N-羰基辛酰基高丝氨酸内酯对八棱海棠实生苗耐盐性的影响

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摘　要：【目的】探究 N-羰基辛酰基高丝氨酸内酯（AHL）家族成员 3OC8-HSL 对苹果耐盐性的调控作用，分析 3OC8-HSL 对实生苗生长、离子平衡及耐盐基因表达的影响，解析其分子调控机制，为果树抗盐砧木改良与栽培提供理论依据。【方法】以苹果常用砧木八棱海棠（Malus robusta）实生苗为研究对象，设置 0 mmol·L⁻¹ NaCl（正常生长条件）和 200 mmol·L⁻¹ NaCl（盐胁迫条件）两种处理，检测 10 μmol·L⁻¹ 的 3OC8-HSL 对植株生长、离子平衡、抗氧化能力及耐盐相关基因表达的影响。【结果】在正常生长条件下，3OC8-HSL 处理显著促进八棱海棠实生苗生长，显著增加株高（+23.74%）、鲜质量（+17.23%）和叶绿素含量（+4.06%），表明 3OC8-HSL 对植物的生长具有促进作用。在盐胁迫条件下，3OC8-HSL 处理增强了实生苗的耐盐性，显著增加株高（+11.61%）、鲜质量（+26.38%）和叶绿素含量（+36.98%），降低丙二醛（MDA）含量（-36.20%），降低 Na⁺含量（-11.01%）并提高 K⁺含量（+19.46%），由此显著降低了 Na⁺/K⁺比值（-22.17%）。转录组分析表明，3OC8-HSL 处理上调了多个耐盐相关通路基因的表达，主要涉及苯丙烷生物合成、谷胱甘肽代谢和木质素合成。【结论】3OC8-HSL 可能通过调控生长发育、离子稳态、次生代谢物合成等通路，增强了八棱海棠实生苗的耐盐能力。

关键词：八棱海棠；盐胁迫；N-羰基辛酰基高丝氨酸内酯；Na⁺/K⁺平衡

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Effect of N-Carbonyloctanoyl homoserine lactone on salt tolerance of Malus robusta seedlings

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Abstract:【Objective】The aim of this study was to investigate the effects of exogenous N-carbonyloctanoyl homoserine lactone (3OC8-HSL) on salt tolerance of Malus robusta seedlings by evaluating growth performance, physiological parameters, and the expression of salt-responsive genes under salt stress.【Methods】A greenhouse pot experiment was conducted with four treatment groups: Including the control group (CK, 0 mmol·L⁻¹ NaCl + water), the 3OC8-HSL treatment group (AC, 0 mmol·L⁻¹ NaCl + 10 μmol·L⁻¹ 3OC8-HSL), salt stress group (Salt, 200 mmol·L⁻¹ NaCl + water), and 3OC8-HSL + salt stress group (AS, 200 mmol·L⁻¹ NaCl + 10 μmol·L⁻¹ 3OC8-HSL). Each treatment was applied to the seedlings for 45 days. 3OC8-HSL solution (10 μmol·L⁻¹) was drench-applied to the root zone on days 1, 7, and 14, while salt stress was imposed by watering with 200 mmol·L⁻¹ NaCl every 3 days. The growth parameters (plant height and fresh mass) were measured at the end of the experiment. The leaf chlorophyll content was determined (total chlorophyll, as well as chlorophyll a and b) as an indicator for photosynthetic status. The malondialdehyde (MDA) content in seedling roots was quantified to assess lipid peroxidation (oxidative stress damage). The leaf Na⁺ and K⁺ concentrations were measured,

and the Na$^+$/K$^+$ ratio was calculated to evaluate ionic homeostasis under each treatment. For molecular analysis, the root samples from salt-stressed seedlings with and without 3OC8-HSL were subjected to RNA sequencing (RNA-seq). Differentially expressed genes (DEGs) between the AS treatment and Salt treatment were identified using DESeq2 (standard: |log$_2$ fold change|＞1 and adjusted p-value＜0.05). The gene Ontology (GO) enrichment analysis was performed to characterize the biological processes enriched among these DEGs. Furthermore, four DEGs associated with stress responses were selected for validation by quantitative real-time PCR (RT-qPCR): *MdPAL*, *MdGST*, *MdHKT1*, and *MdLRR-RLK*.【Results】The Growth and Physiological Responses: Under non-saline conditions, the exogenous 3OC8-HSL markedly promoted the growth of *Malus robusta* seedlings. The treated seedlings exhibited a 23.74% increase in plant height and a 17.23% increase in fresh mass compared with the untreated controls, along with a slight but significant rise in the leaf chlorophyll content (+4.06%). These results indicated that 3OC8-HSL itself had a growth-promoting effect even without stress. Under salt stress (200 mmol·L^{-1} NaCl), 3OC8-HSL application substantially improved seedling performance and stress tolerance. The 3OC8-HSL-treated salt-stressed seedlings grew taller (+11.61% plant height) and heavier (＋26.38% fresh mass than those under salt stress alone. Notably, 3OC8-HSL alleviated salt-induced damage: the treated seedlings maintained significantly higher chlorophyll levels (total chlorophyll + 36.98% *vs* salt control), indicating better photosynthetic capacity under stress. In addition, 3OC8-HSL reduced oxidative damage, as evidenced by a 36.20% reduction in root MDA accumulation under salt stress relative to untreated seedlings. This lower MDA level suggested that 3OC8-HSL would enhance the antioxidant defense, thereby protecting cellular membranes from peroxidation damage caused by salt stress. The Ion Homeostasis: 3OC8-HSL also improved ionic balance in *Malus robusta* under salinity. In the salt-stressed seedlings, 3OC8-HSL treatment led to significantly lower Na$^+$ accumulation and higher K$^+$ retention in plant tissues. Specifically, the Na$^+$ content in the 3OC8-HSL-treated seedlings was 11.01% lower than that in the untreated salt-stressed controls, while the K$^+$ content was 19.46% higher. Consequently, The Na$^+$/K$^+$ ratio, a key indicator of ion homeostasis under salt stress, was reduced by 22.17% in the 3OC8-HSL group compared with the salt treatment alone. This improvement in Na$^+$/K$^+$ homeostasis reflected a better maintenance of ionic equilibrium, which is crucial for salt tolerance. The results suggested that 3OC8-HSL would help seedlings limit sodium uptake or transport and/or enhance potassium uptake, thereby mitigating ion toxicity under high salinity. Consistently, the treated seedlings showed healthier morphology and less salt injury than the untreated ones (greener leaves, less wilting), as observed qualitatively during the experiment. The Gene Expression and Pathway Activation: The transcriptome profiling of roots under salt stress revealed significant molecular changes due to 3OC8-HSL. A total of 560 genes were differentially expressed in the 3OC8-HSL-treated vs. untreated salt-stressed roots, with 177 genes upregulated and 383 downregulated (adjusted *P*＜0.05). The GO enrichment analysis of these DEGs indicated that 3OC8-HSL activated multiple stress-responsive pathways. Many of the upregulated genes were associated with secondary metabolite biosynthesis and defense-related processes. In particular, biological process categories such as phenylpropanoid biosynthetic and metabolic pathways (involved in the synthesis of lignin and other phenolics), glutathione metabolism, response to wounding, and cuticle development were significantly enriched among the 3OC8-HSL-induced genes. These results implied that 3OC8-HSL would trigger a broad reprogramming of the plant's stress response at the molecular level, enhancing both structural and chemical defenses under the salt stress. Importantly, several key salt-tolerance genes were strongly upregulated by 3OC8-HSL treatment. For instance, transcripts of the *MdPAL* (phenylalanine ammonia-lyase, a rate-limiting enzyme

in the phenylpropanoid pathway leading to lignin synthesis) increased 4.6-fold in the 3OC8-HSL-treated roots (after 7 days of salt stress) compared with the untreated controls. The *MdHKT1*, encoding a high-affinity K⁺ transporter involved in Na⁺/K⁺ homeostasis, was upregulated 9.6-fold, and the *MdLRR-RLK*, encoding a leucine-rich repeat receptor-like kinase implicated in stress signal perception, rose by 8.4-fold (both after 7 days). Additionally, the *MdGST* (glutathione S-transferase, involved in detoxification and ROS scavenging via the glutathione pathway) showed a 6.4-fold induction at 24 hours after treatment. The robust induction of these genes, which would play roles in lignin biosynthesis (cell wall fortification), antioxidant activity, ionic transport, and stress signaling, would underscore the multi-faceted mechanism by which 3OC8-HSL would enhance salt tolerance. 【Conclusion】This study demonstrated that the exogenous 3OC8-HSL improved the salt tolerance of *Malus robusta* seedlings by promoting growth, enhancing photosynthetic capacity, maintaining Na⁺/K⁺ homeostasis, and reducing oxidative damage. The transcriptome and RT-qPCR analysis showed that the 3OC8-HSL upregulated the expression of the *MdPAL*, *MdGST*, *MdHKT1*, and *MdLRR-RLK*, and activated pathways related to phenylpropanoid metabolism and glutathione metabolism under the salt stress. These results would provide a theoretical basis for the application of AHL signals in improving salt resistance of apple rootstocks.

Key words: *Malus robusta*; Salt stress; *N*-octanoyl-L-homoserine lactone; Na⁺/K⁺ homeostasis

盐胁迫是制约果树生长发育、降低果实产量与品质的主要非生物胁迫因子[1]。全球约6%~10%的陆地面积受盐渍化影响，特别是在中国西部盐碱地区占据了大量耕地面积[2]。盐胁迫通过引发离子毒害、渗透失衡和氧化损伤抑制果树生长，导致苹果等重要经济作物显著减产[3]。因此，解析果树耐盐机制并开发新型抗逆策略已成为产业可持续发展的迫切需求。

植物主要通过离子平衡、渗透调节、抗氧化机制以及基因表达调控来响应盐胁迫，包括通过SOS信号通路维持离子稳态[4]、合成可溶性物质以调节渗透势[5]、激活抗氧化系统清除活性氧[6]、调控耐盐相关基因网络增强耐逆性[7]。近年研究发现，植物-微生物互作可介导植物的耐盐响应。微生物信号分子*N*-酰基高丝氨酸内酯（AHLs）可被植物识别并诱导抗逆响应。例如，*N*-酰基高丝氨酸内酯家族的3OC6-HSL可通过调节生长素合成、离子平衡以及增强抗氧化能力以提高拟南芥的耐盐性[8-9]，但在果树等木本作物中的相关研究尚未见报道。

笔者以苹果砧木八棱海棠（*Malus robusta*）实生苗为材料，旨在探究AHLs家族成员3OC8-HSL对其耐盐性的潜在调控作用，重点分析3OC8-HSL对实生苗生长、离子平衡及耐盐相关基因表达的影响，并结合转录组数据解析其可能的分子调控机制，为果树砧木改良和抗盐栽培提供理论依据。

1 材料和方法

1.1 试验材料

试验所用砧木为八棱海棠实生苗，购于山东寿禾种业有限公司。试剂：*N*-羰基辛酰基高丝氨酸内酯（3OC8-HSL）（CAS：174495-39-9）购自阿拉丁试剂（上海）有限公司。植物生长所用基质土的土壤配方为丹麦品氏泥炭土（进口土，货号为msh-1013）：江苏培蕾基质（江苏蓓蕾基质科技发展有限公司的播种育苗基质）：蛭石=4:2:1（体积比，后同）。实生苗在华中农业大学玻璃温室中培养，白天温度20~28 ℃，夜间15~20 ℃，相对湿度60%~80%，以自然光照为主，日均光照10~14 h。

1.2 试验方法

1.2.1 八棱海棠种子消毒与种植方法 种子消毒：使用1 mol·L⁻¹的NaOH溶液浸泡八棱海棠种子15 min，去除果胶。随后，使用3%的NaClO消毒15 min，使用无菌水洗涤5~7次。催芽：将消毒后的种子平铺在湿润的灭菌沙土上，放入4 ℃冰箱黑暗培养6~7周。待种子露白后，散播在灭菌的蛭石中，在温室中培养30 d左右后移植至装有灭菌的商道基质：泥炭土：蛭石为4:2:1的混合基质的育苗盆内。实验共设置4个处理组：对照组（CK，蒸馏水）、3OC8-HSL处理组（AC，10 μmol·L⁻¹ 3OC8-HSL）、盐胁迫组（Salt，200 mmol·L⁻¹ NaCl＋蒸馏水）以及

3OC8-HSL＋盐胁迫组（AS，200 mmol·L⁻¹ NaCl＋ 10 µmol·L⁻¹ 3OC8-HSL）。在试验过程中，3OC8-HSL 处理组（AC）和 3OC8-HSL＋盐胁迫处理组（AS）的每株实生苗根部均匀滴加 10 mL 3OC8-HSL 溶液；对照组（CK）和盐胁迫组（Salt）则滴加等体积蒸馏水，以保证试验处理条件一致。每个试验处理组设置 12 株实生苗，总计 48 株。每个处理组随机摆放于培养箱内，以减少位置效应对试验结果的影响。3OC8-HSL 处理分别在移栽后的第 1、7、14 天进行，共计 3 次；而盐处理则采用 200 mmol·L⁻¹ NaCl 溶液，每 3 d 处理 1 次，并持续整个试验周期，以模拟长期盐胁迫环境。所有实生苗在华中农业大学玻璃温室中生长 45 d，其间采用自然光照，并通过通风和遮阳调节环境条件。

1.2.2　八棱海棠实生苗 Na⁺和 K⁺元素检测方法　样品处理：将新鲜八棱海棠实生苗置于 105 ℃的烘箱中杀青 30 min，并在 85 ℃下进行烘干至恒质量，称量干质量。样品消解：称取 5 mg 干样，加入 125 µL 30% H_2O_2 和 250 µL 65% HNO_3 混合液，于消解管中进行消解。将消解管置于加热块上，在 140 ℃下消解 80 min，直至样品完全消解且溶液澄清。元素测定：消解后的样品用去离子水定容，并稀释至终浓度含 3.5%或 7% HNO_3 溶液。Na⁺和 K⁺含量采用电感耦合等离子体发射光谱仪（ICP-OES）进行测定。

1.2.3　八棱海棠实生苗叶绿素含量检测方法　采用植物叶绿素含量检测试剂盒（Chlorophyll Assay Kit，100T/96S，北京索莱宝科技有限公司），按照试剂盒说明书提取叶片叶绿素，在 645 nm 和 663 nm 波长下测定吸光度，计算叶绿素 a、b 及总叶绿素含量。

1.2.4　八棱海棠实生苗丙二醛（MDA）含量检测方法　采用丙二醛（MDA）含量检测试剂盒（Malondialdehyde (MDA) Content Assay Kit，100T/96S，北京索莱宝科技有限公司），参照试剂盒说明书，在 532 nm 波长下比色测定。

1.2.5　转录组测序及分析　转录组测序委托北京擎科生物科技股份有限公司完成。测序获得原始的数据，去除测序读长低质量、接头污染和高含量的未知碱基读长。读长过滤后，采用 HISAT2 软件将 Clean Reads 比对到苹果参考基因组（*Malus domestica* GDDH13 v1.1）。基因表达量以 FPKM（Fragments Per Kilobase of transcript per Million mapped reads）进行归一化。差异表达分析采用 DESeq2，筛选条件为|log₂FoldChange|＞1 且 *P*. adjust＜0.05。对筛选到的差异表达基因（differentially expressed genes，DEGs）通过 topGO 软件进行 GO 功能富集分析，显著性标准为 *P*. adjust＜0.05。

1.2.6　实时荧光定量 PCR 分析　利用 RNAprep Pure 多糖多酚植物总 RNA 提取试剂盒(DP441)（天根生化科技有限公司，北京）提取 RNA。超微量紫外分光光度法检测 RNA 样品纯度，1%琼脂糖凝胶电泳检测 RNA 完整性。采用 PrimeScript™ RT reagent Kit with gDNAEraser（TaKaRa，大连）将 RNA 反转录成 cDNA。用 TBGreen® Premix Ex Taq™II 荧光定量试剂盒(TaKaRa，大连)进行 RT-qPCR 反应。扩增体系 10 µL，每个样品 3 次重复，所用引物序见表 1。

使用 LightCycler® 480 实时荧光定量 PCR 仪（Roche，瑞士）进行扩增，反应程序为：95 ℃ 3 min，95 ℃ 10 s，60 ℃ 5 s，72 ℃ 25 s，40 个循环。以苹果 *EF-1α*（DQ341381）为内参基因，用 2⁻ᴬᴬᶜᵀ 法计算基因相对表达量。

表 1　RT-qPCR 所用引物
Table 1　Primers used in RT-qPCR

基因名称 Gene name	基因号 Gene ID	引物序列（5′－3′） Primer sequence
EF-1α	DQ341381	F:ATTCAAGTATGCCTGGGTGC R:CAGTCAGCCTGTGATGTTCC
MdPAL	MD14G1224400	F:CTTAGTGAGAAAGTCGGTGAGCT R:CTGACAAGAACATGACCTCCTCT
MdGST	MD15G1132200	F:AAATCCACCCAACGTCTACTACC R:CACAAATGCGATCGAACTTCTCTC
MdHKT1	MD05G1258000	F:ATGTGGGATGCAGTTTCAAAGC R:CCTCCTTTAACGTCTCCTCCTTC
MdLRR-RLK	MD17G1099500	F:GGATGAGTATGAAAAGCTCTGCC R:ATGGTTCCTGCTGTCTATGTGAG

1.2.7 数据分析方法 使用 Excel 2020 软件整理数据并作图,采用 GraphPad Prism 9.3.0 软件进行统计分析。数据采用单因素方差分析(one-way ANO-VA)并进行 Tukey 多重比较($P<0.05$)。

2 结果与分析

2.1 施用 3OC8-HSL 对八棱海棠实生苗生长的影响

不同处理对八棱海棠实生苗株高和鲜质量的影响如图1-A所示。正常条件下,3OC8-HSL 处理的幼苗鲜质量和株高分别增加了 17.23% 和 23.74%;在盐胁迫条件下,3OC8-HSL 处理的幼苗鲜质量和株高分别增加了 26.38% 和 11.61%(图1-B~C)。
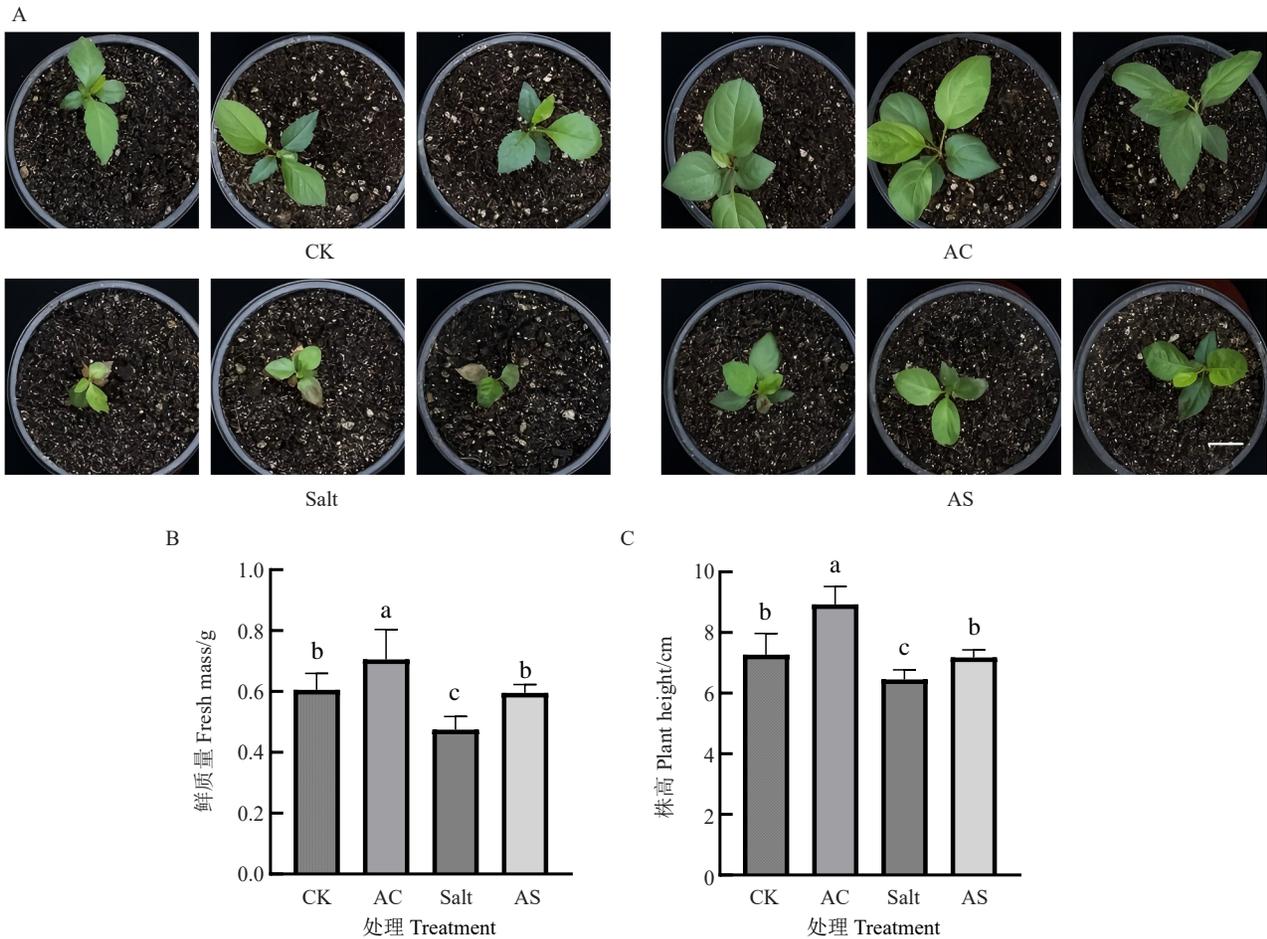

图 1 正常和盐胁迫下施用 3OC8-HSL 对八棱海棠实生苗生长的影响

Fig. 1 Effects of 3OC8-HSL application on the growth of *Malus robusta* seedlings under normal and salt stress conditions

2.2 施用 3OC8-HSL 对八棱海棠实生苗叶绿素和丙二醛(MDA)含量的影响

正常条件下,3OC8-HSL 处理显著提高了八棱海棠幼苗的叶绿素含量,叶绿素总含量、叶绿素 a 和叶绿素 b 含量分别增加了 4.06%、4.10% 和 3.94%(图2-A~C);同时根系的 MDA 含量降低了 2.22%(图2-D)。盐胁迫条件下,3OC8-HSL 处理显著提高了叶绿素含量,叶绿素总含量、叶绿素 a 和叶绿素 b 含量分别增加了 36.98%、40.43% 和 28.15%(图2-A~C);同时根系的 MDA 含量降低了 36.20%(图2-D)。

2.3 施用 3OC8-HSL 对八棱海棠实生苗 Na⁺ 和 K⁺ 含量的影响

正常条件下,3OC8-HSL 处理的八棱海棠幼苗叶片 Na^+ 含量减少了 12.54%(图3-A),K^+ 含量增加了 15.00%(图3-B),Na^+/K^+ 比值降低了 23.98%(图3-C)。盐胁迫条件下,3OC8-HSL 处理的八棱海棠幼苗叶片 Na^+ 含量减少了 11.01%(图3-A),K^+ 含量增加了 19.46%(图3-B),Na^+/K^+ 比值下降了 22.17%(图3-C)。

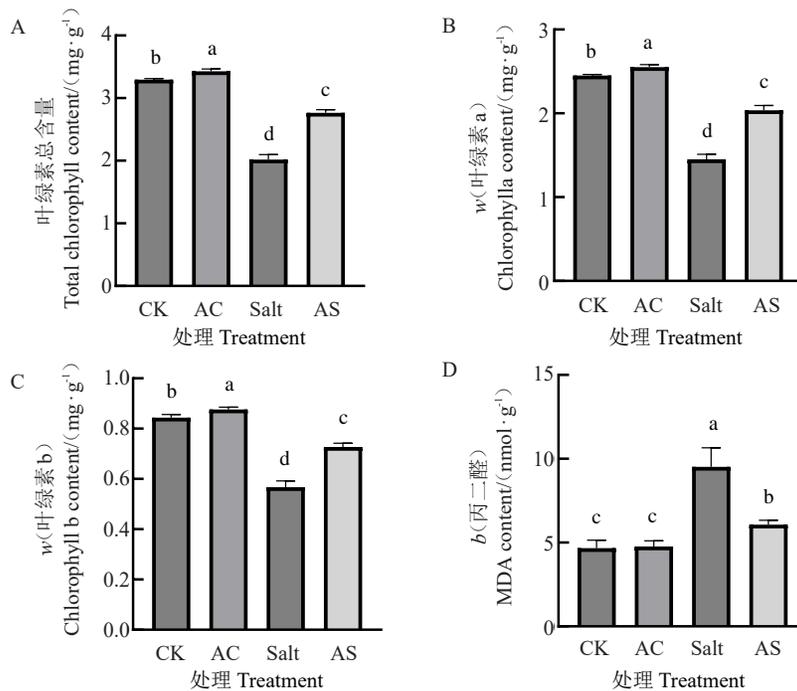### 2.4 施用 3OC8-HSL 对八棱海棠实生苗根系转录组的影响

为探究 3OC8-HSL 增强八棱海棠耐盐性的潜在

图 2　正常和盐胁迫下施用 **3OC8-HSL** 对八棱海棠实生苗叶绿素和 MDA 含量的影响

Fig. 2　Effects of 3OC8-HSL application under normal and salt stress conditions on chlorophyll and MDA contents in *Malus robusta* seedlings
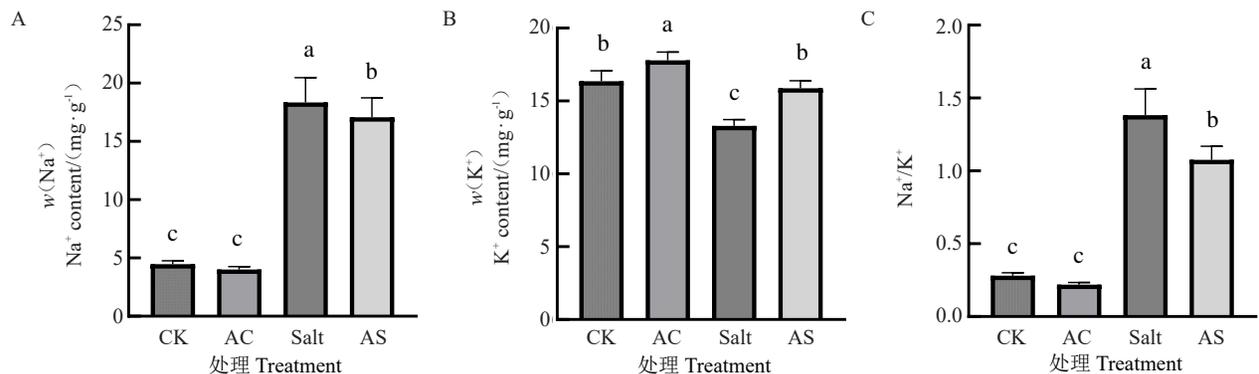

图 3　正常和盐胁迫下施用 **3OC8-HSL** 对八棱海棠实生苗 Na⁺含量和 K⁺含量的影响

Fig. 3　Effects of 3OC8-HSL application under normal and salt stress conditions on Na⁺ and K⁺ content in *Malus robusta* seedlings

机制,利用转录组测序技术分析了盐胁迫条件下八棱海棠根系中受 3OC8-HSL 诱导的差异表达基因。与对照相比,3OC8-HSL 处理产生 560 个 DEGs,其中177 个上调表达,383 个下调表达(图4-A)。这些DEGs的 GO 富集分析发现,生物学过程(biological process,BP)富集的前 5 个类别分别是伤害反应(response to wounding)、次级代谢物生物合成过程(secondary metabolite biosynthetic process)、苯丙烷类化合物生物合成过程(phenylpropanoid biosynthetic process)、苯丙烷类代谢过程(phenylpropanoid metabolic pro-

cess)和角质层发育(cuticle development)(图4-B)。

2.5　盐胁迫下施用 **3OC8-HSL** 诱导八棱海棠实生苗根系抗逆相关基因上调表达

在盐胁迫条件下,基于转录组差异分析结果及GO/KEGG 富集通路,同时参考耐盐相关文献,笔者选取了 4 个代表性抗逆基因(*MdPAL*、*MdGST*、*MdH-KT1* 和 *MdLRR-RLK*)进行 qPCR 验证。结果显示,3OC8-HSL 处理显著上调了八棱海棠根系中 4 个关键基因的表达,包括编码苯丙氨酸解氨酶的 *MdPAL*(MD14G1224400)、编码谷胱甘肽-*S*-转移酶的
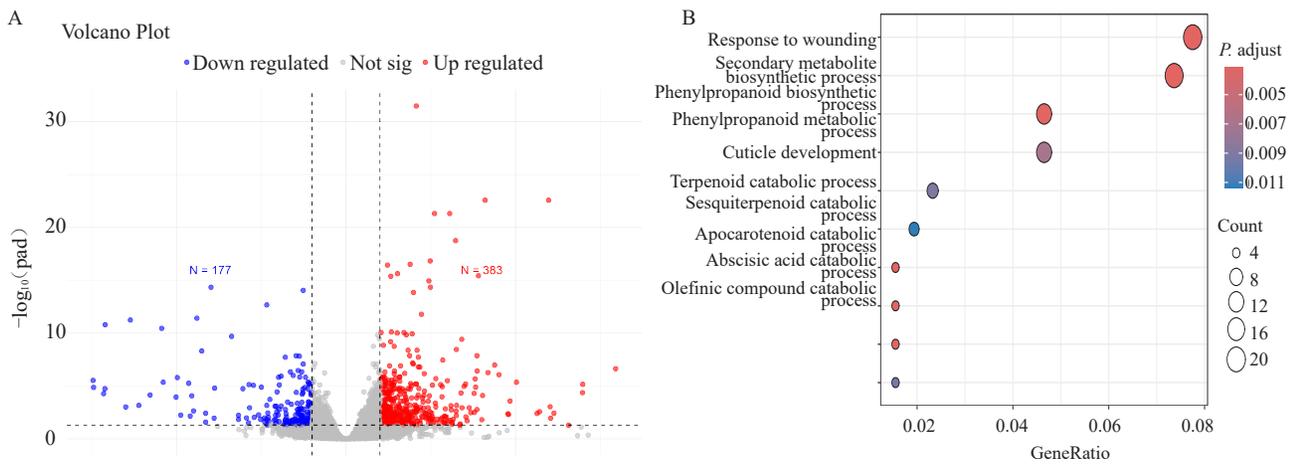
A. 盐胁迫下 3OC8-HSL 处理组与对照组 CK 的基因相对表达量比较。蓝色表示下调基因($\log_2$(FC)＜1,P＜0.05),红色表示上调基因($\log_2$(FC)＞1,P＜0.05),灰色表示非显著变化基因。B.3OC8-HSL vs CK 差异表达基因的 GO 富集分析。选取不重复的丰度前 10 的条目绘制气泡图。

A. Comparison of relative gene expression between the treatment group 3OC8-HSL and the control group CK under salt stress. With down-regulated genes indicated in blue ($\log_2$(FC)＜1,P＜0.05),up-regulated genes in red ($\log_2$(FC)＞1, P＜0.05),and non-significantly altered genes in gray. B. GO enrichment of the DEGs of 3OC8 -HSL vs CK DEGs were GO-enriched. The top 10 entries with unduplicated abundance were selected to draw bubble plots.

图 4 盐胁迫下施加 3OC8-HSL 诱导基因差异表达图

Fig. 4 The application of 3OC8-HSL induces differential gene expression under salt stress

MdGST(MD15G1132200)、编码高亲和性钾转运蛋白的 *MdHKT1*(MD05G1258000)以及编码类受体蛋白激酶的 *MdLRR-RLK*(MD17G1099500)。其中,

MdPAL、*MdHKT1* 和 *MdLRR-RLK* 在处理 7 d 后表达量分别上调 4.6、9.6 和 8.4 倍(P＜0.05 或 P＜0.01),*MdGST* 在 24 h 上调 6.4 倍(P＜0.01)(图5)。
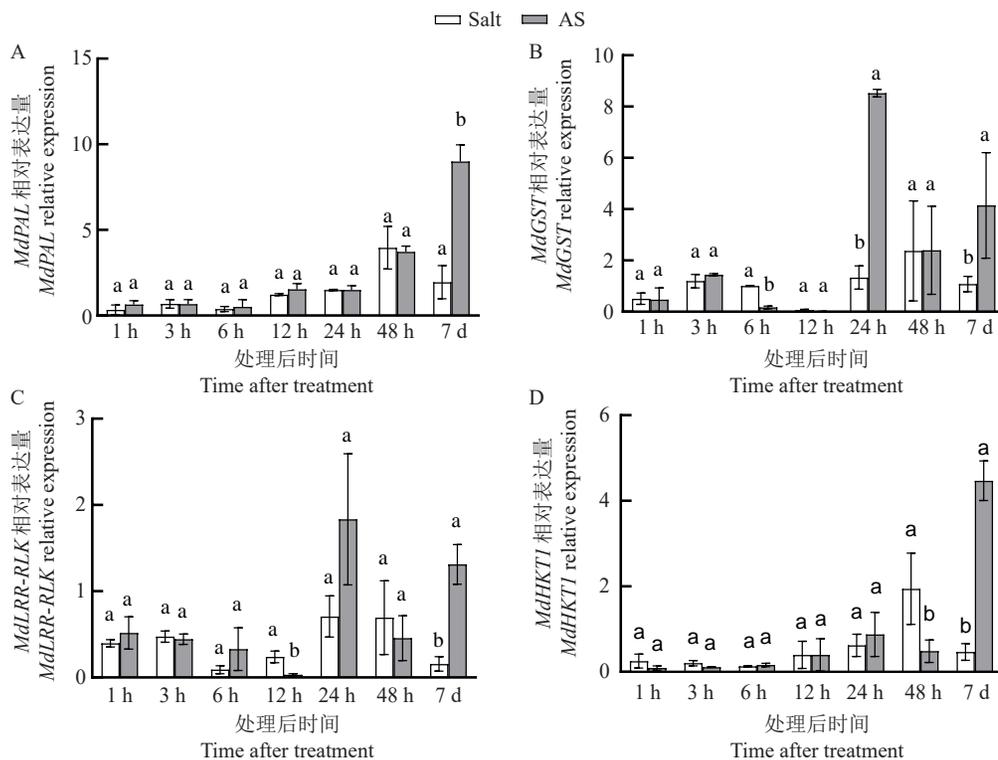

图 5 盐胁迫下 3OC8-HSL 处理调控抗盐基因表达

Fig. 5 Analysis of the regulation of salt-responsive gene expression by 3OC8-HSL treatment under salt stress

3　讨　论

　　N-酰基高丝氨酸内酯（AHLs）作为细菌群体感应信号分子，近年来发现能够被多种植物识别，从而调控植物的生长发育及抗逆性[10-12]。Zhao 等[8]研究发现，施用 3OC6-HSL 可显著提高盐胁迫下拟南芥和小麦的生物量和叶绿素含量，并显著降低 MDA积累量和 Na^+/K^+ 比值，从而提升植物的耐盐性。蔡硕珍[13]也指出，AHLs 可通过激活植物体内的信号转导通路，促进渗透调节物质积累和离子平衡，有效缓解盐胁迫造成的生理损伤。然而，AHLs 在木本果树中的作用鲜有系统报道。笔者首次证明，3OC8-HSL 在八棱海棠实生苗中可显著提升株高、鲜质量及叶绿素含量，优化盐胁迫下的生长表现，拓展了AHLs 在果树耐盐性调控中的应用前景。

　　盐胁迫下，离子毒害和氧化损伤是影响植物生长的主要因素，维持细胞内 Na^+/K^+ 平衡是提高植物耐盐性的关键机制[14-16]。本研究结果显示，3OC8-HSL 处理显著降低了八棱海棠叶片和根系中的 Na^+含量，提高了 K^+ 含量，并有效降低了 Na^+/K^+ 比值，缓解了盐胁迫带来的离子失衡，与 Zhao 等[8]在拟南芥、小麦等草本植物中的研究一致。此外，3OC8-HSL还显著降低了丙二醛含量，表明其可减轻盐胁迫诱导的膜脂过氧化损伤，增强抗氧化能力。综上，3OC8-HSL 可能通过调控 Na^+ 和 K^+ 的吸收与分配，维持离子稳态，并减轻氧化胁迫，从而提高了八棱海棠对盐胁迫的适应性。

　　本试验结果表明，3OC8-HSL 处理诱导了大量差异表达基因。GO 富集分析表明，差异基因主要涉及苯丙烷代谢、谷胱甘肽代谢、角质层发育和胁迫响应等生物学过程和代谢通路。这些通路均与植物的耐盐、抗氧化和细胞稳态密切相关。基于转录组数据、富集结果及相关文献，选取了 4 个代表性耐盐通路的关键基因进行 qPCR 验证，包括调控木质素合成和抗逆性的 MdPAL[17]、参与抗氧化和解毒的MdGST[18]、调节 Na^+/K^+ 平衡的 MdHKT1 以及感知胁迫信号的 MdLRR-RLK[19-21]。结果显示，在 3OC8-HSL 处理下，这些基因的表达显著上调，与转录组数据一致，进一步证明了 3OC8-HSL 可通过激活多条耐盐相关分子通路增强八棱海棠的耐盐性。核心耐盐相关基因的协同上调表明，3OC8-HSL 能多层次调控离子稳态、抗氧化和信号转导等抗逆机制，提升了八棱海棠对盐胁迫的适应能力。研究结果丰富了 AHLs 在木本果树耐盐性调控方面的理论基础，为后续功能基因挖掘与耐盐分子设计育种提供了新思路。

4　结　论

　　本研究结果揭示了 3OC8-HSL 在提升八棱海棠耐盐性中的作用。结果表明，施加 3OC8-HSL 能显著促进八棱海棠实生苗的生长，增强其在盐胁迫下的适应性，具体表现为株高、鲜质量及叶绿素含量增加，Na^+/K^+ 比值下降，MDA 含量降低（$P<0.05$）。3OC8-HSL 可能通过激活苯丙烷生物合成、谷胱甘肽代谢等多条耐盐相关通路，上调 MdPAL、MdGST、MdHKT1、MdLRR-RLK 等关键基因表达，维持离子稳态，增强抗氧化能力，减轻细胞膜损伤。上述结果不仅丰富了 AHLs 信号分子在木本果树耐盐性调控领域的作用机制，也为 AHLs 类物质在果树耐盐性改良及盐碱地高效栽培中的应用提供了理论依据和实践支撑。

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