尚秉琛,何昊,李丹丹,等.油菜素内酯引发对盐胁迫下水稻幼苗生长及生理特性的影响[J].江西农业大学学报,2023,45(4):795-805.
SHANG B C,HE H,LI D D,et al.Effects of brassinolide priming on growth and growth characteristics of rice seedlings under salt stress[J].Acta agriculturae universitatis Jiangxiensis,2023,45(4):795-805.

油菜素内酯引发对盐胁迫下水稻幼苗生长及生理特性的影响

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摘要:【目的】水稻(*Oryza sativa* L.)作为我国主要的粮食作物之一,在日益增长的盐渍化风险下,种植安全受到了严重的威胁。油菜素内脂(brassinosteroid,BR)是一种天然植物激素,可促进细胞的生长与分裂,增强光合作用。因此,探究BR引发对盐胁迫下水稻种子萌发及幼苗生长的影响,选取最适BR浓度,为应对盐碱地对水稻生产安全的制约具有重要意义。【方法】以皖稻34为供试材料。利用100 mmol/L的NaCl溶液模拟盐胁迫,设置浓度分别为0.5,1.0,1.5,2.0,2.5,3.0 mg/L的BR溶液对水稻种子进行引发,以未引发无盐胁迫处理作为对照1(CK),未引发有盐胁迫处理作为对照2(S-CK),测量水稻种子发芽指标以及根苗生长情况,并监测水稻幼苗抗氧化酶活性、糖代谢指标和叶绿素含量。【结果】盐胁迫下水稻生长受到明显抑制,与CK相比水稻种子发芽率,发芽势,发芽指数和活力指数分别降低12.93%、49.13%、39.69%、59.73%;水稻幼苗鲜重和苗长分别降低29.62%、28.60%。超氧化物歧化酶(superoxide dismutase,SOD)、过氧化物酶(peroxidase,POD)和过氧化氢酶(catalase,CAT)活性受到不同程度的抑制,阻碍了叶绿素的合成,然而增加了丙二醛、可溶性糖和脯氨酸含量,并提高了蔗糖磷酸合成酶(sucrose phosphate synthase,SPS)、蔗糖合成酶(sucrose synthase,SS)活性;与S-CK相比,利用BR引发显著提高水稻种子发芽率、发芽势、发芽指数、活力指数等发芽指标($P<0.05$),促进根系幼苗的生长,提高叶绿素a(50.67%)、叶绿素b含量(59.12%),降低了水稻叶片中丙二醛含量(13.61%~22.80%),增加水稻幼苗叶片可溶性糖含量(26.52%~37.51%)、脯氨酸含量(8.84%~21.40%),提高抗氧化酶以及蔗糖代谢酶活性。【结论】BR引发可有效维持水稻正常的光合作用以及相关蔗糖代谢,缓解渗透压并降低膜脂过氧化带来的损伤,提升水稻幼苗抗盐性,其中以1.0 mg/L浓度效果最佳。选取1.0 mg/L浓度BR进行种子引发可提高盐碱地水稻种植安全,确保国家粮食安全体系和战略储备。

关键词:油菜素内酯;种子引发;水稻;盐胁迫
中图分类号:S511 **文献标志码:**A **开放科学(资源服务)标识码(OSID):**
文章编号:1000-2286(2023)04-0795-11

Effects of Brassinolide Priming on Growth and Growth Characteristics of Rice Seedlings under Salt Stress

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收稿日期:2023-05-12 **修回日期:**2023-06-01
基金项目:国家重点研发计划项目(2018YFD3000905)
Project supported by the National Key Research and Development Program Project(2018YFD3000905)
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Abstract: [**Objective**] Rice (*Oryza sativa* L.), one of the staple food crops in China, is under serious threat of cultivation safety under the increasing risk of salinization. Brassinosteroid (BR), a natural plant hormone, promotes cell growth and division and enhances photosynthesis. Therefore, it is significant to investigate the effect of BR triggering of oleuropein lactone (Brassinosteroid, BR) on seed germination and seedling growth of rice under salt stress, and to select the optimum BR concentration for coping with the constraints of saline land on rice production safety. [**Method**] Wandao 34 was used as the test material. 100 mmol/L NaCl solution was set to simulate salt stress, BR solutions with concentrations of 0.5, 1.0, 1.5, 2.0, 2.5 and 3.0 mg/L were set to initiate rice seeds, with the uninitiated salt stress-free treatment as control 1 (CK) and the uninitiated salt stress treatment as control 2 (S-CK). The germination index of rice seeds and the growth of root seedlings were measured, and the antioxidant enzyme activity, sugar metabolism index and chlorophyll content of rice seedlings were monitored. [**Result**] The results showed that the growth of rice was significantly inhibited under salt stress, and the germination rate, germination potential, germination index and vigour index of rice seeds were reduced by 12.93%, 49.13%, 39.69% and 59.73%, respectively, compared with CK; the fresh weight and seedling length of rice seedlings were reduced by 29.62% and 28.60%, respectively. Superoxide dismutase (SOD), peroxidase (POD) and catalase (CAT) activities were inhibited to various degrees and chlorophyll synthesis was hindered, However, the contents of malondialdehyde, soluble sugar and proline were increased, and the activities of sucrose phosphate synthase (SPS) and sucrose synthase (SS) were increased; compared with S-CK, the use of BR triggered a significant increase ($P<0.05$) in the germination indexes of rice seeds, including germination rate, germination potential, germination index and vigor index, and promoted root seedling It increased chlorophyll a (50.67%) and chlorophyll b content (59.12%), reduced malondialdehyde content in rice leaves (13.61%-22.80%), increased soluble sugar content (26.52%-37.51%) and proline content (8.84%-21.40%) in rice seedling leaves, and improved antioxidant enzymes as well as sucrose metabolizing enzyme activities. [**Conclusion**] BR can effectively maintain normal photosynthesis and related sucrose metabolism in rice, relieve osmotic stress and reduce damage caused by membrane lipid peroxidation, and enhance the salt resistance of rice seedlings, with the best effect at 1.0 mg/L. The selection of 1.0 mg/L BR for seed initiation can improve the safety of saline rice cultivation and ensure the national food security system and strategic reserves.

Keywords: brassinolide; seed priming; rice; salt stress

【研究意义】盐胁迫严重影响作物发育及生存，全球有超过20%农田受到盐胁迫的影响，且这一比例仍有上升的风险[1-3]。中国是土壤盐渍化最为严重的国家之一，据统计约8.00×10^6 hm^{2}农田属于盐碱地，占全国耕地面积的7.0%，严重制约生态农业的发展[4-5]。水稻是中国主要粮食作物之一，确保水稻的生产对于国家粮食安全体系及战略储备意义重大，而水稻属于中度盐敏感作物，并且苗期相对于其他生长期更容易受到环境胁迫的影响[6-7]，为保障粮食安全，应对日益增长的盐渍化风险，因此对水稻耐盐性研究具有重要意义。【前人研究进展】种子引发(seed priming)最初于1973年由Heydecker等[10]提出，通常做法是将种子浸没在低水势溶液(通常为引发剂)中缓慢吸水，防止种子胚根的伸出并处于预发芽的代谢状态，也称渗透调节技术[10]。引发通过打破种子休眠期，促进种子萌发之前的生理生化代谢，进行细胞组织以及DNA的修复，提高种子活性，并且出苗整齐一致，增强作物幼苗在低温、重金属毒害、干旱以及盐

碱等胁迫下的抗逆性[10-14]。引发技术在水稻上已有所应用,利用2.5%和5.0%浓度SiO_2以及2.5%和5%浓度的KNO_3溶液显著提高水稻种子萌发指标、幼苗活力、可溶性蛋白以及蔗糖含量,增强水稻抗旱性[15-16]。此外,有学者利用蛋白质组学方法探究引发对于水稻抗逆性机理,结果表明,引发处理显著增加了逆境防御类、能量代谢类等蛋白合成含量和丰度,使种子获得“逆境记忆(stressful memory)”并且提高抗逆性[17]。以上研究均表明,引发技术对于水稻有着广阔的应用前景。【本研究切入点】油菜素内酯(brassinosteroid,BR)又称芸苔素,可促进细胞的生长与分裂,增强光合作用[19-21]。相关研究表明,外源施加BR可有效提高作物的抗旱性、抗高温、抗重金属毒害等抗逆性,增强作物幼苗活力,促进长势,显著减少病害的发生[21-24]。外源施加油菜素内酯已被证实能够提高作物抗盐性:利用油菜素内酯浸根,可促进番茄种子萌发中物质转化,同时抗氧化酶、蔗糖酶活性增强,增强其渗透调节能力以缓解盐胁迫[25];100 mmol/L的NaCl胁迫下,采用0.01 μmol/L的2,4-表油菜素内酯(EBR)溶液对黑麦草浸种处理,可有效提高种子发芽势和活力指数,增强α-淀粉酶活性和根系活力[18];此外,有研究利用BR引发大豆种子,触发了包括脯氨酸、甜菜碱和可溶性糖在内的渗透物的积累,维持组织水分含量,保证幼苗叶片正常的光合作用,缓解盐胁迫的氧化损伤和渗透胁迫[26]。然而,盐胁迫下,利用不同浓度BR引发对水稻幼苗生长的研究较少。【拟解决的关键问题】本研究以水稻品种皖稻34为供试材料,配制不同浓度BR溶液进行引发,分析引发对于盐胁迫下水稻种子萌发、根苗形态指标以及生理指标的影响,为应对盐碱地制约水稻生产提供理论依据。

1　材料与方法

1.1　供试材料

本试验于2022年在安徽农业大学资源与环境学院土壤学实验室进行。供试水稻品种为皖稻34,生育期约144 d,该品种水稻分蘖力强,成穗率高。

1.2　试验设计

1.2.1　种子引发处理　选取发育良好且外观完整的水稻种子,使用0.2%浓度氯化汞消毒10 min,消毒后用蒸馏水冲洗。利用NaCl溶液模拟盐胁迫,将无NaCl胁迫且未经引发样本记作CK,存在NaCl胁迫但未引发样本记作S-CK。供试油菜素内酯为生物技术级别,试验共设6个不同浓度引发处理,即用0.5,1.0,1.5,2.0,2.5,3.0 mg/L浓度的BR溶液(分别以S-0.5、S-1.0、S-1.5、S-2.0、S-2.5、S-3.0表示)对水稻种子进行引发,种子质量与溶液体积比约为1∶3[(W(g)∶V(mL)],在25 ℃的种子发芽箱内静置等待引发24 h,引发结束后将种子用纯水冲洗干净,使用吸水纸吸干表面水分,置于28 ℃的鼓风干燥箱中干燥至原含水量(约13.3%),之后进行播种。

1.2.2　发芽试验　本研究所用标准发芽皿规格为12 cm×12 cm×5 cm,各发芽皿平铺蛭石。选取均匀饱满、大小一致的水稻种子,各处理重复3次,每个重复播种30粒种子,按5行6列均匀摆置。分别加入80 mL的100 mmol/L的NaCl溶液以模拟盐胁迫,保证蛭石被盐溶液淹没;发芽皿放置在28 ℃的光照培养箱中培养,待种子出土后,设定光照4 000 lx,每天光照时长12 h,昼夜温度分别为27 ℃与20 ℃。

1.3　测定项目与方法

(1)发芽指标:水稻播种日记为第1日。

发芽势=(3日内种子发芽总数/种子数)×100　　①

发芽率=(7日内种子发芽总数/种子数)×100%　　②

发芽指数=∑Gt/Dt(Gt为第t天的发芽数,Dt为相应发芽的天数)　　③

活力指数=S∑Gt/Dt(S为幼苗生长势,即胚根和胚芽的平均鲜质量)　　④

(2)幼苗形态指标。播种后第12天,随机选取发育程度一致的水稻幼苗并测量其根苗形态特征。

(3)丙二醛以及相关抗氧化酶活性含量。播种后第15天,各处理中选取长势良好的幼苗,参照王学奎[27]的方法,采用硝基氮蓝四唑(NBT)、愈创木酚法、紫外分光光度计法、硫代巴比妥酸(TBA)染色法、磺

基水杨酸法，分别测定幼苗叶片超氧化物歧化酶（SOD）活性、过氧化物酶（POD）活性、过氧化氢酶（CAT）活性；丙二醛（MDA）含量及游离脯氨酸含量。

（4）幼苗叶片叶绿素含量的测定。参照李合生[28]的方法，采用乙醇提取、紫外分光光度法测定水稻幼苗叶片叶绿素a、叶绿素b含量。

（5）参照刘丽杰[29]的方法，测定水稻幼苗可溶性糖含量。

1.4 数据处理与分析

利用Origin软件进行数据处理，方差分析，并使用SigmaPlot 12.5进行作图。

2 结果与分析

2.1 引发对水稻种子发芽指标的影响

由表1可知，盐胁迫显著降低了水稻种子发芽率、发芽势、发芽指数和活力指数，分别为12.93%、49.13%、39.69%和59.73%（P<0.05）。利用不同浓度油菜素内酯引发可不同程度提高盐胁迫下水稻种子萌发指标，且均达到显著水平，整体表现为随BR浓度的增加，指标呈现先升高后下降的趋势。综合来看，以S-1.0效果最佳，与S-CK相比，发芽率、发芽势、发芽指数、活力指数分别显著提高10.45%、86.43%、52.18%和105.39%，其次为S-2.0与S-1.5处理，而过高浓度BR引发即S-3.0处理对于缓解盐胁迫效果最低。

表1　盐胁迫下水稻发芽指标对油菜素内酯引发的响应

Tab.1　Response of rice germination indicators to oleuropein lactone triggering under salt stress

处理 Treatments	发芽率 Germination percentage	发芽势 Germination potential	发芽指数 Germination index	活力指数 Vigour index
CK	95.33±3.06^{a}	38.67±1.75^{a}	43.53±1.52^{a}	15.67±0.13^{a}
S-CK	83.00±1.71^{d}	19.67±2.15^{e}	27.46±0.67^{d}	6.31±0.12^{e}
S-0.5	88.67±1.53^{bc}	26.67±1.25^{d}	36.10±1.38^{c}	11.05±0.11^{c}
S-1.0	91.67±2.89^{b}	36.67±1.15^{ab}	41.79±1.02^{b}	12.96±0.10^{bc}
S-1.5	92.00±2.07^{b}	35.33±3.06^{b}	38.26±0.78^{bc}	11.96±0.11^{c}
S-2.0	91.00±1.00^{b}	33.67±1.53^{c}	40.38±0.96^{b}	13.56±0.13^{b}
S-2.5	88.67±2.08^{bc}	32.00±2.00^{c}	38.81±1.94^{bc}	12.03±0.10^{bc}
S-3.0	87.67±0.78^{c}	25.33±1.15^{d}	36.95±2.45^{c}	10.05±0.12^{d}

同列数据（平均值±标准差）后不同字母表示在5%水平显著（n=3，最小差异显著法）。S-0.5、S-1.0、S-1.5、S-2.0、S-2.5、S-3.0分别表示用0.5，1.0，1.5，2.0，2.5，3.0 mg/L浓度的BR溶液对水稻种子进行引发处理，CK表示未引发无盐胁迫处理，S-CK表示未引发有盐胁迫处理。

Values（mean±SD）followed by different letters are significantly different at P<0.05（n=3，LSD）.S-0.5，S-1.0，S-1.5，S-2.0，S-2.5，S-3.0 denote rice seeds triggered with BR solutions at 0.5，1.0，1.5，2.0，2.5，3.0 mg/L，respectively，CK denotes no salt stress treatment triggered，and S-CK denotes no salt stress treatment triggered.

2.2 引发对水稻幼苗根苗生长的影响

由图1可知，与CK相比，S-CK显著降低了水稻幼苗鲜重和苗长，分别为29.62%和28.60%。利用各浓度BR溶液引发可显著提高盐胁迫下水稻幼苗生长状况。在盐胁迫处理下，以S-1.0与S-1.5效果最佳，与S-CK相比，幼苗鲜重和苗长分别提高28.22%与25.27%（S-1.0）、30.69%与23.90%（S-1.5），但与CK相比差异仍显著。此外，盐胁迫显著抑制水稻根系的生长，利用不同浓度BR溶液引发可显著缓解盐胁迫（表2）。从根系生长来看，以S-1.0、S-1.5处理缓解盐胁迫效果最佳，S-2.0处理次之，而S-0.5与S-3.0效果最低。

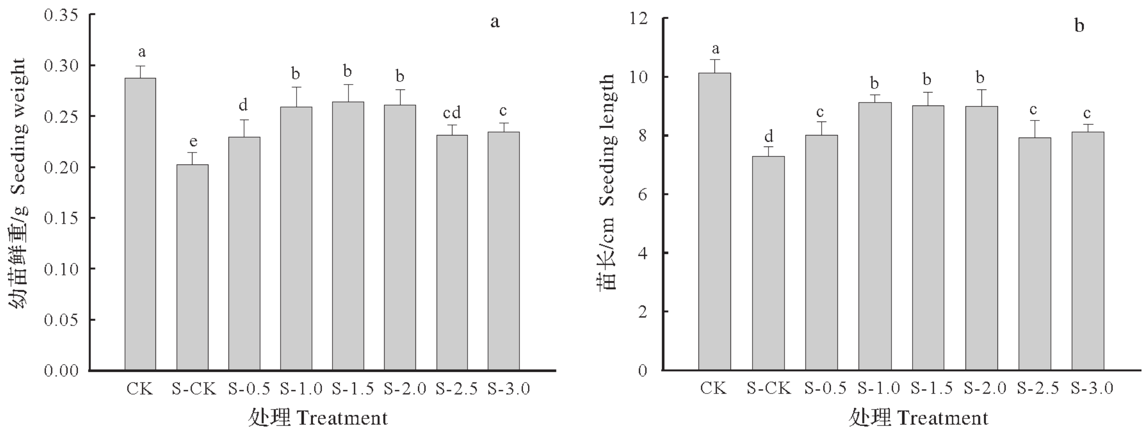


图 1　盐胁迫下水稻苗发育对油菜素内酯引发的响应

Fig.1　Response of rice seedling development to oleuropein lactone triggering under salt stress

表 2　盐胁迫下水稻根发育对油菜素内酯引发的响应

Tab.2　Response of rice root development to oleuropein lactone triggering under salt stress

处理 Treatments	根数 Numbers of roots	根长/cm Root length	根系鲜重/g Root fresh weight	根直径/mm Root diameter
CK	4.29±0.20[a]	9.79±0.43[a]	0.22±0.03[a]	0.25±0.12[ab]
S-CK	3.63±0.19[d]	7.45±0.29[d]	0.16±0.02[d]	0.22±0.11[d]
S-0.5	3.91±0.17[bc]	8.87±0.31[c]	0.18±0.02[c]	0.23±0.13[c]
S-1.0	4.21±0.23[ab]	9.24±0.35[ab]	0.19±0.03[bc]	0.25±0.10[ab]
S-1.5	4.17±0.16[ab]	9.32±0.42[ab]	0.20±0.01[ab]	0.26±0.13[a]
S-2.0	4.20±0.22[ab]	9.02±0.37[bc]	0.19±0.02[bc]	0.25±0.11[ab]
S-2.5	3.94±0.17[bc]	9.13±0.46[b]	0.18±0.02[c]	0.23±0.12[c]
S-3.0	3.82±0.16[c]	8.76±0.29[c]	0.18±0.01[c]	0.24±0.11[bc]

同列数据(平均值±标准差)后不同字母表示在5%水平显著(n=3,最小差异显著法)。S-0.5、S-1.0、S-1.5、S-2.0、S-2.5、S-3.0分别表示用0.5,1.0,1.5,2.0,2.5,3.0 mg/L浓度的BR溶液对水稻种子进行引发处理,CK表示未引发无盐胁迫处理,S-CK表示未引发有盐胁迫处理。

Values(mean±SD)followed by different letters are significantly different at P<0.05(n=3,LSD)。S-0.5,S-1.0,S-1.5,S-2.0,S-2.5,S-3.0 denote rice seeds triggered with BR solutions at 0.5,1.0,1.5,2.0,2.5,3.0 mg/L,respectively,CK denotes no salt stress treatment triggered,and S-CK denotes no salt stress treatment triggered.

2.3　引发对水稻幼苗抗氧化酶活性,丙二醛和脯氨酸含量的影响

由表3可知,与未受到盐胁迫处理CK相比,盐胁迫(S-CK)导致水稻幼苗脯氨酸、丙二醛含量分别增加了49.27%和12.31%。与S-CK相比,利用各浓度BR溶液引发降低了水稻叶片中MDA含量,降幅为13.61%~22.80%,且均达到显著水平(P<0.05);此外,除S-3.0处理,各引发处理显著提高了水稻幼苗脯氨酸含量,增加幅度为8.84%~21.40%,其中S-1.0与S-1.5提升幅度最大。盐胁迫显著降低水稻幼苗SOD、POD和CAT活性,利用BR溶液引发可提高各抗氧化酶的活性,且整体趋势为随溶液浓度升高,呈现先上升后下降。综合来看,以S-1.0与S-1.5效果最佳,SOD、POD和CAT活性分别提高13.94%、26.91%、75.60%(S-1.0)与18.17%、28.56%、71.08%(S-1.5)。

2.4　引发对水稻幼苗叶片叶绿素含量的影响

由图2可知,与未受到盐胁迫CK相比,盐胁迫(S-CK)下叶绿素a、b及总叶绿素含量下降,分别为43.79%、41.08%和43.02%。与S-CK相比,利用BR溶液引发可显著增加水稻幼苗叶片叶绿素含量,其中以S-1.0与S-1.5引发效果最佳,叶绿素a含量、叶绿素b含量分别增加50.67%、59.12%(S-1.0)与48.79%、53.95%(S-1.5);因此总叶绿素含量均显著提升,S-1.0与S-1.5分别为53.16%和50.30%。

表 3　盐胁迫下水稻叶片抗氧化酶活性，丙二醛和脯氨酸含量对油菜素内酯引发的响应

Tab.3　Antioxidant enzyme activity, malondialdehyde and proline content of rice leaves under salt stress in response to oleuropein lactone triggering

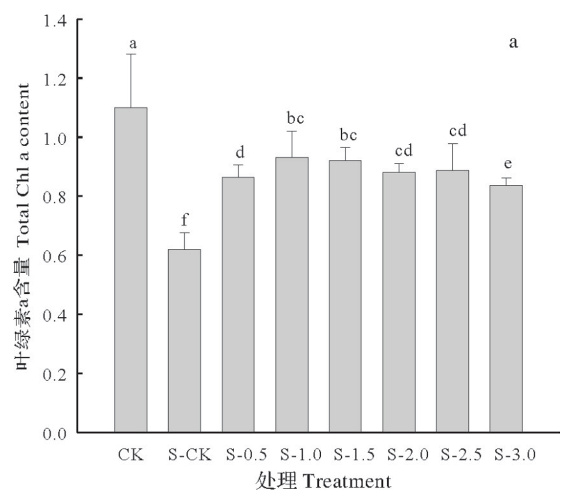
处理 Treatments	丙二醛含量/ (μmol·g^{-1}FW) MDA content	脯氨酸含量/ (μg·g^{-1}) PRO content	超氧化物歧化酶/ (U·g^{-1}FW) SOD activity	过氧化物酶/ (U·g^{-1}·min^{-1}) POD activity	过氧化氢酶/ (U·g^{-1}FW·min^{-1}) CAT activity
CK	16.34±1.64^{e}	122.57±5.65^{e}	227.14±8.17^{a}	132.59±6.21^{a}	198.27±7.69^{a}
S-CK	24.39±2.10^{a}	137.66±6.49^{d}	157.86±3.89^{e}	87.36±5.14^{d}	115.67±3.98^{e}
S-0.5	21.07±1.21^{b}	154.32±5.14^{bc}	167.86±6.14^{d}	103.21±5.30^{b}	177.43±4.25^{c}
S-1.0	19.65±1.35^{cd}	165.36±6.43^{a}	179.86±6.72^{b}	110.87±5.69^{ab}	203.12±6.24^{a}
S-1.5	20.02±0.97^{bc}	167.12±5.22^{a}	186.54±4.99^{b}	112.31±4.12^{ab}	197.89±5.73^{a}
S-2.0	18.83±1.26^{d}	153.96±4.01^{bc}	173.56±5.18^{cd}	106.36±4.97^{b}	185.67±6.30^{bc}
S-2.5	19.26±1.02^{cd}	149.83±3.79^{c}	181.21±5.40^{b}	97.63±5.07^{c}	178.61±7.01^{c}
S-3.0	20.98±1.29^{b}	133.78±3.98^{d}	172.37±5.33^{cd}	95.38±4.13^{c}	166.69±4.61^{d}

同列数据(平均值±标准差)后不同字母表示在5%水平显著(n=3，最小差异显著法)。S-0.5、S-1.0、S-1.5、S-2.0、S-2.5、S-3.0分别表示用0.5，1.0，1.5，2.0，2.5，3.0 mg/L浓度的BR溶液对水稻种子进行引发处理，CK表示未引发无盐胁迫处理，S-CK表示未引发有盐胁迫处理。

Values(mean±SD) followed by different letters are significantly different at P<0.05(n=3, LSD). S-0.5, S-1.0, S-1.5, S-2.0, S-2.5, S-3.0 denote rice seeds triggered with BR solutions at 0.5, 1.0, 1.5, 2.0, 2.5, 3.0 mg/L, respectively, CK denotes no salt stress treatment triggered, and S-CK denotes no salt stress treatment triggered.

2.5　引发对水稻幼苗叶片可溶性糖含量以及相关蔗糖代谢酶活性的影响

由图3可知，与未受到盐胁迫CK相比，盐胁迫(S-CK)下可溶性糖含量提高至32.30%；盐胁迫下，利用BR引发可进一步增加水稻幼苗叶片可溶性糖含量(26.52%~37.51%)，且均达到显著水平(P<0.05)。其中以S-1.0与S-1.5处理可溶性糖含量最高，与S-CK相比分别提高了37.51%与37.19%，两个处理之间无显著差异。此外，与CK相比，盐胁迫增加了SPS、SS活性，分别为13.22%与27.94%；除S-1.5处理外，各引发处理降低了SPS活性(1.74%~11.48%)；而与SPS活性趋势相反，除S-2.0外，各引发处理增加了SS活性(1.67%~6.05%)。



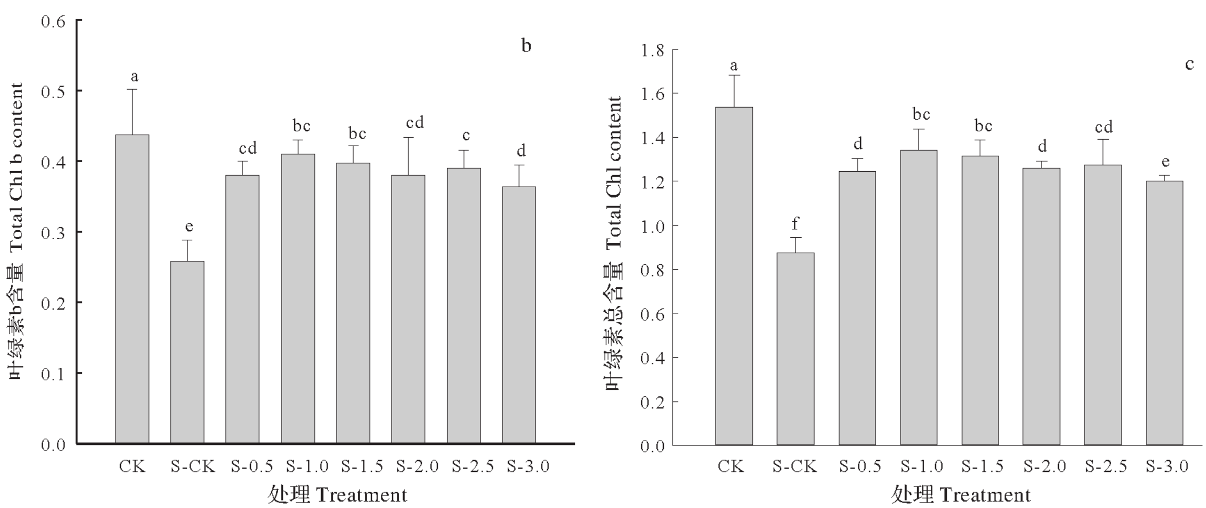
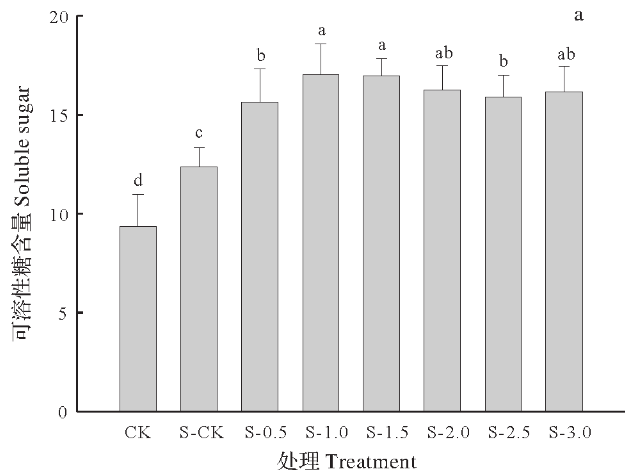


图2　盐胁迫下水稻幼苗叶片叶绿素含量对油菜素内酯引发的响应

Fig.2　Chlorophyll content of rice seedling leaves under salt stress in response to oleuropein lactone triggering

3 讨 论

土壤盐渍化是制约农业生产的重要因素,采用外源激素引发种子提高作物耐盐性有着广阔的应用前景。本研究中,在100 mmol/L的NaCl溶液模拟盐胁迫下,水稻种子发芽率、发芽势、发芽指数和活力指数均显著降低,发芽时间明显延长,利用各浓度BR引发可显著提高水稻各项发芽指标,这与相关学者在黑麦(*Secale cereale* L.)、番茄(*Solanum lycopersicum* L.)、棉花(*Gossypium herbaceum* L.)等作物上的研究结果一致[18,20,25,30]。此外,植物根系是受到盐胁迫最直接的部位,盐胁迫造成离子失衡,水稻根系呼吸作用受阻,迫使根数、根长、根系鲜重和根直径均显著下降,影响作物对于水分和矿质的吸收[31];而利用BR溶液引发可明显缓解盐胁迫对于根苗生长的抑制,表明BR作为一种抗氧化化剂,在引发过程中与植物体内盐离子发生螯合作用缓解胁迫[30-32]。



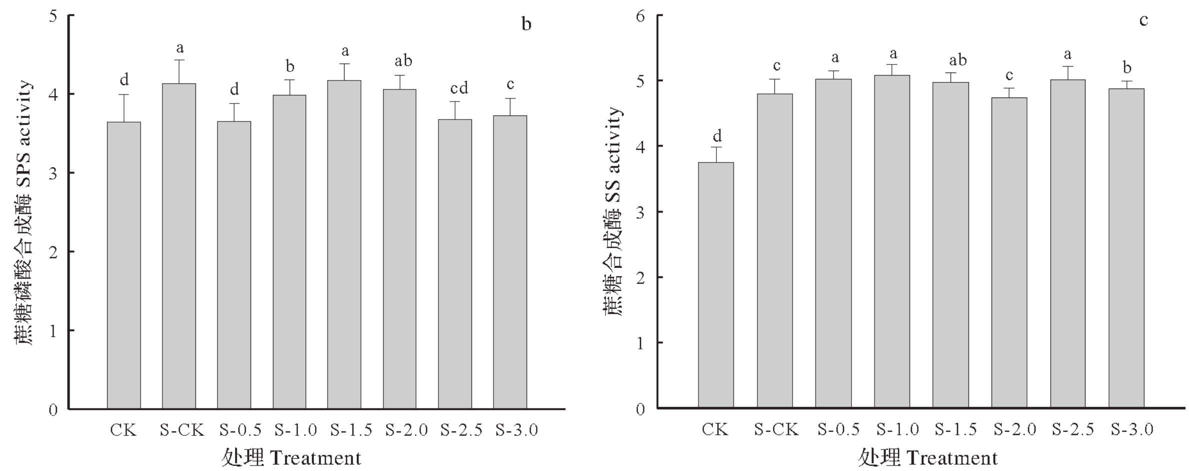


图3　盐胁迫下水稻幼苗叶片可溶性糖含量以及相关蔗糖代谢酶对油菜素内酯引发的响应

Fig.3　Soluble sugar content of rice seedling leaves under salt stress and the response of related sucrose metabolizing enzymes to oleuropein lactone triggering

盐胁迫下,植物幼苗通常受到损伤,导致水稻幼苗积累过多的活性氧(reactive oxygen species ,ROS),种子引发可有效促进细胞膜的修复并保持完整性,提高相关抗氧化酶的活性[10,33]。本研究中,盐胁迫导致水稻幼苗MDA与脯氨酸含量显著提高,而SOD、CAT和POD活性显著降低;而利用BR溶液引发可提高过氧化酶活性,减轻膜脂过氧化损伤,综合来看以S-1.0与S-1.5处理效果最佳,由此可得油菜素内酯作为新型高效的植物激素,同时是一种抗氧化剂,可调控逆境胁迫下植株体的活性氧代谢平衡,更好地抵御逆境胁迫。孙玉珺等[35]研究得出,低温胁迫下,外源施加BR溶液可提高玉米抗氧化酶活性和还原型AsA-GSH的含量,进而清除过量的ROS,其中以0.1 mg/L浓度效果最佳;此外也有学者利用EBR喷施大豆幼苗,证实油菜素内酯激活了抗氧化酶活性,抑制膜脂过氧化并提高氧化应激性,缓解盐碱胁迫[36]。

盐胁迫会影响植物光合作用的效率,主要表现为降低幼苗叶片叶绿素a、叶绿素b含量,这主要是由于盐离子加速叶绿素的分解并且阻碍其合成[37-38]。本研究表明,100 mmol/L的NaCl胁迫显著降低了水稻幼苗叶绿素含量,影响光合性能。外源施加油菜素内酯可提高盐碱、干旱、重金属等逆境胁迫下植物幼苗叶片叶绿素含量[25,37,39]。利用BR引发使得水稻幼苗叶绿素含量维持在较高水平,保证了光合作用,进而促进根系幼苗生物量的增加以及生长,以抵御盐胁迫。其机制可能是,BR引发诱导了水稻幼苗叶片

光合作用的酶特定基因表达，影响了叶绿素的生物合成[36]。此外脯氨酸参与到叶绿素的合成，引发促进脯氨酸含量的提高；并且脯氨酸和可溶性糖含量增加，加速水稻体内氮代谢和碳代谢，利于盐胁迫下叶绿素的合成[38-40]。

可溶性糖和脯氨酸均是分布在植株体内重要的渗透调节物质，二者含量的高低与植物体受到胁迫程度密切相关。本研究中，盐胁迫导致了脯氨酸以及可溶性糖含量的上升，外源添加BR后Pro、可溶性糖呈先增加后降低的趋势，这与在相关学者对辣椒（*Capsicum annuum* L.）、桑树（*Morus alba* L.）盐胁迫的研究中结果一致[40-41]。脯氨酸作为渗透保护剂，有利于维持细胞膜的稳定，清除活性氧，并且作为信号分子激发植物抗胁迫能力；可溶性糖含量可以促进细胞吸水，其含量越高越容易维持作物含水量[31]。BR引发促进了盐胁迫下水稻幼苗脯氨酸、可溶性糖含量的进一步积累，缓解渗透压，促进根系对外界水分的吸收利用，当BR为1.5 mg/L浓度时，脯氨酸含量为最高，而1.0 mg/L浓度时可溶性糖含量达到最大，并且两个处理之间无显著差异。蔗糖合成酶与蔗糖磷酸合成酶是参与植株体蔗糖合成能力的重要酶，盐胁迫导致水稻幼苗SPS、SS活性的增加，是植物的应激性反应[42-43]，BR引发能够进一步增加二者酶活性，表明引发能够促进蔗糖合成速率，保证植株体的正常代谢，提高盐胁迫下水稻生存能力。

4　结　论

盐胁迫显著降低了水稻种子发芽率、发芽势、发芽指数和活力指数；降低了SOD、POD和CAT活性，以及叶绿素a与叶绿素b含量；然而增加了MDA、可溶性糖和脯氨酸含量，并提高了SPS和SS活性。利用油菜素内酯引发可显著提高水稻种子发芽指标，有利于根苗生长，提高叶绿素含量以及抗氧化酶、蔗糖代谢酶活性，进一步提高丙二醛、脯氨酸含量，降低膜脂过氧化损伤，提高水稻抗盐能力。综合来看，以1.0 mg/L浓度的BR溶液引发效果水稻最佳。

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