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## 喷施纳米钼肥对烤烟生长及氮磷钾累积量的影响

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**摘要** 为探明喷施普通钼肥和纳米钼肥对烤烟生长及氮磷钾累积量的影响差异,以云烟87为供试材料,采用盆栽试验,设置5个处理:对照(CK)、钼酸铵(T1)、纳米氧化钼(T2)、纳米钼酸锌(T3)和纳米钼酸钾(T4),对烤烟农艺性状、干物质积累、钼含量和氮磷钾累积量进行分析。结果显示,喷施普通钼肥和纳米钼肥均能有效提高烤烟株高、叶长、叶宽及叶片总糖含量,但以纳米钼酸锌处理最好。纳米钼酸锌处理下,烤烟幼苗叶片鲜质量和干质量分别比喷施钼酸铵处理提高了32.29%和29.95%;与对照相比,喷施钼酸铵、纳米氧化钼、纳米钼酸锌和纳米钼酸钾处理烤烟叶片钼累积量分别提高了18.48倍、17.30倍、11.72倍和16.70倍;喷施钼肥处理烤烟叶片氮磷钾累积量均有增加趋势,其中纳米钼酸锌处理烤烟叶片氮、磷、钾累积量分别比对照提高了30.61%、39.94%和48.78%,比钼酸铵分别提高了18.86%、28.79%和20.92%。表明纳米钼肥促进烤烟生长和氮磷钾吸收的效果优于普通钼肥,其中纳米钼酸锌效果最好。

**关键词** 烤烟; 钼肥; 纳米钼; 纳米肥料; 烟株生长; 氮磷钾

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烤烟是产量和品质并重的叶用型经济作物,烟叶产量主要取决于烟株干物质累积量,质量则与烟株中氮磷钾等养分含量的吸收及其在烟株体内的分配密切相关。氮是构成烟株各器官的重要化学元素,对烟叶产量和品质形成有重要作用<sup>[1-2]</sup>。磷参与烟株体内磷酸、磷脂、植酸和核蛋白等重要物质的合成,能够促进氮代谢和碳水化合物合成与运输,并提高烟叶中糖分含量<sup>[3-4]</sup>。钾是烤烟的品质元素,通过促进烟株体内蛋白质代谢和多种酶反应过程等,提高烤烟香气质、香气量和燃烧性<sup>[5-6]</sup>。

钼是植物生长发育所必需的营养元素之一,参与植物中的生物固氮、硝态氮同化、植物激素合成及活性氧代谢等诸多生物过程<sup>[7-8]</sup>。无论是土施还是叶面喷施,钼肥均可显著提高烟草叶片光合作用和叶绿素含量及稳定性,促进碳水化合物的合成转运,增加干物质的积累,对提高烟叶产量和产值具有促

进作用<sup>[9-10]</sup>。植物体内钼含量低且变幅较大,我国部分植烟区烟叶钼含量在痕量至5.83 mg/kg,平均为1.0 mg/kg左右<sup>[11]</sup>,整体处于较低水平。缺钼可直接影响氮磷钾的吸收与利用,制约烤烟产量和品质的提高。适量施用钼肥可显著提高含钼酶及碳氮代谢相关酶基因的表达<sup>[12]</sup>,促进烤烟氮素吸收与转化,降低烟株体内硝态氮含量,提高氮素利用率<sup>[13]</sup>,并且对烤烟“增糖提钾”具有显著促进作用<sup>[14]</sup>。研究表明,烟叶钼含量与土壤有效钼含量呈极显著正相关,而我国大部分植烟区土壤有不同程度钼缺乏现象<sup>[15]</sup>,仅靠土壤中有效钼不能满足烟株正常生长发育。因此,在钼缺乏的植烟区土壤,及时补充钼肥,对提高烟叶产量和品质具有重要意义。

纳米肥料既有促进作物生长的特点,也具有缓慢释放养分的优点。前期研究发现,低浓度纳米三氧化钼促进大豆生长和提高产量的效果优于钼酸铵

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和普通三氧化钼<sup>[16-17]</sup>。叶面喷施纳米钼酸钾可显著提升冬小麦和油菜的钼含量,提高作物光合作用和产量<sup>[18]</sup>。肖晓璐等<sup>[19]</sup>研究也指出,油菜叶面喷施纳米钼酸钾,可通过增强氮代谢关键酶活而促进叶片内无机氮向有机氮转化,有利于蛋白质合成。目前,纳米钼肥在烟草优质高效生产中的应用未见报道。为此,本研究设置离子钼和纳米钼肥叶面喷施试验,明确离子钼和不同纳米钼肥对烤烟生物量、光合色素和氮磷钾素吸收累积的影响,旨在筛选出烤烟苗期适宜的钼源,为钼肥的有效合理应用提供理论依据。

## 1 材料与方法

### 1.1 供试材料

供试烤烟品种为云烟87。纳米氧化钼、纳米钼酸锌和纳米钼酸钾购自湖北省中澳纳米材料技术有限公司。供试土壤为湖北省武汉市新洲区缺钼酸性黄棕壤,其基本理化性质为:pH 4.69,有机质18.06 g/kg,速效钾62.47 mg/kg,有效磷7.42 mg/kg,碱解氮72.8 mg/kg,有效钼0.10 mg/kg。

### 1.2 试验设计与实施

采用土培方式,试验在华中农业大学盆栽场温室内进行(光照16 h,黑暗8 h,温度25 °C,湿度30%)。烤烟种子在装有蛭石的育苗盘中发芽,培养45 d,长至2叶1心时,选取长势均匀的烟苗移栽至装有4 kg土壤的盆(上径15.5 cm,下径12.5 cm,高17.5 cm)中,每盆1株。土壤中N、P<sub>2</sub>O<sub>5</sub>、K<sub>2</sub>O用量分别为0.24、0.24、0.48 g/kg,试验所用过磷酸钙、硫酸钾均为分析纯(AR),在烟株生长发育期内用去离子水浇灌。

试验设置5个处理:对照(去离子水,CK)、钼酸铵(T1)、纳米氧化钼(T2)、纳米钼酸锌(T3)和纳米钼酸钾(T4),每个处理4次重复。纳米钼肥分散于去离子水,并超声(25 °C,100 W,40 kHz)分散30 min,以获得钼质量浓度均为200 mg/L的悬浮液。当烟苗长到4~5叶期时,进行叶面喷施处理,每3 d喷施1次,共喷施3次[30 mL/(株·d)],早午晚各喷施15 mL),烟株长至9~10片有效叶时进行农艺性状测定及采样分析。在喷施过程中,盆口用透明塑料覆盖以避免纳米颗粒与土壤介质接触。

### 1.3 测定项目及方法

1)纳米钼肥表征。取10 mg纳米钼肥,溶解于50 mL无水乙醇中,超声(25 °C,100 W,40 kHz)处理

30 min,用电镜专用铜网蘸取悬浮液并自然晾干,送至华中农业大学电镜平台(TEM,H7650)观察其形貌和分布。

2)农艺性状调查。按照烟草行业标准YC/T 142—2010《烟草农艺性状调查测量方法》测量烟株高、茎围、最大叶长、最大叶宽和有效叶片数。

3)生物量测定。小心将盆中土壤完全倒出,用水轻轻冲洗土壤,尽可能获取较为完整的根系。收获烟株的叶片和根系用自来水和蒸馏水洗净、擦干后记录鲜质量;将该样品在105 °C杀青30 min,并在60 °C烘干至恒质量后记录干质量。

4)叶绿素含量测定。使用日本Minolta生产的SPAD-502型叶绿素计。色素含量采用95%乙醇提取法测定,取倒数第6片叶剪碎,称取0.2 g叶片于25 mL 95%乙醇中避光浸提24 h,取上清液。以95%乙醇为空白,使用紫外分光光度计分别在649、665和470 nm测定吸光度,计算叶绿素a、叶绿素b、类胡萝卜素和叶绿素a+b含量。每个处理4次重复。

5)植株氮磷钾养分测定。称取烟株各部位粉碎样品0.150 g左右,采用H<sub>2</sub>SO<sub>4</sub>-H<sub>2</sub>O<sub>2</sub>消化。用流动分析仪(FIAstar5000,Sweden)测定总氮、总磷含量,火焰光度计(6400A,上海)测定样品总钾含量。

6)植株钼含量测定。称取约0.20 g样品于50 mL锥形瓶中,加入10 mL的HNO<sub>3</sub>/HClO<sub>4</sub>(9:1,V:V)混酸静置过夜后,在180 °C电热板上完全消化,用去离子水转移定容至25 mL后过滤,使用ICP-MS(EXPEC 7000,FPI)测定植株钼含量。

7)还原糖和总糖含量测定。采用3,5-二硝基水杨酸比色法<sup>[20]</sup>。

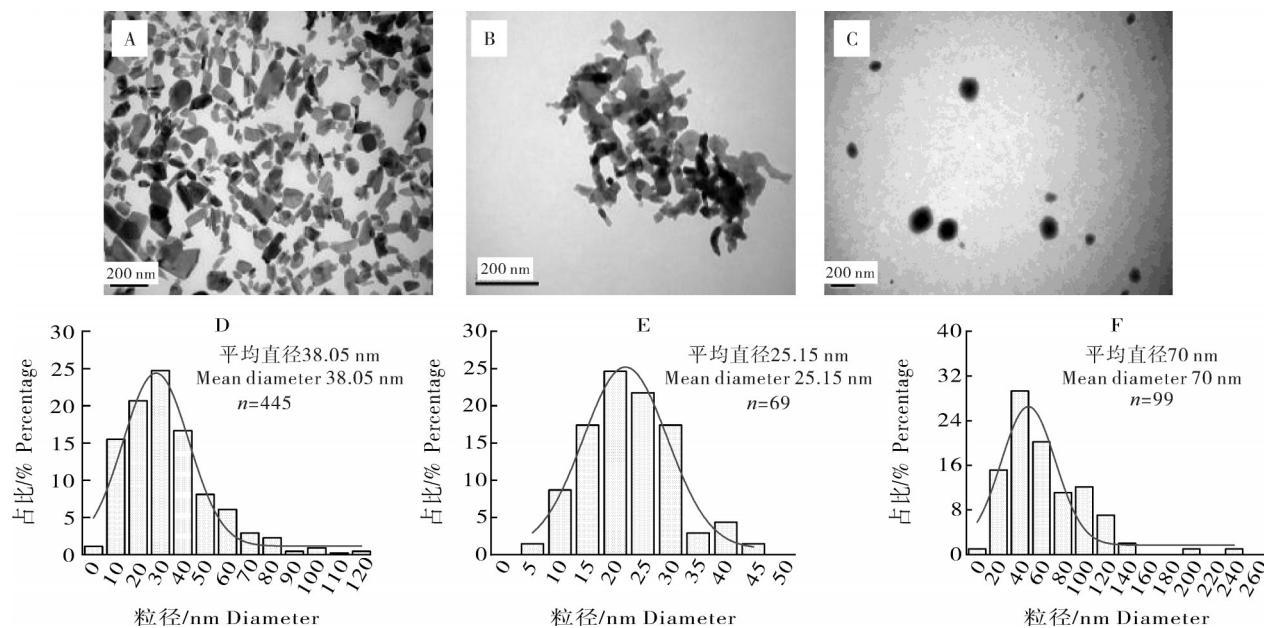
### 1.4 数据处理与分析

采用Excel 2019和IBM SPSS Statistics 23进行试验数据整理和数据统计、使用Duncan's法进行处理间显著性检验,并用Origin 2021软件绘图。

## 2 结果与分析

### 2.1 纳米钼肥表征

透射电子显微镜(TEM)观察显示,纳米氧化钼呈片状结构,且分散较为均匀(图1A),对颗粒的粒径大小进行统计,得到其平均粒径为38.05 nm;纳米钼酸锌呈现不规则结构,分布较为聚集(图1B),平均粒径大小为25.15 nm;纳米钼酸钾呈液滴状并伴有少量介孔(图1C),其平均粒径大小为70.00 nm。



A、B、C 分别为纳米氧化钼、纳米钼酸锌和纳米钼酸钾的 TEM 图;D、E、F 分别为纳米氧化钼、纳米钼酸锌和纳米钼酸钾的粒径分布。  
A, B, C: TEM images of nano molybdenum oxide, nano zinc molybdate and nano potassium molybdate. D, E, F: Particle size distribution of nano molybdenum oxide, nano zinc molybdate, and nano potassium molybdate.

图1 3种纳米钼肥的形貌和粒径分布

Fig.1 Morphology and particle size distribution of three types of nano-molybdenum fertilizers

## 2.2 喷施纳米钼肥对烟株农艺性状的影响

由表1可见,与CK相比,团棵期烤烟最大叶长和最大叶宽均在T3和T4处理下显著增加,增幅分别为23.06%、22.47%和22.89%、26.56%,而喷施钼肥处理对烤烟茎围和有效叶片数影响不大。此外,喷

施不同钼肥对烤烟农艺性状的影响存在显著差异,与T1(钼酸铵)相比,喷施纳米钼酸锌(T3)和纳米钼酸钾(T4)对提高烤烟株高、最大叶长、最大叶宽和有效叶片数等农艺指标作用更好。

表1 不同形态钼肥处理下烟株农艺性状

Table 1 Agronomic traits of flue-cured tobacco under different Mo fertilizers treatments

处理 Treatment	株高/cm Plant height	茎围/cm Stalk circumference	最大叶长/cm Max leaf length	最大叶宽/cm Max leaf width	单株有效叶数 Effective leaves per plant
CK	13.75±0.90ab	4.13±0.22a	22.25±0.75b	13.63±0.74c	10.0±0.7ab
T1	13.25±1.64b	4.23±0.23a	25.13±1.24ab	14.88±1.88bc	9.3±0.4b
T2	14.83±0.54ab	4.13±0.13a	22.88±2.65b	13.50±1.06c	9.3±1.1b
T3	17.13±3.09a	3.88±0.37a	27.38±2.90a	16.75±1.15ab	10.5±0.5ab
T4	17.00±2.32a	3.88±0.12a	27.25±1.60a	17.25±1.09a	10.8±0.4a

注:CK:去离子水;T1:钼酸铵( $(\text{NH}_4)_6\text{Mo}_7\text{O}_{24} \cdot 4\text{H}_2\text{O}$ );T2:纳米氧化钼( $\text{MoO}_3$  NPs);T3:纳米钼酸锌( $\text{Zn}_9\text{Mo}_8\text{O}_{33}$  NPs);T4:纳米钼酸钾( $\text{K}_2\text{MoO}_4$  NPs)。不同小写字母表示根据Duncan's检验不同处理间显著差异( $P<0.05$ )( $n=4$ )。下同。Note: CK: Deionized water; T1: Ammonium molybdate ( $(\text{NH}_4)_6\text{Mo}_7\text{O}_{24} \cdot 4\text{H}_2\text{O}$ ); T2: Nano molybdenum trioxide ( $\text{MoO}_3$  NPs); T3: Nano zinc molybdate ( $\text{Zn}_9\text{Mo}_8\text{O}_{33}$  NPs); T4: Nano potassium molybdate ( $\text{K}_2\text{MoO}_4$  NPs). Different lowercase letters indicate significant differences at 0.05 level ( $n=4$ ) among different treatments according to Duncan's test. The same as below.

## 2.3 喷施纳米钼肥对烤烟生物量的影响

与CK相比,喷施钼肥可提高烟株的生物量,以T3和T4处理最为显著,叶片鲜质量和干质量分别显著提高了32.29%、31.51%和29.93%、24.23%;茎秆鲜质量和干质量分别显著提高了38.50%、53.57%和40.06%、52.95%;根系鲜质量无明显变化,而干质量

显著提高了26.08%和31.17%(图2)。且喷施不同类型钼肥对烤烟叶片生物量的影响差异显著。与T1相比,T3和T4处理下烤烟叶片鲜质量分别显著提高了12.00%和11.34%,干质量提高了11.20%和6.37%。综上,喷施钼肥能够提高烤烟各部位的生物量,且以T3处理效果最佳。

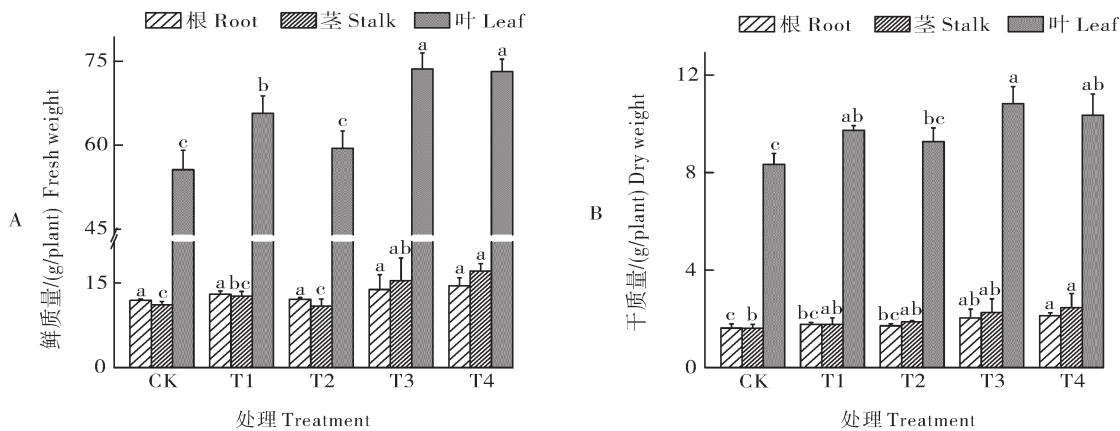


图2 不同形态钼处理下烤烟根茎叶鲜质量(A)和干质量(B)  
Fig.2 Fresh weight(A) and dry weight(B) of root, stalk and leaf of flue-cured tobacco under different Mo fertilizers treatments

#### 2.4 喷施纳米钼肥对烤烟叶片叶绿素含量的影响

喷施钼肥对提高烤烟叶片叶绿素含量具有一定的促进作用(表2)。与CK相比,T1~T4处理均可提高烤烟叶绿素a含量;除T3处理,其他施钼处理均可提高烤烟叶绿素b和类胡萝卜素含量( $P>0.05$ )。综合叶绿素(a+b)含量和SPAD值来看,喷施钼肥可提高团棵期烤烟叶绿素含量。

#### 2.5 喷施纳米钼肥对新鲜烟片总糖和还原糖含量的影响

与CK相比,喷施不同钼肥均可提高烤烟叶片还

原糖含量,增幅为2.73%~22.96%,各施钼处理下叶片还原糖增加幅度略有差异,但均未达到显著水平(图3A)。此外,施用钼肥能够提高叶片总糖含量(图3B),与CK相比,其中T1、T2和T3处理下叶片总糖含量分别显著增加了31.62%、27.49%和39.84%,T4处理提高7.99%( $P<0.05$ )。由此可见,喷施钼肥能够提高烟叶总糖和还原糖含量,这对烟叶碳代谢具有促进作用。

#### 2.6 喷施纳米钼肥对烤烟钼吸收转运的影响

与CK相比,喷施钼肥均可显著提高烤烟根、茎、

表2 不同形态钼处理下烤烟叶绿素含量

Table 2 chlorophyll content in flue-cured tobacco leaves under different Mo fertilizers treatments

处理 Treatment	叶绿素a/(mg/g) Chlorophyll a	叶绿素b/(mg/g) Chlorophyll b	类胡萝卜素/(mg/g) Carotenoid	叶绿素(a+b)/(mg/g) Chlorophyll (a+b)	SPAD
CK	1.22±0.13a	0.37±0.15ab	0.38±0.03a	1.58±0.21ab	52.17±2.46a
T1	1.34±0.36a	0.61±0.19a	0.40±0.11a	1.95±0.33ab	53.03±2.75a
T2	1.56±0.15a	0.45±0.15ab	0.41±0.06a	2.02±0.12a	55.36±1.71a
T3	1.22±0.13a	0.28±0.18b	0.33±0.03a	1.49±0.07b	53.16±2.84a
T4	1.30±0.25a	0.45±0.11ab	0.38±0.08a	1.75±0.36ab	53.68±1.35a

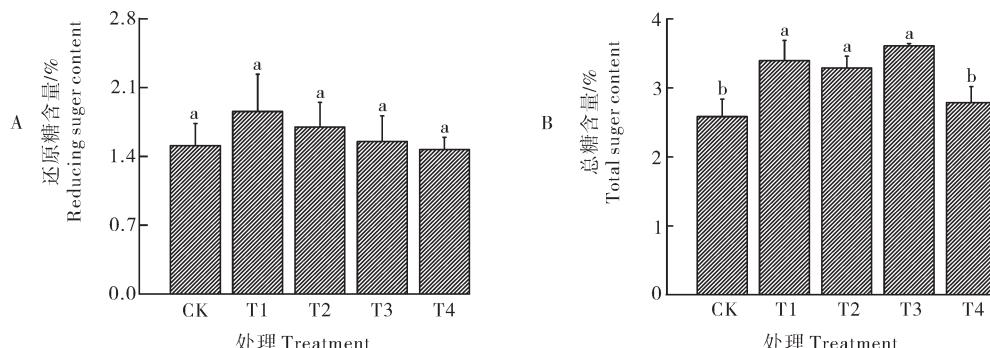


图3 不同形态钼处理下烤烟叶片还原糖(A)和总糖含量(B)

Fig.3 The content of reducing sugars(A) and total sugars(B) in flue-cured tobacco leaves under different Mo fertilizers treatments

叶中钼含量(图4)。以T1为对照,T2处理下烤烟根系和茎秆钼含量分别显著增加了157.69%和30.25%,叶片钼含量无显著差异;T3和T4处理下根

系钼含量分别显著提高了65.38%和46.15%(图4A),而叶片、茎部钼含量则分别显著降低41.48%、14.45%和17.39%、53.12%(图4B)。

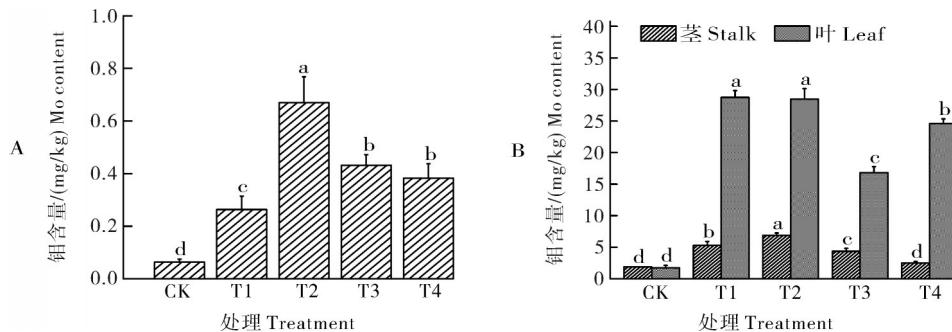


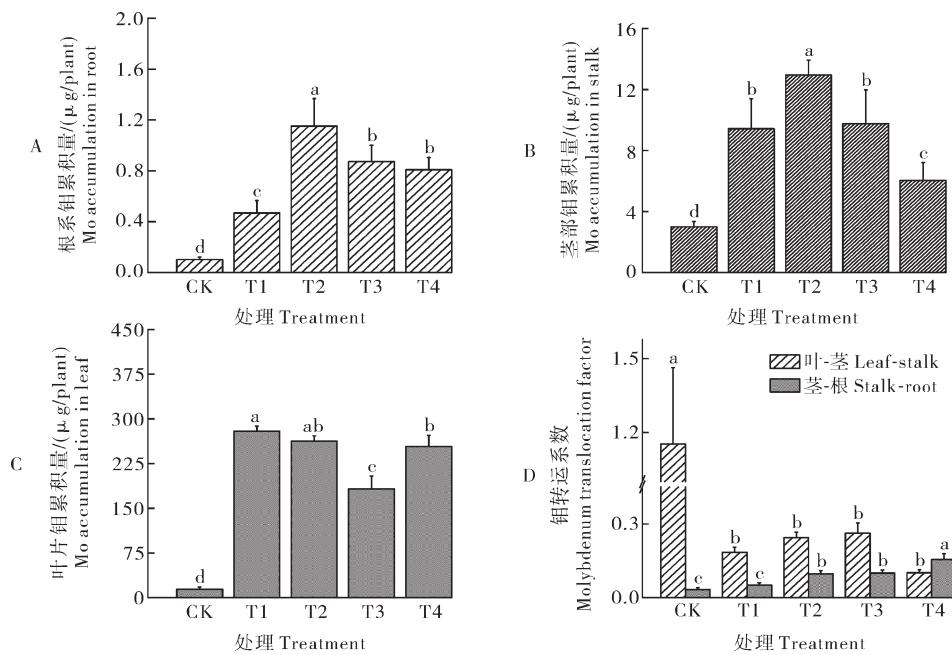
图4 不同形态钼肥处理下烤烟根(A)、茎和叶(B)钼含量

Fig.4 Mo content of root(A), stalk and leaf(B) in flue-cured tobacco under different Mo fertilizers treatments

与CK相比,各钼肥处理均可显著增加烤烟钼累积量,不同器官钼累积量表现为叶>茎>根(图5)。不同钼肥对烟株根、茎和叶片钼累积量的影响具有明显差异。在施钼处理中,与T1相比,T2、T3、T4处理均可显著提高根系钼累积量,增幅分别为145.30%、85.62%和72.19%(图5A);茎部钼累积量在T2处理下显著提高了37.37%,T4处理下显著降低了35.77%(图5B);叶片钼累积量在T2处理下略有降低( $P>0.05$ ),而在T3和T4处理下分别显著降

低了34.68%和9.13%(图5C)。

钼转运系数越大,说明钼的转运能力越强。与T1处理相比,钼从叶片到茎的转运系数在T2和T3处理分别提高35.31%和45.52%,T4处理降低43.76%;钼从茎到根系的转运系数在T2、T3和T4处理分别显著提高了94.17%、99.23%和210.13%(图5D)。总体而言,施钼肥处理中,纳米形态钼肥比普通钼肥具有更高效地将钼从地上部向根部转运的能力。



A:根系钼累积量;B:茎部钼累积量;C:叶片钼累积量;D:钼转运系数。A:Mo accumulation in root;B:Mo accumulation in stalk;C:Mo accumulation in leaf;D:Translocation factor of Mo.

图5 不同形态钼肥处理下烤烟各部位钼累积量和转运系数

Fig.5 The accumulation and translocation factor of Mo in flue-cured tobacco under different Mo fertilizers treatments

## 2.7 喷施纳米钼肥对烤烟氮吸收转运的影响

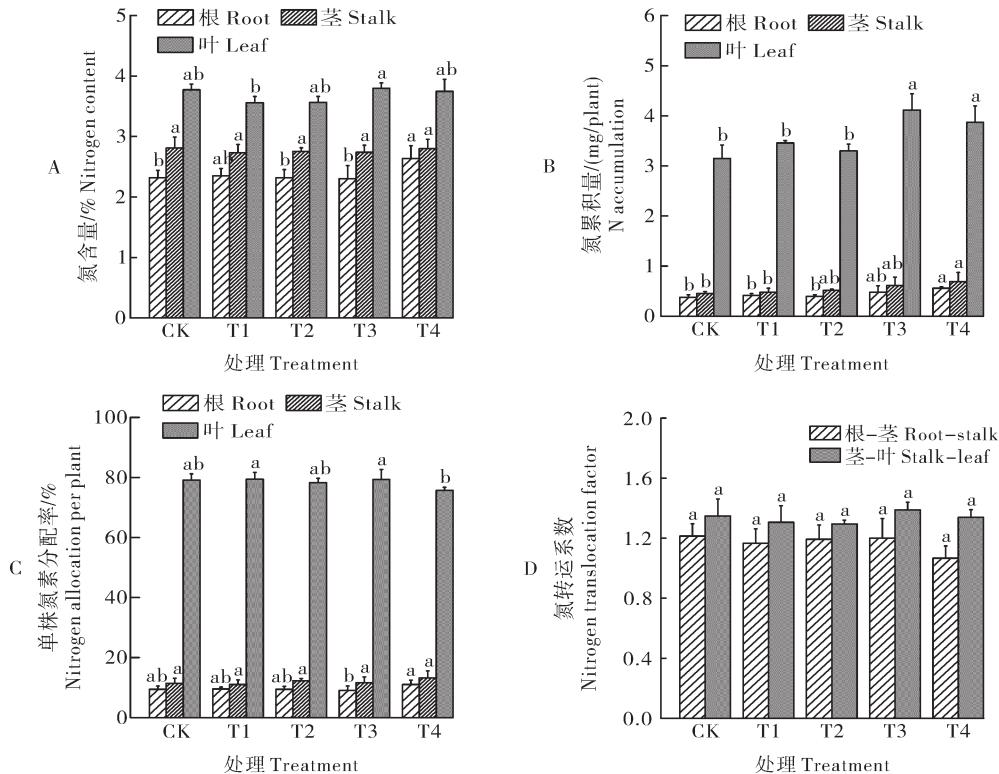
与CK相比,根系氮含量仅在T4处理下显著提

高48.27%,茎秆和叶片氮含量均无明显差异。喷施

纳米钼肥对根系和茎秆氮含量影响不大,叶片氮含

量仅在T3处理下显著增加6.68%(图6A)。烤烟叶片氮累积量在T3和T4处理下显著高于其他处理,分别较CK显著提高30.61%和22.95%,较T1处理提高18.86%和11.88%(图6B)。不同施钼处理下,烤烟根系、茎秆和叶片氮素分配率与CK相比均无显著差异;而与T1相比,仅T4处理下叶片氮素分

配率显著降低4.94%(图6C)。此外,与CK相比,施钼处理对烤烟根系向茎秆的氮转运系数以及茎秆向叶片的氮转运系数均无显著影响,T3处理下茎秆向叶片的氮转运系数最高,这表明该处理下叶片氮含量较高(图6D)。综上,T3处理能够促进团棵期烤烟对氮素的吸收累积并促进氮素向叶片转运。



A:氮含量;B:氮积累量;C:单株氮素分配率;D:氮转运系数。A: Nitrogen content; B: Nitrogen accumulation; C: Nitrogen allocation per plant; D: Translocation factor of nitrogen.

图6 不同形态钼肥处理下烤烟氮的吸收转运

Fig.6 Nitrogen absorption and transport in flue-cured tobacco under different Mo fertilizers treatments

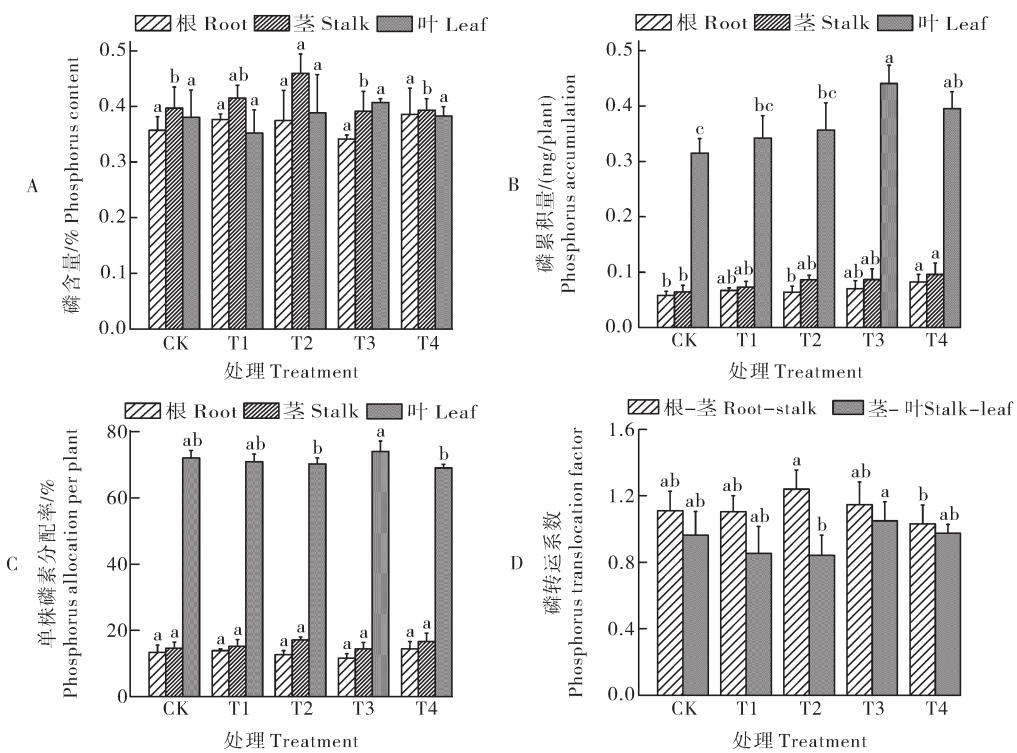
## 2.8 喷施纳米钼肥对烤烟磷吸收转运的影响

与CK相比,施钼处理下烟株根系和叶片磷含量无显著变化,仅在T2处理下茎秆磷含量显著提高15.76%(图7A)。根系和茎秆磷累积量在T4处理下最高,而叶片磷累积量在T3和T4处理较高,分别较CK显著提高了39.94%和25.64%(图7B)。与CK相比,喷施钼肥处理对烤烟根系、茎秆和叶片磷素分配率无明显影响,其中,叶片磷素分配率在T3处理下最高,并显著高于T2和T4处理(图7C)。施钼处理下根部向茎秆的磷转运系数无显著差异,而茎秆向叶片的磷转运系数在T3处理下较T1和T2明显增加了23.53%和25.00%,表明T3处理能够促进磷素从茎秆向叶片转运(图7D)。

## 2.9 喷施纳米钼肥对烤烟钾吸收转运的影响

烤烟根系和茎秆钾含量在施钼处理下(T3除外)

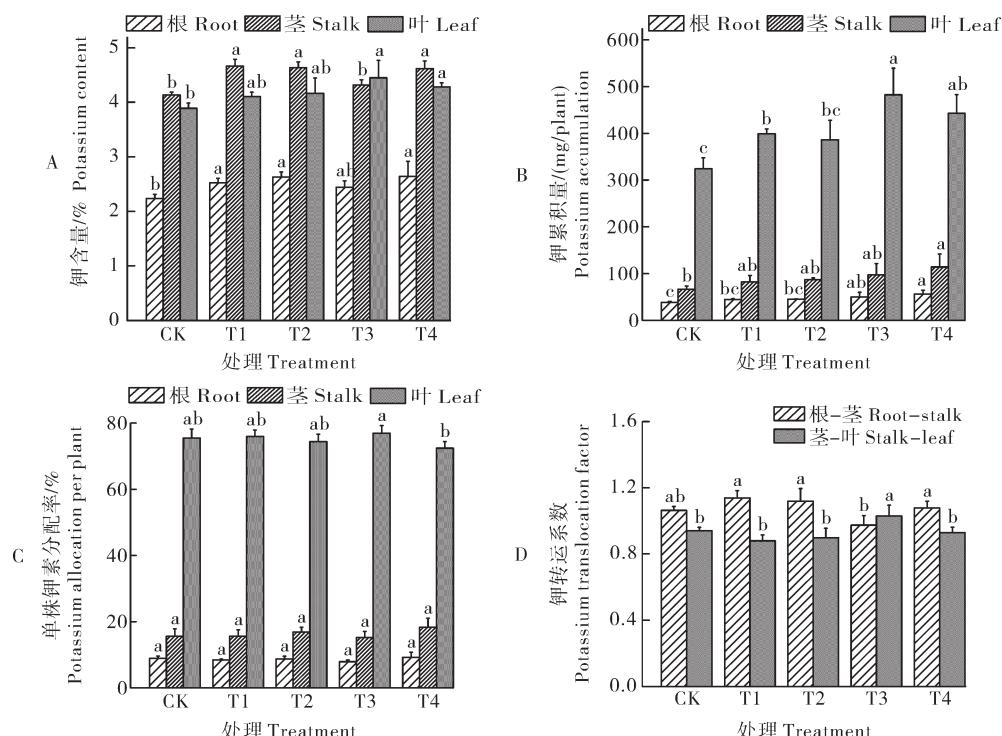
均显著高于CK处理,叶片钾含量则在T3和T4处理下分别较CK显著提高14.35%和10.04%。在喷施钼处理中,与T1相比,T3处理下叶片钾含量增加了8.36%,但差异不显著(图8A)。与CK相比,根系和茎秆钾累积量均在T4处理下显著增加,增幅分别为47.06%和71.28%;叶片钾累积量在T1、T3和T4处理下分别显著提高23.04%、48.78%和36.63%。相较于T1,根系钾累积量在T4处理下显著增加38.09%,叶片钾累积量在T3处理下显著增加20.92%(图8B)。施钼处理对各器官钾素分配无显著影响(图8C)。烤烟根部向茎秆的钾转运系数在各处理下无明显变化,而茎秆向叶片的钾转运系数在T3处理下最高,较CK和T1处理分别显著提高了9.57%和17.05%,表明T3处理能够显著促进钾素从茎秆向叶片转运(图8D)。



A: 磷含量; B: 磷积累量; C: 单株磷素分配率; D: 磷转运系数。A: Phosphorus content; B: Phosphorus accumulation; C: Phosphorus allocation per plant; D: Translocation factor of phosphorus.

图7 不同形态钼肥处理下烤烟磷的吸收转运

Fig.7 Phosphorus absorption and transport in flue-cured tobacco under different Mo fertilizers treatments



A: 钾含量; B: 钾积累量; C: 单株钾素分配率; D: 钾转运系数。A: Potassium content; B: Potassium accumulation; C: Potassium allocation per plant; D: Translocation factor of potassium.

图8 不同形态钼肥处理下烤烟钾的吸收转运

Fig.8 Potassium absorption and transport in flue-cured tobacco under different Mo fertilizers treatments

### 3 讨 论

研究表明,施用纳米微量元素肥料在增强作物光合作用、促进干物质积累、提高产量和品质上的效果要优于普通微量元素肥料<sup>[21-23]</sup>。目前,纳米钼肥在农业生产中展现出良好的效果,可提高大豆<sup>[22]</sup>、鹰嘴豆<sup>[24]</sup>、水稻<sup>[25]</sup>和小白菜<sup>[26]</sup>等的品质和产量。本研究结果表明,喷施钼肥能够提升烟株株高、最大叶长和最大叶宽,增加烤烟生物量,以喷施纳米钼酸锌和纳米钼酸钾(T3和T4)的效果最为显著;原因可能是喷施钼肥提高了烤烟叶片叶绿素a、叶绿素b、类胡萝卜素含量,提高了光合作用效率。光合作用的增强为烤烟生长提供更多的能量和有机物质基础,进而促进干物质累积和生物量的增加。此外,喷施钼肥后,烟叶还原糖和总糖含量增加,表明钼肥有利于提高烟苗碳同化能力,促进碳水化合物的合成,为其他代谢过程提供能量和碳骨架,进一步促进烤烟的生长发育。在所有处理中,喷施纳米钼酸锌促进烤烟生长的效果最佳,这可能是因为纳米钼酸锌可以同时补充钼和锌,这2种元素在光合作用中不可或缺,钼参与硝酸还原酶的组成,锌参与光合作用中CO<sub>2</sub>水合反应,两者的协同作用增强了叶片光合作用,增加了干物质积累,从而提高了烤烟生物量,这一结果与已有研究<sup>[27-28]</sup>一致。

叶面喷施钼肥可显著提高烤烟各部位钼含量和累积量,均表现为叶片>茎>根,这表明叶面喷施钼肥能够通过叶器官向茎秆及地下部转移(图4),这种转移特性对于植物营养的均衡分配具有重要意义。在细胞水平上,纳米颗粒可以穿过细胞壁并被运输到细胞质,通常分散的纳米颗粒比聚集的纳米颗粒更有效进入细胞<sup>[29]</sup>。大量研究表明,纳米材料从叶表面到叶内的运输效率主要受颗粒大小的限制,直径小于50 nm的金属纳米颗粒在叶片表面具有较强的附着能力,能够通过气孔途径进入植物叶片,随着颗粒尺寸的增加,叶片的吸收能力会减弱<sup>[30-32]</sup>。在本研究中,与传统钼肥(钼酸铵)相比,纳米钼肥(纳米氧化钼和纳米钼酸锌)在烤烟地上部向根部的钼转运系数呈明显增加的趋势,这说明纳米钼肥能够被植物叶片吸收并向根部转运,且其转运的能力优于普通钼肥。这主要归功于纳米氧化钼和纳米钼酸锌粒径小,分散性好,使其更容易被植物吸收和转运。

作物钼营养的改善能促进大量元素NPK的协同

吸收。陈志青等<sup>[33]</sup>研究指出,在相同施氮水平下,离子钼和纳米钼肥可显著提高植株各器官的氮素积累量和氮素利用率。本研究中,喷施钼肥对烟株各部位总氮含量无显著影响,这可能是因为底肥中的氮肥能够满足烤烟在团棵期对氮素的吸收利用。但是在喷施纳米钼酸锌和纳米钼酸钾处理下,叶片氮累积量分别较对照处理和离子钼处理显著提高,表明纳米钼肥能够优化氮素在植株内的分配和利用。钾是影响烟叶品质和安全性的重要元素,K<sup>+</sup>通道在植物细胞膜上的存在已经得到广泛认同,因此膜的稳定性对钾的吸收和累积具有影响。已有研究表明,膜的稳定性受钼的间接影响<sup>[34]</sup>,施用钼肥可显著降低叶片质膜透性,提高烟草抗膜脂过氧化胁迫,提高烟株对钾的吸收<sup>[35]</sup>。在本研究中,喷施钼肥处理均能够提高烤烟叶片、茎和根部钾含量和累积量,尤其是喷施纳米钼酸锌和纳米钼酸钾时,叶片钾含量和累积量增加显著。可能是纳米颗粒的电荷性质导致细胞膜通透性改变或促进钾离子通道蛋白基因的表达,促进烟草对钾的吸收<sup>[36]</sup>。

综上,纳米钼肥在增强作物光合作用和促进烤烟生长方面效果显著。在养分吸收方面,纳米钼肥因具有小尺寸、缓释控等独特性质,在提高烤烟各部位钼含量和累积量、优化氮素分配和利用以及提升钾吸收效率等方面优于传统钼肥。本研究中,纳米钼酸锌因同时补充钼和锌2种元素、表现出最佳的促生长和养分累积效果,可为烤烟生产中纳米钼肥的合理应用提供参考。

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## Effects of spraying nano-molybdenum fertilizer on growth and accumulation of nitrogen, phosphorus, and potassium in flue-cured tobacco

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**Abstract** Yunyan 87 was used to study the differences in the effects of spraying ordinary molybdenum fertilizer and nano molybdenum fertilizer on the growth of tobacco and the accumulation of nitrogen-phosphorus-potassium in flue-cured tobacco. A pot experiment with five treatments including control (CK), ammonium molybdate (T1), nano molybdenum oxide (T2), nano zinc molybdate (T3), and nano potassium molybdate (T4) was conducted to analyze the agronomic traits, the accumulation of dry matter, the content of molybdenum, and the accumulation of nitrogen-phosphorus-potassium in tobacco. The results showed that both spraying ordinary molybdenum fertilizer and nano molybdenum fertilizer effectively increased the plant height, leaf length, leaf width, and the content of total sugar in tobacco leaves, but the effect of the treatment with nano molybdenum zinc sulfate was the best. The fresh weight and dry weight of tobacco leaves under nano molybdenum zinc sulfate treatment increased by 32.29% and 29.95% compared to that under T1. The accumulation of molybdenum in tobacco leaves under the T1, T2, T3, T4 increased by 18.48 times, 17.30 times, 11.72 times, and 16.70 times compared to that under the control. The accumulation of nitrogen-phosphorus-potassium in tobacco leaves tended to increase under molybdenum fertilizer treatments. The accumulation of nitrogen, phosphorus, and potassium in tobacco leaves under T3 increased by 30.61%, 39.94%, and 48.78% compared to that under the control, surpassing the increase of 18.86%, 28.79%, and 20.92% under T1. It is indicated that nano molybdenum fertilizer is more effective than ordinary molybdenum fertilizer in promoting the growth of tobacco seedlings and the absorption of nitrogen, phosphorus, and potassium, with nano zinc molybdate (T3) having the best performance.

**Keywords** flue-cured tobacco; molybdenum fertilizer; nano-molybdenum; nano fertilizer; the growth of tobacco; nitrogen-phosphorus-potassium

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