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不同结瘤特性花生品种氮素累积、产量及品质特性对氮肥用量的响应

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摘要: 氮肥减施是提升花生根瘤固氮能力与氮素利用效率的关键措施。花生品种间结瘤固氮特性迥异, 本研究旨在探讨不同结瘤性状花生品种氮素吸收利用的差异。于山东省 3 个试验基点(望城、任城、茌平)开展为期 2 年的大田试验, 设置 120 kg hm⁻² (N120)、60 kg hm⁻² (N60)和 0 kg hm⁻² (N0) 3 个梯度氮肥水平, 比较了普通结瘤品种(CNV)与不结瘤品种(NNV)在氮素累积、氮素利用效率、产量及品质方面对氮肥用量的响应差异。结果表明, 随氮肥投入递减, 不结瘤品种的植株不同部位氮含量、氮素累积量、产量及籽仁蛋白质含量均呈下降趋势; 与 N120 处理相比, N60 处理的整株氮素累积量、产量和籽仁蛋白质含量分别平均降低 18.98%、17.30%和 10.69%, N0 处理分别平均降低 25.13%、13.97%和 11.40%。相比之下, 普通结瘤品种的上述指标在不同氮肥处理下基本保持稳定。Pearson 相关分析显示, 不结瘤品种各器官氮累积量与其产量、籽仁蛋白质含量间均存在显著正相关; 而普通结瘤品种氮素累积量与此二者关联甚微。上述结果表明, 相较于普通结瘤品种, 不结瘤品种的产量、品质及氮素累积对氮肥的响应更为敏感。在花生生产中, 应适度削减氮肥投入, 充分发挥根瘤固氮潜能, 来提升根瘤固氮效率。

关键词: 氮肥; 不结瘤花生品种; 氮素累积; 产量; 籽仁品质

Response of nitrogen accumulation, yield, and quality characteristics of peanut varieties with different nodulation traits to nitrogen fertilizer application rate

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Abstract: Reducing nitrogen (N) application is an effective strategy for enhancing N use efficiency and promoting the N-fixing capacity of peanut root nodules. Given the considerable variation in nodulation traits among peanut cultivars, this study aimed to compare N absorption and utilization between common nodulating variety (CNV) and non-nodulating variety (NNV). A two-year field experiment was conducted across three locations in Shandong, China, to evaluate the responses of CNV and NNV to N fertilizer application rates of 120, 60, and 0 kg hm⁻², focusing on N accumulation, N use efficiency, yield, and quality. The results showed that reduced N fertilization significantly decreased N content, N accumulation, yield, and kernel protein content in NNV. Compared with the N120 treatment, the N60 treatment resulted in average reductions of 18.98% in whole-plant N accumulation, 17.30% in yield, and 10.69% in kernel protein content, while the N0 treatment caused average reductions of 25.13%, 13.97%, and 11.40%, respectively. In contrast, CNV maintained relatively stable N accumulation, yield, and kernel protein content across all N levels. Pearson correlation analysis revealed significant positive correlations between N accumulation in various plant organs and both yield and kernel protein content in NNV, whereas no such correlations were observed in CNV. These findings demonstrate that NNV is more sensitive to N fertilizer in terms of yield, quality, and N accumulation than CNV. Therefore, appropriately reducing N fertilizer input in peanut cultivation may enhance the utilization of biological N fixation by root nodules, thereby improving overall N use efficiency.

Keywords: nitrogen fertilizer; non-nodulated peanut variety; nitrogen accumulation; yield; kernel quality

花生(*Arachis hypogaea* L.)是全球旱区和半旱区重要的经济作物和油料作物,在 100 多个国家种植,全球种植面积达 3200 万公顷,总产 5400 万吨^[1]。中国是世界最大的花生生产国,2022 年播种面积 467.94 万公顷,总产量 1831 万吨,分别位居世界第二和第一^[2]。稳定花生生产对保障农民增收和促进社会贸易发展具有重要作用。

氮素作为花生生长发育所必需的核心营养元素,不仅是花生体内多种化合物(如蛋白质、核酸、叶绿素等)的关键组成成分,还深度参与植株的各类营养代谢过程,其供应状况与花生的生长发育进程、最终产量形成及品质特性密切相关^[3-5]。花生是需氮量较高的作物,通常生产 100 kg 花生荚果需要吸收 4.8~6.3 kg 氮素^[6]。花生属豆科作物,其氮素营养来源包括土壤氮、肥料氮以及根瘤固氮^[7-8],这三者并非孤立存在,而是处于一个动态平衡、相互竞争又相互补充的复杂关系中,共同决定了花生的氮素营养状况。品种^[9]、氮肥形态^[10]和用量^[8]均为影响 3 种氮源供氮量和供氮比例的重要因素,其中氮肥用量的影响程度最大。研究表明,在一定范围内,花生植株吸收肥料氮和土壤氮的绝对量和比例均随施氮量的增加而增加,而土壤中高矿质氮含量会显著抑制根瘤菌活性,导致根瘤固氮的绝对量和比例下降^[8]。近年来,我国花生生产中为追求高产而不断增加氮肥投入。山东省多数花生田施氮量在 112.50~168.75 kg hm⁻²之间,部分甚至超过 225 kg hm⁻²,远高于花生植株实际需求^[11]。过量施氮不仅抑制花生结瘤、固氮^[12],降低氮肥利用效率甚至导致减产^[8],还会引发土壤酸化^[13]、水体富营养化^[14]及增加 N₂O 排放^[15]等一系列环境问题。Huang 等^[8]研究表明,在

0~200 kg hm⁻²施氮量范围内,花生最佳产量施氮量为 150 kg hm⁻²,此时氮肥利用效率较高且损失率较低;超过此量,产量开始下降。Liu 等^[16]研究指出,在 0~60 kg hm⁻²施氮范围内,增施氮肥增加了花生对肥料氮的吸收,但根瘤固氮酶活性、固氮潜力及总固氮量则呈先升后降趋势,在 15 kg hm⁻²时达到峰值。

与普通结瘤花生品种不同,不结瘤花生品种无法形成根瘤,因此其氮素来源仅限于土壤和肥料两部分^[15]。当土壤和肥料供氮不足时,不结瘤品种无法通过根瘤固氮补充氮素需求。比较不同结瘤特性花生品种对氮肥用量的响应差异,对于深入阐明花生 3 种氮源(尤其是根瘤固氮)在产量形成中的作用至关重要。目前,关于不同结瘤特性花生品种对氮肥响应的研究报道尚少。为此,本研究在山东省 3 个试验基点开展为期 2 年的春花生氮肥田间试验,研究氮肥用量对普通结瘤花生品种与不结瘤品种氮素累积、利用效率、产量及品质的影响,以期对花生高效施肥及农业可持续发展提供理论基础和技术支撑。

1 材料与方法

1.1 试验地基本概况

试验于 2019—2020 年在我国山东省花生主产区的 3 个地点进行,分别为位于莱西市望城街道办事处的山东省花生研究所试验农场(简称望城,36°48'N, 120°29'E)、位于济宁市任城区济岱路 9 号的济宁市农业科学院(简称任城,35°27'N, 116°35'E)以及位于聊城市茌平区聊城市农业科学院现代农业产业示范园(简称茌平,36°30'N, 116°17'E)。3 个地点均属温带季风大陆性气候,年降雨量分别为 635.8 mm、

699.5 mm 和 762.8 mm, 年均气温分别为 11.3℃、13.7℃和 14.0℃。任城和茌平点土壤类型均为潮土, 望城点为棕壤。3 个试验点 0~20 cm 耕层土壤基础理化性质见表 1。

表 1 不同试验基点基础土壤理化性质
Table 1 Basic physicochemical properties of soil at different experimental sites

年份 Years	地点 Sites	pH	有机质 Organic matter (g kg ⁻¹)	碱解氮 Alkali- hydrolyzable nitrogen (mg kg ⁻¹)	速效磷 Available phosphorus (mg kg ⁻¹)	速效钾 Available potassium (mg kg ⁻¹)	交换性钙 Exchangeable calcium (cmol kg ⁻¹)
2019	望城 Wangcheng	5.90	9.72	64.10	36.60	72.40	6.90
	任城 Rencheng	6.70	14.60	85.56	40.50	98.20	10.40
	茌平 Chiping	8.40	15.90	87.28	46.40	239.00	52.50
2020	望城 Wangcheng	6.70	10.40	82.20	20.00	114.00	12.20
	任城 Rencheng	6.80	15.60	95.60	37.30	124.00	13.80
	茌平 Chiping	8.40	18.10	103.00	9.65	266.00	78.40

1.2 试验设计

本研究以普通结瘤品种(common nodulating variety, CNV)花育 22 号和不结瘤品种(non-nodulating variety, NNV) BL 为试验材料。设置 3 个施氮水平: 0 kg hm⁻² (N0)、60 kg hm⁻² (N60)和 120 kg hm⁻² (N120)。2 年 3 点的试验方案保持一致。种植制度为春花生-冬小麦-夏玉米两年三熟制。为避免花生连作, 每年试验均选用上年种植玉米的地块。春花生于每年 4 月 28 日至 5 月 5 日播种, 9 月 5 日至 15 日收获。所有化肥均于播前一次性基施, 用旋耕机将肥料均匀混入 0~20 cm 土层。除氮肥外, 各处理均施磷肥 (P₂O₅) 90 kg hm⁻² 和钾肥(K₂O) 120 kg hm⁻²。氮、磷、钾肥分别选用尿素(N ≥ 46%)、过磷酸钙(P₂O₅ ≥ 12%)和硫酸钾(K₂O ≥ 50%)。采用起垄种植花生, 垄宽 85 cm, 垄高 10 cm, 每垄播种 2 行, 穴距 16 cm, 每穴 2 粒。任城和茌平点小区面积 16.2 m², 望城点小区面积 100 m², 每处理重复 3 次。

1.3 植株取样与测定

1.3.1 产量及产量构成因素 收获时每小区选取 5.4 m² 代表性样方。剔除发芽、霉烂及空秕荚果等杂质, 保留具有经济价值的饱果和秕果, 自然风干后称重, 计算单位面积经济产量。随机称取 1 kg 风干荚果, 计算千克果数。每小区连续选取生长一致的 3 穴花生, 统计单株有效果数(饱果与秕果数之和)。

1.3.2 籽仁品质 每小区随机选取 20 个风干荚果, 剥壳后测定籽仁品质指标。按照《GB 5009.6-2016 食品安全国家标准食品中脂肪的测定》中的索氏提取法测定籽仁脂肪含量。采用蒽酮比色法测定^[17]籽仁可溶性糖含量。根据籽仁全氮含量乘以转

换系数 5.43 计算得出籽仁蛋白质含量。

1.3.3 干物质与氮含量测定 收获期每小区选取 3 株代表性植株组成混合样品。将植株分为果壳、籽仁和其他(茎+叶+果针+根)三部分。各器官样品经 105℃杀青 30 min 后, 80℃烘干至恒重称干重, 干样粉碎过 2 mm 筛。采用凯氏定氮法测定各器官全氮含量^[18]。用 Wang 等^[10]和郑永美等^[9]的方法计算植株氮累积量、氮素利用效率和氮肥偏生产力。

植株氮素累积量(kg hm⁻²) =植株干物质量(kg hm⁻²) ×氮含量(g kg⁻¹) /1000 (1)

氮素利用效率(kg kg⁻¹) =荚果产量(kg hm⁻²) /植株氮素累积量(kg hm⁻²) (2)

氮肥偏生产力(kg kg⁻¹) =荚果产量(kg hm⁻²) /施氮量(kg hm⁻²) (3)

1.4 数据分析

本研究中产量和产量构成因素相关数据均为 2 年大田试验结果, 而品质、氮素累积及氮素利用率等相关指标均为 2019 年试验结果。采用 SPSS 25.0 软件进行双因素(品种、施氮量及其互作)方差分析, 检验其对产量、产量构成因素、籽仁品质、氮素累积量及氮素利用效率的影响。采用 Duncan 法在 0.05 显著水平下对不同处理各指标进行多重比较。利用 Pearson 相关系数分析植株氮素累积量与产量及籽仁蛋白质含量间的关系。采用 Origin 2021 软件绘制图表。

2 结果与分析

2.1 产量及产量构成因素

2 年 3 点试验表明, 品种对产量、单株果数和千克果数具有极显著影响(2019 年任城点产量除外),

对单位面积株数无显著影响。氮肥用量及其与品种的互作在多数情况下对产量及产量构成因素影响不显著(表 2)。不结瘤品种在 N60 和 N0 处理下的平均产量均显著低于 N120 处理,降幅分别为 17.30%和 13.97%,单株果数的减少是导致产量下降的主要原因,其中各试验点 N60 处理的单株果数较 N120 下降 1.93%~18.81%,平均下降 7.43%;N0 处理的单株果数较 N120 下降 3.31%~12.71%,平均下降 9.12%。氮肥用量对不结瘤品种的单株果数和千克果数(2019 年望城点除外)的影响均未达显著水平。然而,氮肥用量对普通结瘤品种的产量无显著影响,在所有地点和年份均如此(表 3)。这表明不结瘤品种的产量对氮肥用量的响应较普通结瘤品种更为敏感。

表 2 不同品种及不同氮肥用量对产量及其构成因素的影响的显著性分析
Table 2 Significance analysis of yield and its components under different nitrogen application rates in various varieties

年份 Year	地点 Site	处理 Treatment	产量 Yield (kg hm ⁻²)	单位面积株数 Number of plants per unit area (×10 ⁴ hm ⁻²)	单株果数 Pod number per plant	千克果数 Pod number per kilogram
2019	望城 Wangcheng	V	**	ns	**	**
		N	ns	ns	ns	*
		V×N	ns	ns	ns	*
	任城 Rencheng	V	**	ns	**	**
		N	ns	ns	ns	ns
		V×N	ns	ns	ns	ns
	茌平 Chiping	V	**	ns	**	**
		N	ns	ns	ns	ns
		V×N	ns	ns	ns	ns
2020	望城 Wangcheng	V	**	ns	**	**
		N	ns	ns	ns	ns
		V×N	ns	ns	ns	ns
	任城 Rencheng	V	ns	ns	**	**
		N	ns	ns	ns	ns
		V×N	ns	ns	ns	ns
	茌平 Chiping	V	**	ns	**	**
		N	ns	ns	ns	ns
		V×N	ns	ns	ns	ns
	所有地点平均值 Average of all sites		V	**	ns	**
			N	ns	ns	ns
			V×N	*	ns	ns

V: 品种; N: 氮肥用量; ns: 处理间差异不显著; *: 处理间差异达 0.05 显著水平; **: 处理间差异达 0.01 显著水平。
V: variety; N: nitrogen application rate; ns: no significant difference; *: significant at $P < 0.05$; **: significant at $P < 0.01$.

表 3 氮肥用量对不同品种产量及产量构成因素的影响
Table 3 Yield and yield components under different nitrogen application rates in various varieties

年份 Year	地点 Site	品种 Variety	氮肥用量 N rates (kg hm ⁻²)	产量 Yield (kg hm ⁻²)	单位面积株数 Number of plants per unit area (×10 ⁴ hm ⁻²)	单株果数 Pod number per plant	千克果数 Pod number per kilogram
2019	望城 Wangcheng	CNV	N120	5375.27±572.01 a	23.92±1.04 a	15.02±0.56 c	503.84±42.45 c
			N60	5090.53±862.64 ab	22.88±1.85 ab	15.69±0.81 c	517.96±29.61 c
			N0	5236.37±277.44 a	22.35±0.68 ab	15.33±1.29 c	511.60±35.79 c
		NNV	N120	4236.32±264.63 bc	21.96±2.18 ab	24.12±2.04 a	1204.23±20.03 b

(续表 3)

年份 Year	地点 Site	品种 Variety	氮肥用量 N rates (kg hm ⁻²)	产量 Yield (kg hm ⁻²)	单位面积株数 Number of plants per unit area (×10 ⁴ hm ⁻²)	单株果数 Pod number per plant	千克果数 Pod number per kilogram
2019	望城 Wangcheng	NNV	N60	3736.30±122.08 c	20.20±0.59 b	21.33±1.75 b	1274.86±46.58 b
			N0	3514.06±63.65 c	22.22±2.94 ab	21.04±2.07 b	1347.76±44.30 a
	任城 Rencheng	CNV	N120	5490.81±837.34 a	24.26±1.29 a	16.58±1.27 b	511.76±41.9 b
			N60	5861.37±824.47 a	25.30±1.48 a	16.20±1.72 b	496.15±73.09 b
		NNV	N0	5975.83±980.74 a	24.57±0.33 a	16.48±1.12 b	497.64±19.84 b
			N120	5067.55±300.47 ab	25.63±1.72 a	27.55±2.84 a	843.43±54.46 a
	茌平 Chiping	NNV	N60	3741.79±598.10 bc	23.04±3.83 a	24.72±2.81 a	874.81±75.67 a
			N0	3522.75±693.18 c	23.56±4.73 a	24.03±2.76 a	889.15±7.40 a
			N120	4261.39±548.37 a	20.51±0.94 a	20.85±6.17 bc	664.69±88.60 b
		CNV	N60	4039.06±501.78 a	19.84±2.54 a	22.38±2.61 abc	661.99±64.47 b
			N0	4261.39±645.71 a	21.78±4.54 a	19.21±3.96 c	629.53±106.12 b
			N120	1963.94±256.73 b	23.17±1.38 a	29.50±3.68 a	1667.06±113.61 a
		NNV	N60	1914.54±226.41 b	22.16±2.32 a	29.33±3.09 a	1607.33±51.41 a
			N0	1986.21±319.32 b	22.34±2.33 a	28.12±2.73 ab	1619.50±140.96 a
			N120	4666.90±635.70 a	21.18±2.05 a	15.33±1.50 ab	620.56±9.30 b
2020	望城 Wangcheng	CNV	N60	4346.62±486.07 a	20.50±1.95 a	14.00±0.83 b	685.89±11.04 b
			N0	4052.49±804.15 a	19.78±2.84 a	14.61±3.54 b	657.21±65.60 b
			N120	2392.28±70.70 b	21.84±1.63 a	20.67±1.64 a	1116.12±26.67 a
	任城 Rencheng	NNV	N60	1578.51±49.02 c	18.83±3.54 a	17.39±4.58 ab	1191.03±132.32 a
			N0	2091.61±266.95 bc	20.34±1.00 a	18.78±1.78 ab	1235.53±84.18 a
			N120	3797.78±131.22 a	21.07±3.40 a	14.61±1.06 c	623.46±82.18 b
		CNV	N60	4357.08±420.46 a	20.87±2.99 a	14.44±1.11 c	614.79±56.04 b
			N0	4013.53±583.45 a	20.72±2.69 a	13.72±1.99 c	621.53±77.86 b
			N120	4125.52±306.33 a	21.07±3.99 a	23.39±1.58 a	916.32±56.00 a
		NNV	N60	3888.36±327.02 a	21.07±2.07 a	22.00±1.32 ab	894.77±48.03 a
			N0	3995.41±407.10 a	22.80±2.62 a	20.67±0.87 b	914.46±74.92 a
			N120	5683.62±786.88 a	25.29±2.19 a	14.22±1.86 a	510.09±53.67 b
	茌平 Chiping	CNV	N60	6041.97±208.34 a	25.56±1.92 a	15.17±3.68 a	506.34±34.64 b
			N0	5948.45±327.82 a	24.37±0.46 a	15.11±4.81 a	503.08±15.93 b
			N120	3878.71±372.73 b	25.63±2.05 a	20.11±3.38 a	1131.99±73.77 a
		NNV	N60	3056.47±214.06 c	24.37±1.58 a	19.72±2.56 a	1226.70±108.20 a
			N0	3527.95±477.29 bc	24.59±1.78 a	19.44±1.13 a	1165.42±139.87 a
			N120	4858.71±914.09 a	22.71±2.54 a	16.10±3.29 c	572.40±83.79 b
所有地点 平均值 Average of all sites	CNV	N60	5031.15±895.44 a	22.49±2.97 a	16.31±3.38 c	580.52±89.45 b	
		N0	4914.68±1027.33 a	22.26±2.75 a	15.75±3.18 c	570.10±86.74 b	
		N120	3610.72±1139.38 b	23.22±2.70 a	24.22±4.15 a	1146.52±277.80 a	
	NNV	N60	2985.99±982.36 c	21.61±2.86 a	22.42±4.61 b	1178.25±264.50 a	
		N0	3106.33±870.41 c	22.64±2.72 a	22.01±3.70 b	1195.30±270.42 a	
		N120					

CNV: 普通结瘤品种; NNV: 不结瘤品种; N0: 不施氮; N60: 施氮量 60 kg hm⁻²; N120: 施氮量 120 kg hm⁻²; 不同的小写字母表示在同一试验地点和年份中处理之间的差异达显著水平。

CNV: common nodulating variety; NNV: non-nodulating variety; N0: no nitrogen applied; N60: nitrogen application of 60 kg hm⁻²; N120: nitrogen application of 120 kg hm⁻². Different lowercase letters indicate significant differences among treatments within the same experimental site and year ($P < 0.05$).

2.2 籽仁品质

方差分析表明, 品种对所有地点籽仁脂肪、蛋白质及可溶性糖含量均具有极显著影响。氮肥用量对任城和茌平点籽仁蛋白质含量及 3 个地点蛋白质含量均值具有极显著影响, 但仅对茌平点籽仁脂肪含量和任城点籽仁可溶性糖含量的影响达到显著或极显著水平。氮肥用量对不结瘤品种籽仁蛋白质含量的影响大于对脂肪和可溶性糖含量的影响。氮肥减施降低了不结瘤品种籽仁蛋白质含量, 其中各试验点 N60 处理的籽仁蛋白质含量较 N120 处理降

低 2.72%~15.22%, 平均降低 10.69%; 各试验点 N0 处理的籽仁蛋白质含量较 N120 处理降低 5.73%~14.91%, 平均降低 11.40%。任城和茌平试验点 N120 处理与 N60 和 N0 的差异达显著水平。普通结瘤品种仅在茌平点的蛋白质含量和任城点的可溶性糖含量受氮肥用量的显著影响, 但这一影响并未改变上述 2 个指标在 3 个地点的平均值(图 1)。上述结果表明, 氮肥用量主要影响不结瘤品种籽仁蛋白质含量, 而对普通结瘤品种的品质指标影响较小。

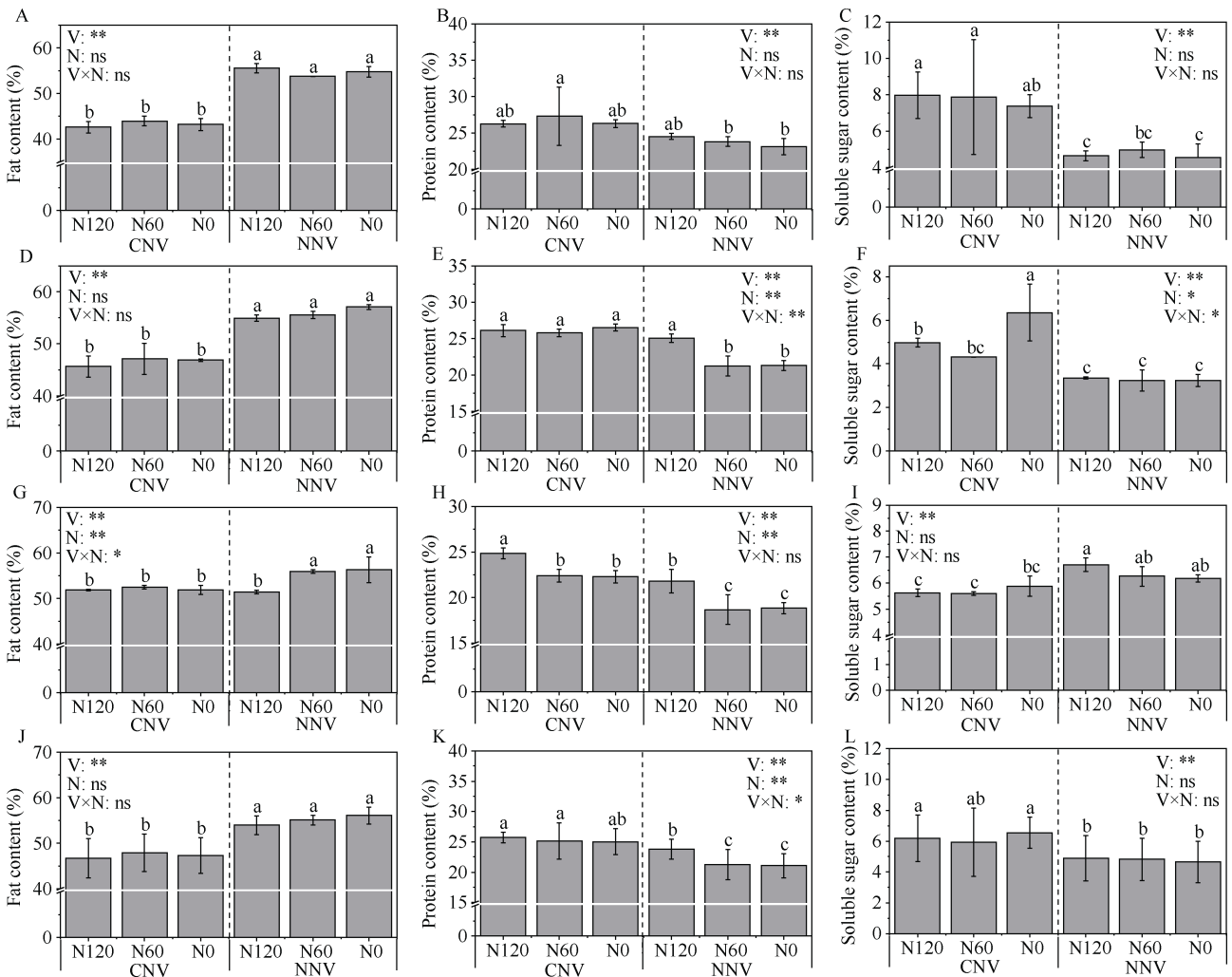


图 1 施氮对不同品种籽仁品质的影响

Fig. 1 Quality of peanut kernel under different nitrogen application rates in various varieties

CNV: 普通结瘤品种; NNV: 不结瘤品种; V: 品种; N: 氮肥; N0: 不施氮; N60: 施氮 60 kg hm⁻²; N120: 施氮 120 kg hm⁻²; 柱上不同字母表示处理间差异达显著水平; ns: 差异不显著; *: 差异达 0.05 显著水平; **: 差异达 0.01 显著水平; A~C: 望城点籽仁的脂肪含量、蛋白质含量、可溶性糖含量; D~F: 任城点籽仁的脂肪含量、蛋白质含量、可溶性糖含量; G~I: 茌平点籽仁的脂肪含量、蛋白质含量、可溶性糖含量; J~L: 3 个地点籽仁的脂肪含量平均值、蛋白质含量平均值、可溶性糖含量平均值。

CNV: common nodulating variety; NNV: non-nodulating variety; V: variety; N: nitrogen; N0: no nitrogen applied; N60: nitrogen application of 60 kg hm⁻²; N120: nitrogen application of 120 kg hm⁻². Different lowercase letters on the bars indicate significant differences among treatments ($P < 0.05$); ns: no significant difference; *: significant at $P < 0.05$; **: significant at $P < 0.01$; A~C: fat content, protein content and soluble sugar content of kernel at Wangcheng site; D~F: fat content, protein content and soluble sugar content of kernel at Rencheng site; G~I: fat content, protein content and soluble sugar content of kernel at Chipping site; J~L: average of fat content, protein content and soluble sugar content of kernel at the three experimental sites.

2.3 氮素累积与氮素利用效率

图2显示, 在3个试验点中, 除望城点果壳的氮含量外, 品种对果壳、籽仁及其他部位的氮含量的影响均达到显著或极显著水平。氮肥用量显著或极显著地影响了任城和茌平2点的果壳与籽仁氮含量, 以及这3个点的平均值。此外, 氮肥用量仅在茌平点对其他部位氮含量的影响达到极显著水平。在多数情况下, 品种与施氮量的交互作用对花生各部位的氮含量无显著影响。对于不结瘤品种, 各部位的氮含量均随氮肥用量减少而降低。与N120处理相比, 各试验点N60和N0处理的果壳氮含量分别平均下降16.49%和18.64%, 籽仁氮含量分别平均下降

10.69%和11.40%, 其他器官氮含量分别平均下降7.94%和9.42%。其中任城和茌平试验点N120处理的果壳和籽仁的氮含量与N60和N0的差异均达显著水平, 而且2个试验点中N120处理的其他器官氮含量与N0处理差异也达显著水平。然而, 在多数情况下, 普通结瘤品种各部位的氮含量对氮肥用量响应不敏感(仅在茌平点观察到籽仁和其他部位氮含量例外, 图2-H, I)。

与氮含量的变化趋势类似, 随着氮肥用量降低, 不结瘤品种在3个试验点的果壳、籽仁及其他部位的氮素累积量均呈下降趋势(图3), 其中N60处理的果壳、籽仁、其他器官和整株氮素累积量较N120

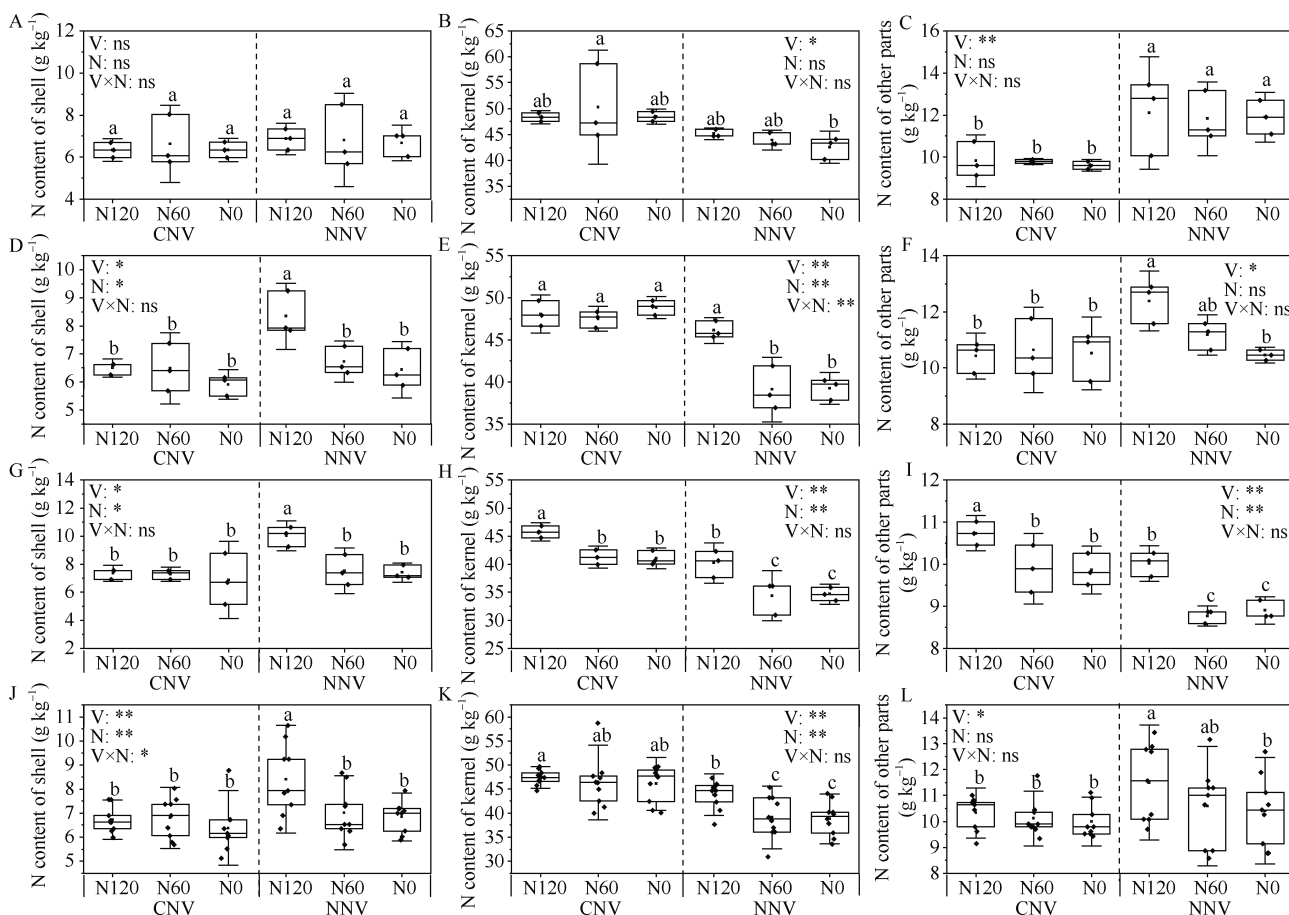


图2 氮肥用量对不同花生品种植株氮含量的影响

Fig. 2 N content of peanut plants under different nitrogen application rates in various varieties

CNV: 普通结瘤品种; NNV: 不结瘤品种; V: 品种; N: 氮肥用量; N0: 不施氮; N60: 施氮 60 kg hm^{-2} ; N120: 施氮 120 kg hm^{-2} ; 箱上不同字母表示处理间差异达显著水平; ns: 差异不显著; *: 差异达 0.05 显著水平; **: 差异达 0.01 显著水平; A~C: 望城点花生果壳、籽仁和其他器官的氮含量; D~F: 任城点花生果壳、籽仁和其他器官的氮含量; G~I: 茌平点花生果壳、籽仁和其他器官的氮含量; J~L: 3 个试验点花生果壳、籽仁和其他器官的氮含量的平均值。

CNV: common nodulating variety; NNV: non-nodulating variety; V: variety; N: nitrogen application rate; N0: no nitrogen applied; N60: nitrogen application of 60 kg hm^{-2} ; N120: nitrogen application of 120 kg hm^{-2} ; ns: no significant difference; *: significant at $P < 0.05$; **: significant at $P < 0.01$; Different lowercase letters on the boxes indicate significant differences among treatments ($P < 0.05$); A~C: nitrogen content of shell, kernel and other parts of peanut plant at Wangcheng site; D~F: nitrogen content of shell, kernel and other parts of peanut plant at Rencheng site; G~I: nitrogen content of shell, kernel and other parts of peanut plant at Chiping site; J~L: average nitrogen content of peanut shells, kernels and other organs at the three test sites.

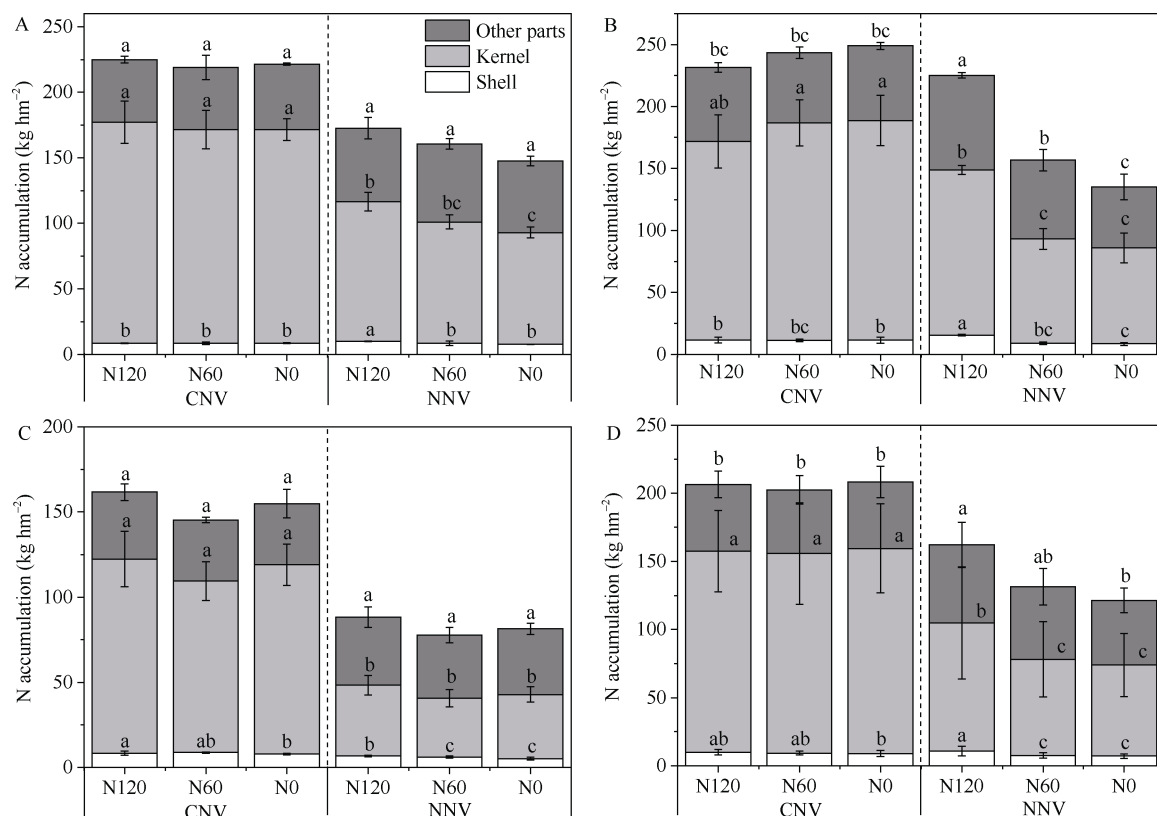


图 3 氮肥用量对不同花生品种植株氮累积量的影响

Fig. 3 N accumulation of peanut plant affected by N application rates in different varieties

CNV: 普通结瘤品种; NNV: 不结瘤品种; V: 品种; N: 氮肥用量; N0: 不施氮; N60: 施氮 60 kg hm⁻²; N120: 施氮 120 kg hm⁻²; 柱上不同字母表示处理间差异达显著水平; A: 望城点花生植株不同器官的氮累积量; B: 任城点花生植株不同器官的氮累积量; C: 在平点花生植株不同器官的氮累积量; D: 3 个地点花生植株不同器官的氮累积量的平均值。

CNV: common nodulating variety; NNV: non-nodulating variety; V: variety; N: nitrogen; N0: no nitrogen applied; N60: nitrogen application of 60 kg hm⁻²; N120: nitrogen application of 120 kg hm⁻²; Different lowercase letters on the bars indicate significant differences among treatments ($P < 0.05$); A: nitrogen accumulation of different parts in peanut plant at Wangcheng site; B: nitrogen accumulation of different parts in peanut plant at Rencheng site; C: nitrogen accumulation of different parts in peanut plant at Chipping site; D: average nitrogen accumulation of different parts in peanut plant at the three experimental sites.

处理分别平均降低 30.25%、24.91%、7.15%和 18.98%，N0 处理各指标分别平均降低 34.96%、28.75%、17.34%和 25.13%。多数情况下，氮肥用量对普通结瘤品种各器官氮累积量的影响不显著。

多数情况下(除任城试验点外)，品种、氮肥用量及其交互作用对氮素利用效率的影响均未达到显著水平。相比之下，对于氮肥偏生产力，品种、氮肥用量及二者互作在多数试验点均呈现显著或极显著影响(望城点互作效应除外)。减少氮肥用量可提高不结瘤品种的氮素利用效率：在任城点，N0 处理的氮素利用效率较 N120 处理显著高出 15.56%；在在平点，N60 处理的氮素利用效率较 N120 处理显著高出 12.45%。相比之下，氮肥用量对普通结瘤品种的氮素利用效率无显著影响(图 4-A~D)。在所有试验点，2 个品种在 N60 处理下的氮肥偏生产力均显著高于

N120 处理(图 4-E~H)。上述结果表明，与普通结瘤花生相比，不结瘤花生植株的氮素吸收、利用对氮肥的响应更为敏感。

2.4 氮素累积量与产量及品质的关系

图 5 展示了不同花生品种各器官氮素累积量与产量的相关性。除望城点其他器官和在平点果壳的氮素累积量外，不结瘤品种在各地点各器官的氮素累积量与产量均呈显著或极显著正相关(图 5-M~X)。然而，在 3 个试验点，普通结瘤品种器官氮累积量与产量的相关性均不显著(图 5-A~L)。图 6 显示了植株氮累积量与籽仁蛋白质含量的关系。除望城和任城点其他器官外，不结瘤品种籽仁的蛋白质含量随各器官的氮素累积量增加而显著提高(图 6-M~X)。在所有试验点，普通结瘤品种籽仁的蛋白质含量虽与各器官的氮素累积量呈正相关，但均未达到显著水平(图 6-A~L)。

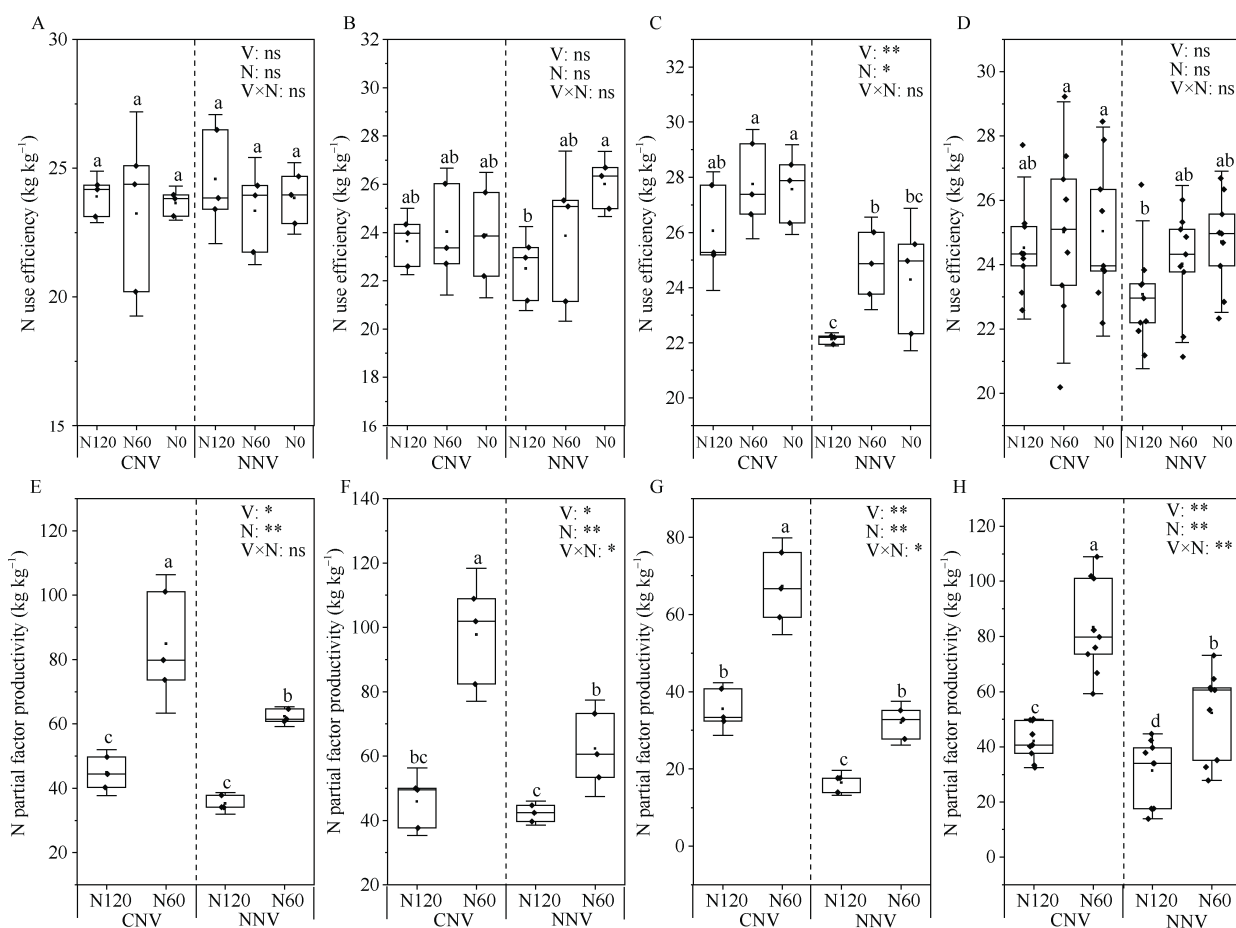
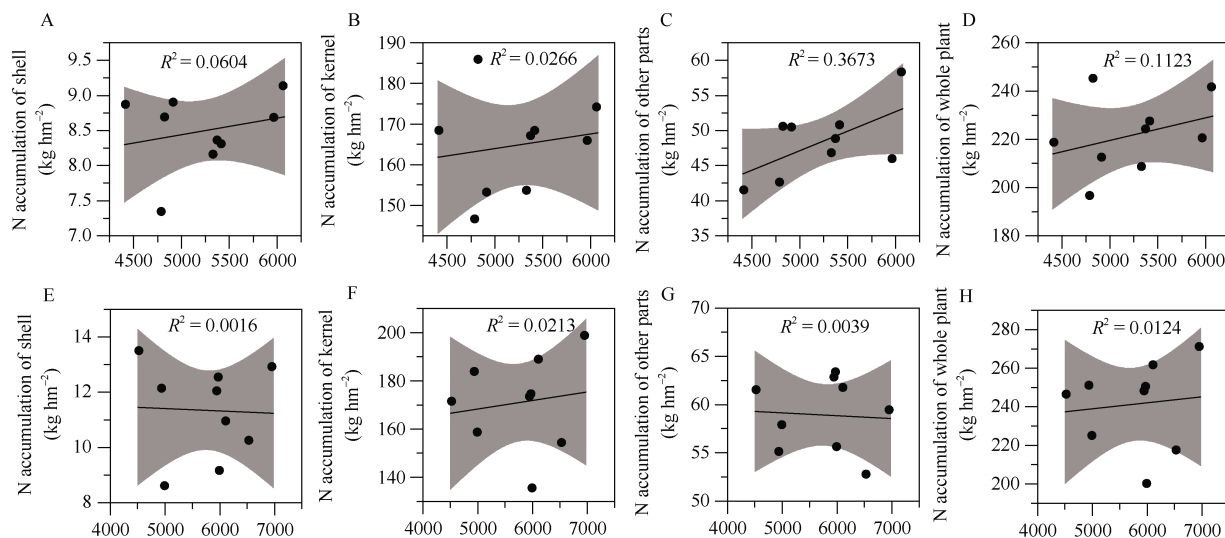


图4 氮肥用量对不同花生品种氮效率的影响

Fig. 4 N efficiency of peanut affected by N application rates in different varieties

CNV: 普通结瘤品种; NNV: 不结瘤品种; V: 品种; N: 氮肥; N0: 不施氮; N60: 施氮 60 kg hm^{-2} ; N120: 施氮 120 kg hm^{-2} ; 柱上不同字母表示处理间差异达显著水平; ns: 差异不显著; *: 差异达 0.05 显著水平; **: 差异达 0.01 显著水平; A~D: 望城、任城、沭平及 3 点平均氮素利用效率; E~H: 望城、任城、沭平及 3 点平均氮肥偏生产力。

CNV: common nodulating variety; NNV: non-nodulating variety; V: variety; N: nitrogen; N0: no nitrogen applied; N60: nitrogen application of 60 kg hm^{-2} ; N120: nitrogen application of 120 kg hm^{-2} ; Different lowercase letters on the boxes indicate significant differences among treatments ($P < 0.05$); ns: no significant difference; *: significant at $P < 0.05$; **: significant at $P < 0.01$; A~D: nitrogen use efficiency at Wangcheng, Rencheng, Chiping and average nitrogen use efficiency at the three experimental sites; E~H: nitrogen partial fertilizer productivity at Wangcheng, Rencheng, Chiping and average nitrogen partial fertilizer productivity at the three experimental sites.



(图5)

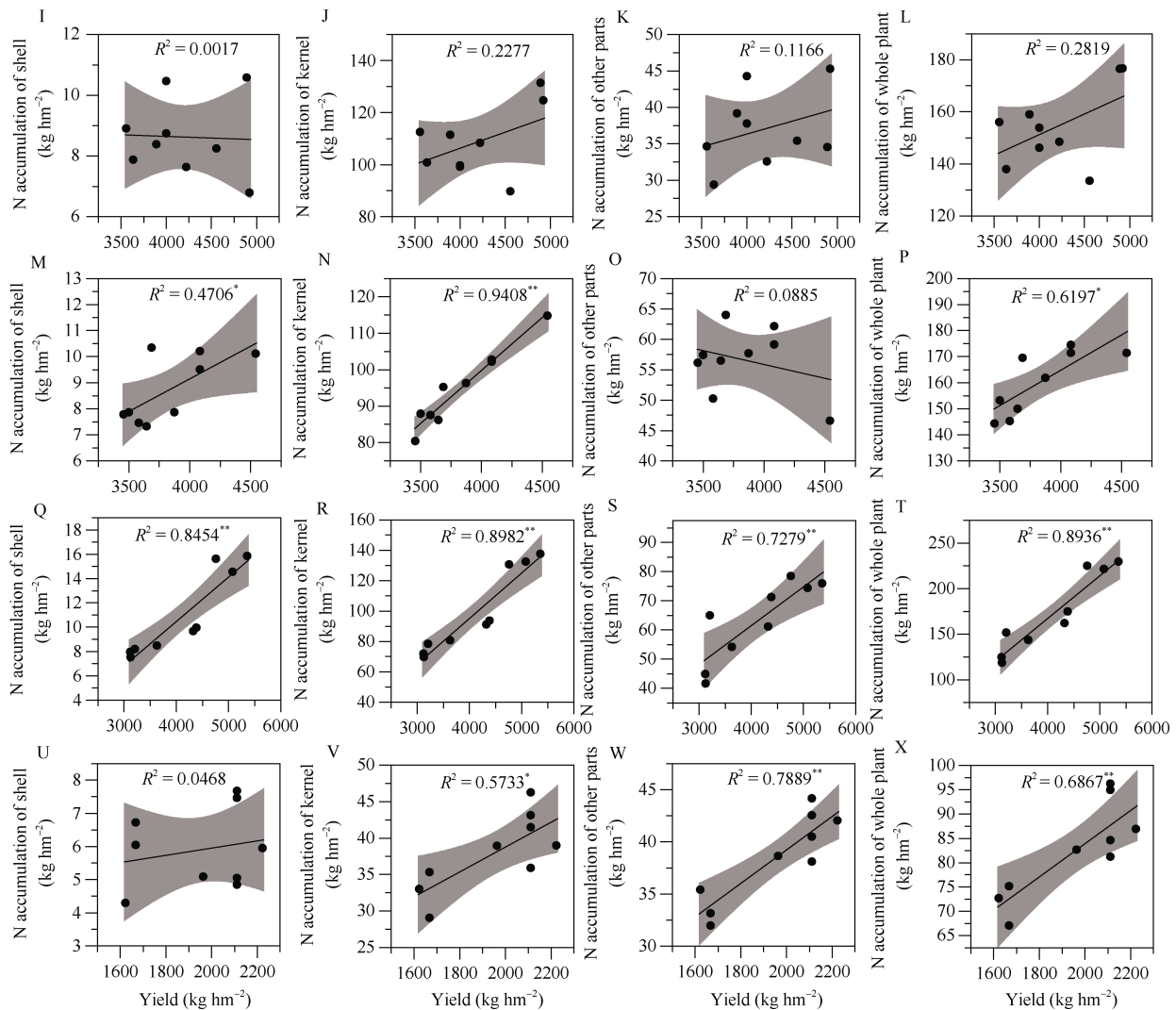
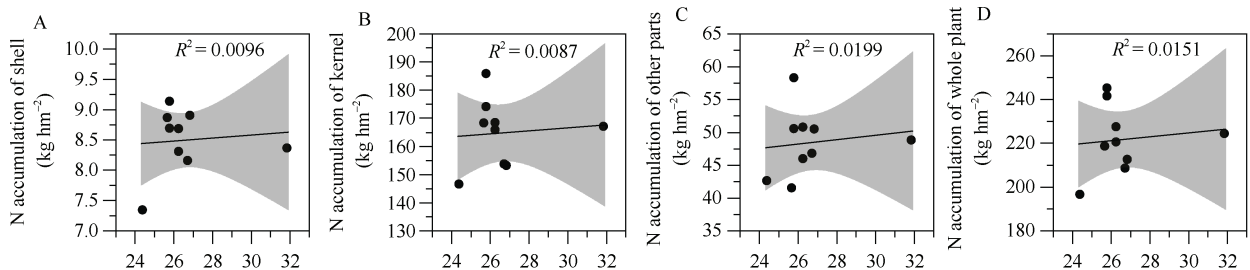


图 5 花生荚果产量与植株氮积累量的相关性分析

Fig. 5 Correlation analysis between pod yield and N accumulation of peanut plants

A~D: 望城点普通结瘤品种的果壳、籽粒、其他部位和整株的氮素积累量与荚果产量之间的相关性; E~H: 任城点普通结瘤品种的果壳、籽粒、其他部位和整株的氮素积累量与荚果产量之间的相关性; I~L: 在平点普通结瘤品种的果壳、籽粒、其他部位和整株的氮素积累量与荚果产量之间的相关性; M~P: 望城点不结瘤品种的果壳、籽粒、其他部位和整株的氮素积累量与荚果产量之间的相关性; Q~T: 任城点不结瘤品种的果壳、籽粒、其他部分和整株的氮素积累量与荚果产量之间的相关性; U~X: 在平点试验点不结瘤品种的果壳、籽粒、其他部位和整株的氮素积累量与荚果产量之间的相关性。*: 相关性达 0.05 显著水平; **: 相关性达 0.01 显著水平。

A~D: correlations between nitrogen accumulation of shell, kernel, other parts, whole plant and pod yield in common variety at Wangcheng site; E~H: correlations between nitrogen accumulation of shell, kernel, other parts, whole plant and pod yield in common variety at Rencheng site; I~L: correlations between nitrogen accumulation of shell, kernel, other parts, whole plant and pod yield in common variety at Chiping site; M~P: correlations between nitrogen accumulation of shell, kernel, other parts, whole plant and pod yield in non-nodulating variety at Wangcheng site; Q~T: correlations between nitrogen accumulation of shell, kernel, other parts, whole plant and pod yield in non-nodulating variety at Rencheng site; U~X: correlations between nitrogen accumulation of shell, kernel, other parts, whole plant and pod yield in non-nodulating variety at Chiping site. *: correlation significant at $P < 0.05$; **: correlation significant at $P < 0.01$.



(图 6)

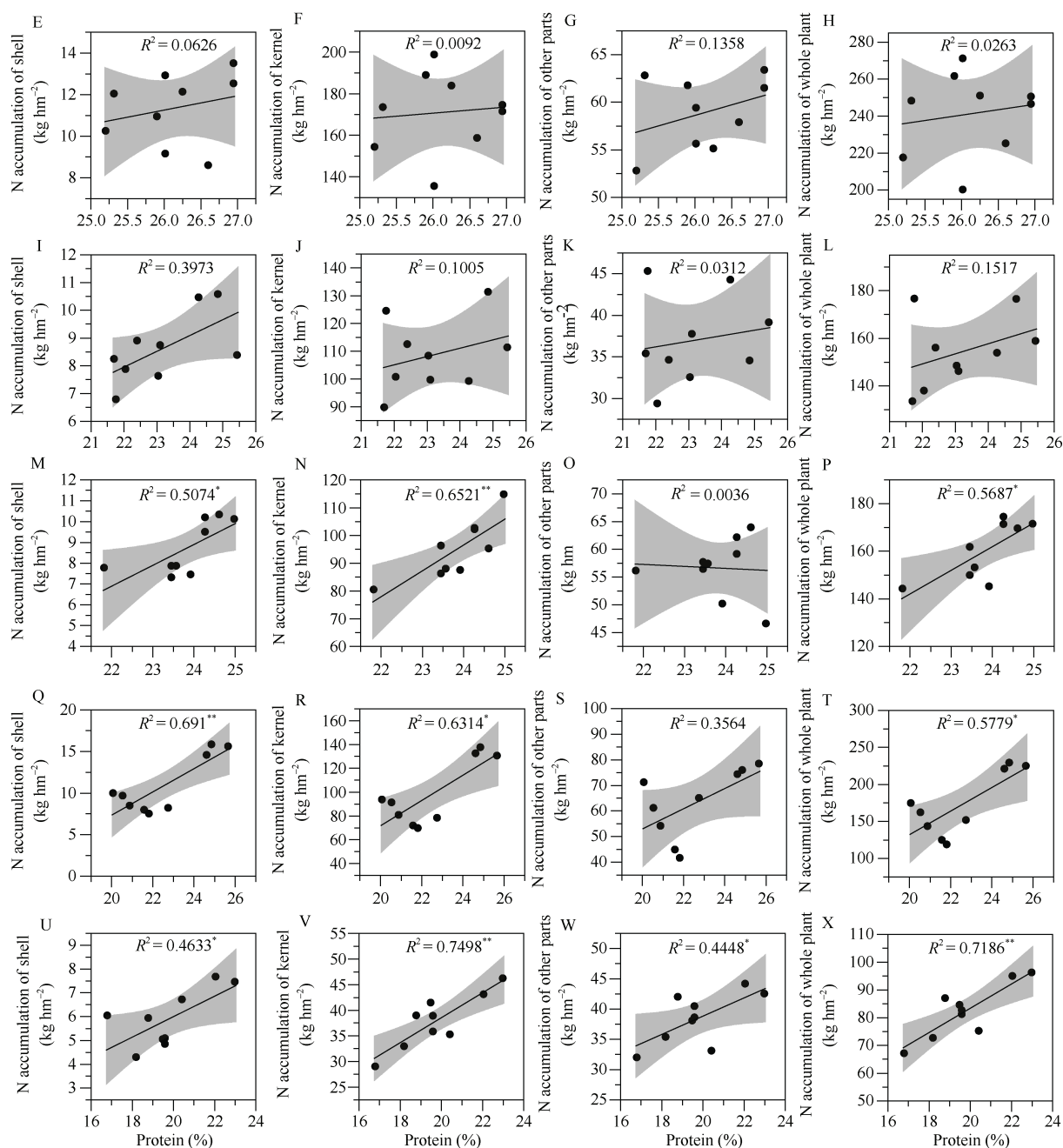


图6 花生籽仁蛋白质含量与植株氮素累积量的相关性分析

Fig. 6 Correlation analysis between protein content and N accumulation of peanut plants

A~D: 望城点普通结瘤品种的果壳、籽粒、其他部位和整株的氮素累积量与籽仁蛋白质含量之间的相关性; E~H: 任城点普通结瘤品种中果壳、籽仁、其他部位和整株的氮素累积量与籽仁蛋白质含量之间的相关性; I~L: 茌平点普通结瘤品种的果壳、籽仁、其他部位和整株的氮素累积量与籽仁蛋白质含量之间的相关性; M~P: 望城点不结瘤品种的果壳、籽仁、其他部位和整株的氮素累积量与籽仁蛋白质含量之间的相关性; Q~T: 任城点不结瘤品种的果壳、籽仁、其他部分和整株的氮素累积量与籽仁蛋白质含量之间的相关性; U~X: 茌平试验点不结瘤品种的果壳、籽粒、其他部位和整株的氮素累积量与籽仁蛋白质含量之间的相关性。*: 相关性达 0.05 显著水平; **: 相关性达 0.01 显著水平。

A~D: correlations between nitrogen accumulation of shell, kernel, other parts and whole plant and kernel protein content in common variety at Wangcheng site; E~H: correlations between nitrogen accumulation of shell, kernel, other parts and whole plant and kernel protein content in common variety at Rencheng site; I~L: correlations between nitrogen accumulation of shell, kernel, other parts and whole plant and kernel protein content in common variety at Chiping site; M~P: correlations between nitrogen accumulation of shell, kernel, other parts and whole plant and kernel protein content in non-nodulating variety at Wangcheng site; Q~T: correlations between nitrogen accumulation of shell, kernel, other parts and whole plant and kernel protein content in non-nodulating variety at Rencheng site; U~X: correlations between nitrogen accumulation of shell, kernel, other parts and whole plant and kernel protein content in non-nodulating variety at Chiping site. *: correlation significant at $P < 0.05$; **: correlation significant at $P < 0.01$.

3 讨论

本研究证实,降低甚至不施用氮肥,并未显著降低普通结瘤花生品种各器官的氮含量或积累量,但却显著抑制了不结瘤花生品种各器官对氮的吸收(图 2 和图 3)。Huang 等^[8]的研究结论与本文存在差异,其研究显示花生植株氮素积累量随施氮量(0~200 kg hm⁻²)增加呈上升趋势,且施氮处理较不施氮处理的氮素积累量高出 41%~75%。究其原因,主要在于结瘤花生的氮素来源有 3 种途径,分别为肥料、土壤以及根瘤固氮^[19]。当氮肥施用量降低时,单株固氮酶活性、根瘤干重及固氮潜力会相应提高^[16],从而增加了植株通过固氮作用获得的氮素积累量。此外,本研究基础土样氮含量亦较高(表 1)。这些因素共同弥补了因氮肥供应不足导致的植株氮素亏缺。而不结瘤花生仅能依赖肥料和土壤获取氮素。当氮肥供应不足或缺失时,植株氮素积累量下降,表明仅靠土壤供氮无法补偿因氮肥供应不足造成的缺氮状况。这亦凸显了根瘤固氮,尤其在氮肥供应不足情境下的重要作用。

氮素与叶绿素合成、光合作用及干物质积累密切相关^[20-21]。花生植株,尤其是荚果(籽仁)中氮素不足,是导致花生减产的主要因素^[8,22-23]。前人研究表明,增施氮肥可显著提高花生产量,获得最佳产量的适宜施氮量范围为 105~180 kg hm⁻² ^[8,24-25]。本研究中普通结瘤花生对氮肥用量的产量响应与前人研究结果不同(表 2)。这种差异主要源于结瘤花生在减氮或不施氮条件下,其根瘤固氮酶活性反而更强^[8,16],进而显著提高固氮能力,补偿外源氮的减少,维持氮素平衡,所以其产量未显著降低。然而,不结瘤花生对氮肥用量的产量响应与结瘤花生迥异,其产量随氮肥用量减少而显著下降。这主要是因为不结瘤品种缺乏根瘤菌共生系统,无法进行生物固氮,其氮素来源完全依赖土壤矿质氮和外源肥料氮。当氮肥供应不足时,植株无法通过固氮作用补偿氮亏缺,导致氮吸收受限,进而影响产量和品质。

花生籽仁中脂肪与蛋白质含量是决定其品质的关键指标,二者分别反映了花生的油用品质和食用品质。Liu 等^[26]与 Zhao 等^[27]的研究表明,花生籽仁的蛋白质含量随氮肥用量增加而提高。本研究则显示,普通结瘤花生与不结瘤花生的蛋白质含量对氮肥用量的响应存在差异,在多数情况下,不结瘤花生籽仁的蛋白质含量随氮肥用量减少而降低;而普通结瘤花生(除在平试验点外)的蛋白质含量对不同

施氮量的响应变化甚微(图 1)。蛋白质的主要组分是氮素,充足的氮供应有利于蛋白质合成,反之则导致其含量下降。这表明氮肥供应不足可能对花生的食用品质产生不利影响。本研究还发现,在多数情况下,不同结瘤特性品种的脂肪含量对氮肥的响应模式相似,即随施氮量减少变化不显著,这与 Zhao 等^[27]的研究结果一致。值得一提的是,本研究中不结瘤花生籽仁的蛋白质含量、植株氮素吸收对氮肥的响应,在任城和茌平点比在望城点更为敏感(图 1~图 4),这可能是因为望城点的土壤类型为棕壤,棕壤通常具有较强的淋溶性,且有机质含量较低(表 1),保水保肥能力差,氮素易随水淋湿,矿化过程不稳定,因此,即使施入氮肥,其有效性也难以持续维持^[28],导致望城点不结瘤花生籽仁的蛋白质含量、植株氮素吸收对氮肥的响应不敏感。相比之下,任城和茌平点的土壤均为潮土,土壤有机质含量高,具有较强的保水保肥能力和较高的缓冲性,氮素在土壤中滞留时间较长,有效性高。氮肥投入能更有效地转化为植株可利用的有效氮^[29]。因此,这类土壤有效氮库的变化对氮肥用量的响应更为敏感,进而显著影响不结瘤花生的氮素吸收与籽仁蛋白质的合成。

由此可见,当前山东省农户花生氮肥用量(112.50~168.75 kg hm⁻²)已显著超出植株实际需求。短期内大幅减少氮肥用量预计不会影响生产水平。现代农业实践中过量施氮严重抑制了根瘤菌的固氮能力,不仅造成资源浪费,亦对环境产生巨大压力。因此,在保障产量的前提下,通过减少化肥氮投入,最大限度地激发根瘤固氮潜力,是提高农田氮素利用效率、减少氮素损失与环境污染的有效途径,也将是未来花生施肥研究的重要方向。

4 结论

普通结瘤花生品种通过根瘤固氮作用有效补偿氮肥减施的亏缺,在 0~120 kg hm⁻² 施氮量范围内,随氮肥用量降低,其产量、籽仁品质及植株氮素积累量均保持稳定,且氮素利用效率大幅提升;而不结瘤品种因完全依赖外源氮,减氮(60 kg hm⁻²)或不施氮(0 kg hm⁻²)导致各器官氮含量与积累量、产量及籽仁蛋白质含量显著下降。这一结果凸显了生物固氮在维持花生生产力中的关键作用,表明当前生产中适度降低氮肥用量(如 60 kg hm⁻² 以下),能够充分激发根瘤固氮潜力,在保证产量基本不减少的同时,优化氮素利用效率,减少环境污染。

References

- [1] Wu Y, Sun Z Q, Qi F Y, et al. Comparative transcriptomics analysis of developing peanut (*Arachis hypogaea* L.) pods reveals candidate genes affecting peanut seed size. *Front Plant Sci*, 2022, 13: 958808.
- [2] 中华人民共和国国家统计局. 中国统计年鉴. 北京: 中国统计出版社, 2022. <https://www.stats.gov.cn/sj/ndsj/2022/indexch.htm>. National Bureau of Statistics of the People's Republic of China. China Statistical Yearbook. Beijing: China Statistics Press, 2022. <https://www.stats.gov.cn/sj/ndsj/2022/indexch.htm> (in Chinese).
- [3] Han F, Guo R, Hussain S, et al. Rotation of planting strips and reduction in nitrogen fertilizer application can reduce nitrogen loss and optimize its balance in maize-peanut intercropping. *Eur J Agron*, 2023, 143: 126707.
- [4] Li G H, Guo X, Sun W, et al. Nitrogen application in pod zone improves yield and quality of two peanut cultivars by modulating nitrogen accumulation and metabolism. *BMC Plant Biol*, 2024, 24: 48.
- [5] 丁红, 徐扬, 张冠初, 等. 不同生育期干旱与氮肥施用对花生氮素吸收利用的影响. *作物学报*, 2022, 48: 695–703.
Ding H, Xu Y, Zhang G C, et al. Effects of drought at different growth stages and nitrogen application on nitrogen absorption and utilization in peanut. *Acta Agron Sin*, 2022, 48: 695–703 (in Chinese with English abstract).
- [6] 王才斌, 吴正锋. 花生营养生理生态与高效施肥. 北京: 中国农业出版社, 2017. p 29.
Wang C B, Wu Z F. Peanut Nutritional Physiology, Ecology, and Efficient Fertilization. Beijing: China Agriculture Press, 2017. p 29 (in Chinese).
- [7] Preissel S, Reckling M, Schläpke N, et al. Magnitude and farm-economic value of grain legume pre-crop benefits in Europe: a review. *Field Crops Res*, 2015, 175: 64–79.
- [8] Huang W H, Yang Y H, Zheng H Y, et al. Excessive N applications reduces yield and biological N fixation of summer-peanut in the North China Plain. *Field Crops Res*, 2023, 302: 109021.
- [9] 郑永美, 孙秀山, 王才斌, 等. 高肥力土壤条件下不同基因型花生对氮素利用的差异. *应用生态学报*, 2016, 27: 3977–3986.
Zheng Y M, Sun X S, Wang C B, et al. Differences in nitrogen utilization characteristics of different peanut genotypes in high fertility soils. *Chin J Appl Ecol*, 2016, 27: 3977–3986 (in Chinese with English abstract).
- [10] Wang C B, Zheng Y M, Shen P, et al. Determining N supplied sources and N use efficiency for peanut under applications of four forms of N fertilizers labeled by isotope ^{15}N . *J Integr Agric*, 2016, 15: 432–439.
- [11] 王春晓, 王世福, 鹿泽启, 等. 花生化肥减施途径与潜力. *花生学报*, 2019, 48(3): 71–75.
Wang C X, Wang S F, Lu Z Q, et al. Route and potential of chemical fertilizer reduction for peanut. *J Peanut Sci*, 2019, 48(3): 71–75 (in Chinese with English abstract).
- [12] Zhao L W, Zheng H J, Wang L Y, et al. The fate and balance of nitrogen on a sloped peanut field on red soil. *Agronomy*, 2022, 12: 2388.
- [13] Wu Z F, Sun X M, Sun Y Q, et al. Soil acidification and factors controlling topsoil pH shift of cropland in central China from 2008 to 2018. *Geoderma*, 2022, 408: 115586.
- [14] Cheng Y, Elrys A S, Wang J, et al. Application of enhanced-efficiency nitrogen fertilizers reduces mineral nitrogen usage and emissions of both N_2O and NH_3 while sustaining yields in a wheat-rice rotation system. *Agric Ecosyst Environ*, 2022, 324: 107720.
- [15] Zheng Y M, Shen P, Sun X W, et al. Quantifying the role of peanut root and root nodule in nitrogen absorption and fixation under four forms of N fertilizers. *J Agric Food Res*, 2022, 9: 100334.
- [16] Liu Y, Yan Z H, Wang J G, et al. Optimizing initial nitrogen application rates to improve peanut (*Arachis hypogaea* L.) biological nitrogen fixation. *Agronomy*, 2023, 13: 3020.
- [17] 陈建勋, 王晓峰. 植物生理学实验指导(第2版). 广州: 华南理工大学出版社, 2006. pp 64–66.
Chen J X, Wang X F. Guidance of Plant Physiological Experiment, 2nd edn. Guangzhou: South China University of Technology Publishers, 2006. pp 64–66 (in Chinese).
- [18] 鲍士旦. 土壤农化分析(第3版). 北京: 中国农业出版社, 2005. pp 42–106.
Bao S D. Soil and Agro-chemistry Analysis, 3rd edn. Beijing: China Agriculture Press, 2005. pp 42–106 (in Chinese).
- [19] Liu Y Y, Wu L H, Baddeley J A, et al. Models of biological nitrogen fixation of legumes. A review. *Agron Sustain Dev*, 2011, 31: 155–172.
- [20] Liu Z X, Gao F, Yang J Q, et al. Photosynthetic characteristics and uptake and translocation of nitrogen in peanut in a wheat-peanut rotation system under different fertilizer management regimes. *Front Plant Sci*, 2019, 10: 86.
- [21] Gao H X, Zhang C C, Zhang L Z, et al. Morphological responses in peanut pod development to intercropping and nitrogen application rates. *Field Crops Res*, 2023, 302: 109101.
- [22] Zhao S C, Lyu J L, Xu X P, et al. Peanut yield, nutrient uptake and nutrient requirements in different regions of China. *J Integr Agric*, 2021, 20: 2502–2511.
- [23] 丁红, 张智猛, 徐扬, 等. 氮素缓解花生干旱胁迫的生理和转录调控机制. *作物学报*, 2023, 49: 225–238.
Ding H, Zhang Z M, Xu Y, et al. Physiological and transcriptional regulation mechanisms of nitrogen alleviating drought stress in peanut. *Acta Agron Sin*, 2023, 49: 225–238 (in Chinese with English abstract).
- [24] Guo P, Ren J Y, Shi X L, et al. Optimized nitrogen application ameliorates the photosynthetic performance and yield potential in peanuts as revealed by OJIP chlorophyll fluorescence kinetics. *BMC Plant Biol*, 2024, 24: 774.
- [25] 杨启睿, 李岚涛, 张潇, 等. 施氮对夏花生产量、品质及光温生理特性的影响. *中国生态农业学报(中英文)*, 2024, 32: 627–639.
Yang Q R, Li L T, Zhang X, et al. Effect of nitrogen application on yield, quality and light temperature physiological characteristics of summer peanut. *Chin J Eco-Agric*, 2024, 32: 627–639 (in Chinese with English abstract).
- [26] 刘跃, 贾永红, 于月华, 等. 北疆氮肥运筹对花生生长发育、产量及品质的影响. *作物杂志*, 2024(3): 119–126.
Liu Y, Jia Y H, Yu Y H, et al. Effects of nitrogen fertilizer management on growth and development, yield and quality of peanut

- in northern Xinjiang. *Crops*, 2024(3): 119–126 (in Chinese with English abstract).
- [27] 赵跃, 吕永超, 陈小姝, 等. 不同施氮水平对黑钙土花生碳氮代谢相关酶活性、产量和品质的影响. *中国油料作物学报*, 2024, 46: 122–128.
- Zhao Y, Lyu Y C, Chen X S, et al. Effects of nitrogen application rates on enzyme activities related to carbon and nitrogen metabolism, yield and quality of peanut in chernozem. *Chin J Oil Crop Sci*, 2024, 46: 122–128 (in Chinese with English abstract).
- [28] 刘沥阳, 华伟, 张诗雨, 等. 东北棕壤长期不同施肥处理轮作大豆氮素吸收和土壤硝态氮特征. *植物营养与肥料学报*, 2020, 26: 10–18.
- Liu L Y, Hua W, Zhang S Y, et al. Nitrogen uptake of soybean and soil nitrate nitrogen under long-term rotation and different fertilization in a brown soil of Northeast China. *J Plant Nutr Fert*, 2020, 26: 10–18 (in Chinese with English abstract).
- [29] Ren G C, Zhang X F, Zhang J B, et al. Effects of straw management and N levels on gross nitrogen transformations in fluvo-aquic soil of the North China Plain. *Sci Total Environ*, 2024, 944: 173652.