阶段氮素积累与转运的相关性

Table 8. Coefficients of correlation between N accumulation and translocation during main growth stages with grain yield and N accumulation or utilization in different plant spacing and reduced slow-released urea combined with conventional urea.

指标 Index	生育时期 Growth stage	植物部位 Plant part	稻谷产量 Grain yield	氮素积累总量 Total N accumulation	穗部氮素增加量 N increase in panicle	氮肥农学利用率 N agronomy efficiency	氮肥表观利用率 N apparent use efficiency
氮素积累量 N accumulation	分蘖盛期-拔节期	整株	0.89**	0.94**	0.93**	0.66**	0.65**
	TS-JS	Whole plant					
	拔节-齐穗期	整株	0.35*	0.39*	0.36*	0.26	0.34*
	JS-FHS	Whole plant					
	齐穗-成熟期	整株	0.79**	0.84**	0.85**	0.54**	0.62**
氮素转运量 N translocation	FHS-MS	Whole plant					
	齐穗-成熟期	茎	0.61**	0.58**	0.64**	0.42**	0.23
	FHS-MS	Stem-sheathe					
	齐穗-成熟期	叶片	0.82**	0.84**	0.85**	0.64**	0.59**
	FHS-MS	Leaf					

集中于机插密度和常规氮肥^[25]互作、缓控释尿素与其他肥料配施^[15,26-27]及缓控释氮肥种类^[28-29]的研究,并未涉及密度和缓释氮肥与常规氮肥配施的互作效应对氮效率的研究。本研究表明,缓释氮肥减量配施和株距及其互作效应对机插杂交籼稻产量、成熟期叶片氮素吸收转运量、穗部氮素增加量及氮肥农学利用率的影响均达极显著水平,且缓释氮肥减量配施对产量、成熟期叶片氮素积累、转运及氮肥利用率的影响显著高于株距。在行距为 30 cm,株距为 16 cm 时,随着缓释氮肥与常规氮肥配施量的增加穗部氮素积累量、产量及氮肥利用率呈增加的趋势,从此研究已发表的试验数据^[30]来看,主要原因是在较高的机插密度下随着缓释氮肥与常规氮肥配施量的增加,群体茎蘖数增大,形成的有效穗多,光合特性及对养分吸收的竞争性增强,未能形成足够的大穗导致穗粒数减少,虽增加了生物量和植株氮含量,提高了氮素的积累量,但过大的机插密度导致群体荫蔽,水稻植株体内氮素滞留量增加,贪青晚熟,不利于茎鞘和叶中的营养物质及氮素向穗部转运,减少了氮素损失,提高了氮素利用率,而与前人研究结果不同的是氮素收获指数明显降低,主要原因是施氮量达到一定水平后,虽然能促进水稻对氮素的吸收,却不利于茎鞘及叶片中的氮素向籽粒中转运,从节本增效的角度考虑,应适当减少缓释氮肥配施量,以缓释氮肥(96 kg/hm²)与常规氮肥(54 kg/hm²)配施量 150 kg/hm²为宜;在株距为 18 cm 下,随着缓释氮肥与常规氮肥配施量的增加各生育时期及生育阶段水稻氮素积累量增多,促进了氮肥的转运及吸收利用,但过高的缓释氮肥配施量并不能促进植株对氮素的吸收,造成氮素的

浪费,茎鞘叶片氮素吸收量少,成穗率低,结实期茎鞘及叶片转运率下降,穗部氮素增加量减少,并没有进一步提高氮素吸收利用率和产量;当机插株距增加到 20 cm 时,通风透光条件好,主要生育时期及生育阶段群体吸收氮素的绝对量少,随着缓释氮肥配施量的增加,水稻群体对氮素的吸收作用增强,植株功能叶感受光的面积增大,光合作用增强^[30],相应的功能叶光响应特征参数越优,越有利于茎鞘和叶片中的氮素向穗部转运,穗部氮素积累量增加,产量及氮素利用率随缓释氮肥与常规氮肥配施量增加显著增大。因此,株距较大时为了获得高产和提高氮素利用率应适当增加缓释氮肥与常规氮肥配施量,这进一步补充和完善了前人^[22,31]研究结果。此外,缓释氮肥减量与常规氮肥配施和机插密度耦合在水稻关键生育时期对于磷、钾及其他养分的协同吸收、转运及分配的影响,以及机插稻产量与各养分吸收利用的关系有待于进一步研究。

水稻氮素吸收、转运与产量、氮素积累及利用率关系的研究^[32-34]已有较多报道。一般认为产量高的水稻群体,成熟期的氮素积累量也高。孙永健等^[33]研究表明,相比茎鞘而言叶片的氮素转运量及转运率对产量及氮素利用率的贡献显著,且叶片氮素转运量、转运率与产量及氮素利用率呈正相关。也有研究认为氮肥运筹不同时,单位面积水稻产量与成熟期氮素积累量呈二次曲线关系。本研究分析了缓释氮肥减量配施和株距下氮素吸收、转运与产量及利用率的关系,结果表明,除拔节至齐穗期氮素积累量与氮肥农学利用率相关性不显著外,主要生育阶段氮素积累量与稻谷产量、氮素积累总量、穗部氮素增加量及氮肥利用率呈显著或极显著正相关,

这与前人研究结果^[35]拔节至抽穗期氮素积累量与产量相关性更高有所差异, 主要是因为在水稻生育前期营养生长过于旺盛, 影响拔节后植株对氮素的吸收, 养分的“源”储备不足, 在机插稻穗分化及灌浆成熟阶段未能有效输到籽粒“库”, 因此, 在水稻高产栽培管理中应适当控制生育前期氮素的吸收。此外本研究显示, 齐穗至成熟期茎鞘、叶片氮素转运量与稻谷产量、氮素积累总量、穗部氮素增加量及氮肥利用率整体上呈显著或极显著正相关, 且叶片相对于茎鞘氮素转运量对机插稻产量及氮素利用率的影响更为显著($r=0.59^{**}\sim 0.85^{**}$), 这可能是缓释氮肥减量配施和株距耦合改善了群体质量, 有效提高了水稻生育后期田间通风透光条件, 从而更有利于叶片中的氮素向籽粒转运, 最终提高了产量和氮素利用率。

4 结论

缓释氮肥减量配施和株距对机插杂交稻主要生育时期氮素积累总量, 结实期叶片、穗部氮素转运与分配以及氮素利用率和产量均存在显著或极显著的影响。本研究中, 株距18 cm, 缓释氮肥(96 kg/hm²)和常规氮肥(54 kg/hm²)配施量为150 kg/hm²为氮肥减量增效最佳的肥密运筹处理, 有利于机插杂交水稻主要生育时期氮素积累, 促进结实期茎鞘、叶片向穗部的氮素转运, 可显著提高稻谷产量和氮肥利用率, 是实现水稻产量和氮肥利用率同步提高的有效调控途径。机插杂交稻主要生育时期的氮素积累量及结实期氮素转运量与稻谷产量、氮素积累总量、穗部氮素增加量及氮肥利用率整体呈显著或极显著的正相关, 尤其以齐穗至成熟期茎鞘、叶片氮素积累量更有利于向籽粒中转运, 显著提高了氮肥农学利用率及稻谷产量, 因此, 缓释氮肥减量配施和株距耦合是进一步提高机插杂交水稻氮素利用率及产量的重要途径。

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