董高艺,彭寄民,李洁,等.叶面喷施水溶性硅肥提高蒜苗产量与品质及土壤肥力[J].山西农业大学学报(自然科学版),2025,45(5):78-86.
Dong G Y, Peng J M, Li J, et al. Foliar application of water-soluble silicon fertilizer improves garlic seedling yield and quality and improves soil fertility[J]. Journal of Shanxi Agricultural University(Natural Science Edition), 2025,45(5):78-86.
doi: 10.13842/j.cnki.issn1671-8151.202507032

叶面喷施水溶性硅肥提高蒜苗产量与品质及土壤肥力

董高艺[1,2],彭寄民[1,2],李洁[2],黄燕[1,2],闵祖璇[1,2],于镇瑞[2,3],聂文敏[4],郑井元[1,2,3*]

(1.湖南农业大学 园艺学院,湖南 长沙 410128;2.湖南省蔬菜研究所,湖南 长沙 410125;
3.湖南大学生物学院 隆平分院,湖南 长沙410125;4.凡美(广州)农业科技有限公司,广东 广州 511400)

摘　要:[目的]本试验旨在探究新型水溶性硅肥不同施肥浓度对蒜苗生长发育及土壤肥力的影响,以期为蒜苗优质高产提供理论支持。[方法]以'四川大蒜'为试验材料,设置3个不同浓度的叶面喷施硅肥处理,即常规施肥+叶面喷施30 L/hm^2(T1)、常规施肥+叶面喷施60 L/hm^2(T2)、常规施肥+叶面喷施120 L/hm^2(T3),以常规施肥+等量清水为对照(CK),先后于大蒜播种出苗后第8、16、24 d进行喷施。定植65 d后采收时,分析不同处理对蒜苗株高、假茎粗、SPAD值、产量、品质、pH、电导率和土壤养分与酶活性的影响。[结果]叶面喷施硅肥蒜苗株高增加4.08~11.58 cm,假茎粗增粗0.90~2.03 mm,SPAD值较CK提高了8.5%~12.5%;显著提高蒜苗产量,且较CK提高2.5%~15.3%,其中以T2处理产量最优;在品质方面,T2、T3处理显著提高蒜苗可溶性糖和维生素C含量,可溶性糖含量增加33.4%~62.2%,维生素C含量增加17.1%~50.1%。喷施硅肥也改善了土壤养分,土壤pH显著提高;仅T2处理的土壤速效钾、碱解氮、有效磷和有机质含量显著高于CK;各处理土壤酶活性亦增加,且T2处理的过氧化氢酶、脲酶、蔗糖酶活性显著高于其它处理,较CK分别提高了11.8%、23.3%、25.5%。[结论]叶面喷施硅肥能促进蒜苗生长,提高蒜苗品质,改善土壤理化性质,提高土壤酶活性,以常规施肥+叶面喷施60 L/hm^2(T2)效果最好。

关键词:水溶性硅肥; 蒜苗; 产量; 品质; 土壤养分; 土壤酶活性
中图分类号:S633.4　　**文献标识码**:A　　**文章编号**:1671-8151(2025)05-0078-09

Foliar application of water-soluble silicon fertilizer improves garlic seedling yield and quality and improves soil fertility

Dong Gaoyi[1,2], Peng Jimin[1,2], Li Jie[2], Huang Yan[1,2], Min Zuxuan[1,2], Yu Zhenrui[2,3], Nie Wenmin[4], Zheng Jingyuan[1,2,3*]

(*1.College of Horticulture, Hunan Agricultural University, Changsha 410128, China; 2.Hunan Vegetable Research Institute, Changsha 410125, China; 3.Longping Branch, School of Biology, Hunan University, Changsha 410125, China; 4.Fanmei (Guangzhou) Agricultural Technology Co., Ltd., Guangzhou 511400, China*)

Abstract: [Objective] Garlic is an important economic crop with a long cultivation history in China. However, with the continuous expansion of planting scale, traditional garlic cultivation heavily reliant on macronutrient fertilizers often leads to chlorosis and stunting of seedlings, thereby limiting yield. Water-soluble silicon fertilizer has demonstrated yield-increasing and quality-improving effects in cereal crops such as wheat, but its application in vegetable crops like garlic seedlings remains less studied. This experiment aimed to explore the effects of different application rates of a new water-soluble silicon fertilizer on the growth and development of garlic seedlings and soil fertility, to provide the theoretical support for high-quality and high-yield garlic seedling production. [Methods] Using 'Sichuan garlic' as the experimental material, three foliar spray treatments with different sili-

收稿日期:2025-07-16　　**修回日期**:2025-09-28
基金项目:国家大宗蔬菜产业技术体系(CARS-23-B14)
作者简介:董高艺(ORCID:0009-0001-3878-4715),硕士研究生,研究方向:土壤重金属治理,E-mail:2141333905@qq.com
* **通信作者**:郑井元,研究员,博士,E-mail:zhengjingyuan2004@hunaas.cn

con fertilizer concentrations were set up (concentrations were expressed in L/hm^2, consistent with reporting conventions for liquid fertilizers in the literatures): conventional fertilization + foliar spraying of 30 L/hm^2 silicon fertilizer (T1), conventional fertilization + foliar spraying of 60 L/hm^2 silicon fertilizer (T2), and conventional fertilization + foliar spraying of 120 L/hm^2 silicon fertilizer (T3). A control(CK) received conventional fertilization plus an equal volume of water. Foliar sprays were applied on the 8th, 16th, and 24th days after sowing and seedling emergence. At harvest, 65 days after transplanting, the effects of the different treatments were analyzed for plant height, pseudostem diameter, SPAD value, yield, quality, soil pH, electrical conductivity, soil nutrient content, and soil enzyme activities. [Results]Compared to CK, foliar spray of silicon fertilizer increased plant height by 4.08～11.58 cm, pseudostem diameter by 0.90～2.03 mm, and SPAD value by 8.5%～12.5%. It significantly increased garlic seedling yield by 2.5%～15.3%, with the T2 treatment yielding the highest. In terms of quality, T2 and T3 treatments significantly increased the soluble sugar and vitamin C contents of seedlings: soluble sugar content rose by 33.4%～62.2%, and vitamin C content by 17.1%～50.1%. Silicon fertilizer spray also improved soil nutrients and significant increased soil pH. Only the T2 treatment resulted in significantly higher soil available potassium, alkali-hydrolyzable nitrogen, available phosphorus, and organic matter content compared to CK. Soil enzyme activities increased across all treatments, with catalase, urease, and sucrase activities in the T2 treatment being significantly higher than in other treatments, showing increases by 11.8%, 23.3%, and 25.5%, respectively, compared to CK. [Conclusion]In summary, foliar application of water-soluble silicon fertilizer promoted garlic seedling growth, improved seedling quality, enhanced soil physical and chemical properties, and increased soil enzyme activities. The most effective treatment was conventional fertilization combined with foliar spraying of silicon fertilizer at 60 L/hm^2 (T2).

Keywords: Water soluble silicon fertilizer, Garlic, Output, Quality, Soil nutrients, Soil enzyme

大蒜(*Allium sativum* L.)幼苗又称蒜苗,属百合科葱属,为1～2年生草本植物,是我国栽培历史悠久的重要经济作物[1]。其营养价值丰富,含有丰富的蛋白质、氨基酸、维生素C和可溶性糖等多种营养成分,且具有较高的药用价值,经常食用能提高人体免疫力,在预防皮肤癌和胃癌等方面发挥积极作用[2-3]。然而,随着大蒜种植规模的持续扩大,生产中面临的问题日益突出,长期连作导致土壤养分失衡,引发大蒜植株生长受阻、蒜头偏小、蒜薹纤细等问题[4]。同时,生产者普遍偏重N、P、K等大量元素肥料的施用,忽视了微量元素的科学配比,而微量元素缺乏会致使大蒜植株矮小、叶片黄化,干扰光合作用等生理代谢过程,最终导致产量下降、品质降低[5-6]。因此,研究更合理的大蒜施肥方式,是打破连作导致的土壤养分失衡、补其微量元素供给缺口的核心途径,可有效缓解植株生长受阻、叶片黄化等问题,避免产量下降与品质降低;同时对保障作物的生产效益、维持其丰富营养与药用价值具有关键意义。

硅作为植物生长的重要营养元素,在促进作物增产、改善品质及提高抗逆性等方面作用显著[7],不仅能改良酸性土壤,增强土壤微生物活性[8-9],还可提升作物光合速率[10],促进根系生长和分枝,进而实现产量提高和品质改善[11]。水溶性硅肥作为一种新型肥料,具有溶解性高、吸收快、施用便捷及环保性强的特点[12],通过叶面喷施可经叶片快速吸收并转移至植株各部位,从而有效提高作物产量和品质。已有研究表明,喷施水溶性硅肥能降低油菜籽粒和豆荚对Cd的吸收并提高其生物量[13]。叶面施肥可显著提升草莓果实的可溶性固形物、可溶性糖含量及糖酸比、硬度[14]。目前,水溶性硅肥在水稻、小麦等粮食作物上多以灌根方式应用[15-16],在蒜苗等蔬菜作物上应用的报道较少。目前,水溶性硅肥对蒜苗的适配性及体内转运机制不明,连作下硅肥调控土壤酶活、改善养分失衡无具体量化研究结果。因此,本试验以'四川大蒜'为材料,探究不同浓度水溶性硅肥对蒜苗生长、产量、品质及土壤养分、酶活性的影响,旨在为硅肥在蒜苗生产中的科学施用提供理论支撑和实践指导。

1　材料与方法

1.1　试验地概况

于2024年10-12月在湖南省湘潭市雨湖区湖南尚勇生态农业发展有限公司蔬菜基地(27°20′～28°05′ N,111°58′～113°05′ E)进行田间试验,试验区为亚热带季风气候,年均气温17.2 ℃,年均降水量1320 mm[17]。试验地土壤类型为水稻土,土壤质地为壤土,基本理化性质为pH值为4.63,电导率为1283 μs/cm,有机质含量为38.63 g/kg,碱

解氮、有效磷、速效钾含量分别为520.79、290.36和874.52 mg/kg。

1.2 试验材料

供试大蒜品种为'四川大蒜',由湖南尚勇生态农业发展有限公司提供。供试硅肥为凡美田含硅水溶肥料(硅含量100 g/L、黄腐酸含量25 g/L、氧化钾含量140 g/L、腐殖酸含量25 g/L),由凡美(广州)农业科技有限公司提供。

1.3 试验设计

试验采用单因素随机区组设计,在常规施复合肥(N∶P_2O_5∶K_2O=15∶15∶15,600 kg/hm^2)基础上,共设4个处理,CK:常规施肥+等量清水;T1:常规施肥+叶面喷施30 L/hm^2(水溶性硅肥加水稀释至500倍,T2、T3同);T2:常规施肥+叶面喷施60 L/hm^2;T3:常规施肥+叶面喷施120 L/hm^2。小区宽1.2 m,长19 m,面积为22.8 m^2,各处理重复3次,共计12个小区。叶面喷施硅肥在大蒜3叶期开始,每隔8 d喷1次,整个生育期共喷施3次。

1.4 样品采集与测定方法

1.4.1 蒜苗农艺性状、SPAD值及产量测定

于蒜苗商品成熟采收期(定植后65 d),各小区随机选取3株长势一致的蒜苗植株,用卷尺测定植株株高,即每处理重复9次;用游标卡尺测定假茎粗;利用SPAD-502叶绿素仪测定蒜苗由外往内数3片叶片的上、中、下3个部位,每个叶片取其平均值作为该叶片的SPAD值,每个植株选3个叶片、每个小区选3个植株,每处理重复9次。

1.4.2 蒜苗品质指标测定

在蒜苗商品成熟采收期(定植后65 d),各小区分别随机选取3株植株,进行可溶性蛋白、氨基酸、维生素C和可溶性糖含量测定,测定试剂盒均购自上海茁彩生物科技有限公司,每指标各处理均重复9次。叶片的可溶性蛋白含量依据《GB 5009.5-2025 食品安全国家标准 食品中蛋白质的测定》、氨基酸含量依据《GB 5009.124-2016 食品安全国家标准 食品中氨基酸的测定》、维生素C含量依据《GB 5009.86-2016 食品安全国家标准 食品中抗坏血酸的测定》、可溶性糖含量依据《GB 5009.8-2023 食品安全国家标准 食品中果糖、葡萄糖、蔗糖、麦芽糖、乳糖的测定》进行测定。

1.4.3 土壤理化指标测定

蒜苗商品成熟采收期(定植后65 d),在各小区0~20 cm耕层使用五点取样法采集土样,混合均匀后测定10项土壤理化指标,每指标各处理均重复9次。土壤pH值采用pH计测定,电导率采用电导率仪测定,有机质含量依据《NY/T 1121.6-2006 土壤检测 第6部分:土壤有机质的测定》、速效钾含量依据《NY/T 889-2004 土壤速效钾和缓效钾含量的测定》、有效磷含量依据《NY/T 1121.7-2014 土壤检测 第7部分:土壤有效磷的测定》、碱解氮含量采用碱解扩散法[18]进行测定。参照关松萌[19]的方法进行土壤酶活性测定,土壤脲酶、蔗糖酶、过氧化氢酶、酸性磷酸酶活性分别采用靛酚蓝比色法、3,5-二硝基水杨酸比色法、高锰酸钾滴定法、磷酸苯二钠比色法测定。

1.5 统计分析

采用Excel 2016进行数据整理,使用单因素方差分析(ANOVA)计算平均值与标准差,用最小显著性差异(LSD)法进行显著性差异分析,采用Prism 8.0、Origin 2022进行绘图。

2 结果与分析

2.1 叶面喷施不同浓度硅肥后蒜苗生长指标

在蒜苗商品成熟采收期测定株高和假茎粗,发现叶面喷施不同浓度硅肥对蒜苗生长有较明显的促进作用,T1、T2、T3处理相比CK的平均株高分别提升了10.13、11.58、4.03 cm,假茎粗分别增粗了2.03、1.65、0.90 mm,T1和T2处理的这2个指标均显著高于对照(表1)。结果表明,适量施用硅肥能够明显促进蒜苗生长,其中T2处理对蒜苗株高的促进效果较为突出,T1处理则在增粗假茎方面表现更优。

2.2 叶面喷施不同浓度硅肥后蒜苗产量及SPAD值

蒜苗叶面喷施不同浓度的硅肥均可提高蒜苗的产量和SPAD含量,但高浓度时指标增幅减少(图1)。随施硅肥浓度的增加,蒜苗产量呈现先上升后下降的趋势,T1、T2、T3处理的蒜苗产量相比CK分别提高了10.9%、15.3%、2.5%,但仅有T2处理与CK存在显著差异,说明T2处理更有利于提高蒜苗产量(图1a)。3个处理的蒜苗叶片SPAD值与CK相比分别提高8.7%、12.5%、8.5%,且均与CK差异显著,但各处理间差异不显著,说明T1、T2、T3处理对提高蒜苗叶片SPAD值的效果相似,均可提高蒜苗商品性(图1b)。

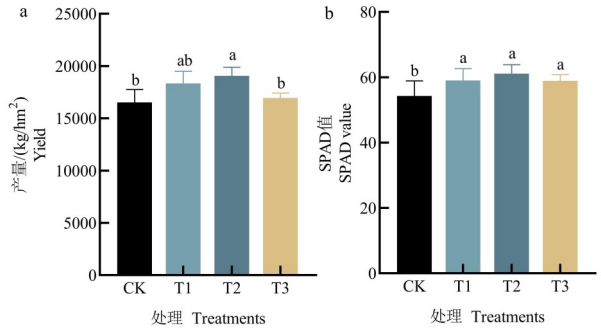
表1　叶面喷施不同浓度硅肥后蒜苗株高、假茎粗

Table 1　Plant height and pseudostem diameter of garlic seedlings after foliar spray with different concentrations of silicon fertilizer

处理 Treatments	株高/cm Plant height	假茎粗/mm Pseudostem diameter of garlic seedlings
CK	61.40±8.35b	7.99±1.36b
T1	71.53±6.59a	10.02±1.19a
T2	72.98±6.55a	9.64±1.09a
T3	65.48±6.41ab	8.89±1.29ab

注:CK为常规施肥+等量清水;T1为常规施肥+叶面喷施30 L/hm^2;T2为常规施肥+叶面喷施60 L/hm^2;T3为常规施肥+叶面喷施120 L/hm^2。同列数据后不同小写字母表示不同处理间差异显著($P<0.05$)。

Note:CK: combination of conventional fertilization and an equal amount of water; T1: conventional fertilization+foliar spraying at 30 L/hm^2; T2: conventional fertilization+foliar spraying at 60 L/hm^2; T3: a combination of conventional fertilization and foliar spraying at a rate of 120 L/hm^2. Different lowercase letters in the same column indicated significant differences between different treatments ($P<0.05$).



CK为常规施肥+等量清水;T1为常规施肥+叶面喷施30 L/hm^2;T2为常规施肥+叶面喷施60 L/hm^2;T3为常规施肥+叶面喷施120 L/hm^2。不同小写字母表示不同处理间差异显著($P<0.05$)。图2~图5同

CK: combination of conventional fertilization and equal amounts of water; T1: conventional fertilization+foliar spraying at 30 L/hm2; T2: conventional fertilization+foliar spraying at 60 L/hm2; T3: a combination of conventional fertilization and foliar spraying at a rate of 120 L/hm2. Different lowercase letters indicated significant differences among different treatments ($P<0.05$). The same as Fig. 2 to Fig. 5

图1　叶面喷施不同浓度硅肥后蒜苗产量及SPAD值

Fig.1　Garlic seedling yield and SPAD value after foliar application of different concentrations of silicon fertilizers

2.3　叶面喷施不同浓度硅肥后蒜苗品质

测定商品成熟采收期的蒜苗的可溶性蛋白、氨基酸、可溶性糖和维生素C含量(图2),结果发现:3个处理的可溶性蛋白与氨基酸含量相比于CK均有提高但差异不显著(图2a和2b);各处理的可溶性糖含量相比于CK显著提高,分别提高33.4%、62.2%和61.1%,以T2处理提升效果最好(图2c);各处理的维生素C含量与CK相比分别提高17.1%、42.9%和50.1%,其中T2、T3处理与CK存在显著差异(图2d)。可见,硅肥的使用可以明显提升蒜苗可溶性糖和维生素C含量,且以T2处理表现最好。

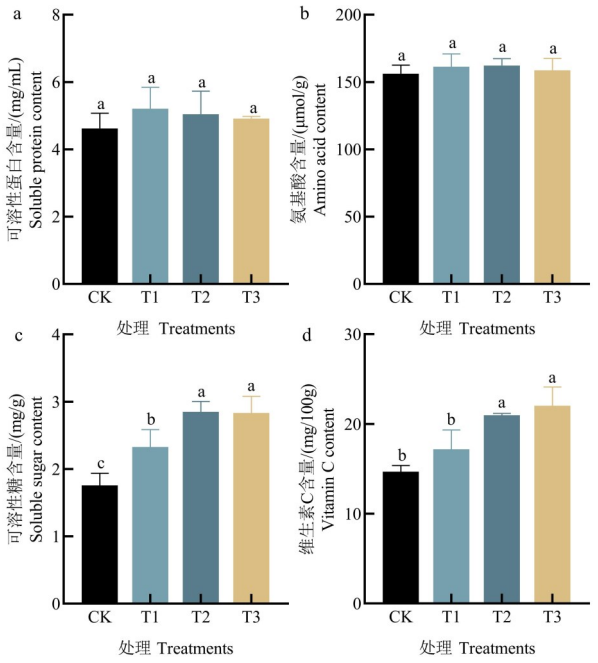


图2　叶面喷施不同浓度硅肥后蒜苗品质

Fig.2　Garlic seedling quality after foliar spraying with different concentrations of silicon fertilizers

2.4　不同处理下蒜苗土壤pH和电导率

不同浓度的硅肥处理均可提高蒜苗土壤的pH和电导率(图3)。由图3a可见,相比CK,T1、T2、T3处理土壤pH分别提高了0.28、0.41、0.27,仅T2处理与CK存在显著差异;由图3b可见,各处理的电导率分别比CK提高了9.0%、5.4%和10.2%,但均差异不显著(图3b)。结果表明,T2处理为调节蒜苗土壤酸碱度的最优选择,可使土壤pH显著提升;而硅肥对土壤电导率的提升效果整体较弱,且未随施肥浓度变化呈现显著差异。

2.5　不同处理下蒜苗土壤养分含量

对商品成熟采收期蒜苗根系土壤的养分指标进行测定,发现随施硅肥浓度的增加,土壤速效钾、碱解氮、有机质和有效磷含量均呈现先升后降

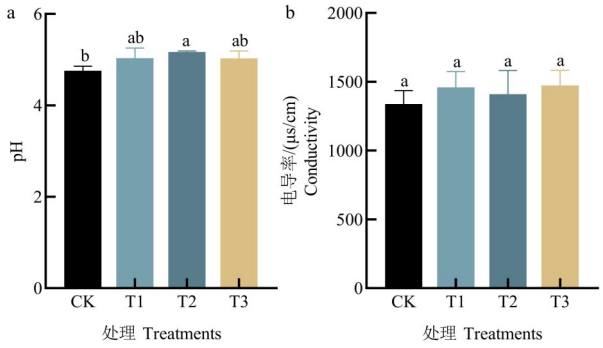


图3 叶面喷施不同浓度硅肥后蒜苗土壤pH和电导率

Fig.3 Soil pH and conductivity of garlic seedlings after foliar application of different concentrations of silicon fertilizers

的趋势(图4)。T1、T2、T3处理速效钾含量相比于CK均有所提高,且T1、T2处理与CK存在显著性差异(图4a);T2处理碱解氮含量相比CK显著提高6.8%,而T1和T3处理均与CK差异不显著(图4b);仅T2处理有机质含量相比CK显著提高4.3%,T1、T3处理均与CK差异不显著(图4c);T1、T2、T3处理有效磷含量相比于CK均有提高,且随施肥浓度增加呈现先升后降的趋势,但仅T2处理与CK存在显著差异(图4d)。结果表明,施用硅肥可促进土壤速效钾、碱解氮、有机质和有效磷含量增加,其中T2处理效果最好。

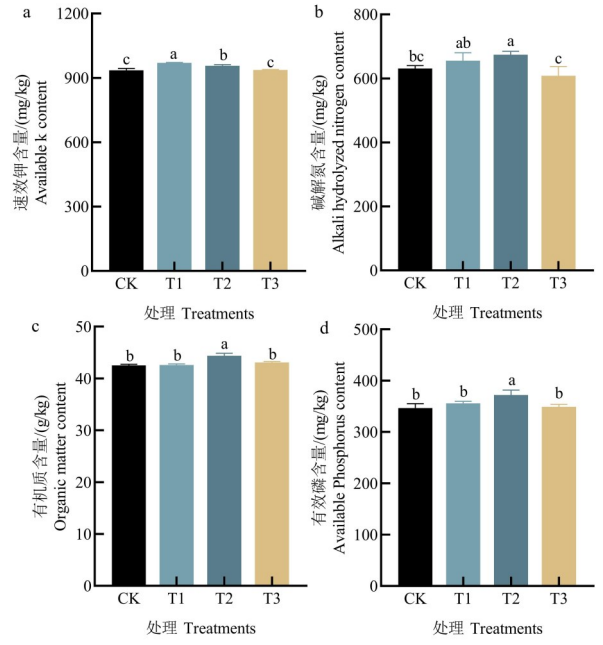


图4 叶面喷施不同浓度硅肥后蒜苗土壤养分含量

Fig.4 The effect of foliar spray with different concentrations of silicon fertilizers on the soil nutrient contents

2.6 叶面喷施不同浓度硅肥后蒜苗土壤酶活性

测定施用硅肥后蒜苗土壤中的过氧化氢酶、脲酶、酸性磷酸酶和蔗糖酶活性,发现随施肥浓度的增加,各处理间过氧化氢酶、脲酶和蔗糖酶活性差异不显著,但T2处理的过氧化氢酶、脲酶和蔗糖酶活性与CK相比增幅最大,而酸性磷酸酶活性基本不变(图5)。其中,T2处理过氧化氢酶活性相比于CK显著提高了11.8%,而T1、T3处理与CK无显著差异(图5a);T2、T3处理脲酶活性相比于CK均显著提高了23.3%和22.4%,而T1处理与CK差异不显著(图5b);T1、T2、T3处理酸性磷酸酶活性相比于CK均有提高但差异不显著(图5c);T2处理蔗糖酶活性与CK相比显著提高了25.5%,T1、T3处理与CK差异不显著(图5d)。结果表明,硅肥对蒜苗土壤过氧化氢酶、蔗糖酶活性的显著促进作用主要在60 L/hm^{2}浓度(T2),对脲酶活性的显著促进在60 L/hm^{2}以上浓度(T2、T3),而对酸性磷酸酶活性无显著调控效果,且各浓度硅肥处理间的过氧化氢酶、脲酶、蔗糖酶活性无显著差异。

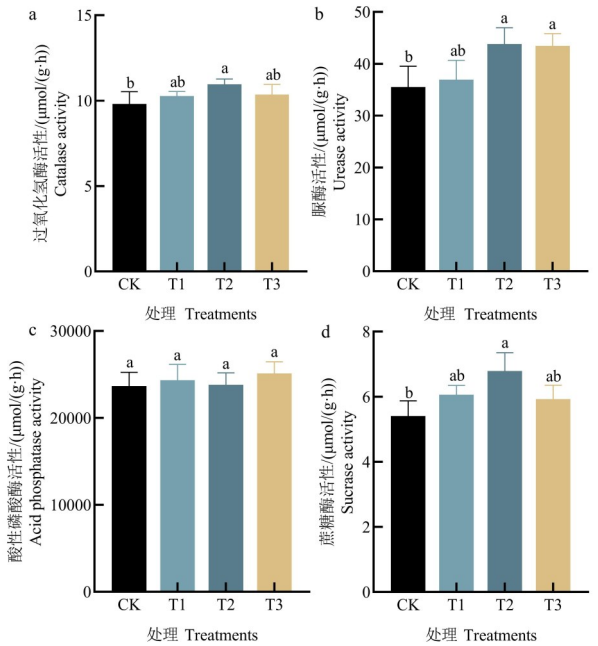


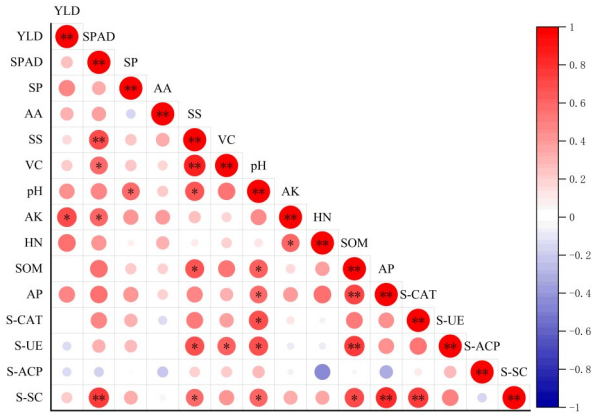
图5 叶面喷施不同浓度硅肥后蒜苗土壤酶活性

Fig.5 Soil enzyme activities after foliar spray with different concentrations of silicon fertilizers

2.7 不同浓度硅肥处理下蒜苗产量、品质指标与土壤养分、酶活性的相关性

不同浓度硅肥处理下蒜苗及土壤各指标相关

性见图6,大蒜产量与土壤速效钾含量呈显著正相关($P<0.05$);蒜苗SPAD值与可溶性糖含量、土壤蔗糖酶活性均呈极显著正相关($P<0.01$),同时与维生素C含量、土壤速效钾含量呈显著正相关;可溶性蛋白含量仅与土壤pH呈显著正相关;可溶性糖含量与维生素C含量呈极显著正相关,且与土壤pH、土壤有机质含量、土壤脲酶活性、土壤蔗糖酶活性均呈显著正相关;维生素C含量与土壤脲酶活性呈显著正相关;在土壤指标之间,土壤pH与土壤有机质含量、土壤有效磷含量及土壤过氧化氢酶活性、土壤脲酶活性、土壤蔗糖酶活性均呈显著正相关,土壤速效钾含量与土壤碱解氮含量呈显著正相关,土壤有机质含量与土壤有效磷含量、土壤脲酶活性均呈极显著正相关,且与土壤蔗糖酶活性呈显著正相关,土壤有效磷含量与土壤蔗糖酶活性呈极显著正相关。综上可见,土壤速效钾、有机质含量及蔗糖酶等酶活性与蒜苗产量、光合能力及品质指标密切相关,土壤pH则通过调控养分有效性与酶活性影响蒜苗生长,展现了硅肥处理下土壤微环境与蒜苗生长品质的关联。



YLD为产量,SPAD为叶绿素含量,SP为可溶性蛋白含量,AA为氨基酸含量,SS为可溶性糖含量,VC为维生素C含量,pH为pH,AK为速效钾含量,HN为碱解氮含量,SOM为有机质含量,AP为有效磷含量,S−CAT为过氧化氢酶活性,S−UE为脲酶活性,S−ACP为酸性磷酸酶活性,S−SC为蔗糖酶活性。*表示显著相关($P<0.05$),**表示极显著相关($P<0.01$)

YLD: yield; SPAD: chlorophyll content; SP: soluble protein content; AA: amino acid content; SS: soluble sugar content; VC: vitamin C content; AK: available potassium content; HN: alkaline nitrogen content; SOM: organic matter content; AP: available phosphorus content; S−CAT: catalase activity; S−UE: urease activity; S−ACP: acid phosphatase activity; S−SC: sucrase activity. * indicated significant correlation at $P<0.05$, while ** indicated extremely significant correlation at $P<0.01$.

图6　不同浓度硅肥处理下蒜苗产量、品质与土壤养分、酶活性的相关性

Fig.6　Correlation of garlic seedling yield, quality indicators, soil nutrients, and soil enzyme activity under different concentrations of silicon fertilizer treatment

3　讨论

3.1　喷施硅肥促进蒜苗增产和品质改善

植株株高和茎粗是反映植物生长状态、抗逆能力及环境适应性的关键指标。夏秀波等[20]研究表明,施用液态硅肥能提高番茄株高、茎粗、单株叶面积、产量、可溶固形物含量等指标。白丽[21]研究发现,水溶性硅肥明显促进绿豆幼苗株高、叶长、可溶性蛋白含量和CAT活性提高。本试验结果表明,在适宜范围内喷施硅肥对蒜苗株高、假茎粗、产量和SPAD值有明显的提升作用,可能是施用硅肥促进了养分吸收,从而促进蒜苗生长,进而提升产量。而随着施硅肥浓度的增加,蒜苗株高、假茎粗、产量及SPAD值呈现先升后降趋势,这表明在适宜浓度范围内,硅肥能有效促进蒜苗生长,但过量施用会导致对蒜苗生长的促进作用减少、经济成本上升。这与余恒志等[22]对甜荞、范福金等[23]对杉木幼苗的研究结果相似。

作物品质是反映植物遗传特性、生理状态及栽培环境的重要指标。本试验结果表明,叶面喷施硅肥能够提高蒜苗可溶性蛋白、氨基酸、可溶性糖和维生素C含量,提升蒜苗营养品质,在硅肥施用量为60 L/hm^2(T2处理)时效果最为明显,这与马迪等[24]对草莓、马倩倩等[25]对青脆李可溶性固形物、维生素C含量的研究结果相似。一方面可能是因为喷施硅肥提高了蒜苗植株内糖代谢关键酶活性、增强光合产物积累及优化抗坏血酸合成途径[26],从而使植株可溶性糖与维生素C含量显著增加,另一方面硅肥中的腐殖酸可通过活化土壤养分,促进根系吸收和光合作用,为蒜苗积累风味物质补充原料[27]。

3.2　喷施硅肥可改良蒜苗土壤肥力

土壤酸化会导致土壤养分有效性降低、结构被破坏、肥力下降且不利于作物生长,而施硅肥能调节土壤酸碱度,提高土壤养分有效性,增强土壤保肥能力。刘振学等[28]发现施硅肥能有效提高土壤pH,本研究结果也表明喷施硅肥能显著提高土壤pH,可能是因为硅肥多为碱性,可中和土壤中的酸性离子,改善酸性土壤环境,这与苏政宇等[8]对

植烟土壤的研究结果相似。

土壤养分含量是植株生长环节中至关重要的因素。陶思敏等[29]研究结果表明,施硅肥可有效提高稻田土壤养分含量,改善土壤结构。蒋亚等[30]对水稻的研究发现,施硅肥对土壤全氮和阳离子交换量有显著影响,对速效钾和有效磷含量影响较小。本研究结果表明,叶面喷施硅肥能提高土壤速效钾、碱解氮、有机质和有效磷含量,可能是因为硅肥通过叶片吸收后运输至根系,促进根系发育和有机酸分泌,加速土壤中无效态氮磷钾向速效态转化,间接使有机质积累和速效养分保留,从而增强蒜苗植株对氮磷钾的吸收能力,促进蒜苗生长,增加蒜苗生物量;但提升效果不太明显,可能是叶面喷施硅肥主要作用于叶片,养分直接被植株吸收利用,进入土壤较少,对土壤养分含量影响较小。然而,根施养分虽能直接补充到土壤中,但不合理根施会破坏土壤结构,降低土壤透气性,影响土壤微生物群落[31],而叶面喷施可减少土壤盐渍化风险[32],避免土壤肥力衰退与生产力下降,更有利于大蒜生产。

土壤过氧化氢酶活性与土壤有机质含量密切相关,能反映有机质的分解情况;土壤中的脲酶通过催化尿素分解为铵态氮和二氧化碳,为植物提供氮源,调控土壤氮素循环并改善根系养分吸收能力;蔗糖酶是反映土壤碳循环强度、微生物活性的重要指标;酸性磷酸酶是酸性土壤磷素有效性的关键调控酶,可催化有机磷分解成植物所需的无机磷[33]。陈雷等[34]研究发现,施硅肥能有效提高花生土壤过氧化氢酶、酸性磷酸单酯酶、纤维素酶等的活性,促进土壤中有机成分的转化利用,从而改善土壤环境。刘梓桐等[35]研究表明,硅肥可显著提高番茄基质酸性磷酸酶、蔗糖酶活性,从而促进番茄生长发育。本研究结果也表明,与CK相比,叶面喷施不同浓度硅肥可显著提高土壤过氧化氢酶、脲酶和蔗糖酶活性,可能是硅肥叶面喷施改善了植物营养,促进了根系发育与根系分泌物增加,从而增加土壤中各种酶的活性,进而改善土壤养分;也可能是硅肥中的腐殖酸通过改善微环境,促进微生物代谢,保护酶分子结构三大途径,促进产酶微生物生长繁殖,从而使特定酶类(碳、氮、磷循环酶为核心)增多,硅肥对水稻土壤[36]、油菜土壤[37]的研究可说明这一点。

鉴于叶面喷施适宜浓度的硅肥在促进蒜苗增产、改善品质及调节土壤理化性质方面的显著效果,下一步可深入探究不同施肥方式在不同品种植株、不同类型土壤及不同栽培条件下大蒜产量、品质的差异与最佳施用量;同时,可进一步明确硅肥通过调控土壤理化性质从而影响微生物群落结构及关键代谢活动的机制,为硅肥在蒜苗及其它作物生产中的科学应用提供更坚实的理论依据。

4 结论

本研究以不施肥处理(CK)为对照,探究了叶面喷施硅肥对蒜苗生长及土壤环境的影响。结果表明,叶面喷施硅肥效果显著,蒜苗层面,可有效促进生长发育,显著提升产量并改善品质;土壤层面,能提高土壤pH及养分含量,增强土壤酶活性。其核心作用机制是通过多重途径优化土壤微环境,调节土壤pH至适宜蒜苗养分吸收的范围,提升土壤有效养分供给,并增强土壤酶活性以加速养分转化,为蒜苗生长提供优质条件,最终促进其生长与品质提升。综合各项指标,硅肥施用量为60 L/hm^{2}时最佳,可为蒜苗生产实践提供参考。

参 考 文 献

[1]尹彦舒,崔曼,崔伟国,等. 大蒜连作障碍形成机理的研究进展[J]. 生物资源,2018,40(2):141-147.
Yin Y S, Cui M, Cui W G, et al. Research progress on formation mechanism of garlic continuous cropping obstacle[J]. Biotic Resources,2018,40(2):141-147.

[2]韩战强,赵博,马亚姣,等. 大蒜产品的功能及其在动物生产中的应用研究进展[J]. 饲料研究,2023,46(22):171-174.
Han Z Q,Zhao B,Ma Y J,et al. Research progress on function of garlic products and their application in animal production[J]. Feed Research,2023,46(22):171-174.

[3]Zhang Y, Liu X P, Ruan J, et al. Phytochemicals of garlic: promising candidates for cancer therapy[J]. Biomedicine & Pharmacotherapy,2020,123:109730.

[4]华智超,高淼,汪甜,等. 不同连作年限不同生长时期对大蒜土壤性质的影响[J]. 中国土壤与肥料,2023(6):97-101.
Hua Z C,Gao M,Wang T,et al. Effects of different continuous cropping years and growth stages on soil properties of garlic[J]. Soil and Fertilizer Sciences in China,2023(6):97-101.

[5]张小玲. 微量元素对草莓生长、果实品质及抗病性的影响研究[J]. 河南农业,2024(24):28-30.
Zhang X L. Effects of trace elements on growth, fruit quality and disease resistance of strawberry[J]. Henan Nongye, 2024(24):28-30.

[6]胡世平,冷德良,肖建强,等. 大蒜科学施肥及注意事项[J].

长江蔬菜,2019(17):70-72.
Hu S P, Leng D L, Xiao J Q, et al. Scientific fertilization methods and points for attention of garlic [J]. Journal of Changjiang Vegetables, 2019(17):70-72.

[7]王永刚,康怀启,王会海,等. 硅肥的研究及其在农业生产上的应用[J]. 中国果菜,2018,38(8):48-50,64.
Wang Y G, Kang H Q, Wang H H, et al. Research and application of silicon fertilizer in agriculture production [J]. China Fruit & Vegetable, 2018, 38(8):48-50,64.

[8]苏政宇,马啸,陈军华,等. 施用硅肥对丰都植烟土壤真菌多样性的影响[J]. 河南科学,2025,43(4):524-533.
Su Z Y, Ma X, Chen J H, et al. Effects of silicon fertilizer application on fungal diversity of tobacco-planted soil in Fengdu [J]. Henan Science, 2025, 43(4):524-533.

[9]Wang B H, Chu C B, Wei H W, et al. Ameliorative effects of silicon fertilizer on soil bacterial community and pakchoi (*Brassica chinensis* L.) grown on soil contaminated with multiple heavy metals[J]. Environmental Pollution, 2020, 267: 115411.

[10]廖晓丽,薛可馨,蔡思莹,等. 外源硅添加对楠木幼苗生长及光合特性的影响[J]. 热带亚热带植物学报,2024,32(6):772-780.
Liao X L, Xue K X, Cai S Y, et al. Effects of exogenous silicon on growth and photosynthetic characteristics of *Phoebe bournei* seedlings [J]. Journal of Tropical and Subtropical Botany, 2024, 32(6):772-780.

[11]王斌,华晓琴,戴建昊,等. 喷施硅对设施葡萄生理特性和品质的影响[J]. 石河子大学学报(自然科学版),2025,43(1):68-73.
Wang B, Hua X Q, Dai J H, et al. Effects of silicon sprays on physiological characteristics and quality of grapes under protection [J]. Journal of Shihezi University (Natural Science), 2025, 43(1):68-73.

[12]任红玉,李爽,赵慧莉,等. 叶面喷施不同硅源制剂对水稻植株养分吸收的动态影响[J]. 吉林农业大学学报,2017,39(5):596-602.
Ren H Y, Li S, Zhao H L, et al. Dynamic effect of foliar application of different silicon compounds on rice nutrient absorption[J]. Journal of Jilin Agricultural University, 2017, 39(5):596-602.

[13]焦玉字,夏存艳,何孟轲,等. 叶面喷施水溶性壳聚糖和硅肥对两种冬油菜镉吸收的影响[J]. 生态学杂志,2023,42(12):2836-2843.
Jiao Y Z, Xia C Y, He M K, et al. Effects of foliar application of water-soluble chitosan and silicon fertilizers on cadmium uptake of two winter rapeseed cultivars[J]. Chinese Journal of Ecology, 2023, 42(12):2836-2843.

[14]周艳孔,陆利民,倪秀红,等. 不同叶面肥对大棚草莓生长和果实品质的影响[J]. 中国果树,2017(1):34-36.
Zhou Y K, Lu L M, Ni X H, et al. Effects of different foliar fertilizers on strawberry growth and fruit quality in greenhouse [J]. China Fruits, 2017(1):34-36.

[15]Liang Y Q, Liao M, Fang Z P, et al. How silicon fertilizer improves nitrogen and phosphorus nutrient availability in paddy soil[J]. Journal of Zhejiang University: Science B, 2021, 22(7):521-532.

[16]耿若飞,程志杰,王二伟,等. 叶面喷施硅肥对干旱胁迫下冬小麦生理特性和产量的影响[J]. 江苏农业科学,2024,52(1):112-116.
Geng R F, Cheng Z J, Wang E W, et al. Effects of foliar spraying of silicon fertilizer on physiological characteristics and yield of winter wheat under drought stress [J]. Jiangsu Agricultural Sciences, 2024, 52(1):112-116.

[17]湘潭市气象局. 气象预警公报[EB/OL].(2024-07-24)[2025-09-16] https://weather.cma.cn/web/alarm/43030441600000_20240724091302.html.
Xiangtan Meteorological Bureau. Weather Warning Bulletin [EB/OL]. (2024-07-24) [2025-09-16] https://weather.cma.cn/web/alarm/43030441600000_20240724091302.html.

[18]鲍士旦. 土壤农化分析3版[M]. 北京:中国农业出版社,2000: 30-58.
Bao S D. Soil agriculture chemical analysis 3rd[M]. Beijing: China Agriculture Press, 2000: 30-58.

[19]关松荫. 土壤酶及其研究法[M]. 北京:农业出版社,1986:294-297.
Guan S Y. Soil enzymes and research methods [M]. Beijing: Agricultural Press, 1986:294-297.

[20]夏秀波,梁潇,张伟,等. 增施液态硅肥对设施番茄生长、产量及品质的影响[J]. 长江蔬菜,2025(6):81-84.
Xia X B, Liang X, Zhang W, et al. Effects of adding liquid silicon fertilizer on growth, yield and quality of protected tomato [J]. Journal of Changjiang Vegetables, 2025(6):81-84.

[21]白丽. 水溶性硅肥对绿豆种子萌发及幼苗生长的影响[J]. 现代农业科技,2025(9):1-3,10.
Bai L. Effects of water-soluble silicon fertilizer on mung bean seed germination and seedling growth [J]. Modern Agricultural Science and Technology, 2025(9):1-3,10.

[22]余恒志,聂蛟,李英双,等. 施硅量对甜荞倒伏及产量的影响[J]. 中国农业科学,2018,51(14):2664-2674.
She H Z, Nie J, Li Y S, et al. Effects of silicon application rate on common buckwheat lodging and yield [J]. Scientia Agricultura Sinica, 2018, 51(14):2664-2674.

[23]范福金,叶义全,张文晶,等. 硅对杉木幼苗生长和光合特性的影响[J]. 福建林业科技,2024,51(1):54-61.
Fan F J, Ye Y Q, Zhang W J, et al. Effects of silicon on the growth and photosynthetic characteristics of *Cunninghamia lanceolata* seedlings [J]. Journal of Fujian Forestry Science and Technology, 2024, 51(1):54-61.

[24]马迪,潘少香,宋烨,等. 外源液态硅肥处理对草莓品质的影响[J]. 中国果菜,2024,44(12):46-51,64.
Ma D, Pan S X, Song Y, et al. The effect of exogenous liquid silicon fertilizer treatment on strawberry quality [J]. China Fruit & Vegetable, 2024, 44(12):46-51,64.

[25]马倩倩,彭莞云,黄涛,等. 硅肥施用方式和浓度对青脆李果实品质的影响[J]. 中国农学通报,2025,41(4):39-43.
Ma Q Q, Peng G Y, Huang T, et al. Effect of fertilization

methods and concentrations of silicon fertilizer on fruit quality of plum 'Qingcui'[J]. Chinese Agricultural Science Bulletin, 2025,41(4):39-43.

[26]刘月,刘海河,张彦萍,等. 外源硅对厚皮甜瓜果实品质及相关酶活性的影响[J]. 中国瓜菜,2021,34(12):28-32.
Liu Y,Liu H H,Zhang Y P,et al. Effects of exogenous silicon on fruit quality and related enzyme activities of muskmelon[J]. China Cucurbits and Vegetables,2021,34(12):28-32.

[27]梁一凡,严定伟,罗菲,等. 腐殖酸钾对植烟土壤养分及烤烟油分相关品质的影响[J]. 江苏农业科学,2025,53(8):233-241.
Liang Y F, Yan D W, Luo F, et al. Impacts of potassium humate on nutrients in tobacco planting soil and oil content related quality of flue-cured tobacco[J]. Jiangsu Agricultural Sciences,2025,53(8): 233-241.

[28]刘振学,孙汉友,汪兴隆,等. 施用硅肥对土壤碱度的影响研究[J]. 粉煤灰综合利用,2004(4):39-40.
Liu Z X,Sun H Y,Wang X L,et al. Study on effect of silicon fertilizer on alkalinity of soils[J]. Fly Ash Comprehensive Utilization,2004(4):39-40.

[29]陶思敏,娄运生,邢钰媛,等. 夜间增温下施用生物炭和硅肥对稻田土壤养分含量的影响[J]. 江苏农业科学,2021,49(15):198-206.
Tao S M,Lou Y S,Xing Y Y,et al. Effects of biochar and silicate fertilization on soil nutrient content of paddy field under night-time temperature increase [J]. Jiangsu Agricultural Sciences,2021,49(15):198-206.

[30]蒋亚,蔡景行,吴道明,等. 硅肥对土壤理化性质及水稻产量与养分含量的影响[J]. 贵州农业科学,2023,51(7):50-55.
Jiang Y,Cai J H,Wu D M,et al. Effects of silicon fertilizer on soil physicochemical properties, rice yield and plant nutrients [J]. Guizhou Agricultural Sciences,2023,51(7):50-55.

[31]沈彦辉,周新刚,吴凤芝. 不同施硅方式对土壤化学性状及土壤酶活性的影响[J]. 中国蔬菜,2015(11):34-39.
Shen Y H,Zhou X G,Wu F Z. Effects of different silicon fertilization patterns on soil chemical property and soil enzyme activity[J]. China Vegetables,2015(11):34-39.

[32]梁胜贤,刘春成,胡超,等. 叶面喷施硅肥对再生水灌溉水稻叶际细菌群落结构及功能基因的影响[J]. 环境科学,2024,45(1):555-566.
Liang S X,Liu C C,Hu C,et al. Effects of foliar application of silicon fertilizers on phyllosphere bacterial community and functional genes of paddy irrigated with reclaimed water[J]. Environmental Science,2024,45(1): 555-566.

[33]张伟伟. 间作对西瓜生理生化特性及根际土壤特性影响的研究[D].成都:四川农业大学,2017.
Zhang W W. Study on the effects of intercropping on physiological and biochemical characteristics of watermelon and rhizosphere soil properties[D]. Chengdu: Sichuan Agricultural University, 2017.

[34]陈雷,贺群岭,张枫叶,等. 硅对连作花生根系生长发育·土壤酶活性·产量和品质的影响[J]. 安徽农业科学,2024,52(24):123-126.
Chen L,He Q L,Zhang F Y,et al. Effects of silicon on root growth, soil enzyme activity, yield and quality of peanut under continuous cropping [J]. Journal of Anhui Agricultural Sciences,2024,52(24):123-126.

[35]刘梓桐,金宁,孟鑫,等. 硅肥对番茄生长及基质理化性质的影响[J]. 江苏农业学报,2024,40(10):1914-1922.
Liu Z T,Jin N,Meng X,et al. Effects of silicon fertilizer on tomato growth and physicochemical properties of substrate[J]. Jiangsu Journal of Agricultural Sciences, 2024, 40(10): 1914-1922.

[36]杜泽云,陶思敏,娄运生,等. 施用生物炭和硅肥对增温稻田土壤酶活性的影响[J]. 江苏农业科学,2023,51(1):225-231.
Du Z Y, Tao S M, Lou Y S, et al. Impacts of biochar and silicate fertilization application on soil enzyme activities under nighttime warming in paddy soil [J]. Jiangsu Agricultural Sciences,2023,51(1):225-231.

[37]符慧娟,李星月,李其勇,等. 光合细菌与硅肥对油菜及土壤环境的影响[J]. 西南农业学报,2020,33(6):1209-1214.
Fu H J, Li X Y, Li Q Y, et al. Effects of photosynthetic bacteria and silicon fertilizer on rape and soil environment[J]. Southwest China Journal of Agricultural Sciences, 2020, 33(6):1209-1214.

(编辑:郭玥微)