

林义月,李阳,汪本福,等.氮肥运筹对机直播水稻产量、品质及氮素利用率的影响[J].华中农业大学学报,2023,42(2):93-98.  
DOI:10.13300/j.cnki.hnlkxb.2023.02.012

## 氮肥运筹对机直播水稻产量、品质及氮素利用率的影响

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**摘要** 为研究不同的氮肥运筹处理对机直播水稻的产量、稻米品质以及氮肥利用率的影响,在机械直播条件下,以南粳9108和黄华占为材料,在大田总氮量210 kg/hm<sup>2</sup>的条件下,设置3种不同的氮肥运筹,基肥:分蘖肥:幼穗分化肥分别为N1(5:2:3)、N2(3:4:3)、N3(无:6:4),并以不施氮肥(N0)作为对照。结果显示,南粳9108和黄华占都在基肥:分蘖肥:幼穗分化肥为3:4:3时产量最高,分别为9 691.2、11 596.1 kg/hm<sup>2</sup>,与其他处理差异显著;稻米的糙米率、精米率、整精米率在处理间差异不显著,但直链淀粉、蛋白质含量随着穗肥比例的增加而升高,表现为N3>N2>N1,垩白率、垩白度随穗肥比例的增加而降低,表现为N1>N2>N3。水稻各个生育时期在3:4:3的处理下,氮素吸收显著高于其他处理并且氮素农学利用率、氮肥利用率表现为N2>N3>N1。研究结果表明,在施氮量相同的情况下,氮肥运筹N2(3:4:3)可显著提高水稻产量和氮素利用率,而N3(无:6:4)处理显著提高稻米营养品质和外观品质。

**关键词** 直播稻;机直播;氮肥运筹;产量;稻米品质;氮素利用率

**中图分类号** S511.506.2    **文献标识码** A    **文章编号** 1000-2421(2023)02-0093-06

直播稻是一种重要的水稻栽培模式,可以有效降低育秧成本;同时,随着农村劳动力逐渐减少,直播稻作为轻简栽培技术可以显著提高劳动生产效率,越来越受关注。然而,在实际生产中农户习惯照搬传统移栽水稻的施肥方式用于直播水稻生产中,很少根据直播稻的需肥特点施肥,这往往造成肥料浪费、产量较低以及环境污染。

氮肥施用量及施用方式均会影响直播水稻的有效穗数、每穗实粒数<sup>[1-2]</sup>。林忠成等<sup>[3]</sup>研究认为当基蘖肥比例较高时,水稻的群体碳氮代谢比较协调,能有效提高产量和氮肥利用率。而赵峰等<sup>[4]</sup>认为直播稻从萌发到出苗需要一段时间,需肥量较少,如果采取移栽稻的施肥方式可能造成前期肥料过多流失,从而导致后期肥料供应不足。许炜等<sup>[5]</sup>指出氮肥后移和注重追肥可以有效提高直播稻的产量。氮素后移,也可能影响灌浆结实和稻米品质的形成。陈梦云等<sup>[6]</sup>研究表明,在水稻生长过程中提高幼穗肥的施用比例可以提高精米率、整精米率,能显著改善稻米的碾磨和营养品质,但可能会降低稻米的外观及蒸

煮食味品质。随着机械化进程的加速,水稻机械直播成为水稻生产的重要发展方向,相比传统人工撒播,机械直播可以建立更为合理的群体。目前关于机械直播水稻条件下氮肥高效运筹规律的研究还比较少,本研究在总氮210 kg/hm<sup>2</sup>的条件下,探讨不同的氮肥运筹处理对机直播水稻南粳9108和黄华占的产量、稻米品质以及氮肥利用率的影响,旨在为机械直播水稻的高效氮肥管理提供理论依据。

## 1 材料与方法

### 1.1 试验材料与设计

本试验于2020—2021年在湖北省农业科学院粮食作物研究所核心试验区进行。土壤养分状况:硝态氮5.78 mg/kg,铵态氮2.45 mg/kg,速效磷141.1 mg/kg,速效钾153.4 mg/kg。

供试材料为南粳9108(梗稻)和黄华占(籼稻),设置3种氮肥运筹模式,即基肥:分蘖肥:幼穗分化肥=5:2:3模式(N1)、基肥:分蘖肥:幼穗分化肥=3:4:3模式(N2)、基肥:分蘖肥:幼穗分化肥=无:6:4

收稿日期:2022-08-20

基金项目:国家水稻产业技术体系(CARS-01-02A);湖北省重点研发计划项目(2021BBA229)

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模式(N3)以及不施氮肥模式(N0)。试验采取直播机播种,播种量4.0 kg/667 m<sup>2</sup>,播种规格25 cm×14 cm。肥料分别采用尿素、过磷酸钙和氯化钾,N 210 kg/hm<sup>2</sup>,P<sub>2</sub>O<sub>5</sub> 90 kg/hm<sup>2</sup>,K<sub>2</sub>O 150 kg/hm<sup>2</sup>。钾肥以基肥:分蘖肥:幼穗分化肥=4:3:3比例施用,磷肥在施基肥时一次性施入。试验小区间筑埂并用塑料薄膜保护单排单灌,防止肥水互串。2 a试验设计相同,病虫草害的管理方式按照当地常规栽培措施进行。

## 1.2 测定指标与方法

1)产量和产量构成。成熟期取样,每小区选有代表性的1 m<sup>2</sup>稻株调查有效穗数、每穗粒数、结实率、千粒重等产量构成因子,同时每小区收割3 m<sup>2</sup>进行测产。

2)稻米品质测定。稻谷收割后晾干存放,将待测样品于干燥通风处存放、晾干1周。参照中华人民共和国国家标准GB/T 17891—1999《优质稻谷》测定精米率、整精米率、垩白率、垩白度、蛋白质、直链淀粉含量。并采用RVA Super 3型淀粉黏滞快速分析仪测定稻米的RVA谱。

3)氮含量及氮素利用效率测定。在拔节期、齐穗期、成熟期取样,105 ℃杀青1 h后80 ℃烘干至恒质量。将烘干后的植物器官粉碎,采用浓H<sub>2</sub>SO<sub>4</sub>碳化,H<sub>2</sub>O<sub>2</sub>高温消煮,并用SmartChem4.0全自动化学分析仪测定样品含氮量。

氮素总积累量(total nitrogen accumulation, TNA)=稻谷产量×稻谷含氮量+稻草产量×稻草含氮量;氮肥偏生产力(partial factor productivity of applied N, PFP)=施氮区产量/氮肥施用量;氮素收获指数(nitrogen harvest index, NHI)=植株成熟期籽粒含氮量/氮素总积累量×100%;氮肥农学利用率(N agronomic efficiency, NAE)=(施氮区产

量-无氮区产量)/施氮量;氮肥利用率(N recovery efficiency, NRE)=(施氮区籽粒氮素含氮量-不施氮区籽粒氮素含氮量)/施氮量×100%。

### 1.3 数据统计方法

本试验采用Excel软件、DPS数据处理系统等软件进行数据处理和分析,采用最小显著法(LSD法)分析试验数据的差异显著性。

## 2 结果与分析

### 2.1 氮肥运筹对机直播水稻产量及其构成因素的影响

由表1可知,在相同施氮量的条件下不同的肥料运筹对南粳9108和黄华占水稻品种的产量影响显著。南粳9108 N2的处理2 a产量平均为9 691.2 kg/hm<sup>2</sup>,比N3处理高656.4 kg/hm<sup>2</sup>,比N1处理高939.6 kg/hm<sup>2</sup>;2 a黄华占的产量平均为11 596.1 kg/hm<sup>2</sup>,均是N2处理最高,较N3和N1处理分别增产1 537.9 kg/hm<sup>2</sup>和1 549.0 kg/hm<sup>2</sup>。南粳9108品种在N3处理和N1处理间产量差异不显著,而黄华占在N3处理产量显著高于N1处理。

穗粒数和有效穗数是影响产量的主要因素,其中南粳9108在N2处理下每穗粒数最多(106.50),分别比N3(102.37)和N1(96.05)提高了4.03%、10.87%;在N2处理下黄华占每穗粒数均值(136.60)比N3(121.66)、N1(114.53)分别提高了12.28%、19.27%。在N2处理下南粳9108有效穗数均值最大(261.67),分别比N3(257.79)和N1(247.17)提高了1.51%、5.87%;在N2处理下黄华占平均有效穗数(263.33)比N3(200.00)和N1(216.00)分别提高了31.67%、21.91%。南粳9108和黄华占在结实率和千粒重方面没有显著差异。

表1 氮肥运筹对机直播水稻产量及其构成因素的影响

Table 1 Effects of nitrogen fertilizer management on the yield and constituent factors of mechanized rice

Varieties	Treatments	穗粒数 Spikelets per panicle	结实率/% Filled grain percent	千粒重/g 1 000 grain weight	有效穗数/(×10 <sup>4</sup> /hm <sup>2</sup> ) Effective panicle	产量/(kg/hm <sup>2</sup> ) Yield
南粳9108 Nanjing9108	N3	102.37b	91.85ab	23.53ab	257.79ab	9 034.8b
	N2	106.50a	91.89a	23.74a	261.67a	9 691.2a
	N1	96.05b	90.48b	23.13ab	247.17b	8 751.6b
	N0	87.78c	85.15c	22.94b	184.00c	6 347.1c
黄华占 Huanghuazhan	N3	121.66b	79.90a	26.92a	200.00b	10 058.2b
	N2	136.60a	83.35a	27.12a	263.33a	11 596.1a
	N1	114.53b	78.52a	26.53a	216.00b	10 047.0b
	N0	113.34b	73.28b	26.30a	175.89c	7 715.4c

注:同列数据后不同字母表示处理间在5%水平差异显著,下同。Note: The different letters after the same column of data indicate a significant level of 5% difference between treatments, the same as below.

## 2.2 氮肥运筹对机直播水稻稻米品质的影响

由表2可知,2021年(2020年稻米品质分析材料遗失)3个氮素运筹处理间南梗9108和黄华占的糙米率、精米率、整精米没有显著差异,南梗9108在N2处理下糙米率最高(81.33%);黄华占在N1处理下糙米率最高(78.55%);南梗9108在N3处理下直链淀粉含量比N2、N1分别显著增加了4.96%、5.87%;黄华占在N3处理下直链淀粉比N2、N1分别增加了

4.31%、5.07%;南梗9108的N3处理蛋白质含量比N2、N1分别提高了3.48%、3.35%,黄华占N3处理蛋白质含量比N2、N1分别提高了3.19%、2.70%。不同氮肥处理对南梗9108和黄华占的垩白粒率和垩白度有显著影响,均表现为N1>N2>N3,其中南梗9108的N1处理垩白粒率比N2、N3分别提高了68.68%、26.33%;黄华占N1的垩白粒率比N2、N3分别提高了21.56%、43.91%。

表2 氮肥运筹对2021年机直播水稻稻米品质的影响

Table 2 Effects of nitrogen application on rice quality of mechanical direct seeding rice in 2021 %

Varieties	Treatments	糙米率 Brown rice rate	整精米率 Head rice rate	精米率 White rice rate	直链淀粉含量 Amylose content	蛋白质含量 Protein content	垩白粒率 Chalk white rate	垩白度 Chalk white degree
南梗9108 Nanjing 9108	N3	80.00a	59.37a	63.54a	11.00a	8.02a	9.72b	18.02b
	N2	81.33a	62.65a	65.35a	10.48b	7.75b	7.28b	19.14b
	N1	80.67a	57.16a	65.12a	10.39b	7.76ab	12.28a	25.60a
	N0	78.28a	41.14b	62.71b	10.93b	7.42b	9.83b	19.68b
黄华占 Huanghuazhan	N3	78.07a	60.42a	63.12a	14.50a	8.73a	9.95b	2.40b
	N2	77.65a	62.65a	64.13a	13.90ab	8.46b	11.78b	2.71b
	N1	78.55a	59.37a	63.61a	13.80b	8.50b	14.32a	3.69a
	N0	76.26a	54.59a	60.97a	14.51a	8.24c	19.35a	4.72a

注:因2020年稻米品质分析材料遗失,仅有2021年数据,下同。Note: In 2020 materials for analyzing rice quality were lost, only 2021 data were shown, the same in Table 3.

## 2.3 氮肥运筹对机直播水稻RVA谱特征值的影响

3种氮肥运筹方式对水稻RVA谱特征值的影响见表3,N0处理下,南梗9108和黄华占的峰值黏度、热浆黏度、崩解值和最终黏度均表现最高,南梗9108在N3处理下稻米的峰值黏度、热浆黏度、崩解值和最终黏度均表现最高,且显著高于N2和N1处理;消

减值在N2处理下表现最高;峰值时间在各处理间显著不差异。黄华占在N2处理下峰值黏度、热浆黏度、崩解值和最终黏度最大;消减值在N1处理下最高;峰值时间在各处理间不存在明显变化。2个水稻品种的糊化温度均在N1处理下较高,南梗9108达到77.1℃,而黄华占则达到86.1℃,且与N3、N1存在显著差异。

表3 氮肥运筹对2021年机直播水稻RVA谱特征值的影响

Table 3 Eigenvalues of RVA spectrum of machine-based live broadcast rice in 2021

Varieties	Treatments	峰值黏度/ (mPa·s) Peak viscosity	热浆黏度/ (mPa·s) Hot viscosity	崩解值/ (mPa·s) Break down	最终黏度/ (mPa·s) Final viscosity	消减值/ (mPa·s) Set back	峰值时间/ min Peak time	糊化温度/℃ Pasting temperature
南梗9108 Nanjing 9108	N3	3 043b	1 830b	1 230a	2 428a	-624b	5.6a	76.3b
	N2	2 820c	1 651c	1 076b	2 156b	-528a	5.6a	76.3b
	N1	2 765c	1 744b	1 017b	2 244b	-543a	5.6a	77.1a
	N0	3 323a	2 056a	1 267a	2 685a	-638b	5.6a	76.2b
黄华占 Huanghuazhan	N3	3 270c	2 067c	1 050c	3 157b	-104b	6.1a	77.1c
	N2	3 313b	2 195b	1 191b	3 228b	-115c	6.1a	84.8b
	N1	3 223d	2 153b	1 069c	3 181b	-57a	6.1a	86.1a
	N0	3 694a	2 353a	1 316a	3 440a	-222d	6.1a	76.2c

## 2.4 氮肥运筹对机直播水稻氮素利用率的影响

由表4可知,在不同的氮肥运筹处理下南梗9108

水稻的氮肥偏生产力、氮素收获指数、氮素总积累量均是N2处理最高,分别为45.73 kg/kg、47.30%、

102.03 kg/hm<sup>2</sup>, 均显著高于N3和N1处理; 氮素农学利用率、氮肥利用率表现为N2>N3>N1, 且达到了显著水平。黄华占水稻的氮肥偏生产力、氮素收获指数、氮素总积累也是在N2处理最高, 2 a 平均值分

别为54.13 kg/kg、50.69%、151.99 kg/hm<sup>2</sup>, 达到显著水平, 其中氮素农学利用效率、氮素利用率也表现为N2>N3>N1。可见, 氮肥运筹中氮肥后移增加穗肥比例可以提高水稻的氮素利用率。

表4 氮肥运筹处理下机直播水稻吸收氮能力及利用效率

Table 4 Nitrogen uptake capacity and utilization efficiency of direct seeding rice under nitrogen fertilizer treatment

品种 Varieties	处理 Treatment	氮素总积累量/ (kg/hm <sup>2</sup> ) TNA	氮肥偏生产力/ (kg/kg) PFP	氮素收获指 数/% NHI	氮素农学利用效 率/% NAE	氮素利用率/% NUE
南梗9108 Nanjing 9108	N3	100.99a	43.35ab	45.86a	10.96b	11.77b
	N2	102.03a	45.73a	47.30a	14.14a	16.76a
	N1	93.99b	41.29b	45.32a	9.77b	9.98b
	N0	54.80c	32.24c	40.14b		
黄华占 Huanghuazhan	N3	134.86b	51.30ab	44.49b	14.56ab	12.89b
	N2	151.99a	54.13a	50.69a	17.39a	15.83a
	N1	136.87b	47.97b	47.63a	11.19b	12.63b
	N0	82.58c	36.74c	45.30a		

### 3 讨论

#### 3.1 氮肥运筹对机直播水稻产量的影响

研究表明, 合理施用氮肥可以显著增加水稻有效穗数和每穗粒数, 从而提高产量<sup>[7-8]</sup>。本试验结果表明, 机械直播南梗9108和黄华占在施氮量210 kg/hm<sup>2</sup>条件下, 南梗9108在N2处理下产量达到9 691.2 kg/hm<sup>2</sup>, 比N1处理产量增加了939.6 kg/hm<sup>2</sup>, 其他不同氮肥处理间也存在显著差异; 黄华占的产量在N2处理下达到11 596.1 kg/hm<sup>2</sup>, 比N1处理产量增加了1 549.1 kg/hm<sup>2</sup>。试验中南梗9108和黄华占每穗粒数均在N2处理下达到最大值, 与薛亚光等<sup>[9]</sup>研究结果一致。范立慧等<sup>[10]</sup>、石丽红等<sup>[11]</sup>的研究也表明, 适当减少基肥中氮肥的比例、增加穗肥的比例, 可使成穗率增加、每穗粒数增多, 从而影响产量。本研究结果表明, 水稻在氮肥运筹N2处理中的有效穗数、每穗粒数增多从而获得高产, 说明选择合理的氮肥施用比例可以有效增加水稻的穗数和每穗粒数从而保证产量。

#### 3.2 氮肥运筹对机直播水稻稻米品质的影响

周婵婵等<sup>[12]</sup>认为水稻的施氮时期及施氮比例都会对稻米的品质产生影响。王瑞琴等<sup>[13]</sup>研究指出, 氮肥后移对垩白度、垩白率的下降有显著效果。本试验中2个水稻品种在施氮总量相同时, 糜米率、精米率、整精米率在氮肥运筹处理下表现的差异不显著, 但垩白率、垩白度在氮肥运筹处理下存在显著差异, 垢白度和垩白率随着后期氮肥增加而降低的趋势在N3处理下表现最低, 表明氮肥后移能增加稻米的外观品质。氮肥可以提高籽粒中蛋白质的积累,

尤其在幼穗分化期施用氮肥更能起到显著的效果<sup>[14-15]</sup>。增加穗肥比例也会使直链淀粉和蛋白质含量显著提高<sup>[16]</sup>。稻米的蛋白质含量随着施氮量的增加而增加, 而食味品质则是有所下降<sup>[17]</sup>。本研究中直链淀粉、蛋白质在N3(无:6:4)时含量最高, 说明穗肥所占比例越高直链淀粉和蛋白质含量就越高, 和前人研究结果一致<sup>[18]</sup>。也有研究表明, 前氮后移不会对稻米的碾磨品质和外观品质产生消极影响, 也不会影响稻米的食味品质, 反而可以提高水稻的碾磨品质, 增加其营养品质<sup>[19]</sup>, 但是会降低稻米的垩白度、垩白率等外观品质, 降低稻米的胶稠度等味觉品质。RVA谱特性与蒸煮食味品质密切相关, 研究表明峰值黏度越高、崩解值越大、消减值较小且为负值的食味品质好, 米饭冷热适宜, 口感较佳<sup>[20]</sup>。万靓军等<sup>[21]</sup>研究发现穗肥过高或者过低都会影响RVA谱的变化, 会导致淀粉峰值黏度降低、崩解值减小、消减值变大。本试验中南梗9108在N3处理下稻米的峰值黏度、热浆黏度、崩解值和最终黏度均最高, 且显著高于N2和N1处理, 消减值在N2处理下表现最高, 峰值时间在各处理间没有显著差异。黄华占在N2处理下峰值黏度、热浆黏度、崩解值和最终黏度最高; 因此, 协调好氮肥在水稻各个时期的施用比例可以有效提高稻米品质。

#### 3.3 氮肥运筹对机直播水稻氮素利用率的影响

合理的分配氮肥比例能提高水稻吸氮量和氮素利用率<sup>[22]</sup>。本研究结果表明, 2个水稻品种的氮素总积累量、氮肥偏生产力、氮素收获指数、氮素农学利用率和氮素利用率均在N2(3:4:3)处理下达到最大

值,与贾维强等<sup>[23]</sup>的结果相一致。因此,基肥、分蘖肥与穗肥比例为3:4:3处理时可作为合理的氮肥运筹,能够有效提高水稻成熟期氮素积累量和氮肥利用率。

本研究中南粳9108和黄华占在施氮量210 kg/hm<sup>2</sup>条件下,不同的氮肥运筹处理对机直播水稻的产量、稻米品质、氮素吸收利用率有显著的影响。当基肥、分蘖肥与穗肥比例为3:4:3时产量最高,氮肥运筹为无:6:4的处理下稻米品质最优。综合考虑产量、稻米品质、氮肥利用率,合理高效的基肥、分蘖肥与穗肥比例为3:4:3,其次是无:6:4。因此,选择合适的氮肥运筹方式是水稻机械直播达到高产优质的关键。

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## Effects of nitrogen management on yield, quality and nitrogen use efficiency of rice with machine direct seeding

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**Abstract** Nanjing 9108 and Huanghuazhan were used as materials under machine direct seeding. Under total nitrogen 210 kg/hm<sup>2</sup> in the field, three different nitrogen fertilizer treatments including N1 (base fertilizer 5: tiller fertilizer 2: young spike fertilizer 3), N2 (3:4:3) and N3 (none:6:4) were set up, and no nitrogen fertilizer (N0) was used as the control to study the effects of different nitrogen management on the yield, quality and nitrogen fertilizer utilization efficiency of rice with machine direct seeding. The results showed that the yield of the two rice varieties was the highest when the fertilization ratio was 3:4:3. The average yield of Nanjing 9108 and Huanghuazhan was as high as 9 691.2 kg/hm<sup>2</sup> and 11 596.1 kg/hm<sup>2</sup>, significantly different from that of other treatments. The brown rice rate, milled rice rate and head rice rate of rice were not significantly different among treatments, but the content of amylose and protein increased with the increase of panicle fertilizer ratio in the decreasing order of N3 > N2 > N1. The chalkiness rate and chalkiness decreased with the increase of panicle fertilizer ratio in the decreasing order of N1 > N2 > N3. The rice quality of N3 (none:6:4) was significantly higher than that of other treatments. The nitrogen absorption of rice at stage of each growth under the treatment of 3:4:3 was significantly higher than that of other treatments. The nitrogen agronomic efficiency and nitrogen use efficiency were N2 > N3 > N1, reaching a significant level. It is indicated that, N2 (3:4:3) significantly affect the yield and nitrogen use efficiency of rice under the same nitrogen application rate, and N3 ( none:6:4 ) significantly affect the rice quality.

**Keywords** direct seeding rice; machine direct seeding; nitrogen fertilizer management; yield; rice quality; nitrogen use efficiency

(责任编辑:张志钰)