硫肥对双低油菜产量与品质的影响①

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摘 要

在澳大利亚新南威尔士州缺硫土壤上进行了硫、氮不同水平组合对双低油菜(Canola)的影响试验。结果表明，试验条件下施用硫肥可显著提高油菜产量及含油量。低硫(S_{10})或无硫(So)条件下，一定量的氮肥(N_{80})可提高子粒内的含硫量，但高硫条件下，高量氮肥则降低含硫量。植株体内的含硫量随生育进程趋于降低。施硫处理在抽苔期出现一吸硫高峰，而对照呈指数下降；但在开花期与角果充实期则保持相对稳定。氮肥对生长前期(莲座期与抽苔期)植株(茎、叶)含硫量的影响不显著，而中、后期(开花、角果充实期)，则随施氮量的增加而显著降低。高量氮肥(N_{160})会降低子粒内的硫代葡萄糖甙含量；施硫，特别是在高施硫量条件下，其含量则明显增加，但仍远低于子粒硫代葡萄糖甙40μ mol/g的标准，因而不会影响脱油饼粕的饲喂质量。

关键词 双低油菜 硫 产量 品质

油菜(*Brassica napus*)是需硫较高的作物之一，正常情况下相当于大麦等禾谷类作物需硫量的3～10倍[5,11,12]。在高氮条件下，作物需要更多的硫以进行正常代谢和生长发育。在缺硫条件下，若增施氮肥则会降低作物产量并且增加作为中间产物非蛋白质氮如氨基酸态、酰胺态氮及硝态氮的累积[2,25,34]。此外，缺硫土壤增施氮肥还会因淋洗作用导致地下水硝酸盐累积而造成环境问题[34]。油菜需要一定量的土壤N、S比率[3,11,15]，适宜供硫会使作物因元素的协同作用而提高体内的N、S水平[20,28,29,30,36]。

对氮、硫的肥效及其交互作用研究，因所处的自然地理及环境、气候条件等而异。Beaton等(1986)在加拿大西部试验，施硫可大幅度提高Canola油菜籽产量(较对照高10倍)[4]；Donald等(1993)在缺硫的土壤上进行N、S配合施用，结果对子粒及生物量均无明显肥效[8]。Randall等(1986)认为，N肥主要通过油菜子粒产量的提高而使单位面积产油量提高3倍，而硫肥对产油量的提高则主要是通过油菜籽含油量的增加[27]。

氮、硫平衡对油菜的生长发育至关重要，因S和N的同化具有相互依存性[7,9]，作物对硫的需求量受供氮水平的强烈制约。Zhao等(1993)在英国的试验结果，某些缺硫土壤施用N、S后对油菜子粒产量、含油量、蛋白质及硫代葡萄糖甙含量均有显著的影响[41]。据报道，施N150kg/hm^2，S 32kg/hm^{2}即可以达到试验条件下的油菜高产；但施N量增加到250kg/hm^{2}时，油菜产量还会因施硫量的增加而进一步提高[39]。Zhao等(1993)报导，缺硫条件下施N量超过150kg/hm^{2}后产量不再增加，但施S 50kg/hm^2，再增施N肥至300kg/hm^2，产量还可以提高10.7%[41]。说明N、S配施，调节土壤的N、S平衡，对充分发挥肥效，提高油菜产量具有重要作用。

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本研究是在澳大利亚旱作温带地区油菜－牧草－牧草－油菜的农业系统中进行，旨在探讨缺硫土壤条件下，施S对提高油菜产量与含油量的效应和不同施S水平下S、N对油菜生物量、硫的吸收积累以及子粒内硫代葡萄糖甙含量的影响等。

一、材料与方法

（一）试验条件

试验于1993～1994年分别设在新南威尔士州的Wellington及相距约200公里的Cudal镇（南纬33° 17′ 东经48° 44′ ）。多年平均降水量650mm，但分配极不均衡，Cudal1994年生长季总降水量不足200mm，导致大多作物干旱死亡。

供试品种为澳大利亚双低冬油菜（Canola）品种奥斯卡（*Brassica napus* cv. Oscar）。作物前茬为苜蓿及地中海三叶草，且有放牧羊群习惯，土壤干旱且无灌水条件。当地习惯施肥量为N 20～40kg/hm^2，P 20～30kg/hm^2。油菜于4月播种，11～12月收获。供试土壤的理化性状见表1。

表 1 试前土壤理化性状（Wellington, 1993, Cudal, 1994）

Table 1 Results of soil analysis before the experiments from Wellington and Cudal

采样深度(cm) Sampling depth	0～15	15～30	30～60	60～90	90-
土壤颜色 Soil colour	棕色 Brown	红棕 Red brown	黄棕 Yellow brown	黄棕 Yellow brown	黄红 Yellow red
土壤质地 Soil texture	砂粘壤粘壤 Sandy clay loam	粘土 Clay loam	粘土 Clay	粘土 Clay	Clay
pH (1:5土水化) (Soil:water)	5.7	6.0	7.0	7.7	8.0
(1:5 0.5molL^{-1} $CaCl_2$)	4.7(5.6)[1)]	4.9(7.2)	6.0	6.7	7.1
有机碳(C%) Organic carbon	1.9				
NO_3-N(mg/kg)	9(8)	2	<2	<2	<2
SO_4^{2-}-S(MCP)(mg/kg)	2	1	1	1	1
(KCl_{40})(mg/kg)	3(3.1)	4	3	3	3
P (Lactate) (mg/kg)	1				
(Colwell) (mg/kg)	7				
K (meq/100g)	0.9				
阳离子交换量(cmol/kg) Cation exchange capacity	9.2				

1) 怀灵顿的分析结果 Result from Wellington

（二）试验设计

试验共设5个氮素(N)水平即：0、20、40、80、160kg/hm^2（分别以N_0、N_{20}、N_{40}、N_{80}、N_{160}表示）；4个硫素(S)水平：0、10、20、40kg/hm^2（分别以S_0、S_{10}、S_{20}、S_{40}表示）。氮肥为尿素（含N46%），硫肥用普通过磷酸钙（含S 11%，P 8.8%）并用三聚磷肥（含P 20.7%）调节，使各处理含P均为32kg/hm^2[三聚磷肥量(kg/hm^2)＝(32-普钙施用量×8.8%)/20.7%]。小区面积为1.8m×25m，3次重复，随机区组排列。肥料在播种时一次施于行间。

(三)分析测定

在油菜生长的4个生育期即莲座期(约40天)、抽苔期(约70天)、开花期(约110天)和角果充实期(约150天),随机采样,样品分为完全展开幼叶及其余部分两种,因展开幼叶对缺硫诊断更为敏感[33]。作物成熟后记录子粒产量并取样分析。所有样品测定干物重,并用X射线荧光光谱法测定全硫及子粒内的硫代葡萄糖甙含量[21,26,35,42]。利用核磁共振法测定含油量;用烘干法测定子粒含水量。结果应用Genstat 5进行变异分析及显著性差异检验。

二、试验结果

(一)硫、氮施用对油菜产量与生物量的影响

两试验点的统计结果表明,试验条件下硫肥能显著提高油菜的产量。在Cudal点各施硫处理子粒产量均显著高于对照,平均增产37%~105%。其中以施S 20kg/hm²的产量最高,相当于对照产量的2倍(表2)。Wellington点硫肥肥效更为突出,施S 40kg/hm²时仍有增产潜力,但增产幅度以施S10kg/hm²最大(图1)。N肥在低、中量时对油菜籽产量的影响不显著,高量N肥(相对于地旱作条件下的习惯施肥量而言,下同),尤其在无S(S_0)或低S条件下则显著降低油菜子粒产量。Cudal点施N160kg/hm²,在无硫或施S10kg/hm²时,产量较对照降低76.8%;Wellington点表现出相似结果(见表2,图1),但S、N的交互作用差异不显著。

表 2　S、N对油菜子粒产量(kg/hm²)的影响①(cudal, 1994)

Table 2　Effect of S and N on yield of oilseed rape

施S量 S rate (kg/hm²)	施N量 N rate (kg/hm²)					
	0	20	40	80	160	平均值 Average
0	354	368	315	195	82	263
10	473	455	442	322	110	360
20	492	617	497	607	478	538
40	454	462	419	409	353	419
平均值 Average	443	475	418	383	256	
$p<0.05$	LSD(S) = 79.2		LSD(N) = 88.7		LSD(S×N) = 177.4	

① 油菜子粒含水量为8.5%, Seeds moisture 8.5%.

对油菜不同生育期生物量的影响,硫肥的效果明显高于氮肥。尽管S肥的作用在Cudal的开花期及Wellington的莲座期没有达到差异显著性水准,而氮肥在Cudal的开花期对生物量的影响差异极显著(表3)。此外,硫、氮对生物量的肥料效应Wellington明显高于Cudal,而S、N的交互效应几乎在各生育期均未达到显著性差异。

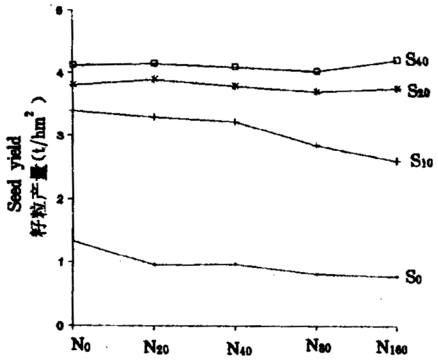

图1 S、N对油菜子粒产量的影响（Wellington，1993）
Fig.1 Effect of s and N on yield of oilseed rape

表 3 硫、氮施用对油菜不同生育期生物量(kg/hm²)的影响（Wellington，1993；Codal，1994）
Table 3 Effect of sulfur and nitrogen supply on biomass (DM, kg/hm²) of rape at growth stages

用量(kg/hm²) Rate		莲座期 Rosette		抽苔期 Stem eongation		开花期 Flowering		充实期 Pod filling
S	N	Wellington	Cudal	Wellington	Cudal	Wellington	Cudal	Cudal
0	0	147.5	136.5	694.5	583.5	1218.0	1290.0	16425
10	0	156.0	226.4	1000.5	673.5	1593.0	1095.0	20070
20	0	159.6	204.0	1056.0	786.0	1873.5	1317.0	24675
40	0	158.1	154.7	991.5	687.0	1821.0	1200.0	21000
0	20	153.9	126.3	682.5	570.0	1287.0	1384.5	24450
10	20	171.6	186.0	1119.0	696.0	2125.5	1251.0	24150
20	20	158.1	184.7	972.0	754.5	2058.0	1150.5	24765
40	20	167.6	176.7	1146.0	762.0	2068.5	1705.5	25950
0	40	143.7	142.2	696.0	658.2	1161.0	1138.5	20910
10	40	155.4	144.0	1077.0	703.5	1702.5	1389.0	29040
20	40	164.0	171.9	889.5	627.0	2326.5	1465.5	24030
40	40	162.5	145.4	1176.0	753.0	2235.0	1477.5	23865
0	80	150.3	183.2	718.5	700.5	1261.5	1582.5	20730
10	80	167.7	129.2	1126.5	601.5	2044.5	1459.5	22020
20	80	165.5	216.2	1159.5	736.5	2271.0	1465.0	31455
40	80	160.5	148.8	1155.0	858.0	1816.5	1527.0	25260
0	160	153.5	156.9	739.5	592.5	1225.5	1473.0	17685
10	160	174.3	180.0	1050.0	885.0	1656.0	1795.5	28515
20	160	174.8	159.8	1167.0	793.5	2448.0	1639.5	27600
40	160	150.5	188.1	1360.5	718.5	2778.0	1774.5	29100
显著性[1] Significance	S	NS	*	**	*	**	NS	**
	N	NS	NS	*	NS	*	**	NS
	S×N	NS	NS	NS	NS	*	NS	NS

1) NS：差异不显著 Not significant; * $p<0.05$; ** $p<0.01$.

(二)硫、氮施用对油菜子粒含油量与产油量的影响

适量供氮可增加油菜子粒蛋白质含量而含油量相应降低[14,41]。相反,硫则利于蛋白质向脂肪的转化而使含油量提高,蛋白质含量降低[17,31]。也有研究表明,施硫后因稀释效应而使油菜子粒中油浓度降低或没有影响[4,14]。但产油量却因油菜子粒产量的增加而显著提高[4,40]。在本研究中,含油量均随施S量的增加而提高,但随施N量的增加却出现不同程度地降低。统计结果(表4,图2)表明,产油量与油菜子粒产量相关密切($R^2=0.92$)。

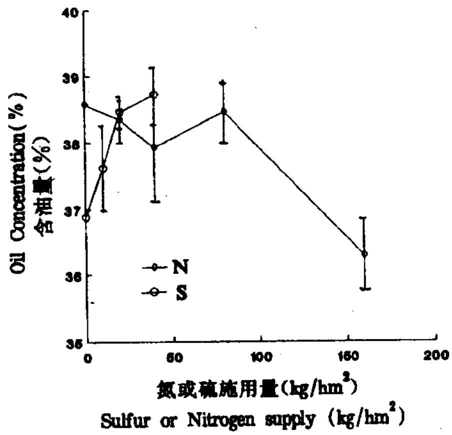

图2 氮硫施用对含油量的影响(Cudal. 1994)

Fig. 2 Oil Concentration affected by sulfur and nitrogen application

表 4 S、N对油菜子粒含油量(%)及产油量(t/hm²)的影响(Wellington, 1993)

Table 4 Effect of S and N on oil content(%) and oil yield(t/hm²) of oilseed rape in wellington

N(kg/hm²)	S(kg/hm²) 0		10		20		40		平均值 mean	
	含油量 oil cont	产油量 oil yield	含油量 oil cont	产油量 oil yield	含油量 oil cont	产油量 oil yield	含油量 oil cont	产油量 oil yield	含油量 oil cont	产油量 oil yield
0	37.22	0.459	43.30	1.347	46.14	1.608	45.39	1.717	43.01	1.283
20	40.20	0.358	43.45	1.313	46.32	1.651	46.03	1.751	44.00	1.268
40	38.78	0.345	41.96	1.239	45.88	1.595	45.74	1.717	43.09	1.224
80	37.85	0.284	40.32	1.051	45.21	1.532	46.12	1.701	42.38	1.142
160	36.82	0.262	39.52	0.940	45.24	1.547	46.18	1.780	41.94	1.132
平均值 mean	38.17	0.342	41.71	1.178	45.76	1.586	45.89	1.733		

LSD $p<0.05$	S 含油量 Oil cont.	S 产油量 Oil yield	N 含油量 Oil cont.	N 产油量 Oil yield	S×N 含油量 Oil cont.	S×N 产油量 Oil yield
	1.90	0.08	1.22	0.08	2.45	0.18

(三)硫、氮施用对油菜吸收累积硫的影响

施用硫肥可显著提高油菜子粒的硫浓度。在低硫(S_{10})和无硫(S_0)条件下,施一定量的N肥(N_{80}和N_{40})也可提高子粒S浓度,但高量N肥(N_{160})则显著降低S浓度(图3)。这种影响对油菜植株(茎、叶)S浓度也有相似趋势,在生长中,后期尤为显著(图4)。

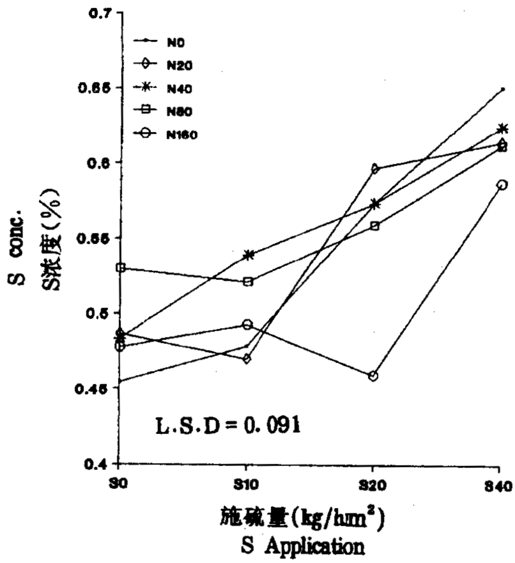

图3 N、S施氮对子粒含硫量的影响(Cudal,1994)

Fig.3 Seed S Conc. affected by S and application

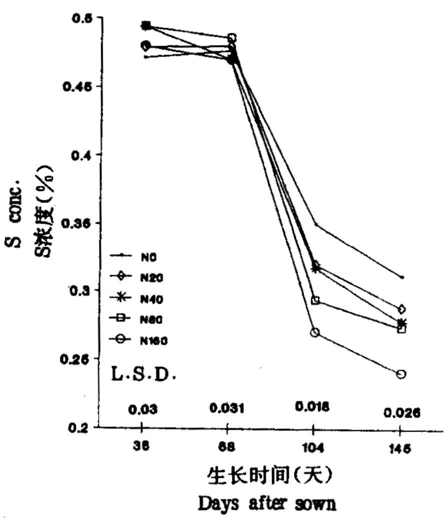

图4 施氮对不同生长期植株硫浓度的影响 (Cudal, 1994)

Fig.4 Effect of nitrogen on S conc. during growth stages

从不同生育期植株硫浓度的变化动态可见,硫浓度随油菜的生育进程趋于降低,但各施硫处理均在抽苔期(68天)出现一吸收高峰。S_{20}处理的拟合曲线符合二次方程:$Y = -0.0156X^2 + 0.0012X + 0.5276(R^2 = 0.804)$;而对照则呈指数下降,$Y = 3.7205X^{-0.595}(R^2 = 0.935)$(图5)。但从开花(104天)至角果充实期(145天)各处理均保持相对稳定。

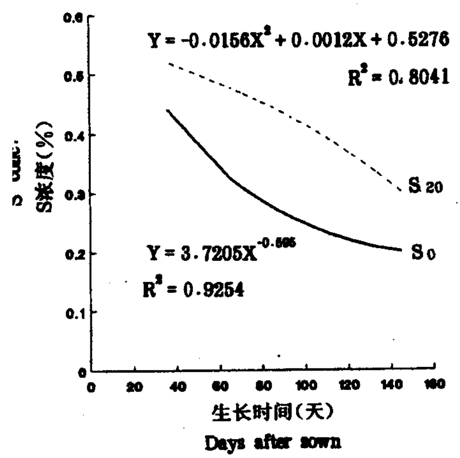

图5 植株硫浓度随时间的变化

Fig.5 Plant S conc. changes with time

硫肥施用对植株不同生育期硫的吸收累积具有明显的促进作用(图6)。施S40kg/hm²处理，角果充实期的吸S量(24.49kg/hm²)比对照(10.45kg/hm²)提高了134.4%；在开花期，施硫处理植株的吸S量较对照提高30.3%～121.6%。而氮肥施用虽对植株硫浓度产生一定影响(图4)，但对同一生育期植株硫的吸收累积量(干物重×S%)没有显著影响(图6)。

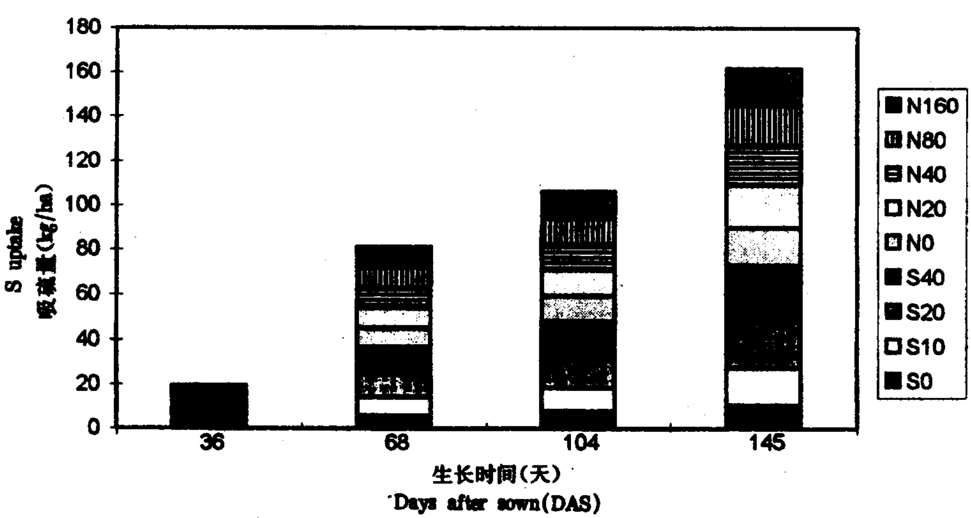

图6 氮硫对植株硫吸收累积的效应(Cudal, 1994)

Fig.6 Effect of N and S on plant S uptake and accumulation

(四)硫、氮施用对油菜子粒硫代葡萄糖甙含量的影响

油菜子粒脱油饼粕因含有高量的蛋白质(30%~39%)[1,6],是良好的畜禽饲料。但所含有的硫代葡萄糖甙经水解后会产生有毒的异硫氰酸盐(R-S-C≡N)和恶唑烷硫酮(R-N = C = S)等,含量较高时会导致动物食欲下降,生长率降低以及非反刍动物的甲状腺肿大等症状[1,13,16,19,24]。据报导,施用硫肥会增加脱油饼粕中硫代葡萄糖甙的含量[10,11,32],尤其对高硫代葡萄糖甙的品种[33]。但也有供硫充足时,子粒内硫代葡萄糖甙含量随施N量的增加而提高的报道[41]。

本研究结果表明,高剂量氮肥(N_{160})会显著降低油菜子粒的硫代葡萄糖甙含量,相反,高量施硫则明显提高其含量。因油菜子粒内的硫代葡萄糖甙含量与含硫量呈显著的指数相关($Y = 1.1572e^{3.5289x}, R^2 = 0.8273$)。试验所用的澳大利亚目前广泛栽培的双低油菜品种一卡诺拉(Canola)子粒内,即使在最高施硫水平下(S_{40})总硫代葡萄糖甙含量仍远低于国家规定标准(小于40μ mol/g)。这与Nuttal等(1987)的研究结果,即施用硫肥虽能增加Canola—双低油菜硫代葡萄糖甙含量,但不会因过量增加而影响饲喂质量的结果是一致的[11,22]。

硫、氮施用还对收获期油菜子粒含水量具有不同的影响。种子含水量随施硫量的增加而降低但随施氮量的增加而有所提高。

三、讨 论

氮、硫平衡是保障油菜正常生长发育的生理基础[3,7,9,11,15]。两年试验结果表明,在缺硫土壤,施用硫肥可显著提高油菜子粒产量;单施氮肥减产的原因主要是加剧了土壤N、S的平衡失调。因在当地油菜—牧草(苜蓿)—牧草(地中海三叶草)—油菜的轮作制度下,并经放牧羊群,其排泄物有利土壤氮素累积,使土壤有效氮含量相对较高。此外,气候干旱且无灌水条件也阻碍肥效(尤其是N肥肥效)的正常发挥。据研究,施用硫肥可提高作物对水分的利用率而在某种程度上增强作物的耐旱性[38]。Wellington的油菜子粒产量与生物量普遍高于Cudal的相应处理也说明这一点。由Cudal的产量结果可见,似乎以$S_{20}N_{20}$为最高产量组合,再增施N或S均有减产趋势,但Wellington在S_{40}以上时似乎仍有增产潜力。说明,硫是本试验条件下土壤的主要限制因子。

缺硫土壤条件下,充足供S有利于蛋白质向脂肪的转化[17,31]或通过促进含硫多酶复合体及含硫辅酶生物素的活性而促进由氨基酸向脂肪酸的合成[18]。当供S不足时,有限的S只能参予植物基本代谢产物(如氨基酸、蛋白质)的合成,供S充足时,才能满足植物进行上述的转化与合成。同时,油菜子粒的蛋白质含量与含油量可在一定的范围内表现为相对增减变化[14,41]。N肥通常有利于蛋白质的合成并且在缺硫条件下导致氨基酸、酰胺的累积[2,25,34],而蛋白质含量的增加则意味着含油量的降低。

对于低硫或无硫条件下,低量N肥促进油菜子粒及茎叶中S的吸收累积现象虽已被许多研究者所证明[20,28,29,30,36,41],但其作用机理目前尚不清楚。SO_4^{2-}是否可作为NH_4^+的相伴离子由协同作用而促进了吸收,但当高浓度时则因大量的NH_4^+优先占据了原生质膜的结合点位而减少了SO_4^{2-}(或其它离子)进入质膜的机率所致,尚待进一步研究。

抽苔期的吸硫高峰似乎对油菜产量起着重要作用。因该期植株生长量大,是由营养生长向生殖生长的转折点,并且随之而来的开花结实也需要大量的S。因此,前期(即莲座期)硫肥的供

应充足与否对需S高峰期是十分重要。有关试验报导迟于莲座期以后追施硫肥会导致产量的严重损失[15,22,27]。

对施硫油菜子粒中硫代葡萄糖甙含量的提高，主要是因足量硫的供给为油菜向这一所特有的二次代谢产物的合成提供了丰富的原料。同时促进了硫代葡萄糖甙合成产物的前体物质如半胱氨酸要是因足量硫的供给为油菜向这一所特有的二次代谢产物的合成提供了丰富的原料。同时促进了硫代葡萄糖甙合成产物的前体物质如半胱氨酸、蛋氨酸的过量增加等，为硫代葡萄糖甙的合成提供了充足的库源。而增施N肥显然会因油菜子粒硫浓度的减少以及硫代葡萄糖甙合成库源的削弱而阻碍其合成。当然，关于硫代葡萄糖甙合成的机理以及许多中间代谢产物的结构目前仍处于探讨中。

值得提出的是，虽然在最高施硫水平下，对本试验所用的双低油菜品种硫代葡萄糖甙的含量增加远低于国家规定标准，但对于高硫代葡萄糖甙含量的传统品种，则应引起重视。

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EFFECT OF SULFUR APPLICATION ON YIELD AND QUALITY OF CANOLA DOUBLE LOW OILSEED RAPE (*BRASSICA NAPUS CV.* OSCAR)

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Summary

Sulfur (S) and nitrogen (N) applicaton to canola (double low oilseed rape) was conducted on S deficient soil in New South Wales, Australia. The results indicated that sulfur supply increased seed yield and oil content significantly, certain amount of N (eg. N_{80}) with low (S_{10}) or without S (S_0) might increase seed S concentration but high rate N with high S could depress it.

Generally, S concentration in vegetative parts were decreased with plant development. There was a peak of S uptake appearing at stem elongation with S supply ($Y=-0.0156X^2+0.0012X+0.5276$, $R^2=0.804$) but exponential decrease ($Y=3.7205X^{-0.595}$, ($R^2=0.935$) without S. The S concentration in vegetative parts remained relatively stable during flowering and pod filling stages. There was no significant effect of N supply on vegetative S concentration during earlier growth stages (eg. rosette and stem elongation) but the concentration at middle and late stages (eg. flowering and pod filling) was significantly decreased by N application.

Total glucosinolates were decreased by high rate N (N_{160}) but increased by S because of a close correlation between seed S and glucosinolate concentration ($Y=1.1572e^{3.5289x}$, $R^2=0.8273$). However, even at highest rate of S, the glucosinolate concentration was still far below the standard (40μ mol/g in whole seed) so that the oil free meal would not affect feeding quality of animals.

Key Words Oilseed rape Sulfur Nitrogen Double low Yield Quality