

氯酸钾对花生生长的毒害效应

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摘要 氯酸盐是一类毒性强的氧化剂, 曾被作为非选择性除草剂和脱叶剂大量施用, 近年来, 氯酸钾作为产期调控剂也在龙眼(*Dimocarpus longan*)反季节生产中大量应用。然而, 氯酸根离子强氧化性对生物体有明显的毒害效应, 其残留及次生污染物对水体和土壤环境也存在较强的污染效应。龙眼园通常间种花生(*Arachis hypogaea*), 该文实验研究了氯酸钾和氯化钠对花生生长的毒害效应。结果表明, 当浸种溶液的 KClO_3 浓度高于 $50 \text{ mg} \cdot \text{L}^{-1}$ 时, 花生种子的发芽率和胚根长度大大降低, 幼芽的电解质渗漏率和过氧化氢酶活性显著升高; 当土壤中 KClO_3 浓度高于 $50 \text{ mg} \cdot \text{kg}^{-1}$ 时, 会使花生幼苗叶片质膜透性增大, 而硝酸还原酶活性、叶绿素含量和根系活力显著降低, 氯酸钾的毒害效应远远超过氯化钠的盐害效应, 高于 $50 \text{ mg} \cdot \text{kg}^{-1}$ 的 KClO_3 还能使花生荚果期植株的光合速率、蒸腾速率、叶绿素含量、根系活力、生物量合成和根瘤菌的数量显著降低。结论是, 土壤中的 KClO_3 浓度高于 $50 \text{ mg} \cdot \text{kg}^{-1}$ 时, 即会显著影响花生植株的正常生长。

关键词 花生 作物 氯酸钾 毒害效应 污染生态

TOXIC EFFECTS OF POTASSIUM CHLORATE ON PEANUT GROWTH

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Abstract Chlorates are a group of oxidizers with strong toxic effects that can cause significant damage to plants. However, chlorates have been used as a non-selective herbicide, defoliant and desiccant. It was found that potassium chlorate can induce flowering in longan (*Dimocarpus longan*). It has been widely used in longan orchards in recent years, especially in north Thailand and south China, but research has shown that potassium chlorate is toxic to organisms. It can also contaminate soil and water. The aim of this study was to determine the effects of potassium chlorate stress on the growth and physiological response of peanut (*Arachis hypogaea*).

The main method used to induce flower initiation in longan for off-season production is the application of potassium chlorate under the tree canopy. Most research efforts have been devoted to determining the optimum time and amount of application. Little is known about the phytotoxic effects of potassium chlorate on peanut plants, which usually is planted within longan orchards. In this paper, the effects of potassium chlorate on the growth of peanut plants were studied. Using the soil culture method, six potassium chlorate treatments were used to assess its effects on seed germination, chlorophyll content, levels of electrolytic leakage (EL), membrane permeability (MP), and activities of nitrate reductase (NR) and catalase (CAT) in peanut seedling leaves, as well as the biomass and number of *Rhizobium*, and the transpiration and photosynthetic rates in mature peanut plants. The results showed that: when the concentration of potassium chlorate was higher than $50 \text{ mg} \cdot \text{L}^{-1}$, the germination rates of peanut seeds and root lengths were greatly reduced, while the amount of electrolytic leakage and the activity of CAT were increased significantly. When the concentration of potassium chlorate was higher than $50 \text{ mg} \cdot \text{kg}^{-1}$ in soil, its phytotoxic effects resulted in a significant increase in MP in seedling leaves, and a decrease in NR, chlorophyll, biomass and the number of *Rhizobium*, and a reduction in transpiration and photosynthesis. It can be concluded that soil concentrations of potassium chlorate higher than $50 \text{ mg} \cdot \text{kg}^{-1}$ would have a significantly negative effect on the growth of peanut plants.

Key words Peanut (*Arachis hypogaea*), Crop, Potassium chlorate, Toxicity effects, Pollution ecology

氯酸盐是植物必需微量元素氯在环境中的存在形式之一,但氯酸根离子强氧化性却对许多植物具有明显的毒性。文献记载,除苔藓外,氯酸盐对绿色植物生长有 3 到 6 个月的持续毒害作用,其毒性不但对牵牛花(*Pharbitis nil*)、加拿大蓟(*Cirsium arvense*)和詹森草(*Sorghum halepense*)等杂草具有良好的控制效果,而且对棉花(*Gossypium*)、玉米(*Zea mays*)、亚麻(*Linum tenuifolium*)和大豆(*Glycine max*)等农作物具有脱叶功能,对微生物也有毒害作用,因此氯酸盐曾被作为非选择性除草剂、脱叶剂和土壤消毒剂而大量施用(Crafts & Robbins, 1962; Klingman & Ashton, 1975; Agaev *et al.*, 1986)。同时,由于工业上大量使用 ClO_2 和 Cl_2 进行纸浆漂白、自来水消毒、水产养殖以及食品保鲜和废水废气处理等,其过程中产生的副产物(Disinfection by-products, DBPs)也含有大量的(高/亚)氯酸根离子(Siddiqui *et al.*, 1993; Veschetti *et al.*, 2005);另外,含(高)氯酸钾的炸药、烟火和火箭推进器燃料中的(高)氯酸根离子也最终归趋于土壤和水环境(Logan, 2001),这无疑给农业生态环境和人类健康带来潜在威胁。为此, ClO_4^- 、 ClO_3^- 和 ClO_2^- 都包括在美国联邦法规饮用水优先控制的消毒副产物目录中,美国环保署(USEPA)推荐在出厂水中 ClO_2 、 ClO_3^- 和 ClO_2^- 总剩余浓度不得大于 $10 \text{ mg} \cdot \text{L}^{-1}$,世界卫生组织建议(高)氯酸根在饮用水中的含量应减到尽可能少(USEPA, 2002a, 2000b; WHO, 2005)。哥伦比亚环保部(MEBC, 2005)对环境水质中的氯酸盐限制标准(建议)为:饮用水源 $2.4 \text{ mg} \cdot \text{L}^{-1}$,畜牧饮用水 $3 \text{ mg} \cdot \text{L}^{-1}$,海水养殖用水 $5 \text{ mg} \cdot \text{L}^{-1}$,淡水养殖用水 $30 \text{ mg} \cdot \text{L}^{-1}$ 。

当前,氯酸钾大量应用于龙眼(*Dimocarpus longan*)产期调控是其进入环境的另一条重要途径。自从 1998 年台湾学者颜昌瑞等(1998)利用氯酸钾作为植物生长调节剂给龙眼催花获得成功以来,我国福建、广西、广东、海南等龙眼主产区以及泰国等东南亚国家和美国夏威夷及佛罗里达也开展了试验和推广研究,均获得良好效果(陈美媛等, 2001; 贺海英和王泽槐, 2001; 柯冠武, 2001; 温永盟, 2001; Subhadrabandhu & Yapwattanaphun, 2001),经过几年的试验探索,龙眼产期化学调控技术不断成熟和推广(李建光等, 2003; 韩剑等, 2003; 曾祥有等, 2004; Manochai *et al.*, 2005)。此外,氯酸钾对热带果树芒果(*Mangifera indica*)也有一定的催花促果作用(Subhadrabandhu & Yapwattanaphun, 2001)。应用

氯酸钾调控龙眼产期技术,既可对常规栽培不结果的部分龙眼树进行催花挂果,减少或避免“大小年”的出现,又可保证龙眼鲜果在不同季节特别是在节假日均衡供应市场,这对提高龙眼市场竞争力和产品附加值、保证龙眼生产健康发展有重要意义(Huang *et al.*, 2005; Kanaree & Pankasemsuk, 2005),近年泰国以氯酸钾处理的龙眼产量约占全年总产的 40%,占出口外销龙眼一半以上(Anupunt & Sukhvibul, 2005)。广东茂名市近 5 年来推广氯酸钾生产反季节龙眼面积近 $6\,667 \text{ hm}^2$,增加经济效益近千万元。但是,随着氯酸钾对果树花期调控技术的推广,施用氯酸钾的果园日渐增多,氯酸根离子毒性及其残留次生污染对农业生态环境产生的消极影响越来越受到关注,其生态风险不容忽视。

目前,有关氯酸盐对植物的毒害机理还研究不多。已有研究证明,氯酸根离子在常温下对藻类(Rosemarin *et al.*, 1986, 1990, 1994; Wuk & Hutchinson, 1995; Dolf *et al.*, 1998; Stauber, 1998)、小麦(*Triticum aestivum*)(Aberg, 1947)、番茄(*Lycopersicon esculentum*)(Hofstra, 1977)和水稻(*Oryza sativa*)(Borges *et al.*, 2004)有明显的浓度梯度毒害效应。氯酸钾每分子含有 3 个氧,且 ClO_3^- 的结构是 SP^3 杂化类型,导致其具有强氧化性。Aberg(1947)首先提出氯酸根离子本身对植物细胞无毒,但转化为亚氯酸根和次氯酸根后就表现出毒性,同时植物根系对 ClO_3^- 和 NO_3^- 的吸收机制是一致的,氯酸根通过与硝酸盐竞争硝酸根载体而被吸收;其后也有许多研究证实,植物吸收 ClO_3^- ,会抑制植物细胞对 NO_3^- 的吸收和运输,导致植物缺氮进而影响植物的生理、营养和生殖生长(Solomonsson & Vennesland, 1972; Balch, 1987)。也有研究证明, ClO_3^- 被植物根系吸收并输送到植物各器官后,其强氧化性对植物有直接的毒害效应(Borges *et al.*, 2004),并且 ClO_3^- 及其转化的 ClO_2^- 在植物体内的积累,会增加植物体内过氧化氢酶的含量,提高植物细胞的呼吸效率(Klingman & Ashton, 1975),降低植物对碳水化合物合成,致使叶片提前脱落,植物过早衰老(Wright & Sprengel, 1996; Brown, 1997)。但也有研究证实,部分微生物和植物中硝酸还原酶缺失的突变体如拟南芥突变体等对氯酸盐具有免疫能力,可以利用氯酸盐作为筛选这些突变体生物的有效工具(Singh *et al.*, 1977; Doddema *et al.*, 1978)。同时,研究发现有些厌氧细菌拥有一套与一般生物不同的氯酸根代谢系统,可借助氯酸还原酶将 ClO_3^- 转化为 ClO_2^- ,

再由亚氯酸歧化酸(Chlorete dismutase)直接分解为无毒的 Cl^- , 因此这些微生物是环境中降解 ClO_3^- 的主力军和“生态工具”¹⁾(Wallace *et al.*, 1996; Logan, 1998; Xu *et al.*, 2004; Steinberg *et al.*, 2005)。但类似的代谢途径是否在动物和植物中存在, 仍有待进一步研究。

此外, 目前有关氯酸盐对豆科作物的影响研究还少见报道。花生(*Arachis hypogaea*)是我国主要经济作物, 在我国南方部分龙眼果园等也有套种花生、大豆的习惯。施用氯酸钾和其它污染途径带来的氯酸根离子, 很有可能会对花生等作物产生影响, 如国内生产氯酸钾的主要厂家之一的广西贺州光明化工厂, 就曾出现农民与厂家发生氯酸钾污染水稻、花生的污染纠纷。此外, 由于花生具有根瘤菌, 这与龙眼菌根有相似之处, 同时已有研究证明植物根系大都不能选择氯酸根与硝酸盐, 两者的竞争是否会在固氮根瘤上有所体现仍有待研究, 为此我们选择花生作为材料, 研究氯酸钾及其残留对花生生长的影响, 旨在为明确氯酸盐对豆科作物的生态毒理提供参考。

1 材料和方法

1.1 供试材料

花生品种选用生产上应用较广的‘粤油 19’, 盆栽供试土壤采用华南农业大学农学院试验田 0~20 cm 土层的粘壤土, pH 值 5.48, 全氮 $0.92 \text{ g} \cdot \text{kg}^{-1}$, 速效氮 $112.32 \text{ mg} \cdot \text{kg}^{-1}$, 全磷 $1.15 \text{ g} \cdot \text{kg}^{-1}$, 速效磷 $48.32 \text{ mg} \cdot \text{kg}^{-1}$, 全钾 $22.20 \text{ g} \cdot \text{kg}^{-1}$, 速效钾 $126.65 \text{ mg} \cdot \text{kg}^{-1}$, 有机质 $16.30 \text{ g} \cdot \text{kg}^{-1}$, EC 值 $0.25 \text{ mS} \cdot \text{cm}^{-1}$, Cl^- 为 $0.033 \text{ mg} \cdot \text{kg}^{-1}$, 主要重金属指标符合国家土壤环境质量标准。

所用 KClO_3 试剂为市售化学纯, 幼苗光照培养室培养时使用去离子水, 盆栽使用双蒸水。

1.2 实验设计

为区别氯酸钾强氧化性与盐害对花生萌发和幼苗生长的毒害效应, 花生种子萌发和苗期的实验同时以同浓度的氯化钠为对照实验。谭允阳等(1995)研究表明, Cl^- 对花生植株的胁迫临界浓度在 500~1 000 之间, 所以氯酸钾强氧化性对花生植株的毒害效应不设氯化钠的对照实验。

1.2.1 种子发芽实验

将 KClO_3 和 NaCl 分别用去离子水(Milli-Q water)配成 0、10、20、50、100、200 $\text{mg} \cdot \text{L}^{-1}$ 的浓度梯度处理, 每个处理设置 4 个重复, 将每个重复的 25 粒花生种子培养在直径 15 cm 的培养皿中, 上下均为相同浓度的试剂浸泡过的双层滤纸, 然后把培养皿置于 25 $^{\circ}\text{C}$ 的培养箱中, 保持培养皿湿润, 进行发芽试验。5 d 后测量花生种子的发芽率、胚根长、胚芽过氧化氢酶活性和胚根研磨前后其渗漏液的电导率。

1.2.2 幼苗生长实验

将花生种子用双蒸水浸泡 24 h 后, 选择饱满且大小均匀一致的种子置于 25 $^{\circ}\text{C}$ 的黑暗培养箱中培养 48 h, 选择发芽均匀的种苗各 3 棵, 种在盛有供试土壤 1 kg, 盆高 15 cm、口径 15 cm、盆底有排水孔和托盆的陶瓷盆中, 置于温度 25 $^{\circ}\text{C}$, 光照强度 12 000 Lux, 空气相对湿度约 85% 的光照培养箱进行培养, 定期加等量去离子水保持土壤湿润。幼苗预培养生长 15 d 后, 分别向各盆土壤中施加溶解有 KClO_3 或 NaCl 各 0、10、20、50、100、200 mg 的溶液, 各设 6 个处理, 每处理 3 个重复, 加药 5 d 后测量幼苗叶片质膜透性、硝酸还原酶、叶绿素和根系活力。

1.2.3 荚果期植株生长实验

将花生种子用双蒸水浸泡 24 h 后, 选择饱满且大小均匀一致的种子置于 25 $^{\circ}\text{C}$ 的黑暗培养箱中培养 48 h, 选择发芽均匀的种苗各 3 棵, 种在盆高 18 cm、口径 25 cm、盆底有排水孔的陶瓷盆中(陶瓷盆置于朝阳屋檐下, 遮雨不遮光), 各盆装有供试土壤 5 kg, 定期浇等量双蒸水, 保持土壤湿润。一个月后一次性施加 KClO_3 处理, 各处理的土壤施加的 KClO_3 浓度分别为 0、50、100、200、400、800 $\text{mg} \cdot \text{kg}^{-1}$, 共设 6 个处理 3 个重复。两个月后测定植株的光合速率、叶绿素含量和根系活力。4 个月收获后测定植株的生物量和根瘤菌数量。

1.3 实验方法

胚根电解质渗漏率: 各处理称 0.2 g 胚根, 用 20 ml 去离子水浸泡 3 h 后, 用 DDS-11 型电导仪测量研磨前后溶液的电导度, 以相对电导度(研磨前后电导度比值)表示胚根电解质渗漏率。叶片质膜透性: 各处理称取 0.5 g 花生苗期顶部叶片用 20 ml 去离子水浸泡 3 h 后, 用 DDS-11 型电导仪测出浸出液在煮沸前后的电导度, 计算相对电导(研磨前后电导度比值)来表示幼苗叶片质膜透性。

1) Bliven AR (1996). *Chlorate Respiring Bacteria: Isolation, Identification, and Effects on Environmentally Significant Substrates*. MS Thesis, Department of Chemical and Environmental Engineering, University of Arizona, Tucson, AZ.

酶液制备：分别取胚根 0.25 g 与苗期叶片 0.5 g 加入 2.5 ml 0.05 mol·L⁻¹磷酸缓冲液(pH = 7.2)(内含 5% 聚乙烯基吡咯烷酮 PVP)及少量石英砂,冰浴下研磨成匀浆,0 ~ 4 ℃,20 000 × g 离心 20 min,取上层清液用于酶活性测定。

过氧化氢酶活性：用 0.05 mol·L⁻¹磷酸缓冲液(pH = 7.2)把 0.6 ml 30% 的 H₂O₂ 稀释至 100 ml 作为底物,在比色杯中依次加入 1 ml 底物、1.9 ml 0.05 mol·L⁻¹磷酸缓冲液、100 μl 酶液后迅速用封口膜封口摇匀,立即放入分光光度计内在 240 nm 波长下测定 OD₂₄₀ 值,每 30 s 读数一次,连续读 6 次,过氧化氢酶活性以 H₂O₂ μmol·min⁻¹·g⁻¹ 为活力单位。

硝酸还原酶活性：采用陈薇和张德颐(1980)的活体法。

叶绿素：取主茎倒数第三叶按 Arnon(1949)法测定叶绿素含量。

光合速率与蒸腾速率：在自然光照强度 1 430 ~ 1 450 μmol quanta·m⁻²·s⁻¹,温度 37 ℃ 的上午,用英国 PPS 公司生产的 CIRS-II 型便携式光合作用测定仪,测定主茎顶叶的光合作用。

根系活力：TTC 比色法测定根系活力(邹琦, 2000)。

2 结果与分析

2.1 KClO₃ 对花生种子萌发的影响

从图 1 可见,花生种子经氯酸钾和氯化钠处理后,其发芽率和根长均随处理浓度的升高而降低,电解质渗漏率和过氧化氢酶活性则随处理浓度的升高而升高。在 0 ~ 200 mg·L⁻¹ 范围内,经氯化钠处理的花生种子发芽率、根长、电解质渗漏率和过氧化氢酶活性的变化不大,均无显著差异;而与 CK 对照,经氯酸钾处理的花生种子发芽率、根长、电解质渗漏率和过氧化氢酶活性在 50 mg·L⁻¹ 后变化显著,说明在此处理浓度范围内,氯酸钾强氧化性对花生种子萌发造成的毒害效应远远超过氯化钠的盐害,且氯酸钾浓度高于 50 mg·L⁻¹ 时即会影响花生种子的正常萌发。

2.2 KClO₃ 对花生苗期生长的影响

花生幼苗经氯酸钾和氯化钠处理后,叶片质膜透性随处理浓度的升高而升高,硝酸还原酶活性、叶

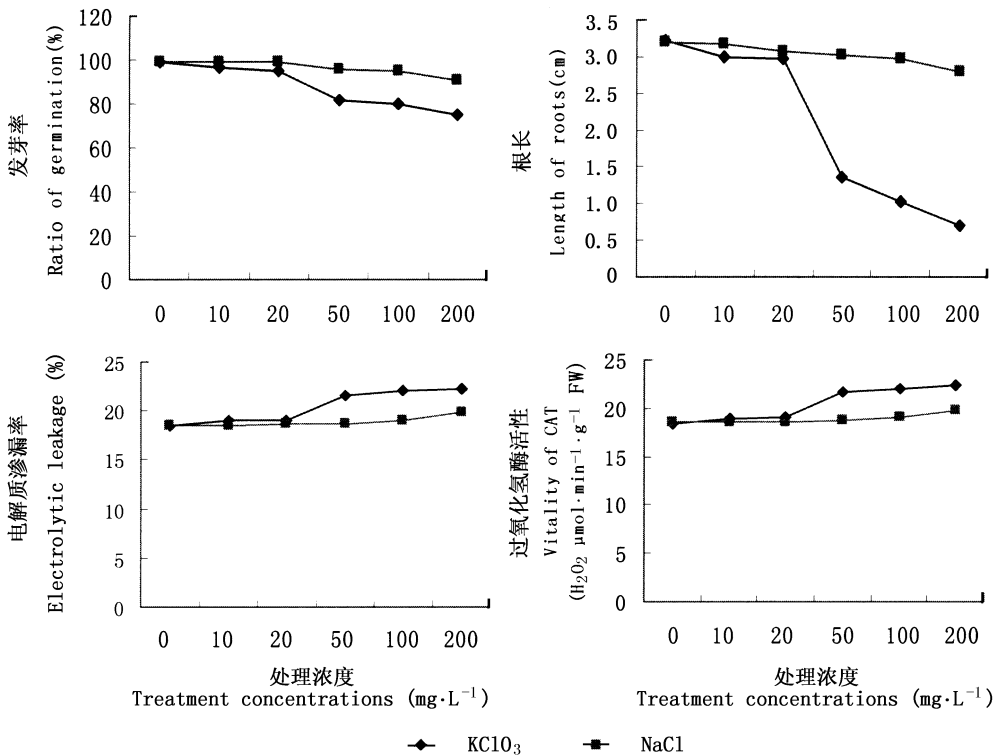


图 1 KClO₃ 对花生种子萌发的影响

Fig.1 Effects of KClO₃ on germination of peanut seeds

绿素含量和根系活力则随处理浓度的升高而降低(图2)。在0~200 mg•kg⁻¹范围内,氯化钠处理的花生幼苗叶片质膜透性、硝酸还原酶活性、叶绿素含量和根系活力随处理浓度的升高变化不大且缓慢,而经氯酸钾处理过花生幼苗叶片质膜透性、硝酸还原酶活性、叶绿素含量和根系活力在高于50 mg•kg⁻¹后变化显著,说明在此浓度处理范围内,氯酸钾强氧化性对花生幼苗的毒害效应远远高于氯化钠的盐害效应,且氯酸钾浓度高于50 mg•kg⁻¹时即会严

重影响花生幼苗的正常生长。

2.3 KClO₃ 对花生荚果期植株的影响

从表1可知,花生荚果期植株的蒸腾速率、光合速率、叶绿素含量和根系活力均随氯酸钾处理土壤浓度的升高而降低,且氯酸钾浓度为50 mg•kg⁻¹时,花生植株的蒸腾速率、叶绿素a的含量和根系活力与对照相比差异显著;氯酸钾浓度达到100 mg•kg⁻¹时,光合速率和叶绿素b的含量差异达到显著。

花生收获时(表2),花生植株和果实的生物量

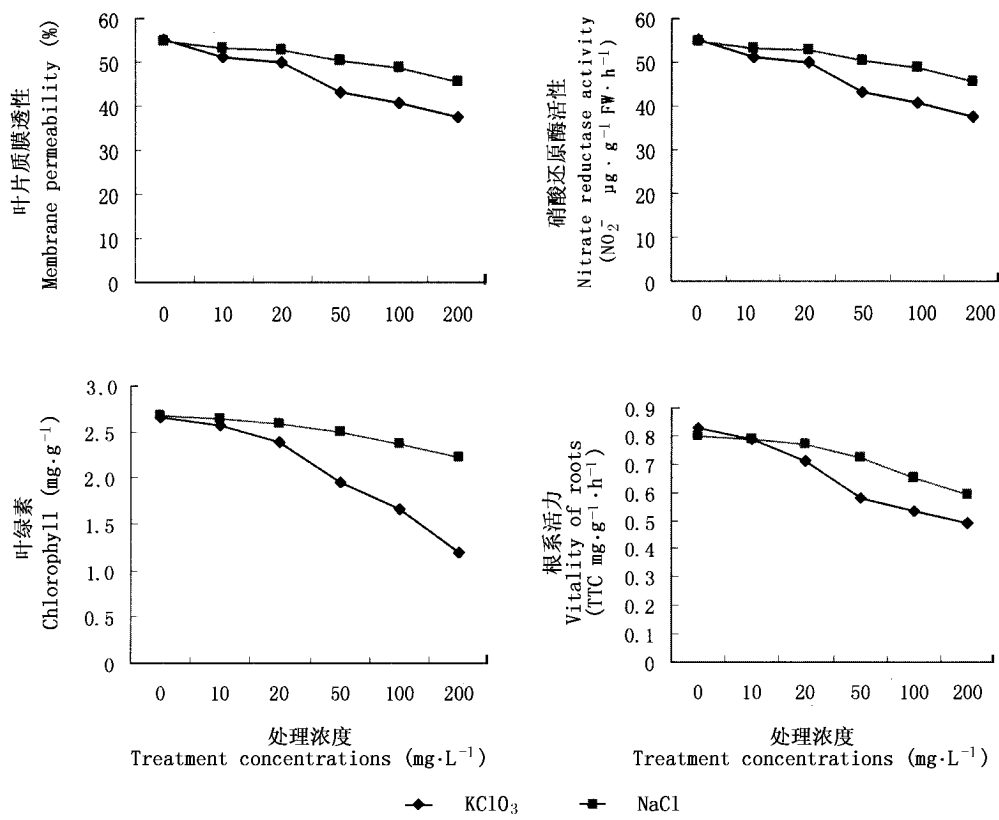


图2 KClO₃ 对花生幼苗某些生理指标的影响

Fig.2 Effects of KClO₃ on some physiological index of peanut seedling

表1 KClO₃ 对花生成年植株某些生理指标的影响

Table 1 Effects of KClO₃ on some physiological index of peanut plant

KClO ₃ 浓度 Potassium chlorate concentration (mg•kg ⁻¹)	蒸腾速率 Transpiration rate (mmol•m ⁻² •s ⁻¹)	光合速率 Photosynthesis rate (µmol•m ⁻² •s ⁻¹)	叶绿素 a Chlorophyll a (mg•g ⁻¹)	叶绿素 b Chlorophyll b (mg•g ⁻¹)	根系活力 Vitality of roots (TTC mg•g ⁻¹ •h ⁻¹)
CK	19.78 ± 0.63 ^a	26.70 ± 1.16 ^a	1.19 ± 0.01 ^a	0.46 ± 0.01 ^a	0.62 ± 0.01 ^a
50	16.21 ± 0.18 ^b	24.85 ± 0.55 ^a	1.11 ± 0.01 ^b	0.44 ± 0.01 ^a	0.56 ± 0.02 ^b
100	12.66 ± 0.98 ^c	21.60 ± 1.61 ^b	0.91 ± 0.01 ^c	0.38 ± 0.01 ^b	0.52 ± 0.01 ^{bc}
200	10.43 ± 0.58 ^d	19.47 ± 0.43 ^{bc}	0.62 ± 0.01 ^d	0.23 ± 0.01 ^c	0.47 ± 0.01 ^c
400	9.36 ± 0.36 ^{de}	17.63 ± 0.38 ^c	0.36 ± 0.02 ^e	0.17 ± 0.02 ^d	0.42 ± 0.02 ^d
800	8.48 ± 0.28 ^e	16.80 ± 0.21 ^c	0.27 ± 0.02 ^f	0.14 ± 0.01 ^e	0.35 ± 0.03 ^e

表中同列数据中字母不相同的表示差异显著 Means within a column followed with different letters are different significantly (DMRT method, *p* < 0.05)

表 2 KClO_3 对花生植株生物量和根瘤菌数量的影响
Table 2 Effects of KClO_3 on biomass and number of *rhizobium* of peanut plant

KClO_3 浓度 Potassium chlorate concentration ($\text{mg}\cdot\text{kg}^{-1}$)	植株总鲜重 Fresh weight of total plant (g)	地上部鲜重 Fresh weight of stem (g)	地上部干重 Dry weight of stem (g)	荚果鲜重 Fresh weight of fruits (g)	根瘤菌数量(个) Number of <i>Rhizobium</i>
CK	77.30 ± 6.37^a	46.71 ± 5.78^a	15.21 ± 2.08^a	27.11 ± 2.98^a	128.25 ± 11.00^a
50	56.28 ± 11.30^{ab}	42.88 ± 9.29^{ab}	13.28 ± 2.64^a	11.44 ± 1.95^b	100.25 ± 4.61^b
100	45.53 ± 6.08^b	28.45 ± 5.38^{bc}	8.18 ± 1.74^b	14.39 ± 2.85^b	90.50 ± 3.97^b
200	24.30 ± 2.82^c	17.16 ± 2.43^c	5.98 ± 0.57^b	4.22 ± 1.01^c	69.00 ± 6.42^c
400	22.93 ± 3.32^c	16.91 ± 2.32^c	4.92 ± 0.66^b	3.34 ± 0.86^c	53.00 ± 4.65^{cd}
800	15.47 ± 4.26^c	11.54 ± 2.73^c	3.79 ± 1.21^b	0.49 ± 0.18^c	44.25 ± 3.09^d

表中同列数据中字母不相同的表示差异显著 Means within a column followed with different letters are different significantly (DMRT method, $p < 0.05$)

以及根瘤菌数量均随氯酸钾浓度的升高而降低,氯酸钾浓度为 $50\text{ mg}\cdot\text{kg}^{-1}$ 时,荚果鲜重和根瘤菌数量与对照相比差异显著,氯酸钾浓度达到 $100\text{ mg}\cdot\text{kg}^{-1}$ 时,植株总鲜重、地上部鲜重及干重差异也达到显著。这说明氯酸钾在土壤中的浓度高于 $50\text{ mg}\cdot\text{kg}^{-1}$ 时,就会影响花生植株的正常生长和根系结瘤和结荚果数。

3 讨 论

本实验中,氯酸钾对花生种子萌发和幼苗生长的影响以氯化钠为对照,结果说明,在本研究相同浓度的处理范围内,氯酸钾强氧化性对花生种子萌发和幼苗生长的毒害远远超过氯化钠的盐害,谭允阳等(1995)曾对花生植株耐氯程度研究证明, $\text{Cl}^- \leq 500\text{ mg}\cdot\text{kg}^{-1}$ 时,对花生植株生长无不良影响,因此,本实验的浓度设置可以排除 Cl^- 的盐害效应。种子萌发过程中,氯酸钾浓度超过 $50\text{ mg}\cdot\text{L}^{-1}$ 时,其强氧化性不但会大大降低发芽率和胚根伸长,而且破坏了根膜透性,致使电解质渗漏率和过氧化氢酶活性升高。氯酸钾在土壤中的浓度超过 $50\text{ mg}\cdot\text{kg}^{-1}$ 时,不仅严重破坏幼苗叶片质膜透性,致使幼苗期叶片硝酸还原酶、叶绿素和根系活力均显著降低,而且会使成年植株的光合速率、蒸腾速率、叶绿素 a 和 b 的含量、根系活力以及收获时植株和荚果的生物量甚至根瘤菌数量显著下降。究其机理,可能是氯酸钾强氧化性破坏了硝酸还原酶等花生氮素代谢中硝态氮转化的关键酶和硝酸还原的限速酶,使花生在幼苗期未能正常建立共生固氮体系,导致花生植株对土壤无机态氮的利用受到限制,最终影响生物量和根瘤菌的形成。Girija 等(2002)研究表明,高浓度 ($50\text{ mmol}\cdot\text{L}^{-1}\text{ NaCl}$) 盐灌溉胁迫可导致花生幼苗脯氨酸(Proline)和甜菜碱(Glycinebetaine, GB)持续增加,但氯酸钾强氧化性是否如此有待检验。

Borges 等(2004)曾就氯酸钾在不同温度下产生的毒性对水稻根和叶等组织细胞的生理生化和形态解剖的毒害效应做过深入研究,结果发现,低温下氯酸钾产生的毒性对水稻影响较小,但在常温下,氯酸钾除增加过氧化氢酶外,还会使叶绿体外膜消失,降低叶绿体的生化效率,进而影响叶片的光合速率;同时,还会不同程度的损坏根毛和根系内外表皮细胞,影响硝酸还原酶的活动。这和本试验得出的常温下高浓度氯酸钾严重影响花生种子的萌发、幼苗和成年植株各项生理指标的结论是一致的,但在低温下氯酸钾对花生毒害效应的研究还有待开展。

本试验在进行中还发现,常温下生长的花生植株加入氯酸钾后,植株叶片变黄,有落叶现象,整个植株生长缓慢甚至停止生长,浓度越大,有关受害症状越严重,大约 20 d 后才逐渐恢复生长,但其抗旱性大大降低,且其后各生育期均有所延缓;同时,由于氯酸钾在土壤中容易淋失和分解,因此,氯酸钾在不同水分条件下对不同生育期花生生长、根瘤菌固氮甚至土壤微生物的毒害效应也有待进一步深入探究,氯酸钾对花生植株各组织器官形态结构和生化过程特别是植物-根瘤菌固氮共生体系的影响也有待开展。

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