氮磷钾配施对填充型烤烟烟碱含量的影响*

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摘 要 以东北填充型烤烟品种"龙江 911"为试验材料,通过正交回归田间试验,建立了氮、磷、钾肥与烤烟上部叶片烟碱含量的回归效应模型,并对各因子和交互作用进行了分析,模拟计算得出以降低上部叶片烟碱含量为目标的优化施肥方案.对模型解析表明,随施氮量增加,上部叶片烟碱含量呈先上升后下降趋势;随施磷量增加,烟碱含量呈上升趋势;随施钾量增加,烟碱含量呈急剧下降趋势.双因素效应大小依次为:氮钾>磷钾>氮磷,在一定范围内,氮磷、磷钾与烟碱含量表现为负相关,存在拮抗作用;而氮钾则相反,存在促进作用.对氮、磷、钾肥与烤烟上部叶片烟碱含量模型的综合分析得出:在植烟土壤为河淤土的生产区,烟田的基础施肥量建议为:氮肥 33.5~47.8 kg·hm^{-2},磷肥 40.2~63.6 kg·hm^{-2},钾肥 78.0~119.6 kg·hm^{-2}.

关键词 烤烟 烟碱含量 肥料 施肥模型

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Effects of combined fertilization of N, P, and K on nicotine content of filling type flue-cured tobacco.
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Abstract: An orthogonal regression field experiment was conducted to study the effects of combined fertilization of N, P, and K on the nicotine content in the upper leaves of filling type flue-cured tobacco (*Nicotiana tobacum*) variety "Longjiang 911" from Northeast China. The regression effect models of N, P, and K fertilization rates and upper leaf nicotine content were established, and the effects of the fertilization rates and their interactions were analyzed. Based on these, an optimized NPK fertilization scheme was drawn up to reduce the nicotine content in the upper leaves of "Longjiang 911". The model analyses showed that the nicotine content in the upper leaves of "Longjiang 911" decreased after an initial increase with the increasing fertilization rate of N, increased with the increasing fertilization rate of P, and had a sharp decrease with the increasing fertilization rate of K. The two-factor effects of NKP on the nicotine content were in the order of NK>PK>NP. Within a certain range of fertilization rates, NP and PK had negative correlations with the nicotine content, suggesting the antagonistic effects between N and P and between P and K, while NK was on the contrary, suggesting the synergistic effects between N and K. A comprehensive analysis on the regression effect models of N, P, and K fertilization rates and upper leaf nicotine content showed that the basal fertilization rates of N, P, and K for the tobacco production on warp soil were recommended as 33.5-47.8 kg·hm^{-2}, 40.2-63.6 kg·hm^{-2}, and 78.0-119.6 kg·hm^{-2}, respectively.

Key words: flue-cured tobacco; nicotine content; fertilizer; fertilization model.

烟碱是烤烟中含氮生物碱的主要成分,约占总生物碱的 90% 以上,烟叶中烟碱含量是评价烟叶质量的关键指标之一[1].在所有影响烟碱积累和含量的因素中,施肥是重要因子之一[2-3].黑龙江省是我国优质填充型烤烟生产基地.多年来,生产上氮、磷、

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钾肥的施用多以经验施肥为主,导致烤烟叶片中烟碱含量过高,烟叶化学成分的协调性不够,尤其是上部烟叶,不太适合进入配方,从而影响了烟叶的品质和工业可用性[4]. 目前有关氮、磷、钾肥对烤烟烟碱含量的影响已有较多研究,发现以氮肥对烤烟烟碱含量的影响较大,二者之间呈极显著正相关[5],增施磷肥能够提高上部烟叶烟碱含量,降低下部烟叶烟碱含量[6],而施钾肥可以降低烟碱含量[7]. 但是,这些研究大多集中于某一单因子对烤烟烟碱含量的影响,而有关氮、磷、钾多因素对烤烟烟碱尤其是东北填充型烤烟烟碱含量的影响研究鲜见报道. 为此,本研究在大田试验条件下采用二次回归最优组合设计和计算机模拟寻优的方法,拟建立氮、磷、钾肥与烤烟上部烟叶烟碱含量的经验回归模型,分析氮、磷、钾肥对烤烟上部烟叶烟碱含量的影响及其交互作用,为东北填充型烤烟达到优质烟叶烟碱量(1.5% ~3.5%)[8-9]提供科学依据.

1 材料与方法

1.1 试验区概况

试验在位于黑龙江省宁安市的中国烟草东北农业试验站进行,该区属于第二积温带(44°58′ N,129°06′ E),无霜期 130 ~ 140 d,大田生长期(5—9 月)年均降雨量约 450 mm. 土壤类型为河淤土,土壤质地为壤土,是东北填充型烤烟的主要植烟土壤. 土壤理化性质为: 有机质 27.7 $g \cdot kg^{-1}$, 全氮 1.9 $g \cdot kg^{-1}$,全磷 1.6 $g \cdot kg^{-1}$,全钾 13.0 $g \cdot kg^{-1}$,碱解氮 87 $mg \cdot kg^{-1}$,速效磷 36 $mg \cdot kg^{-1}$,速效钾 300 $mg \cdot kg^{-1}$. 供试烤烟品种为"龙江 911". 试验于 2009 年进行,5 月 12 日移栽烟苗,地膜覆盖,采用定株施肥和双侧施肥,施肥深度为 10 cm. 氮肥选硝酸铵(N 34.4%),磷肥选重过磷酸钙(P_2O_5 46%),钾肥选硫酸钾(K_2O 50%).

1.2 试验设计

试验采用"3414"二次回归最优设计,3 个因素为氮(N)、磷(P)、钾(K);4 个水平为:0 水平指不施肥,2 水平指当地最佳施肥量,1 水平等于 2 水平×0.5,3 水平等于 2 水平×1.5;共 14 个处理组合(表 1 和表 2). 小区面积不小于 99 m^2,重复间设走道 50 cm,小区之间筑埂隔离,各小区设灌水口和排水口,独立排灌,四周设保护行 1.8 ~2.2 m.

1.3 测定项目与方法

试验中每个处理单独采收,采收时选取各处理中成熟一致的上部叶片(15、16、17、18叶位),5次重复. 取样后在 105 ℃杀青 30 min、60 ℃烘 30 h、粉碎过 40 目筛,装入塑料袋中密封保存. 采用自动分析仪法测定样品的烟碱含量[10].

表 1 试验施肥水平及编码
Table 1 Levels and codes of the experimental factors

肥料 Fertilizer	施肥水平 Fertilization level ($kg \cdot hm^{-2}$)			
	0	1	2	3
N	0	22.50	45.00	67.50
P_2O_5	0	33.75	67.50	101.25
K_2O	0	67.50	135.00	202.50

表 2 施肥方案
Table 2 Fertilizer application program

处理 Treatment	N ($kg \cdot hm^{-2}$)	P_2O_5 ($kg \cdot hm^{-2}$)	K_2O ($kg \cdot hm^{-2}$)
$N_0P_0K_0$	0	0	0
$N_0P_2K_2$	0	67.50	135.0
$N_1P_2K_2$	22.5	67.50	135.0
$N_2P_0K_2$	45.0	0	135.0
$N_2P_1K_2$	45.0	33.75	135.0
$N_2P_2K_2$	45.0	67.50	135.0
$N_2P_3K_2$	45.0	101.25	135.0
$N_2P_2K_0$	45.0	67.50	0
$N_2P_2K_1$	45.0	67.50	67.5
$N_2P_2K_3$	45.0	67.50	202.5
$N_3P_2K_2$	67.5	67.50	135.0
$N_1P_1K_2$	22.5	33.75	135.0
$N_1P_2K_1$	22.5	67.50	67.5
$N_2P_1K_1$	45.0	33.75	67.5

1.4 数据处理

试验数据采用 Excel 和 DPS 软件进行统计分析. 采用单因素方差分析(one-way ANOVA)和最小显著差异法(LSD)比较不同处理间的差异. 利用 DPS 软件建立二次多项式回归模型,并对模型进行模拟和检验.

2 结果与分析

2.1 氮、磷、钾肥与烟碱含量经验模型的建立

由表 3 可知,不同肥料处理间的烤烟上部叶片烟碱含量达到显著差异,说明不同氮、磷、钾肥配施对烤烟上部叶片烟碱含量有显著影响.

由于各变量的量纲不同,对数据进行标准化处理,建立 N、P、K 施用量与上部叶片烟碱含量(Y)的回归经验模型:

$$Y=0.061+0.202N+0.251P-0.525K-0.129N^2-0.003P^2-0.021K^2-0.007N\times P+0.716N\times K-0.368P\times K \quad (1)$$

回归方程 F 值为 2.383 ($F_{0.01}=3.07$, $F_{0.05}=$

表 3　不同肥料处理的烤烟上部叶片烟碱含量

Table 3　Nicotine content in the upper leaves of flue-cured tobacco under different fertilizer treatments (mean±SD)

处理 Treatment	烟碱含量 Nicotine content (%)
$N_0P_0K_0$	3.1±0.4abc
$N_0P_2K_2$	2.4±0.2d
$N_1P_2K_2$	2.3±0.4bcd
$N_2P_0K_2$	3.0±0.3ab
$N_2P_1K_2$	2.4±0.1bcd
$N_2P_2K_2$	3.3±0.2ab
$N_2P_3K_2$	2.9±0.2abc
$N_2P_2K_0$	3.1±0.4a
$N_2P_2K_1$	3.0±0.3abcd
$N_2P_2K_3$	2.9±0.1d
$N_3P_2K_2$	3.0±0.2cd
$N_1P_1K_2$	2.8±0.2ab
$N_1P_2K_1$	3.3±0.3abcd
$N_2P_1K_1$	3.0±0.2abcd

不同小写字母表示差异显著($P<0.05$) Different small letters meant significant difference at 0.05 level.

2.20)[11],说明该数学模型在 0.05 水平显著;相关系数 $R=0.918$,说明模型拟合性较好,复相关系数 $R^2=0.843$,表明氮、磷、钾肥对上部叶片烟碱含量的影响占所有影响因素的 84.3%,而其他因素的影响和误差占 15.7%.

2.2　模型各因素效应分析

2.2.1 单因素效应对烟碱含量的影响　通过模型(1)中的一次项标准回归系数的绝对值大小可以直接判断氮、磷、钾肥对烤烟上部叶片烟碱含量的影响程度. 一次项系数中氮肥(N)和磷肥(P)为正值,钾肥(K)为负值,表明氮肥和磷肥与烟碱含量呈正相关关系,钾肥与烟碱含量呈负相关关系,影响程度依次为:钾肥>磷肥>氮肥. 单因素分析采用降维法,分析不同施肥水平下上部叶片烟碱含量的变化规律,即在 3 个因素中,固定 2 个因素于 0 水平,做 X-Y 折线图(图 1). 从图 1 可以看出,氮肥呈先上升后下降趋势,氮肥施用量为 22.5 $kg \cdot hm^{-2}$时上部叶片烟碱含量最高,磷肥呈上升趋势,钾肥呈急剧下降趋势.

2.2.2 双因素交互效应对烟碱含量的影响　将其中 2 个因素水平设为 0,可以得到以下子模型:

$$Y=0.061+0.202N+0.251P-0.129N^2-0.003P^2-0.007N\times P \quad (2)$$

$$Y=0.061+0.251P-0.525K-0.003P^2-0.021K^2-0.368P\times K \quad (3)$$

$$Y=0.061+0.202N-0.525K-0.129N^2-0.021K^2+0.716N\times K \quad (4)$$

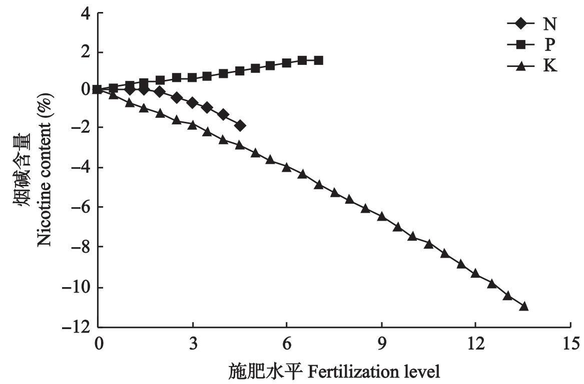

图 1　N、P、K 单因素对烤烟上部叶片烟碱含量的影响

Fig. 1　Effects of N, P, K fertilizer on nicotine content in the upper leaves of flue-cured tobacco.

将氮、磷、钾的不同施肥水平值分别代入方程(2)、(3)、(4)计算得出标准化后的上部烟叶烟碱含量(表 4). 通过以上 3 个子模型可知,氮肥和磷肥、磷肥和钾肥对上部叶位烟碱含量表现为拮抗作用,氮肥和钾肥对上部叶位烟碱含量表现为促进作用. 由表 4 可知,中氮高磷、低钾高磷和低氮低钾时烟碱含量最高,低氮低磷、高钾高磷和低氮高钾时烟碱含量最低. 随着氮肥水平的提高,烟碱含量呈上升趋势,但当磷肥水平在 2 和 3 及钾肥水平在 0 和 1 时,随着氮肥的增加烟碱含量呈先上升后下降的趋势. 随着磷肥水平的提高,烟碱含量呈上升趋势,但当钾肥水平在 3 时,随着磷肥的增加,烟碱含量呈先上升后下降趋势. 随着钾肥水平的提高,烟碱含量呈下降趋势,但当氮肥水平在 3 时,随着钾肥的增加,烟碱含量呈上升趋势. 说明氮、磷、钾肥对上部烟叶烟碱含量的影响存在一个适宜的范围,低于或高于这个范围都无法降低上部烟叶的烟碱含量.

2.3　优化施肥方案的选择

根据单因素、双因素交互效应结果及氮、磷、钾肥与烤烟烟碱含量的经验模型,为了在当地生态环境条件下取得最适宜的施肥方案,本研究采用频数分析法[11]进行模型的优化. 在试验约束条件范围内($0\leq R\leq 3$),经计算机模拟寻优得到了 $4^3=64$ 套组合方案,将这 64 个理论值按一定的区域统计频率,频次分布见表 5. 一般认为,优质烟叶的烟碱含量为 1.5% ~3.5%,其中上部叶位是 2.5% ~3.5%,中部叶位是 2.0% ~2.8%,下部叶位是 1.5% ~2.0%[10]. 大田试验中当上部烟叶烟碱含量在 2.5% ~3.5%范围内,氮肥水平主要分布在 1 水平至 3 水平,即施氮量为 22.5 ~67.5 $kg \cdot hm^{-2}$;磷肥水平主要分布在 0 水平至 3 水平,即施磷量为

表 4 双因素交互效应对烟碱含量的影响
Table 4 Effects of two factors interaction on the nicotine content

因素 Factor	水平 Level			
氮/磷 N/P	0	1	2	3
0	-1.249	-0.929	-0.619	-0.317
1	-0.615	-0.306	-0.005	0.288
2	-0.337	-0.038	0.254	0.537
3	-0.414	-0.125	0.157	0.430
磷/钾 P/K	0	1	2	3
0	-0.768	-0.525	-0.340	-0.213
1	0.333	0.068	-0.254	-0.634
2	1.426	0.654	-0.176	-1.064
3	2.510	1.231	-0.107	-1.502
氮/钾 N/K	0	1	2	3
0	2.584	0.478	-1.685	-3.907
1	1.651	0.533	-0.644	-1.878
2	0.362	0.231	0.042	-0.205
3	-1.282	-0.426	0.372	1.112

0 ~ 101.25 kg · hm^{-2};钾肥水平主要分布在 1 水平至 2 水平,即施钾量为 67.5 ~ 135 kg · hm^{-2}.

计算 41 个方案中各个因子的加权平均数和标准误,并进行参数的区间估计(表 6).当上部烟叶烟碱含量在 2.5% ~ 3.5% 时,大田试验适宜的氮肥施用量为 33.47 ~ 47.75 kg · hm^{-2},磷肥施用量为 40.17 ~ 63.55 kg · hm^{-2},钾肥施用量为 77.96 ~ 119.6 kg · hm^{-2}.

表 5 烟碱含量为 2.5% ~ 3.5%时 41 个施肥方案中各变量取值的频率分布
Table 5 Frequency distribution of variable values in 41 fertilizer application schemes with nicotine content between 2.5% and 3.5%

水平 Level	氮肥 N	频率 Frequency (%)	磷肥 P_2O_5	频率 Frequency (%)	钾肥 K_2O	频率 Frequency (%)
0	5	12.2	9	22.0	7	17.1
1	10	24.4	11	26.8	15	36.6
2	14	34.2	11	26.8	12	29.3
3	12	29.3	10	24.4	7	17.1

表 6 优化施肥方案
Table 6 Optimum fertilizer application scheme

因素 Factor	加权平均数 Mean of additive weight	标准误 Standard error	95% 的分布区间 Distribution range of 95%	
			下限 Lower limit	上限 Upper limit
氮肥 N	40.61	3.53	33.5	47.8
磷肥 P_2O_5	51.86	5.79	40.2	63.6
钾肥 K_2O	98.78	10.30	78.0	119.6

3 讨 论

施肥是影响烤烟叶片烟碱合成和积累的重要外部因素[12].研究表明,氮、磷、钾肥配施对烟叶的化学成分有显著影响[13],其中以氮素对烟碱含量和积累的影响最显著[14].汪耀富等[15]研究表明,施氮量与烟叶中烟碱含量呈正相关.招启柏等[16]研究认为,不同时期氮肥对烟碱合成的贡献有显著差别,尤其在烤烟打顶前后施氮肥对烟碱含量的影响最明显;不同氮素形态对烟碱含量的影响也存在差异,成熟期烟碱含量随硝态氮施用比例的增加而下降.本研究通过建立氮、磷、钾肥与上部叶片烟碱含量之间的经验模型发现,氮肥与上部叶片烟碱含量呈正相关关系,但是随施氮量的增加,上部叶片烟碱含量呈先上升后下降的趋势,这与烤烟生长期间的土壤矿化氮含量[17]和烤烟不同时期对氮素的利用量有直接关系,本试验是以松花江和牡丹江流域的填充型烤烟为材料,因此,与其生长的河淤土的供氮水平有密切关系.烤烟植株对氮素的大量需求主要集中在旺长阶段,而烟株生长后期土壤氮素营养供应不足减少了烟株特别是上部叶片对氮素的积累[18].

有关磷肥对烟碱的影响主要集中在磷素与氮素的配比上,磷肥与 NH_4^+-N 配合施用能显著促进烟碱的合成,而与 NO_3^--N 配合施用的效果则不明显,说明磷不能直接参与生物碱的合成,但能加速烟碱合成之前的硝酸还原等过程[19].本研究表明,磷肥与上部叶片烟碱含量呈正相关,这与肖庆礼等[6]的部分研究结果相似,不同的是随着磷肥的增加烟碱含量并未出现下降趋势(图 1),这可能是由于施入磷肥的上限不够大,对烟碱合成和积累的时间未出现显著影响,另外长期施入磷肥使土壤速效磷积累过多也可能是导致烟碱增加的原因[20].

钾肥对改善烤烟品质有显著作用[21],被认为是烤烟的品质元素.一般情况下,烟碱含量随钾肥用量的增加而显著降低,不同施钾水平与烟碱含量间表现为极显著负相关[22].本研究表明,钾肥与上部叶片烟碱含量呈负相关关系,这可能与烤烟是喜钾作物有关,烤烟大量吸收钾元素降低了对氮元素的吸收[23],从而抑制了烟碱的合成;并且增施钾肥导致植株生物学产量增加,由此形成的稀释效应超过了氮肥合成烟碱的作用,这可能是导致烟碱含量下降的另一个原因.氮、磷、钾双因素对烟碱含量的影响

依次为氮钾>磷钾>氮磷，在一定的值域内，氮肥和磷肥、磷肥和钾肥互作与烟碱含量表现为负相关，即存在拮抗作用；而氮肥和钾肥互作则相反，即存在促进作用. 但是高于或低于这个值域则表现出相反的效果，因此，氮、磷、钾肥互作存在一个合理的值域，在这个值域内可以降低上部叶片的烟碱含量，提高叶片的工业可用性和降低对人体的危害.

4　结　　论

以国际优质烟叶上部叶片烟碱含量 2.5% ~ 3.5%[8-9]为目标函数，建立了填充型烤烟氮、磷、钾肥与烤烟烟碱含量的经验模型，并进行优化. 结果表明，上部叶片烟碱含量达到优质烟叶指标的田间氮肥施用量为 33.5 ~ 47.8 kg · hm^{-2}，磷肥施用量为 40.2 ~ 63.6 kg · hm^{-2}，钾肥施用量为 78.0 ~ 119.6 kg · hm^{-2}，即 N : P : K = 1 : 1.3 : 2.4. 试验中建立的回归经验模型在一定范围内能够指导烤烟生产，但是应用于实际烤烟生产中还需要结合产量、产值及品质等指标进行更系统的研究.

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