Title

Transcriptional and structural analysis of non-specific lipid transfer proteins modulated by fungal endophytes in Antarctic plants under drought

Abstract

Lipid transfer proteins (LTPs) play crucial roles in various biological processes in plants, such as pollen tube adhesion, phospholipid transfer, cuticle synthesis, and response to abiotic stress. While a few members of the non-specific LTPs (nsLTPs) have been identified, their structural characteristics remain largely unexplored. Given the observed improvement in the performance of Antarctic plants facing water deficit when associated with fungal endophytes, this study aimed to assess the role of these symbiotic organisms in the transcriptional modulation of putative nsLTPs. The study focused on identifying and characterizing two nsLTP in the Antarctic plant Colobanthus quitensis that exhibit responsiveness to drought stress. Furthermore, we investigated the influence of Antarctic endophytic fungi on the expression profiles of these nsLTPs, as these fungi have been known to enhance plant physiological and biochemical performance under water deficit conditions. Through 3D modeling, docking, and molecular dynamics simulations with different substrates, the conducted structural and ligand-protein interaction analyses showed that differentially expressed nsLTPs displayed the ability to interact with various ligands, with a higher affinity towards palmitoyl-CoA. Overall, our findings suggest a regulatory mechanism for the expression of these two nsLTPs in Colobanthus quitensis under drought stress, further modulated by the presence of endophytic fungi.

Authors

Morales-Quintana L.; Rabert C.; Mendez-Yañez A.; Ramos P.

Author full names

Morales-Quintana, Luis (36731136500); Rabert, Claudia (6505650402); Mendez-Yañez, Angela (57195593304); Ramos, Patricio (54788288200)

Author(s) ID

36731136500; 6505650402; 57195593304; 54788288200

Year

2024

Source title

Physiologia Plantarum

Volume

176.0

Issue

3

Art. No.

e14359

DOI

10.1111/ppl.14359

Link

https://www.scopus.com/inward/record.uri?eid=2-s2.0-85194415857&doi=10.1111%2fppl.14359&partnerID=40&md5=3e4d4f78d136b0785a5e6f046f239bb4

Affiliations

Multidisciplinary Agroindustry Research Laboratory, Instituto de Ciencias Biomédicas, Facultad Ciencias de la Salud, Universidad Autónoma de Chile, Talca, Chile; Instituto de Ciencias Biomédicas, Facultad Ciencias de la Salud, Universidad Autónoma de Chile, Temuco, Chile; Plant-microorganisms Interaction Laboratory, Instituto de Ciencias Biológicas, Universidad de Talca, Talca, Chile

Authors with affiliations

Morales-Quintana L., Multidisciplinary Agroindustry Research Laboratory, Instituto de Ciencias Biomédicas, Facultad Ciencias de la Salud, Universidad Autónoma de Chile, Talca, Chile; Rabert C., Instituto de Ciencias Biomédicas, Facultad Ciencias de la Salud, Universidad Autónoma de Chile, Temuco, Chile; Mendez-Yañez A., Multidisciplinary Agroindustry Research Laboratory, Instituto de Ciencias

Biomédicas, Facultad Ciencias de la Salud, Universidad Autónoma de Chile, Talca, Chile; Ramos P., Plant-microorganisms Interaction Laboratory, Instituto de Ciencias Biológicas, Universidad de Talca, Talca, Chile

Index Keywords

Antarctic Regions; Carrier Proteins; Droughts; Endophytes; Fungi; Gene Expression Regulation, Plant; Molecular Dynamics Simulation; Plant Proteins; Stress, Physiological; carrier protein; lipid transfer protein; plant protein; Antarctica; drought; endophyte; fungus; gene expression regulation; genetics; metabolism; molecular dynamics; physiological stress; physiology

Chemicals/CAS

carrier protein, 80700-39-6; Carrier Proteins, ; lipid transfer protein, ; Plant Proteins,

Funding Details

Agencia Nacional de Investigación y Desarrollo, ANID; Fondo Nacional de Desarrollo Científico y Tecnológico, FONDECYT, (1240771, 1220782); Fondo Nacional de Desarrollo Científico y Tecnológico, FONDECYT

Funding Texts

The Agencia Nacional de Investigaci\u00F3n y Desarrollo (ANID, Chile) [FONDECYT #1240771 to P.R.; FONDECYT # 1220782 to ANILLO L. M-Q. #ATE220014 to LM-Q and PR] supported the work. The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

References

Abbas K., Li J., Gong B., Lu Y., Wu X., Lu G., Gao H., Drought Stress Tolerance in Vegetables: The Functional Role of Structural Features, Key Gene Pathways, and Exogenous Hormones, Int J Mol Sci., 24, 18, (2023); Acuna-Rodriguez I.S., Ballesteros G.I., Atala C., Gundel P.E., Molina-Montenegro M.A., Hardening Blueberry Plants to Face Drought and Cold Events by the Application of Fungal Endophytes, Agronomy, 12, (2022); Acuna-Rodriguez I.S., Newsham K.K., Gundel P.E., Torres-Diaz C., Molina-Montenegro M.A., Functional roles of microbial symbionts in plant cold tolerance, Ecol. Lett., 23, pp. 1034-1048, (2020); Almagro Armenteros J.J., Tsirigos K.D., Sonderby C.K., Nordahl Petersen T., Winther O., Brunak S., von Heijne G., Nielsen H., SignalP 5.0 improves signal peptide predictions using deep neural networks, Nat. Biotechnol., 37, pp. 420-423, (2019); Balmant K.M., Lawrence S.R., Duong B.V., Zhu F., Zhu N., Nicklay J., Chen S., Guard cell redox proteomics reveals a role of lipid transfer protein in plant defense, J. Proteomics., 242, (2021); Barrera A., Hereme R., Ruiz-Lara S., Larrondo L.F., Gundel P.E., Pollmann S., Molina-Montenegro M.A., Ramos P., Fungal Endophytes Enhance the Photoprotective Mechanisms and Photochemical Efficiency in the Antarctic Colobanthus quitensis (Kunth.) Bartl. Exposed to UV-B Radiation, Front. Ecol. Evol., 8, (2020); Bjellqvist B., Basse B., Olsen E., Celis J.E., Reference points for comparisons of two-dimensional maps of proteins from different human cell types defined in a pH scale where isoelectric points correlate with polypeptide compositions, Electrophoresis., 15, pp. 529-539, (1994); Bjellqvist B., Hughes G.J., Pasquali C., Paquet N., Ravier F., Sanchez J.-C., Frutiger S., Hochstrasser D.F., The focusing positions of polypeptides in immobilized pH gradients can be predicted from their amino acid sequences, Electrophoresis., 14, pp. 1023-1031, (1993); Blein J.P., Coutos-Thevenot P., Marion D., Ponchet M., From elicitins to lipid-transfer proteins: a new insight in cell signalling involved in plant defence mechanisms, Trends Plant Sci., 7, pp. 293-296,

(2002); Boutrot F., Chantret N., Gautier M.F., Genome-wide analysis of the rice and Arabidopsis non-specific lipid transfer protein (nsLtp) gene families and identification of wheat nsLtp genes by EST data mining, BMC Genomics, 9, (2008); Cameron K.D., Teece M.A., Smart L.B., Increased accumulation of cuticular wax and expression of lipid transfer protein in response to periodic drying events in leaves of tree tobacco, Plant Physiol., 140, pp. 176-183, (2006); Chae K., Kieslich C.A., Morikis D., Kim S.C., Lord E.M., A gain-of-function mutation of Arabidopsis lipid transfer protein 5 disturbs pollen tube tip growth and fertilization, Plant Cell., 21, pp. 3902-3914, (2009); Chaves M., Flexas J., Pinheiro C., Photosynthesis under drought and salt stress: regulation mechanisms from whole plant to cell, Annals of Botany, 103, 4, pp. 551-560, (2009); Cheng H.C., Cheng P.T., Peng P., Lyu P.C., Sun Y.J., Lipid binding in rice non-specific lipid transfer protein-1 complexes from Oryza sativa, Protein Sci., 13, pp. 2304-2315, (2004); Cuba-Diaz M., Cerda G., Rivera C., Gomez A., Genome size comparison in Colobanthus quitensis populations show differences in species ploidy, Polar Biol., 40, pp. 1475-1480, (2017); Douliez J.P., Michon T., Elmorjani K., Marion D., Structure, biological and technological functions of lipid transfer proteins and indolines, the major lipid binding proteins from cereal kernels, Journal of Cereal Science, 32, pp. 1-20, (2000); Douliez J.P., Pato C., Rabesona H., Molle D., Marion D., Disulfide bond assignment, lipid transfer activity and secondary structure of a 7-kDa plant lipid transfer protein, LTP2, Eur. J. Biochem., 268, pp. 1400-1403, (2001); Dunn M.A., Hughes M.A., Zhang L., Pearce R.S., Quigley A.S., Jack P.L., Nucleotide sequence and molecular analysis of the low-temperature induced cereal gene, BLT4, Mol. Gen. Genet., 229, pp. 389-394, (1991); Edqvist J., Blomqvist K., Nieuwland J., Salminen T.A., Plant lipid transfer proteins: are we finally closing in on the roles of these enigmatic proteins?, J Lipid Res., 59, pp. 1374-1382, (2018); Edstam M.M., Blomqvist K., Eklof A., Wennergren U., Edqvist J., Coexpression patterns indicate that GPI-anchored non-specific lipid transfer proteins are involved in accumulation of cuticular wax, suberin and sporopollenin, Plant Mol. Biol., 83, pp.

625-649, (2013); Edstam M.M., Viitanen L., Salminen T.A., Edqvist J., Evolutionary History of the Non-Specific Lipid Transfer Proteins, Molecular Plant, 4, 6, pp. 947-964, (2011); Elnitsky M.A., Hayward S.A.L., Rinehart J.P., Denlinger D.L., Lee R.E., Cryoprotective dehydration and the resistance to inoculative freezing in the Antarctic midge, Belgica antarctica, J. Exp. Biol., 211, pp. 524-530, (2008); Fardella C., Oses R., Torres-Diaz C., Molina-Montenegro M.A., Antarctic fungal endophytes as tool for the reintroduction of native plant species in arid zones, Bosque, 35, pp. 235-239, (2014); Gaete-Eastman C., Morales-Quintana L., Herrera R., Moya-Leon M.A., In-silico analysis of the structure and binding site features of an α-expansin protein from mountain papaya fruit (VpEXPA2), through molecular modeling, docking, and dynamics simulation studies, J. Mol. Model., 21, 5, (2015); Gago J., Nadal M., Clemente-Moreno M.J., Figueroa C.M., Medeiros D.B., Cubo-Ribas N., Cavieres L.A., Gulias J., Fernie A.R., Flexas J., Bravo L.A., Nutrient availability regulates Deschampsia antarctica photosynthetic and stress tolerance performance in Antarctica, Journal of experimental botany, 74, 8, pp. 2620-2637, (2023); Ganie S.A., Ahammed G.J., Dynamics of cell wall structure and related genomic resources for drought tolerance in rice, Plant Cell Rep., 40, pp. 437-459, (2021); Gasteiger E., Gattiker A., Hoogland C., Ivanyi I., Appel R.D., Bairoch A., ExPASy: the proteomics server for in-depth protein knowledge and analysis, Nucleic Acids Res., 31, pp. 3784-3788, (2003); Guo C., Ge X., Ma H., The rice OsDIL gene plays a role in drought tolerance at vegetative and reproductive stages, Plant Mol. Biol., 82, pp. 239-253, (2013); Guo L., Yang H., Zhang X., Yang S., Lipid transfer protein 3 as a target of MYB96 mediates freezing and drought stress in Arabidopsis, J. Exp. Bot., 64, pp. 1755-1767, (2013); Hall T.A., BioEdit: a user-friendly biological sequence alignment editor and analysis program for Windows 95/98/NT, Nucl. Acids. Symp. Ser., 41, pp. 95-98, (1999); Han G.W., Lee J.Y., Song H.K., Chang C., Min K., Moon J., Shin D.H., Kopka M.L., Sawaya M.R., Yuan H.S., Kim T.D., Choe J., Lim D., Moon H.J., Suh S.W., Structural basis of non-specific lipid binding in maize lipid-transfer protein

complexes revealed by high-resolution X-ray crystallography, J. Mol. Biol., 308, pp. 263-278, (2001); Hare P.D., Cress W.A., Van Staden J., Dissecting the roles of osmolyte accumulation during stress, Plant Cell Environ., 21, pp. 535-553, (1998); Hereme R., Morales-Navarro S., Ballesteros G., Barrera A., Ramos P., Gundel P.E., Molina-Montenegro M.A., Fungal Endophytes Exert Positive Effects on Colobanthus quitensis Under Water Stress but Neutral Under a Projected Climate Change Scenario in Antarctica, Front. Microbiol., 11, (2020); Heredia A., Biophysical and biochemical characteristics of cutin, a plant barrier biopolymer, Biochim Biophys Acta., 1620, 1-3, pp. 1-7, (2003); Homeyer N., Gohlke H., Free energy calculations by the Molecular Mechanics Poisson-Boltzmann surface area method, Mol. Inf., 31, pp. 114-122, (2012); Humphrey W., Dalke A., Schulten K., VMD: Visual molecular dynamics, J. Mol. Graph., 14, pp. 33-38, (1996); Jacq A., Pernot C., Martinez Y., Domergue F., Payre B., Jamet E., Et al., The Arabidopsis lipid transfer protein 2 (AtLTP2). is involved in cuticle-cell wall interface integrity and in etiolated hypocotyl permeability, Front. Plant Sci., 8, (2017); Jegou S., Douliez J.P., Molle D., Boivin P., Marion D., Purification and structural characterization of LTP1 polypeptides from beer, J. Agric. Food Chem., 48, pp. 5023-5029, (2000); Jorgensen W.L., Maxwell D.S., Tirado-Rives J., Development and testing of the OPLS all-atom force field on conformational energetics and properties of organic liquids, J. Am. Chem. Soc., 118, pp. 11225-11236, (1996); Jose-Estanyol M., Gomis-Ruth F.X., Puigdomenech P., The eight-cysteine motif, a versatile structure in plant proteins, Plant Physiol. Biochem., 42, pp. 355-365, (2004); Kader J.C., Lipid transfer proteins in plants, Annu. Rev. Plant Physiol. Plant Mol. Biol., 47, pp. 627-654, (1996); Kielbowicz-Matuk A., Rey P., Rorat T., Theorgan-dependent abundance of a Solanum lipid transfer proteinis up-regulated up on osmotic constraints and associated with cold acclimation ability, J Exp Bot, 59, pp. 2191-2203, (2008); Laskoswki R.A., MacArthur M.W., Moss D.S., Thorton J.M., PROCHECK: a program to check the stereo chemical quality of protein structures, J. Appl. Cryst., 26, pp. 283-291, (1993); Li F., Fan K., Guo X., Liu J., Zhang

K., Lu P., Genome-wide identification, molecular evolution and expression analysis of the non-specific lipid transfer protein (nsLTP). family in Setaria italica, BMC Plant Biol, 22, (2022); Li X., Zhao C., Zhang T., Wang G., Amombo E., Xie Y., Fu J., Exogenous Aspergillus aculeatus enhances drought and heat tolerance of perennial ryegrass, Frontiers in Microbiology, 12, (2021); Lin K.F., Liu Y.N., Hsu S.T., Samuel D., Cheng C.S., Bonvin A.M., Lyu P.C., Characterization and structural analyses of non-specific lipid transfer protein 1 from mung bean, Biochemistry, 44, pp. 5703-5712, (2005); Ma Y., Dias M.C., Freitas H., Drought and salinity stress responses and microbe-induced tolerance in plants, Frontiers in Plant Science, 11, (2020); Maldonado A.M., Doerner P., Dixon R.A., Lamb C.J., Cameron R.K., A putative lipid transfer protein involved in systemic resistance signaling in Arabidopsis, Nature., 419, pp. 399-403, (2002); Mateluna P., Valenzuela-Riffo F., Morales-Quintana L., Herrera R., Ramos P., Transcriptional and computational study of expansins differentially expressed in the response to inclination in radiata pine, Plant Physiol. Biochem., 115, pp. 12-24, (2017); Mathur P., Roy S., Insights into the plant responses to drought and decoding the potential of root associated microbiome for inducing drought tolerance, Physiol Plant., 172, 2, pp. 1016-1029, (2021); Maxwell K., Johnson G.N., Chlorophyll fluorescence—a practical guide, J. Exp. Bot., 51, pp. 659-668, (2000); Molina-Montenegro M.A., Oses R., Torres-Diaz C., Atala C., Zurita-Silva A., Ruiz-Lara S., Root-endophytes improve the ecophysiological performance and production of an agricultural species under drought condition, AoB Plants, 8, (2016); Moller I.M., Jensen P.E., Hansson A., Oxidative modifications to cellular components in plants, Annu. Rev. Plant Biol., 58, pp. 459-481, (2007); Morales-Quintana L., Barrera A., Hereme R., Jara K., Rivera-Mora C., Valenzuela-Riffo F., Gundel P.E., Pollmann S., Ramos P., Molecular and structural characterization of expansins modulated by fungal endophytes in the Antarctic Colobanthus quitensis (Kunth.) Bartl. Exposed to drought stress, Plant Physiol Biochem., 168, pp. 465-476, (2021); Morales-Quintana L., Fuentes L., Gaete-Eastman C., Herrera R., Moya-Leon

M.A., Structural characterization and substrate specificity of VpAAT1 protein related to ester biosynthesis in mountain papaya fruit, J. Mol. Graph. Model., 29, 5, pp. 635-642, (2011); Morales-Quintana L., Moya M., Santelices-Moya R., Cabrera-Ariza A., Rabert C., Pollmann S., Ramos P., Improvement in the physiological and biochemical performance of strawberries under drought stress through symbiosis with Antarctic fungal endophytes, Front. Microbiol., 13, (2022); Ostergaard J., Vergnolle C., Schoentgen F., Kader J.C., Acyl-binding lipid-transfer proteins from rape seedlings, a novel category of proteins interacting with lipids, Biochim. Biophys. Acta – Biomembranes., 1170, pp. 109-117, (1993); Parnikoza I., Maidanuk D.N., Kozeretska I.A., Are Deschampsia antarctica Desv. and Colobanthus quitensis (Kunth.) bartl. migratory relicts?, Cytol. Genet., 41, pp. 36-40, (2007); Pasquato N., Berni R., Folli C., Folloni S., Cianci M., Pantano S., Helliwell J.R., Zanotti G., Crystal structure of peach Pru p 3, the prototypic member of the family of plant non-specific lipid transfer protein pan-allergens, J. Mol. Biol., 356, pp. 684-694, (2006); Perez-Alonso M.M., Guerrero-Galan C., Scholz S.S., Kiba T., Sakakibara H., Ludwig-Muller J., Krapp A., Oelmuller R., Vicente-Carbajosa J., Pollmann S., Harnessing symbiotic plant-fungus interactions to unleash hidden forces from extreme plant ecosystems, J Exp Bot., 24, (2020); Petrushin I.S., Vasilev I.A., Markova Y.A., Drought Tolerance of Legumes: Physiology and the Role of the Microbiome, Curr Issues Mol Biol., 45, 8, pp. 6311-6324, (2023); Potocka I., Baldwin T.C., Kurczynska E.U., Distribution of lipid transfer protein 1 (LTP1). epitopes associated with morphogenic events during somatic embryogenesis of Arabidopsis thaliana, Plant Cell Rep., 31, pp. 2031-2045, (2012); Pyee J., Yu H., Kolattukudy P.E., Identification of a lipid transfer protein as the major protein in the surface wax of broccoli (Brassica oleracea). leaves, Arch. Biochem. Biophys., 311, pp. 460-468, (1994); Ramirez C.F., Cavieres L.A., Sanhueza C., Vallejos V., Gomez-Espinoza O., Bravo L.A., Saez P.L., Ecophysiology of Antarctic Vascular Plants: An Update on the Extreme Environment Resistance Mechanisms and Their Importance in Facing

Climate Change, Plants (Basel)., 13, 3, (2024); Ramos P., Parra-Palma C., Figueroa C.R., Zuniga P.E., Valenzuela-Riffo F., Gonzalez J., Gaete-Eastman C., Morales-Quintana L., Cell wall-related enzymatic activities and transcriptional profiles in four strawberries (Fragaria x ananassa). cultivars during fruit development and ripening, Sci. Hortic., 238, pp. 325-332, (2018); Ramos P., Rivas N., Pollmann S., Casati P., Molina-Montenegro M.A., Hormonal and physiological changes driven by fungal endophytes increase Antarctic plant performance under UV-B radiation, Fungal Ecol., 34, pp. 76-82, (2018); Rizhsky L., Liang H., Shuman J., Shulaev V., Davletova S., Mittler R., When defense pathways collide: the response of Arabidopsis to a combination of drought and heat stress, Plant Physiol., 134, pp. 1683-1696, (2004); Robinson S.A., Tobin A.K., Wasley J., Living on the edge – plants and global change in continental and maritime Antarctica, Glob. Chang. Biol., 9, pp. 1681-1717, (2003); Saez P.L., Rivera B.K., Ramirez C.F., Vallejos V., Cavieres L.A., Corcuera L.J., Bravo L.A., Effects of temperature and water availability on light energy utilization in photosynthetic processes of Deschampsia antarctica, Physiologia plantarum, 165, 3, pp. 511-523, (2019); Sali A., Blundell T.L., Comparative protein modelling by satisfaction of spatial restraints, J. Mol. Biol., 234, pp. 779-815, (1993); Santiago I.F., Rosa C.A., Rosa L.H., Endophytic symbiont yeasts associated with the Antarctic angiosperms Deschampsia antarctica and Colobanthus quitensis, Polar Biol., 40, pp. 177-183, (2017); Segura A., Moreno M., Garcia-Olmedo F., Purification and antipathogenic activity of lipid transfer proteins (LTPs). from the leaves of Arabidopsis and spinach, FEBS Lett., 332, pp. 243-246, (1993); Schnurr J., Shockey J., Browse J., The acyl-CoA synthetase encoded by LACS2 is essential for normal cuticle development in Arabidopsis, Plant Cell, 16, pp. 629-642, (2004); Sippl M.J., Recognition of errors in three-dimensional structures of proteins, Proteins, 17, pp. 355-362, (1993); Tamura K., Stecher G., Kumar S., MEGA11: Molecular evolutionary genetics analysis Version 11, Molecular Biology and Evolution, 38, pp. 3022-3027, (2021); Tapia G., Morales-Quintana L., Parra C., Berbel A., Alcorta M.A.,

Study of nsLTPs in Lotus japonicus genome reveal a specific epidermal cell member (LjLTP10). regulated by drought stress in aerial organs with a putative role in cutin formation, Plant Mol. Biol., 82, pp. 485-501, (2013); Tatrai Z.A., Zsuzsanna R.S., Mancarella S., Orsini F., Gianquinto G., Morphological and physiological plant responses to drought stress in Thymus citriodorus, Intern. J. Agron., 2016, (2016); Thompson J.D., Higgins D.G., Gibson T.J., CLUSTAL W: Improving the sensitivity of progressive multiple sequence alignment through sequence weighting, position-specific gap penalties and weight matrix choice, Nucleic Acids Res., 22, pp. 4673-4680, (1994); Torres-Diaz C., Gallardo-Cerda J., Lavin P., Oses R., Carrasco-Urra F., Atala C., Acuna-Rodriguez I.S., Convey P., Molina-Montenegro M.A., Biological interactions and simulated climate change modulates the ecophysiological performance of Colobanthus quitensis in the antarctic ecosystem, PLoS One, 11, (2016); Torres-Schumann S., Godoy J.A., Pintor-Toro J.A., A probable lipid transfer protein gene is induced by NaCl in stems of tomato plants, Plant Mol, Biol., 18, pp. 749-757, (1992); Trevino M.B., O'Connell M.A., Three drought responsive members of the non-specific lipid-transfer protein gene family in Lycopersicon pennellii show different developmental patterns of expression, Plant Physiol., 116, pp. 1461-1468, (1998); Trott O., Olson A.J., AutoDock Vina: Improving the speed and accuracy of docking with a new scoring function, efficient optimization, and multithreading, J. Comput. Chem., 31, pp. 455-461, (2010); Valenzuela-Riffo F., Tapia G., Parra-Palma C., Morales-Quintana L., Understanding the roles of Lys33 and Arg45 in the binding-site stability of LjLTP10, an LTP related to drought stress in Lotus japonicus, J Mol Model., 21, (2015); Wang N.J., Lee C.C., Cheng C.S., Lo W.C., Yang Y.F., Chen M.N., Lyu P.C., Construction and analysis of a plant non-specific lipid transfer protein database (nsLTPDB), BMC Genomics., 13, (2012); Wani Z.A., Ashraf N., Mohiuddin T., Riyaz-Ul-Hassan R., Plant- endophyte symbiosis, an ecological perspective, Appl. Microbiol. Biotechnol., 7, pp. 2955-2965, (2015); Wiederstein M., Sippl M.J., ProSA-web: interactive web service for the

recognition of errors in three-dimensional structures of proteins, Nucleic Acids Res., 35, pp. W407-W410, (2007); Xu Y., Zheng X., Song Y., Zhu L., Yu Z., Gan L., Zhou S., Liu H., Wen F., Zhu C., NtLTP4, a lipid transfer protein that enhances salt and drought stresses tolerance in Nicotiana tabacum, Scientific Reports, 8, (2018); Yeats T.H., Rose J.K., The biochemistry and biology of extracellular plant lipid-transfer proteins (LTPs), Protein Science, 17, pp. 191-198, (2008); Zegaoui Z., Planchais S., Cabassa C., Djebbar R., Belbachir O.A., Carol P., Variation in relative water content, proline accumulation, and stress gene expression in two cowpea landraces under drought, Journal of Plant Physiology, 218, pp. 26-34, (2017)

Correspondence Address

P. Ramos; Plant-microorganisms Interaction Laboratory, Instituto de Ciencias Biológicas, Universidad de Talca, Talca, Chile; email: pramos@utalca.cl

Publisher

John Wiley and Sons Inc

ISSN

00319317

CODEN

PHPLA

PubMed ID

38797943.0

Language of Original Document

English

Abbreviated Source Title

Physiol. Plant.

Document Type

Article

Publication Stage

Final

Source

Scopus

EID

2-s2.0-85194415857