# Aluminium Toxicity in Rice Cultivars and Some Ameliorative Methods

Balaji Meriga

DeepScience

# Aluminium Toxicity in Rice Cultivars and Some Ameliorative Methods

**Balaji Meriga**
Department of Biochemistry, Sri Venkateswara University,
Tirupati-517502 Andhra Pradesh, India

DeepScience

*Published, marketed, and distributed by:*

Deep Science Publishing, 2025
USA | UK | India | Turkey
Reg. No. MH-33-0523625
www.deepscienceresearch.com
editor@deepscienceresearch.com
WhatsApp: +91 7977171947

ISBN: 978-93-7185-879-3

E-ISBN: 978-93-7185-623-2

https://doi.org/10.70593/978-93-7185-623-2



**Citation:** Meriga, B. (2025). *Aluminium Toxicity in Rice Cultivars and Some Ameliorative Methods*. Deep Science Publishing. https://doi.org/10.70593/978-93-7185-623-2

# Preface

Rice is a staple food crop for more than half of the global population. Its yields are limited by many factors including Aluminium (Al) toxicity. Al is a major abiotic stress factor affecting crop productivity, especially in acidic soils where soluble forms of aluminium becomes toxic to plants. Despite its importance, the physiological, biochemical, and molecular mechanisms of Al toxicity and tolerance in rice remain incompletely understood. This book is a comprehensive exploration into the intricate responses of rice seedlings to aluminium stress, with focus on cultivar-specific differences in tolerance and injury.

The investigations presented herein were undertaken to decipher how different rice cultivars-VIK, IR-8, IR-64, PB, and SUR-respond to varying concentrations and durations of aluminium exposure. Particular focus was given to changes in growth parameters, aluminium accumulation, cellular and histological alterations, membrane lipid peroxidation, antioxidant enzyme responses, metabolic adaptations, and molecular markers associated with tolerance.

The findings reveal that Al stress significantly hinders growth, root-shoot development, and nutrient uptake, particularly under lower pH conditions and in younger seedlings. However, PB and SUR cultivars demonstrated marked resilience, evident from their minimal growth inhibition, reduced oxidative damage, and efficient antioxidant responses. Histological studies revealed effective compartmentalization of aluminium in tolerant cultivars, minimizing injury to root tissues. Elevated activity of key enzymes in the pentose phosphate pathway and TCA cycle, alongside enhanced exudation of citric acid, reflect metabolic adjustments in PB and SUR. Moreover, protein profiling and DNA analysis identified potential molecular markers and stress-inducible components associated with tolerance.

This book not only enriches our understanding of aluminium-induced stress responses but also underscores potential physiological and molecular markers that could be leveraged in rice breeding programs for developing Al-tolerant cultivars. The insights presented here aim to contribute towards sustainable agricultural practices and improved food security in regions with acidic soils.

We hope that researchers, students, plant physiologists, agronomists, and molecular biologists will find this work a valuable resource in the field of plant stress physiology and crop improvement.

Balaji Meriga

# Table of Contents

# REFERENCES


1. Yu H, Lin T, Meng X, et al. A route to de novo domestication of wild allotetraploid rice. *Cell*. 2021;184(5):1156-1170.e14. doi:10.1016/j.cell.2021.01.013
2. Donald l, Sparaks, Balwanth, et al. the chemistry of soil acidity. Environmental soil chemistry 2024; 9 (3); 381-410.
3. Ellinger D, Sode B, Falter C, Voigt CA. Resistance of callose synthase activity to free fatty acid inhibition as an indicator of Fusarium head blight resistance in wheat. *Plant Signal Behav*. 2014;9(7):e28982. doi:10.4161/psb.28982
4. Wang X, Zheng G, Chen T, et al. Effect of phosphate amendments on improving the fertilizer efficiency and reducing the mobility of heavy metals during sewage sludge composting. *J Environ Manage*. 2019;235:124-132. doi:10.1016/j.jenvman.2019.01.048.
5. Wang L, Jiang X, Sun B, et al. Spectroscopy and Photochemistry of [Al, N, C, O, H]: Connectivity to Aluminium-Bearing Species in the Universe. *Chemistry*. 2024;30(39):e202401397. doi:10.1002/chem.202401397.
6. Wang Y, Li H, Zhang J, et al. Effect of aluminum combined with ApoEε4 on Tau phosphorylation and Aβ deposition. *J Trace Elem Med Biol*. 2021; 64:126700. doi:10.1016/j.jtemb.2020.126700.
7. Castro, G. S. A., and Carlos Alexandre Costa Crusciol. "Effects of superficial liming and silicate application on soil fertility and crop yield under rotation." *Geoderma* 195 (2013): 234-242.
8. Duan W, Lu F, Cui Y, et al. Genome-Wide Identification and Characterisation of Wheat *MATE* Genes Reveals Their Roles in Aluminium Tolerance. *Int J Mol Sci*. 2022;23(8):4418. Published 2022 Apr 16. doi:10.3390/ijms23084418.
9. Zuev EV, Lebedeva TV, Yakovleva OV, et al. Genetic Diversity for Effective Resistance in Wheat Landraces from Ethiopia and Eritrea to Fungal Diseases and Toxic Aluminum Ions. *Plants (Basel)*. 2024;13(8):1166. Published 2024 Apr 22. doi:10.3390/plants13081166.
10. Mosa A, Selim EM, El-Kadi SM, et al. Ecotoxicological assessment of toxic elements contamination in mangrove ecosystem along the Red Sea coast, Egypt. *Mar Pollut Bull*. 2022;176:113446. doi:10.1016/j.marpolbul.2022.113446.
11. Ranjan A, Sinha R, Lal SK, Bishi SK, Singh AK. Phytohormone signalling and cross-talk to alleviate aluminium toxicity in plants. *Plant Cell Rep*. 2021;40(8):1331-1343. doi:10.1007/s00299-021-02724-2.

12. Chauhan DK, Yadav V, Vaculík M, et al. Aluminum toxicity and aluminum stress-induced physiological tolerance responses in higher plants. *Crit Rev Biotechnol*. 2021;41(5):715-730. doi:10.1080/07388551.2021.1874282.
13. Chakraborty S, Mishra A, Verma E, Tiwari B, Mishra AK, Singh SS. Physiological mechanisms of aluminum (Al) toxicity tolerance in nitrogen-fixing aquatic macrophyte Azolla microphylla Kaulf: phytoremediation, metabolic rearrangements, and antioxidative enzyme responses. *Environ Sci Pollut Res Int*. 2019;26(9):9041-9054. doi:10.1007/s11356-019-04408-7.
14. Rahimzadeh MR, Rahimzadeh MR, Kazemi S, Amiri RJ, Pirzadeh M, Moghadamnia AA. Aluminum Poisoning with Emphasis on Its Mechanism and Treatment of Intoxication. *Emerg Med Int*. 2022;2022:1480553. Published 2022 Jan 11. doi:10.1155/2022/1480553.
15. Mishra N, Jiang C, Chen L, Paul A, Chatterjee A, Shen G. Achieving abiotic stress tolerance in plants through antioxidative defense mechanisms. *Front Plant Sci*. 2023;14:1110622. Published 2023 Jun 2. doi:10.3389/fpls.2023.1110622.
16. Ofoe R, Thomas RH, Asiedu SK, Wang-Pruski G, Fofana B, Abbey L. Aluminum in plant: Benefits, toxicity and tolerance mechanisms. *Front Plant Sci*. 2023;13:1085998. Published 2023 Jan 13. doi:10.3389/fpls.2022.1085998.
17. Zhang S, Geng L, Fan L, et al. Spraying silicon to decrease inorganic arsenic accumulation in rice grain from arsenic-contaminated paddy soil. *Sci Total Environ*. 2020;704:135239. doi:10.1016/j.scitotenv.2019.135239.
18. Kumar S, Kumar S, Mohapatra T. Interaction Between Macro- and Micro-Nutrients in Plants. *Front Plant Sci*. 2021;12:665583. Published 2021 May 10. doi:10.3389/fpls.2021.665583.
19. Guo C, Shabala S, Chen ZH, Zhou M, Zhao C. Aluminium tolerance and stomata operation: Towards optimising crop performance in acid soil. *Plant Physiol Biochem*. 2024;210:108626. doi:10.1016/j.plaphy.2024.108626.
20. Ofoe R, Thomas RH, Asiedu SK, Wang-Pruski G, Fofana B, Abbey L. Aluminum in plant: Benefits, toxicity and tolerance mechanisms. *Front Plant Sci*. 2023;13:1085998. Published 2023 Jan 13. doi:10.3389/fpls.2022.1085998.
21. Ropelewska M, Gross MH, Konieczny I. DNA and Polyphosphate in Directed Proteolysis for DNA Replication Control. *Front Microbiol*. 2020;11:585717. Published 2020 Oct 2. doi:10.3389/fmicb.2020.585717.
22. Kobayashi Y, Kobayashi Y, Watanabe T, et al. Molecular and physiological analysis of $Al^{3+}$ and $H^{+}$ rhizotoxicities at moderately acidic conditions. *Plant Physiol*. 2013;163(1):180-192. doi:10.1104/pp.113.222893.
23. Abreha KB, Enyew M, Carlsson AS, et al. Sorghum in dryland: morphological, physiological, and molecular responses of sorghum under drought stress. *Planta*. 2021;255(1):20. Published 2021 Dec 11. doi:10.1007/s00425-021-03799-7.
24. Pugazhendhi A, Govindasamy C, Sharma A. Heavy metal accumulation in root and shoot tapioca plant biomass grown in agriculture land situated around the magnesite mine tailings. *Environ Res*. 2024;257:119287. doi:10.1016/j.envres.2024.119287.
25. Yazicioglu H, Hocaoglu-Ozyigit A, Ucar B, et al. Physiological alterations and genotoxic damage under combined aluminum and cadmium treatments in Bryophyllum daigremontianum

clones. *Mol Biol Rep*. 2024;51(1):1019. Published 2024 Sep 27. doi:10.1007/s11033-024-09936-1.
26. Sasaki H, Arai H, Kikuchi E, Saito H, Seki K, Matsui T. Novel electron microscopic staining method using traditional dye, hematoxylin. *Sci Rep*. 2022;12(1):7756. Published 2022 May 16. doi:10.1038/s41598-022-11523-y.
27. Chlipala E, Bendzinski CM, Chu K, et al. Optical density-based image analysis method for the evaluation of hematoxylin and eosin staining precision. *J Histotechnol*. 2020;43(1):29-37. doi:10.1080/01478885.2019.1708611.
28. Admire L, Carson M, Crawford K, Nguyen E, Daniels T. Hair root staining with Hematoxylin: Increasing the rate of obtaining DNA profiles in forensic casework. *Forensic Sci Int*. 2023;343:111544. doi:10.1016/j.forsciint.2022.111544.
29. González-Santana IH, Márquez-Guzmán J, Cram-Heydrich S, Cruz-Ortega R. Conostegia xalapensis (Melastomataceae): an aluminum accumulator plant. *Physiol Plant*. 2012;144(2):134-145. doi:10.1111/j.1399-3054.2011.01527.x.
30. de Haan K, Zhang Y, Zuckerman JE, et al. Deep learning-based transformation of H&E stained tissues into special stains. *Nat Commun*. 2021;12(1):4884. Published 2021 Aug 12. doi:10.1038/s41467-021-25221-2.
31. Li N, Lin Z, Yu P, Zeng Y, Du S, Huang LJ. The multifarious role of callose and callose synthase in plant development and environment interactions. *Front Plant Sci*. 2023;14:1183402. Published 2023 May 31. doi:10.3389/fpls.2023.1183402.
32. Ding Y, Wang Z, Ren M, et al. Iron and callose homeostatic regulation in rice roots under low phosphorus. *BMC Plant Biol*. 2018;18(1):326. Published 2018 Dec 4. doi:10.1186/s12870-018-1486-z.
33. Silva S, Rodriguez E, Pinto-Carnide O, et al. Zonal responses of sensitive vs. tolerant wheat roots during Al exposure and recovery. *J Plant Physiol*. 2012;169(8):760-769. doi:10.1016/j.jplph.2012.01.011.
34. Xu S, Wu L, Li L, et al. Aluminum-Induced Alterations to the Cell Wall and Antioxidant Enzymes Involved in the Regulation of the Aluminum Tolerance of Chinese Fir (*Cunninghamia lanceolata*). *Front Plant Sci*. 2022;13:891117. Published 2022 Apr 28. doi:10.3389/fpls.2022.891117.
35. Wang B, Andargie M, Fang R. The function and biosynthesis of callose in high plants. *Heliyon*. 2022;8(4):e09248. Published 2022 Apr 5. doi:10.1016/j.heliyon.2022.e09248.
36. Drs M, Krupař P, Škrabálková E, et al. Chitosan stimulates root hair callose deposition, endomembrane dynamics, and inhibits root hair growth. *Plant Cell Environ*. 2025;48(1):451-469. doi:10.1111/pce.15111.
37. Okada K, Yachi K, Nguyen TAN, et al. Defense-related callose synthase PMR4 promotes root hair callose deposition and adaptation to phosphate deficiency in Arabidopsis thaliana. *Plant J*. 2024;120(6):2639-2655. doi:10.1111/tpj.17134.
38. Ahmed B, Khan MS, Musarrat J. Toxicity assessment of metal oxide nano-pollutants on tomato (Solanum lycopersicon): A study on growth dynamics and plant cell death. *Environ Pollut*. 2018;240:802-816. doi:10.1016/j.envpol.2018.05.015.
39. Nguyen TN, Son S, Jordan MC, Levin DB, Ayele BT. Lignin biosynthesis in wheat (Triticum aestivum L.): its response to waterlogging and association with hormonal levels. *BMC Plant Biol*. 2016;16:28. Published 2016 Jan 25. doi:10.1186/s12870-016-0717-4.

40. Sun C, Lu L, Liu L, et al. Nitrate reductase-mediated early nitric oxide burst alleviates oxidative damage induced by aluminum through enhancement of antioxidant defenses in roots of wheat (Triticum aestivum). *New Phytol*. 2014;201(4):1240-1250. doi:10.1111/nph.12597.
41. Parrotta L, Faleri C, Del Casino C, et al. Biochemical and cytological interactions between callose synthase and microtubules in the tobacco pollen tube. *Plant Cell Rep*. 2022;41(5):1301-1318. doi:10.1007/s00299-022-02860-3
42. Kumar V, Gill KD. Oxidative stress and mitochondrial dysfunction in aluminium neurotoxicity and its amelioration: a review. *Neurotoxicology*. 2014;41:154-166. doi:10.1016/j.neuro.2014.02.004.
43. Mansoor S, Ali A, Kour N, et al. Heavy Metal Induced Oxidative Stress Mitigation and ROS Scavenging in Plants. *Plants (Basel)*. 2023;12(16):3003. Published 2023 Aug 20. doi:10.3390/plants12163003.
44. Mansoor S, Ali Wani O, Lone JK, et al. Reactive Oxygen Species in Plants: From Source to Sink. *Antioxidants (Basel)*. 2022;11(2):225. Published 2022 Jan 25. doi:10.3390/antiox11020225.
45. Smirnoff N, Arnaud D. Hydrogen peroxide metabolism and functions in plants. *New Phytol*. 2019;221(3):1197-1214. doi:10.1111/nph.15488.
46. Impellitteri F, Yunko K, Martyniuk V, et al. Physiological and biochemical responses to caffeine and microplastics in Mytilus galloprovincialis. *Sci Total Environ*. 2023;890:164075. doi:10.1016/j.scitotenv.2023.164075.
47. Datta N, Kar PK, Saha SK. Primary stress response and biochemical profile of Labeo rohita (Hamilton, 1822) experimentally parasitized with Argulus bengalensis (Ramakrishna, 1951). *J Fish Biol*. 2022;100(6):1375-1387. doi:10.1111/jfb.15048.
48. Jankowska M, Augustyn B, Maliszewska J, et al. Sublethal biochemical, behavioral, and physiological toxicity of extremely low dose of bendiocarb insecticide in Periplaneta americana (Blattodea: Blattidae). *Environ Sci Pollut Res Int*. 2023;30(16):47742-47754. doi:10.1007/s11356-023-25602-8.
49. Abramova A, Bride J, Oger C, et al. Metabolites derived from radical oxidation of PUFA: NEO-PUFAs, promising molecules for health?. *Atherosclerosis*. 2024;398:118600. doi:10.1016/j.atherosclerosis.2024.118600.
50. Iyer, S., Kumar, A., Savolainen, A. *et al.* Molecular rearrangement of bicyclic peroxy radicals is a key route to aerosol from aromatics. *Nat Commun* **14**, 4984 (2023). https://doi.org/10.1038/s41467-023-40675-2.
51. Ruszczycky MW, Liu HW. Initiation, Propagation, and Termination in the Chemistry of Radical SAM Enzymes. *Biochemistry*. 2024;63(24):3161-3183. doi:10.1021/acs.biochem.4c00518.
52. Yang, S., Hu, C., Chen, X. *et al.* Crosstalk between metabolism and cell death in tumorigenesis. *Mol Cancer* **23**, 71 (2024). https://doi.org/10.1186/s12943-024-01977-1.
53. Lima JS, Andrade OVS, Santos LCD, et al. Soybean Plants Exposed to Low Concentrations of Potassium Iodide Have Better Tolerance to Water Deficit through the Antioxidant Enzymatic System and Photosynthesis Modulation. *Plants (Basel)*. 2023;12(13):2555. Published 2023 Jul 5. doi:10.3390/plants12132555.
54. Liang X, Ou Y, Zhao H, Qian R, Sun C, Lin X. Short-chain aldehydes increase aluminum retention and sensitivity by enhancing cell wall polysaccharide contents and pectin

demethylation in wheat seedlings. *J Hazard Mater*. 2022;433:128743. doi:10.1016/j.jhazmat.2022.128743.

55. Teng Y, Xiao Y, Sun H, Hu J, Guo J, Yu H. Cadmium-induced mitochondrial dysfunction and oxidative damage in leaves of Solanum nigrum L. *Plant Physiol Biochem*. 2025;225:110016. doi:10.1016/j.plaphy.2025.110016.
56. Pádua M, Cavaco AM, Aubert S, Bligny R, Casimiro A. Effects of copper on the photosynthesis of intact chloroplasts: interaction with manganese. *Physiol Plant*. 2010;138(3):301-311. doi:10.1111/j.1399-3054.2009.01335.x
57. Jomova, K., Alomar, S.Y., Alwasel, S.H. *et al.* Several lines of antioxidant defense against oxidative stress: antioxidant enzymes, nanomaterials with multiple enzyme-mimicking activities, and low-molecular-weight antioxidants. *Arch Toxicol* **98**, 1323–1367 (2024). https://doi.org/10.1007/s00204-024-03696-4.
58. Mishra N, Jiang C, Chen L, Paul A, Chatterjee A, Shen G. Achieving abiotic stress tolerance in plants through antioxidative defense mechanisms. *Front Plant Sci*. 2023;14:1110622. Published 2023 Jun 2. doi:10.3389/fpls.2023.1110622.
59. Mnafgui W, Hajlaoui H, Rizzo V, Muratore G, Elleuch A. Priming with EDTA, IAA and Fe alleviates Pb toxicity in Trigonella Foneum graecum L. growth: Phytochemicals and secondary metabolites. *J Biotechnol*. 2022;356:42-50. doi:10.1016/j.jbiotec.2022.07.006
60. Wang Y, Li J, Pan Y, Chen J, Liu Y. Metabolic Responses to Manganese Toxicity in Soybean Roots and Leaves. *Plants (Basel)*. 2023;12(20):3615. Published 2023 Oct 19. doi:10.3390/plants12203615.
61. Jomova K, Raptova R, Alomar SY, et al. Reactive oxygen species, toxicity, oxidative stress, and antioxidants: chronic diseases and aging. *Arch Toxicol*. 2023;97(10):2499-2574. doi:10.1007/s00204-023-03562-9.
62. Taggar GK, Gill RS, Gupta AK, Sandhu JS. Fluctuations in peroxidase and catalase activities of resistant and susceptible black gram (Vigna mungo (L.) Hepper) genotypes elicited by Bemisia tabaci (Gennadius) feeding. *Plant Signal Behav*. 2012;7(10):1321-1329. doi:10.4161/psb.21435.
63. Challabathula D, Analin B, Mohanan A, Bakka K. Differential modulation of photosynthesis, ROS and antioxidant enzyme activities in stress-sensitive and -tolerant rice cultivars during salinity and drought upon restriction of COX and AOX pathways of mitochondrial oxidative electron transport. *J Plant Physiol*. 2022;268:153583. doi:10.1016/j.jplph.2021.153583.
64. Zhang, W., Sheng, J., Xu, Y. *et al.* Role of brassinosteroids in rice spikelet differentiation and degeneration under soil-drying during panicle development. *BMC Plant Biol* **19**, 409 (2019). https://doi.org/10.1186/s12870-019-2025-2.
65. Angon PB, Islam MS, Kc S, et al. Sources, effects and present perspectives of heavy metals contamination: Soil, plants and human food chain. *Heliyon*. 2024;10(7):e28357. Published 2024 Mar 26. doi:10.1016/j.heliyon.2024.e28357.
66. Ur Rahman S, Han JC, Ahmad M, et al. Aluminum phytotoxicity in acidic environments: A comprehensive review of plant tolerance and adaptation strategies. *Ecotoxicol Environ Saf*. 2024;269:115791. doi:10.1016/j.ecoenv.2023.115791.
67. Rahimzadeh MR, Rahimzadeh MR, Kazemi S, Amiri RJ, Pirzadeh M, Moghadamnia AA. Aluminum Poisoning with Emphasis on Its Mechanism and Treatment of Intoxication. *Emerg Med Int*. 2022;2022:1480553. Published 2022 Jan 11. doi:10.1155/2022/1480553.

68. Stincone A, Prigione A, Cramer T, et al. The return of metabolism: biochemistry and physiology of the pentose phosphate pathway. *Biol Rev Camb Philos Soc*. 2015;90(3):927-963. doi:10.1111/brv.12140.
69. Riyazuddin R, Nisha N, Ejaz B, et al. A Comprehensive Review on the Heavy Metal Toxicity and Sequestration in Plants. *Biomolecules*. 2021;12(1):43. Published 2021 Dec 28. doi:10.3390/biom12010043.
70. Fuentes-Ugarte N, Herrera SM, Maturana P, Castro-Fernandez V, Guixé V. Structural and Kinetic Insights Into the Molecular Basis of Salt Tolerance of the Short-Chain Glucose-6-Phosphate Dehydrogenase From *Haloferax volcanii*. *Front Microbiol*. 2021;12:730429. Published 2021 Sep 28. doi:10.3389/fmicb.2021.730429
71. Zama N, Kirkman K, Mkhize N, Tedder M, Magadlela A. Soil Acidification in Nutrient-Enriched Soils Reduces the Growth, Nutrient Concentrations, and Nitrogen-Use Efficiencies of *Vachellia sieberiana* (DC.) Kyal. & Boatwr Saplings. *Plants (Basel)*. 2022;11(24):3564. Published 2022 Dec 17. doi:10.3390/plants11243564
72. Zhao Y, Cui Y, Huang S, et al. Genome-Wide Analysis of the Glucose-6-Phosphate Dehydrogenase Family in Soybean and Functional Identification of *GmG6PDH2* Involvement in Salt Stress. *Front Plant Sci*. 2020;11:214. Published 2020 Feb 26. doi:10.3389/fpls.2020.00214
73. Sedighi-Pirsaraei N, Tamimi A, Sadeghi Khamaneh F, Dadras-Jeddi S, Javaheri N. Boron in wound healing: a comprehensive investigation of its diverse mechanisms. *Front Bioeng Biotechnol*. 2024;12:1475584. Published 2024 Oct 30. doi:10.3389/fbioe.2024.1475584
74. Baj J, Flieger W, Teresiński G, et al. Magnesium, Calcium, Potassium, Sodium, Phosphorus, Selenium, Zinc, and Chromium Levels in Alcohol Use Disorder: A Review. *J Clin Med*. 2020;9(6):1901. Published 2020 Jun 18. doi:10.3390/jcm9061901
75. Duart VM, Caires EF, de Oliveira ÉC, Matiello RR. 2024. Magnesium alleviates aluminum toxicity in wheat and maize seedlings. *Technology in Agronomy* 4: e025 doi: 10.48130/tia-0024-0022
76. Daverkausen-Fischer L, Pröls F. Regulation of calcium homeostasis and flux between the endoplasmic reticulum and the cytosol. *J Biol Chem*. 2022;298(7):102061. doi:10.1016/j.jbc.2022.102061
77. Hou Y, Li Z, Zheng Y, Jin P. Effects of $CaCl_2$ Treatment Alleviates Chilling Injury of Loquat Fruit (*Eribotrya japonica*) by Modulating ROS Homeostasis. *Foods*. 2021;10(7):1662. Published 2021 Jul 19. doi:10.3390/foods10071662
78. Santangeli M, Steininger-Mairinger T, Vetterlein D, Hann S, Oburger E. Maize (Zea mays L.) root exudation profiles change in quality and quantity during plant development - A field study. *Plant Sci*. 2024;338:111896. doi:10.1016/j.plantsci.2023.111896
79. Silva S, Rodriguez E, Pinto-Carnide O, et al. Zonal responses of sensitive vs. tolerant wheat roots during Al exposure and recovery. *J Plant Physiol*. 2012;169(8):760-769. doi:10.1016/j.jplph.2012.01.011
80. Wdowiak, A., Podgórska, A. & Szal, B. Calcium in plants: an important element of cell physiology and structure, signaling, and stress responses. *Acta Physiol Plant* **46**, 108 (2024). https://doi.org/10.1007/s11738-024-03733-w
81. Szurman-Zubrzycka M, Chwiałkowska K, Niemira M, et al. Aluminum or Low pH - Which Is the Bigger Enemy of Barley? Transcriptome Analysis of Barley Root Meristem Under Al and

Low pH Stress. *Front Genet*. 2021;12:675260. Published 2021 May 19. doi:10.3389/fgene.2021.675260
82. Bhukya N, Hazarika S, Rangappa K, Thakuria D, Narzari R, Debnath S. Comparative stress physiological analysis of aluminium stress tolerance of indigenous maize (*Zea mays* L.) cultivars of eastern Himalaya. *Heliyon*. 2024;10(11):e31570. Published 2024 May 18. doi:10.1016/j.heliyon.2024.e31570
83. Run Y, Cheng X, Dou W, et al. Wheat potassium transporter TaHAK13 mediates $K^+$ absorption and maintains potassium homeostasis under low potassium stress. *Front Plant Sci*. 2022;13:1103235. Published 2022 Dec 23. doi:10.3389/fpls.2022.1103235
84. Sardans J, Peñuelas J. Potassium Control of Plant Functions: Ecological and Agricultural Implications. *Plants (Basel)*. 2021;10(2):419. Published 2021 Feb 23. doi:10.3390/plants10020419
85. Xu X, Du X, Wang F, et al. Effects of Potassium Levels on Plant Growth, Accumulation and Distribution of Carbon, and Nitrate Metabolism in Apple Dwarf Rootstock Seedlings. *Front Plant Sci*. 2020;11:904. Published 2020 Jun 23. doi:10.3389/fpls.2020.00904
86. Bojórquez-Quintal E, Escalante-Magaña C, Echevarría-Machado I, Martínez-Estévez M. Aluminum, a Friend or Foe of Higher Plants in Acid Soils. *Front Plant Sci*. 2017;8:1767. Published 2017 Oct 12. doi:10.3389/fpls.2017.01767
87. Faria JMS, Teixeira DM, Pinto AP, Brito I, Barrulas P, Carvalho M. Aluminium, Iron and Silicon Subcellular Redistribution in Wheat Induced by Manganese Toxicity. *Applied Sciences*. 2021; 11(18):8745. https://doi.org/10.3390/app11188745
88. Barra PJ, Viscardi S, Jorquera MA, Duran PA, Valentine AJ, de la Luz Mora M. Understanding the Strategies to Overcome Phosphorus-Deficiency and Aluminum-Toxicity by Ryegrass Endophytic and Rhizosphere Phosphobacteria. *Front Microbiol*. 2018;9:1155. Published 2018 Jun 1. doi:10.3389/fmicb.2018.01155
89. Aziz T, Farid A, Haq F, Kiran M, Ullah A, Zhang K, Li C, Ghazanfar S, Sun H, Ullah R, et al. A Review on the Modification of Cellulose and Its Applications. *Polymers*. 2022; 14(15):3206. https://doi.org/10.3390/polym14153206
90. Khan F, Siddique AB, Shabala S, Zhou M, Zhao C. Phosphorus Plays Key Roles in Regulating Plants' Physiological Responses to Abiotic Stresses. *Plants (Basel)*. 2023;12(15):2861. Published 2023 Aug 3. doi:10.3390/plants12152861
91. Yang JL, Fan W, Zheng SJ. Mechanisms and regulation of aluminum-induced secretion of organic acid anions from plant roots. *J Zhejiang Univ Sci B*. 2019;20(6):513-527. doi:10.1631/jzus.B1900188
92. Egorov AM, Ulyashova MM, Rubtsova MY. Bacterial Enzymes and Antibiotic Resistance. *Acta Naturae*. 2018;10(4):33-48.
93. Liu Y, Sun L, Zhang P, Wan J, Wang R, Xu J. Lanthanum Inhibits Primary Root Growth by Repressing Auxin Carrier Abundances in *Arabidopsis*. *Front Plant Sci*. 2017;8:1661. Published 2017 Sep 25. doi:10.3389/fpls.2017.01661
94. Liu YY, Wang RL, Zhang P, Sun LL, Xu J. Involvement of reactive oxygen species in lanthanum-induced inhibition of primary root growth. *J Exp Bot*. 2016;67(21):6149-6159. doi:10.1093/jxb/erw379
95. Yang LT, Qi YP, Jiang HX, Chen LS. Roles of organic acid anion secretion in aluminium tolerance of higher plants. *Biomed Res Int*. 2013;2013:173682. doi:10.1155/2013/173682

96. Xiao M, Wu F. A review of environmental characteristics and effects of low-molecular weight organic acids in the surface ecosystem. *J Environ Sci (China)*. 2014;26(5):935-954. doi:10.1016/S1001-0742(13)60570-7
97. Nandi A, Yan LJ, Jana CK, Das N. Role of Catalase in Oxidative Stress- and Age-Associated Degenerative Diseases. *Oxid Med Cell Longev*. 2019;2019:9613090. Published 2019 Nov 11. doi:10.1155/2019/9613090
98. Yang Z, Zhao P, Peng W, Liu Z, Xie G, Ma X, An Z, An F. Cloning, Expression Analysis, and Functional Characterization of Candidate Oxalate Transporter Genes of *HbOT1* and *HbOT2* from Rubber Tree (*Hevea brasiliensis*). *Cells*. 2022; 11(23):3793. https://doi.org/10.3390/cells11233793
99. Li M, Zhang L, Zhang Q, et al. Impacts of Citric Acid and Malic Acid on Fermentation Quality and Bacterial Community of Cassava Foliage Silage. *Front Microbiol*. 2020;11:595622. Published 2020 Dec 14. doi:10.3389/fmicb.2020.595622
100. Su, C., Wang, J., Feng, J. *et al. OsAlR3* regulates aluminum tolerance through promoting the secretion of organic acids and the expression of antioxidant genes in rice. *BMC Plant Biol* **24**, 618 (2024). https://doi.org/10.1186/s12870-024-05298-9
101. Bojórquez-Quintal E, Escalante-Magaña C, Echevarría-Machado I, Martínez-Estévez M. Aluminum, a Friend or Foe of Higher Plants in Acid Soils. *Front Plant Sci*. 2017;8:1767. Published 2017 Oct 12. doi:10.3389/fpls.2017.01767
102. Mossor-Pietraszewska T. Effect of aluminium on plant growth and metabolism. *Acta Biochim Pol*. 2001;48(3):673-686.
103. Angulo-Bejarano PI, Puente-Rivera J, Cruz-Ortega R. Metal and Metalloid Toxicity in Plants: An Overview on Molecular Aspects. *Plants (Basel)*. 2021;10(4):635. Published 2021 Mar 27. doi:10.3390/plants10040635
104. Vasilachi IC, Stoleru V, Gavrilescu M. Analysis of Heavy Metal Impacts on Cereal Crop Growth and Development in Contaminated Soils. *Agriculture*. 2023; 13(10):1983. https://doi.org/10.3390/agriculture13101983
105. Blasco B, Leroy D, Fidock DA. Antimalarial drug resistance: linking Plasmodium falciparum parasite biology to the clinic. *Nat Med*. 2017;23(8):917-928. doi:10.1038/nm.4381
106. Teh MR, Armitage AE, Drakesmith H. Why cells need iron: a compendium of iron utilisation. *Trends Endocrinol Metab*. 2024;35(12):1026-1049. doi:10.1016/j.tem.2024.04.015
107. Emamverdian A, Ding Y, Mokhberdoran F, Xie Y. Heavy metal stress and some mechanisms of plant defense response. *ScientificWorldJournal*. 2015;2015:756120. doi:10.1155/2015/756120
108. Fan W, Ge G, Liu Y, Wang W, Liu L, Jia Y. Proteomics integrated with metabolomics: analysis of the internal causes of nutrient changes in alfalfa at different growth stages. *BMC Plant Biol*. 2018;18(1):78. Published 2018 May 4. doi:10.1186/s12870-018-1291-8
109. Stepanova M, Nikiforov A, Tennikova T, Korzhikova-Vlakh E. Polypeptide-Based Systems: From Synthesis to Application in Drug Delivery. *Pharmaceutics*. 2023;15(11):2641. Published 2023 Nov 20. doi:10.3390/pharmaceutics15112641
110. Chandhok, S., Pereira, L., Momchilova, E.A. *et al.* Stress-mediated aggregation of disease-associated proteins in amyloid bodies. *Sci Rep* **13**, 14471 (2023). https://doi.org/10.1038/s41598-023-41712-2

111. Panda SK, Baluska F, Matsumoto H. Aluminum stress signaling in plants. *Plant Signal Behav*. 2009;4(7):592-597. doi:10.4161/psb.4.7.8903
112. Hasan N, Choudhary S, Naaz N, Sharma N, Laskar RA. Recent advancements in molecular marker-assisted selection and applications in plant breeding programmes. *J Genet Eng Biotechnol*. 2021;19(1):128. Published 2021 Aug 27. doi:10.1186/s43141-021-00231-1
113. Chen P, Sjogren CA, Larsen PB, Schnittger A. A multi-level response to DNA damage induced by aluminium. *Plant J*. 2019;98(3):479-491. doi:10.1111/tpj.14231
114. McKenna JF, Gumber HK, Turpin ZM, et al. Maize (*Zea mays* L.) Nucleoskeletal Proteins Regulate Nuclear Envelope Remodeling and Function in Stomatal Complex Development and Pollen Viability. *Front Plant Sci*. 2021;12:645218. Published 2021 Feb 17. doi:10.3389/fpls.2021.645218
115. Ayala A, Muñoz MF, Argüelles S. Lipid peroxidation: production, metabolism, and signaling mechanisms of malondialdehyde and 4-hydroxy-2-nonenal. *Oxid Med Cell Longev*. 2014;2014:360438. doi:10.1155/2014/360438
116. Szurman-Zubrzycka M, Nawrot M, Jelonek J, Dziekanowski M, Kwasniewska J, Szarejko I. ATR, a DNA Damage Signaling Kinase, Is Involved in Aluminum Response in Barley. *Front Plant Sci*. 2019;10:1299. Published 2019 Oct 22. doi:10.3389/fpls.2019.01299
117. Agarwal A, Barbăroșie C, Ambar R, Finelli R. The Impact of Single- and Double-Strand DNA Breaks in Human Spermatozoa on Assisted Reproduction. *International Journal of Molecular Sciences*. 2020; 21(11):3882. https://doi.org/10.3390/ijms21113882
118. Demirkiran A, Marakli S, Temel A, Gozukirmizi N. Genetic and epigenetic effects of salinity on in vitro growth of barley. *Genet Mol Biol*. 2013;36(4):566-570. doi:10.1590/S1415-47572013000400016
119. Zhang X, Long Y, Huang J, Xia J. Molecular Mechanisms for Coping with Al Toxicity in Plants. *Int J Mol Sci*. 2019;20(7):1551. Published 2019 Mar 28. doi:10.3390/ijms20071551
120. Niedziela A, Domżalska L, Dynkowska WM, Pernisová M, Rybka K. Aluminum Stress Induces Irreversible Proteomic Changes in the Roots of the Sensitive but Not the Tolerant Genotype of Triticale Seedlings. *Plants (Basel)*. 2022;11(2):165. Published 2022 Jan 8. doi:10.3390/plants11020165
121. Bianconi I, Aschbacher R, Pagani E. Current Uses and Future Perspectives of Genomic Technologies in Clinical Microbiology. *Antibiotics (Basel)*. 2023;12(11):1580. Published 2023 Oct 30. doi:10.3390/antibiotics12111580
122. Enesi RO, Dyck M, Chang S, Thilakarathna MS, Fan X, Strelkov S and Gorim LY (2023) Liming remediates soil acidity and improves crop yield and profitability - a meta-analysis. *Front. Agron.* 5:1194896. doi: 10.3389/fagro.2023.1194896
123. Hodson MJ, Evans DE. Aluminium-silicon interactions in higher plants: an update. *J Exp Bot*. 2020;71(21):6719-6729. doi:10.1093/jxb/eraa024
124. Caubet, M., Cornu, S., Saby, N.P.A. *et al.* Agriculture increases the bioavailability of silicon, a beneficial element for crop, in temperate soils. *Sci Rep* **10**, 19999 (2020). https://doi.org/10.1038/s41598-020-77059-1
125. Zhang H, Sun X, Hwarari D, et al. Oxidative Stress Response and Metal Transport in Roots of *Macleaya cordata* Exposed to Lead and Zinc. *Plants (Basel)*. 2023;12(3):516. Published 2023 Jan 23. doi:10.3390/plants12030516

126. Negasa G, Tadesse K, Gerenfes D, et al. Impact of silicate fertilizer on soil properties and yield of bread wheat in Nitisols of tropical environment. *Heliyon*. 2023;9(12):e22933. Published 2023 Nov 28. doi:10.1016/j.heliyon.2023.e22933
127. Ng JF, Ahmed OH, Jalloh MB, Omar L, Kwan YM, Musah AA, Poong KH. Soil Nutrient Retention and pH Buffering Capacity Are Enhanced by Calciprill and Sodium Silicate. *Agronomy*. 2022; 12(1):219. https://doi.org/10.3390/agronomy12010219
128. Kopittke PM, Gianoncelli A, Kourousias G, Green K, McKenna BA. Alleviation of Al Toxicity by Si Is Associated with the Formation of Al-Si Complexes in Root Tissues of Sorghum. *Front Plant Sci*. 2017;8:2189. Published 2017 Dec 21. doi:10.3389/fpls.2017.02189
129. Yoshida, Tomohiro, Hiroaki Kudo, Koichiro Sera, Atsushi Sato, Shigeru Kamei, Lanpo Zhao, Hongbin Wang, and Shigenao Kawai. 2018. "High Phosphorus Utilization and Silicon Amelioration of Aluminium Toxicity by Puccinellia Chinampoensis Ohwi under Sodic Conditions". *International Journal of Plant & Soil Science* 22 (1):1-14. https://doi.org/10.9734/IJPSS/2018/39559.
130. Vega I, Nikolic M, Pontigo S, Godoy K, Mora MdLL, Cartes P. Silicon Improves the Production of High Antioxidant or Structural Phenolic Compounds in Barley Cultivars under Aluminum Stress. *Agronomy*. 2019; 9(7):388. https://doi.org/10.3390/agronomy9070388
131. Serafini S, Santos MM, Aoun Tannuri AC, et al. Is hematoxylin-eosin staining in rectal mucosal and submucosal biopsies still useful for the diagnosis of Hirschsprung disease?. *Diagn Pathol*. 2017;12(1):84. Published 2017 Dec 6. doi:10.1186/s13000-017-0673-9
132. Thepbandit W, Athinuwat D. Rhizosphere Microorganisms Supply Availability of Soil Nutrients and Induce Plant Defense. *Microorganisms*. 2024;12(3):558. Published 2024 Mar 11. doi:10.3390/microorganisms12030558
133. Peng A, Yu K, Yu S, et al. Aluminum and Fluoride Stresses Altered Organic Acid and Secondary Metabolism in Tea (*Camellia sinensis*) Plants: Influences on Plant Tolerance, Tea Quality and Safety. *Int J Mol Sci*. 2023;24(5):4640. Published 2023 Feb 27. doi:10.3390/ijms24054640
134. Li W, Ullah S, Xu Y, et al. Effects of Elevated Aluminum Concentration and Distribution on Root Damage, Cell Wall Polysaccharides, and Nutrient Uptake in Different Tolerant *Eucalyptus* Clones. *Int J Mol Sci*. 2022;23(21):13438. Published 2022 Nov 3. doi:10.3390/ijms232113438
135. Kumar, P., Tokas, J. & Singal, H.R. Amelioration of Chromium VI Toxicity in Sorghum (*Sorghum bicolor* L.) using Glycine Betaine. *Sci Rep* **9**, 16020 (2019). https://doi.org/10.1038/s41598-019-52479-w
136. Sharma U, Mishra S, Gautam N, Gupta BK. Qualitative and quantitative assay of glucose 6 phosphate dehydrogenase in patients attending tertiary care center. *BMC Res Notes*. 2020;13(1):298. Published 2020 Jun 22. doi:10.1186/s13104-020-05145-8
137. Fussy A, Papenbrock J. An Overview of Soil and Soilless Cultivation Techniques-Chances, Challenges and the Neglected Question of Sustainability. *Plants (Basel)*. 2022;11(9):1153. Published 2022 Apr 24. doi:10.3390/plants11091153
138. Holland C, Ryden P, Edwards CH, Grundy MM. Plant Cell Walls: Impact on Nutrient Bioaccessibility and Digestibility. *Foods*. 2020;9(2):201. Published 2020 Feb 16. doi:10.3390/foods9020201

139. Bojórquez-Quintal E, Escalante-Magaña C, Echevarría-Machado I, Martínez-Estévez M. Aluminum, a Friend or Foe of Higher Plants in Acid Soils. *Front Plant Sci*. 2017;8:1767. Published 2017 Oct 12. doi:10.3389/fpls.2017.01767
140. Soltys D, Rudzińska-Langwald A, Kurek W, Gniazdowska A, Sliwinska E, Bogatek R. Cyanamide mode of action during inhibition of onion (Allium cepa L.) root growth involves disturbances in cell division and cytoskeleton formation. *Planta*. 2011;234(3):609-621. doi:10.1007/s00425-011-1429-5
141. Lang L, Pettkó-Szandtner A, Tunçay Elbaşı H, et al. The DREAM complex represses growth in response to DNA damage in *Arabidopsis*. *Life Sci Alliance*. 2021;4(12):e202101141. Published 2021 Sep 28. doi:10.26508/lsa.202101141
142. Li G, Moore JK. Microtubule dynamics at low temperature: evidence that tubulin recycling limits assembly. *Mol Biol Cell*. 2020;31(11):1154-1166. doi:10.1091/mbc.E19-11-0634
143. Ma Y, Bai C, Zhang X, Ding Y. Nitrate Increases Aluminum Toxicity and Accumulation in Root of Wheat. *Agriculture*. 2022; 12(11):1946. https://doi.org/10.3390/agriculture12111946
144. Kariya K, Tsuchiya Y, Sasaki T, Yamamoto Y. Aluminium-induced cell death requires upregulation of NtVPE1 gene coding vacuolar processing enzyme in tobacco (Nicotiana tabacum L.). *J Inorg Biochem*. 2018;181:152-161. doi:10.1016/j.jinorgbio.2017.09.008
145. Yang, ZB., Rao, I.M. & Horst, W.J. Interaction of aluminium and drought stress on root growth and crop yield on acid soils. *Plant Soil* **372**, 3–25 (2013). https://doi.org/10.1007/s11104-012-1580-1
146. Basavaraj PS, Jangid KK, Babar R, Gangana Gowdra VM, Gangurde A, Shinde S, Tripathi K, Patil D, Boraiah KM, Rane J, Harisha CB, Halli H, Sammi Reddy K and Prabhakar M (2024) Adventitious root formation confers waterlogging tolerance in cowpea (*Vigna unguiculata* (L.) Walp.). *Front. Sustain. Food Syst*. 8:1373183. doi: 10.3389/fsufs.2024.1373183
147. Liu J, Shi B, Zhang M, Liu G, Ding Z and Tian H (2022) Transition Zone1 Negatively Regulates *Arabidopsis* Aluminum Resistance Through Interaction With Aconitases. *Front. Plant Sci.* 12:827797. doi: 10.3389/fpls.2021.827797
148. Harper S, Menzies N. Phytotoxic Effects of Al on Root Growth Are Confounded in the Presence of Fulvic and Humic Acids. *Soil Systems*. 2023; 7(3):68. https://doi.org/10.3390/soilsystems7030068
149. Ur Rahman S, Qin A, Zain M, et al. Pb uptake, accumulation, and translocation in plants: Plant physiological, biochemical, and molecular response: A review. *Heliyon*. 2024;10(6):e27724. Published 2024 Mar 7. doi:10.1016/j.heliyon.2024.e27724
150. Sosnowski J, Truba M, Vasileva V. The Impact of Auxin and Cytokinin on the Growth and Development of Selected Crops. *Agriculture*. 2023; 13(3):724. https://doi.org/10.3390/agriculture13030724
151. Friero, I., Alarcón, M.V., Gordillo, L. *et al.* Abscisic acid is involved in several processes associated with root system architecture in maize. *Acta Physiol Plant* **44**, 28 (2022). https://doi.org/10.1007/s11738-022-03360-3
152. Le Gall H, Philippe F, Domon JM, Gillet F, Pelloux J, Rayon C. Cell Wall Metabolism in Response to Abiotic Stress. *Plants (Basel)*. 2015;4(1):112-166. Published 2015 Feb 16. doi:10.3390/plants4010112

153. Diehl D, Knott M, Schaumann GE. Purification effects show seed and root mucilage's ability to respond to changing rhizosphere conditions. *Biopolymers*. 2023;114(8):e23561. doi:10.1002/bip.23561
154. Sekiya, N., Goto, M., Mae, A. *et al.* Shoot and root responses of rice plants to belowground environmental heterogeneity within a local rice farming community. *Discov Agric* **2**, 118 (2024). https://doi.org/10.1007/s44279-024-00138-8
155. Mourad, A.M.I., Farghly, K.A., Börner, A. *et al.* Candidate genes controlling alkaline-saline tolerance in two different growing stages of wheat life cycle. *Plant Soil* **493**, 283–307 (2023). https://doi.org/10.1007/s11104-023-06232-y
156. Zayed O, Hewedy OA, Abdelmoteleb A, et al. Nitrogen Journey in Plants: From Uptake to Metabolism, Stress Response, and Microbe Interaction. *Biomolecules*. 2023;13(10):1443. Published 2023 Sep 25. doi:10.3390/biom13101443
157. Balbaa MG, Osman HT, Kandil EE, et al. Determination of morpho-physiological and yield traits of maize inbred lines (*Zea mays* L.) under optimal and drought stress conditions [published correction appears in Front Plant Sci. 2022 Nov 15;13:1069938. doi: 10.3389/fpls.2022.1069938.]. *Front Plant Sci*. 2022;13:959203. Published 2022 Jul 28. doi:10.3389/fpls.2022.959203
158. Fromm H. Root Plasticity in the Pursuit of Water. *Plants (Basel)*. 2019;8(7):236. Published 2019 Jul 22. doi:10.3390/plants8070236
159. Prijović M, Soković D, Maksimović JD, Maksimović V, Milosavljević D, Babić S, Stepić M, Sabovljević A. Response of Different Perennial Ryegrass Varieties to Water Stress. *Agriculture*. 2025; 15(9):917. https://doi.org/10.3390/agriculture15090917
160. Zhao CR, You ZL, Chen DD, et al. Structure of a fungal 1,3-β-glucan synthase. *Sci Adv*. 2023;9(37):eadh7820. doi:10.1126/sciadv.adh7820
161. Yamauchi T, Rajhi I, Nakazono M. Lysigenous aerenchyma formation in maize root is confined to cortical cells by regulation of genes related to generation and scavenging of reactive oxygen species. *Plant Signal Behav*. 2011;6(5):759-761. doi:10.4161/psb.6.5.15417
162. Hashim AM, Alharbi BM, Abdulmajeed AM, Elkelish A, Hozzein WN, Hassan HM. Oxidative Stress Responses of Some Endemic Plants to High Altitudes by Intensifying Antioxidants and Secondary Metabolites Content. *Plants (Basel)*. 2020;9(7):869. Published 2020 Jul 9. doi:10.3390/plants9070869
163. Juan CA, Pérez de la Lastra JM, Plou FJ, Pérez-Lebeña E. The Chemistry of Reactive Oxygen Species (ROS) Revisited: Outlining Their Role in Biological Macromolecules (DNA, Lipids and Proteins) and Induced Pathologies. *Int J Mol Sci*. 2021;22(9):4642. Published 2021 Apr 28. doi:10.3390/ijms22094642
164. Gentile F, Arcaro A, Pizzimenti S, et al. DNA damage by lipid peroxidation products: implications in cancer, inflammation and autoimmunity. *AIMS Genet*. 2017;4(2):103-137. Published 2017 Apr 18. doi:10.3934/genet.2017.2.103
165. Torres M, Rosselló CA, Fernández-García P, Lladó V, Kakhlon O, Escribá PV. The Implications for Cells of the Lipid Switches Driven by Protein-Membrane Interactions and the Development of Membrane Lipid Therapy. *Int J Mol Sci*. 2020;21(7):2322. Published 2020 Mar 27. doi:10.3390/ijms21072322

166. Bolton JL, Dunlap T. Formation and Biological Targets of Quinones: Cytotoxic versus Cytoprotective Effects. *Chem Res Toxicol*. 2017;30(1):13-37. doi:10.1021/acs.chemrestox.6b00256
167. Slater JA, Zhou S, Puscheck EE, Rappolee DA. Stress-induced enzyme activation primes murine embryonic stem cells to differentiate toward the first extraembryonic lineage. *Stem Cells Dev*. 2014;23(24):3049-3064. doi:10.1089/scd.2014.0157
168. Hu S-H, Jinn T-L. Impacts of Mn, Fe, and Oxidative Stressors on MnSOD Activation by AtMTM1 and AtMTM2 in *Arabidopsis*. *Plants*. 2022; 11(5):619. https://doi.org/10.3390/plants11050619
169. Zheng M, Liu Y, Zhang G, Yang Z, Xu W, Chen Q. The Applications and Mechanisms of Superoxide Dismutase in Medicine, Food, and Cosmetics. *Antioxidants (Basel)*. 2023;12(9):1675. Published 2023 Aug 27. doi:10.3390/antiox12091675
170. Guengerich FP. Mechanisms of Cytochrome P450-Catalyzed Oxidations. *ACS Catal*. 2018;8(12):10964-10976. doi:10.1021/acscatal.8b03401
171. Hadwan MH, Hussein MJ, Mohammed RM, et al. An improved method for measuring catalase activity in biological samples [published correction appears in Biol Methods Protoc. 2024 Apr 26;9(1):bpae025. doi: 10.1093/biomethods/bpae025.]. *Biol Methods Protoc*. 2024;9(1):bpae015. Published 2024 Mar 5. doi:10.1093/biomethods/bpae015
172. Anwar S, Alrumaihi F, Sarwar T, et al. Exploring Therapeutic Potential of Catalase: Strategies in Disease Prevention and Management. *Biomolecules*. 2024;14(6):697. Published 2024 Jun 14. doi:10.3390/biom14060697
173. Jiang Z, Wang M, Nicolas M, et al. Glucose-6-Phosphate Dehydrogenases: The Hidden Players of Plant Physiology. *Int J Mol Sci*. 2022;23(24):16128. Published 2022 Dec 17. doi:10.3390/ijms232416128
174. Peng Z, Wang Y, Geng G, et al. Comparative Analysis of Physiological, Enzymatic, and Transcriptomic Responses Revealed Mechanisms of Salt Tolerance and Recovery in *Tritipyrum*. *Front Plant Sci*. 2022;12:800081. Published 2022 Jan 5. doi:10.3389/fpls.2021.800081
175. Igbokwe IO, Igwenagu E, Igbokwe NA. Aluminium toxicosis: a review of toxic actions and effects. *Interdiscip Toxicol*. 2019;12(2):45-70. doi:10.2478/intox-2019-0007
176. Wanichthanarak K, Boonchai C, Kojonna T, Chadchawan S, Sangwongchai W, Thitisaksakul M. Deciphering rice metabolic flux reprograming under salinity stress via *in silico* metabolic modeling. *Comput Struct Biotechnol J*. 2020;18:3555-3566. Published 2020 Nov 20. doi:10.1016/j.csbj.2020.11.023
177. Hernández-Ochoa EO, Melville Z, Vanegas C, et al. Loss of S100A1 expression leads to $Ca^{2+}$ release potentiation in mutant mice with disrupted CaM and S100A1 binding to CaMBD2 of RyR1. *Physiol Rep*. 2018;6(15):e13822. doi:10.14814/phy2.13822
178. ten Hoopen F, Cuin TA, Pedas P, et al. Competition between uptake of ammonium and potassium in barley and Arabidopsis roots: molecular mechanisms and physiological consequences. *J Exp Bot*. 2010;61(9):2303-2315. doi:10.1093/jxb/erq057
179. Scarnati MS, Clarke SG, Pang ZP, Paradiso KG. Presynaptic Calcium Channel Open Probability and Changes in Calcium Influx Throughout the Action Potential Determined Using AP-Waveforms. *Front Synaptic Neurosci*. 2020; 12:17. Published 2020 Apr 24. doi:10.3389/fnsyn.2020.00017

180. Colin L, Ruhnow F, Zhu JK, Zhao C, Zhao Y, Persson S. The cell biology of primary cell walls during salt stress. *Plant Cell*. 2023;35(1):201-217. doi:10.1093/plcell/koac292
181. Long Y, Peng J. Interaction between Boron and Other Elements in Plants. *Genes (Basel)*. 2023;14(1):130. Published 2023 Jan 3. doi:10.3390/genes14010130
182. O'Day DH. Phytochemical Interactions with Calmodulin and Critical Calmodulin Binding Proteins Involved in Amyloidogenesis in Alzheimer's Disease. *Biomolecules*. 2023;13(4):678. Published 2023 Apr 15. doi:10.3390/biom13040678
183. Coskun D, Britto DT, Li M, Oh S, Kronzucker HJ. Capacity and plasticity of potassium channels and high-affinity transporters in roots of barley and Arabidopsis. *Plant Physiol*. 2013;162(1):496-511. doi:10.1104/pp.113.215913
184. Udensi UK, Tchounwou PB. Potassium Homeostasis, Oxidative Stress, and Human Disease. *Int J Clin Exp Physiol*. 2017;4(3):111-122. doi:10.4103/ijcep.ijcep_43_17
185. Sharma T, Dreyer I, Riedelsberger J. The role of K(+) channels in uptake and redistribution of potassium in the model plant Arabidopsis thaliana. *Front Plant Sci*. 2013;4:224. Published 2013 Jun 27. doi:10.3389/fpls.2013.00224
186. Ragel P, Raddatz N, Leidi EO, Quintero FJ, Pardo JM. Regulation of $K^+$ Nutrition in Plants. *Front Plant Sci*. 2019;10:281. Published 2019 Mar 20. doi:10.3389/fpls.2019.00281
187. Burg ED, Remillard CV, Yuan JX. Potassium channels in the regulation of pulmonary artery smooth muscle cell proliferation and apoptosis: pharmacotherapeutic implications. *Br J Pharmacol*. 2008;153 Suppl 1(Suppl 1):S99-S111. doi:10.1038/sj.bjp.0707635
188. Huang Y, Hu N, Yang X, Zhou S, Song M, Zhang J, Chen X, Du X, He D. Root Response to $K^+$-Deprivation in Wheat (*Triticum aestivum* L.): Coordinated Roles of HAK Transporters, AKT2 and SKOR $K^+$-Channels, and Phytohormone Regulation. *Agriculture*. 2025; 15(9):993. https://doi.org/10.3390/agriculture15090993
189. Hasanuzzaman M, Bhuyan MHMB, Nahar K, Hossain MS, Mahmud JA, Hossen MS, Masud AAC, Moumita, Fujita M. Potassium: A Vital Regulator of Plant Responses and Tolerance to Abiotic Stresses. *Agronomy*. 2018; 8(3):31. https://doi.org/10.3390/agronomy8030031
190. Sustr M, Soukup A, Tylova E. Potassium in Root Growth and Development. *Plants*. 2019; 8(10):435. https://doi.org/10.3390/plants8100435
191. Meller S, Frossard E, Luster J. Phosphorus Allocation to Leaves of Beech Saplings Reacts to Soil Phosphorus Availability. *Front Plant Sci*. 2019;10:744. Published 2019 Jun 6. doi:10.3389/fpls.2019.00744
192. Omara-Ojungu, C., Lukac, M. Effects of MicroChar on Phosphorus Availability and Pea Growth. *J Soil Sci Plant Nutr* (2025). https://doi.org/10.1007/s42729-025-02508-7
193. He, H., He, L. & Gu, M. Signal transduction during aluminum-induced secretion of organic acids in plants. *Biol Plant* **59**, 601–608 (2015). https://doi.org/10.1007/s10535-015-0537-7
194. Xu H, Yan S, Gerhard E, et al. Citric Acid: A Nexus Between Cellular Mechanisms and Biomaterial Innovations. *Adv Mater*. 2024;36(32):e2402871. doi:10.1002/adma.202402871
195. Santoro, V., Schiavon, M. & Celi, L. Role of soil abiotic processes on phosphorus availability and plant responses with a focus on strigolactones in tomato plants. *Plant Soil* **494**, 1–49 (2024). https://doi.org/10.1007/s11104-023-06266-2
196. Zhou Y, Yang Z, Xu Y, et al. Soybean NADP-Malic Enzyme Functions in Malate and Citrate Metabolism and Contributes to Their Efflux under Al Stress. *Front Plant Sci*. 2018;8:2246. Published 2018 Jan 10. doi:10.3389/fpls.2017.02246

197. Juarez-Navarro K, Ayala-Garcia VM, Ruiz-Baca E, Meneses-Morales I, Rios-Banuelos JL, Lopez-Rodriguez A. Assistance for Folding of Disease-Causing Plasma Membrane Proteins. *Biomolecules*. 2020; 10(5):728. https://doi.org/10.3390/biom10050728
198. Sigel A, Sigel H, Sigel RKO. Coordination Chemistry of Nucleotides and Antivirally Active Acyclic Nucleoside Phosphonates, including Mechanistic Considerations. *Molecules*. 2022;27(9):2625. Published 2022 Apr 19. doi:10.3390/molecules27092625
199. Luo F, Zhu D, Sun H, et al. Wheat Selenium-binding protein TaSBP-A enhances cadmium tolerance by decreasing free $Cd^{2+}$ and alleviating the oxidative damage and photosynthesis impairment. *Front Plant Sci*. 2023;14:1103241. Published 2023 Feb 7. doi:10.3389/fpls.2023.1103241
200. Li J, Zhang M, Sun J, et al. Heavy Metal Stress-Associated Proteins in Rice and *Arabidopsis*: Genome-Wide Identification, Phylogenetics, Duplication, and Expression Profiles Analysis. *Front Genet*. 2020;11:477. Published 2020 May 8. doi:10.3389/fgene.2020.00477
201. Li M, Feng J, Zhou H, et al. Overcoming Reproductive Compromise Under Heat Stress in Wheat: Physiological and Genetic Regulation, and Breeding Strategy. *Front Plant Sci*. 2022;13:881813. Published 2022 May 13. doi:10.3389/fpls.2022.881813
202. Balzano S, Sardo A, Blasio M, et al. Microalgal Metallothioneins and Phytochelatins and Their Potential Use in Bioremediation. *Front Microbiol*. 2020;11:517. Published 2020 Apr 28. doi:10.3389/fmicb.2020.00517
203. Luo Y, Zhang Y, Xiong Z, et al. Peptides Used for Heavy Metal Remediation: A Promising Approach. *Int J Mol Sci*. 2024;25(12):6717. Published 2024 Jun 18. doi:10.3390/ijms25126717
204. Jackson M, Stevens CM, Zhang L, Zgurskaya HI, Niederweis M. Transporters Involved in the Biogenesis and Functionalization of the Mycobacterial Cell Envelope. *Chem Rev*. 2021;121(9):5124-5157. doi:10.1021/acs.chemrev.0c00869
205. Liu A, Zhu Y, Wang Y, et al. Molecular identification of phenylalanine ammonia lyase-encoding genes *EfPALs* and *EfPAL2*-interacting transcription factors in *Euryale ferox*. *Front Plant Sci*. 2023;14:1114345. Published 2023 Mar 21. doi:10.3389/fpls.2023.1114345
206. Yan H, Pei X, Zhang H, et al. MYB-Mediated Regulation of Anthocyanin Biosynthesis. *Int J Mol Sci*. 2021;22(6):3103. Published 2021 Mar 18. doi:10.3390/ijms22063103
207. Ambastha V, Friedmann Y, Leshem Y. Laterals take it better - Emerging and young lateral roots survive lethal salinity longer than the primary root in Arabidopsis. *Sci Rep*. 2020;10(1):3291. Published 2020 Feb 24. doi:10.1038/s41598-020-60163-7
208. Jomova, K., Alomar, S.Y., Alwasel, S.H. *et al.* Several lines of antioxidant defense against oxidative stress: antioxidant enzymes, nanomaterials with multiple enzyme-mimicking activities, and low-molecular-weight antioxidants. *Arch Toxicol* **98**, 1323–1367 (2024). https://doi.org/10.1007/s00204-024-03696-4
209. Cannan WJ, Pederson DS. Mechanisms and Consequences of Double-Strand DNA Break Formation in Chromatin. *J Cell Physiol*. 2016;231(1):3-14. doi:10.1002/jcp.25048
210. Dos Santos Á, Cook AW, Gough RE, et al. DNA damage alters nuclear mechanics through chromatin reorganization. *Nucleic Acids Res*. 2021;49(1):340-353. doi:10.1093/nar/gkaa1202
211. Kobylińska A, Reiter RJ, Posmyk MM. Melatonin Protects Cultured Tobacco Cells against Lead-Induced Cell Death *via* Inhibition of Cytochrome c Translocation. *Front Plant Sci*. 2017;8:1560. Published 2017 Sep 14. doi:10.3389/fpls.2017.01560

212. Zargar SM, Farhat S, Mahajan R, Bhakhri A, Sharma A. Unraveling the efficiency of RAPD and SSR markers in diversity analysis and population structure estimation in common bean. *Saudi J Biol Sci*. 2016;23(1):139-149. doi:10.1016/j.sjbs.2014.11.011
213. Ningombam L, Hazarika BN, Singh YD, Singh RP, Yumkhaibam T. Aluminium stress tolerance by *Citrus* plants: a consolidated review. *Physiol Mol Biol Plants*. 2024;30(5):705-718. doi:10.1007/s12298-024-01457-2
214. Ho TH, Do TH, Tong HD, Meijer EJ, Trinh TT. The Role of Chloride ion in the Silicate Condensation Reaction from ab Initio Molecular Dynamics Simulations. *J Phys Chem B*. 2023;127(36):7748-7757. doi:10.1021/acs.jpcb.3c04256
215. da Silveira Sousa Junior G, Hurtado AC, de Cassia Alves R, Gasparino EC, Dos Santos DMM. Silicon attenuates aluminum toxicity in sugarcane plants by modifying growth, roots morphoanatomy, photosynthetic pigments, and gas exchange parameters. *Sci Rep*. 2024;14(1):4717. Published 2024 Feb 27. doi:10.1038/s41598-024-53537-8
216. Verma KK, Song X-P, Li D-M, Singh M, Rajput VD, Malviya MK, Minkina T, Singh RK, Singh P, Li Y-R. Interactive Role of Silicon and Plant–Rhizobacteria Mitigating Abiotic Stresses: A New Approach for Sustainable Agriculture and Climate Change. *Plants*. 2020; 9(9):1055. https://doi.org/10.3390/plants9091055
217. Pontigo S, Godoy K, Jiménez H, Gutiérrez-Moraga A, Mora ML, Cartes P. Silicon-Mediated Alleviation of Aluminum Toxicity by Modulation of Al/Si Uptake and Antioxidant Performance in Ryegrass Plants. *Front Plant Sci*. 2017;8:642. Published 2017 Apr 25. doi:10.3389/fpls.2017.00642
218. Kopittke PM, Gianoncelli A, Kourousias G, Green K, McKenna BA. Alleviation of Al Toxicity by Si Is Associated with the Formation of Al-Si Complexes in Root Tissues of Sorghum. *Front Plant Sci*. 2017;8:2189. Published 2017 Dec 21. doi:10.3389/fpls.2017.02189
219. Shwethakumari U, Pallavi T, Prakash NB. Influence of Foliar Silicic Acid Application on Soybean (*Glycine max* L.) Varieties Grown across Two Distinct Rainfall Years. *Plants (Basel)*. 2021;10(6):1162. Published 2021 Jun 8. doi:10.3390/plants10061162
220. Quiñones MA, Lucas MM, Pueyo JJ. Adaptive Mechanisms Make Lupin a Choice Crop for Acidic Soils Affected by Aluminum Toxicity. *Front Plant Sci*. 2022;12:810692. Published 2022 Jan 5. doi:10.3389/fpls.2021.810692
221. Ryan PR, Raman H, Gupta S, Horst WJ, Delhaize E. A second mechanism for aluminum resistance in wheat relies on the constitutive efflux of citrate from roots. *Plant Physiol*. 2009;149(1):340-351. doi:10.1104/pp.108.129155
222. Li, W., Finnegan, P.M., Dai, Q. *et al.* Metabolic acclimation supports higher aluminium-induced secretion of citrate and malate in an aluminium-tolerant hybrid clone of *Eucalyptus*. *BMC Plant Biol* **21**, 14 (2021). https://doi.org/10.1186/s12870-020-02788-4
223. Ranea-Robles P, Houten SM. The biochemistry and physiology of long-chain dicarboxylic acid metabolism. *Biochem J*. 2023;480(9):607-627. doi:10.1042/BCJ20230041
224. Alva, A.K. and Edwards, D.G. 1990. Response of lupin cultivars to low concentration of calcium and higher activity of aluminium in dilute nutrient solutions. J. Plant Nutr. 13: 57-76.
225. Asada, K. 1992. APX- a hydrogen peroxide-scavenging enzyme in plants. Physiol. Plant. 85: 235-241.

226. Asada, K. 1994. Production and action of active oxygen in photosynthetic tissue. In CH Foyer, PM Mullineaux, eds, Causes of Photooxidative Stress and Amelioration of Defence Systems in Plants. CRC. Boca Ranton, FL, pp, 77-104.
227. Awad, A.S., Edwardson, D.G. and Mulhain, P.J. 1976. Effect of pH and phosphate on sub soil aluminium and on growth and composition of kikuyu grass. Plant Soil. 45: 531-532
228. Bartlett, R.J. and Riego, D.C. 1972. Effect of chelation on the toxicity of aluminium. Plant Soil. 37: 419-423.
229. Basu, U., Basu, A. and Taylor, G.J. 1994a. Differential exudation of polypeptides by roots of aluminium-resistant and aluminium-sensitive cultivars of Triticum aestivum L. in response to aluminium stress. Plant Physiol. 106: 151-158.
230. Bengtsson, B., Asp, H.. Jensen, P. and Berggren, D. 1988. Influence of aluminium on phosphate and calcium uptake in beech (Fagus sylvatica) grown in nutrient solution and soil solution. Physiol. Plant. 74: 299-305.
231. Bengtsson, H.A. and Jensen, P. 1991. Influence of aluminium on phosphorus and calcium localization in roots of beech (Fagus sylvatica). Physiol. Plant. 83: 41-46.
232. Botstein, D., White, R.L., Skoolnick, M. and Davis, R.W. 1980. Construction of a genetic linkage map in man using restriction fragment length polymorphisms. Am. J. Hum. Genet. 32:
233. Cakmak, I. and Marschner, H. 1988. Increase in membrane permeability and exudation in roots of zinc deficient plants. J. Plant Physiol. 132: 356-361.
234. Campbell, L.G. and Lafever, H.N. 1978. Heritability and gene effects for aluminium tolerance in wheat, proc. Fifth Int. Wheat Genet. Symp. New Delhi, India, pp, 963-977.
235. Campbell, T.A., Jackson, P.R. and Xia, Z.L. 1994. Effects of aluminium stress on Alfalfa root proteins. J. Plant. Nutr. 17: 461-471.
236. Chang, Y.C., Yamamoto, Y. and Matsumoto, H. 1999. Enhancement of callose production by a combination of aluminium and iron in suspension-cultured tobacco (Nicotiana tabacum) cells. Soil Sci. Plant Nutr. 45 (2): 337-347.
237. Clarkson, D.T. and Sanderson, J. 1971. Inhibition of the uptake and long-distance transport of calcium by aluminium and other polyvalent cations. J. Exp. Bot. 22: 837-851.
238. Dakora. F.D.. Joseph, C.M. and Phillips, D.A. 1993. Alfalfa (Medicago satira L.). root exudates contain isolavanoids in the presence of Rhizobium meliloti. Plant physiol. 101: 819-824.
239. Demeke. T., Adams, R.P. and Chibbar. R. 1992. Potential taxonamic use of random amplifie olymorphic DNA (RAPD): a case study in Brassica. Theor. Appl. Genet. 84: 990-994
240. Foy. C.D. 1984. Physiological effects of hydrogen, aluminium and manganese toxicities in acid soil. In F Adams, ed. soil acidity and liming. American society of Agronomy, Madison, WI pp. 57-97.
241. Foy. C.D. and Brown, J.C. 1964. Toxic factors in acid soils. II. Differential aluminium tolerance of plant sciences. Soil Sci. Soc. Am. Proc. 28: 27-32
242. Foy, C.D., Burns, G.R., Brown, J.C. and Flemming, A.L. 1965. Differential aluminium tolerance of two wheat varieties associated with plant-induced pH changeas around their roots Soil Sci. Soc. Am. Proc. 29: 64-67.
243. Foy. C.D. Fleming, A.L. and Armiger. W.J. 1969. Aluminium tolerance of soybean varieties in relation to calcium nutrition. Agron. J. 61: 505-511.

244. Foyer. C. H. Descouvrieres. P. and Kuner, K. J. 1994 Protection against oxygen radical: an important defense mechanism studied in transgenic plants. Plant Cell Environ. 17: 507-523.
245. Frantzios, G., Galatis, B. and Apostolakos, P. 2000. Aluminium effects on microtubule organization in dividing root-tip cells of Triticum turgidum I. Mitotic cells. New Phytol. 145. 211-224
246. Fuente, J.M.D., Rodriguez, V.R., Ponce, J.L.C and estrella, L.H. 1997. Aluminium tolerance in transgenic plants by alteration of citrate synthesis. Science. 276. 1566-1568
247. Gardner, W.K., Barber, D.A. and Parbery, D.G. 1983. The acquisition of phosphorus by Lupinus albus L. Ill. The probable mechanism by which phosphorus movement in the soil/ root interface is enhanced. Plant Soil. 70: 107-124.
248. Godbold. D.L. 1991. Aluminium decreases root growth and Ca and Mg uptake in Picea abies seedlings. In: Plant-Soil interactions at low pH ( Ed. By R. J. wright, V. C. Baligar & R. P. Murrmann), Pp. 747-753. Kluwer Academic Publishers. Dordrecht.
249. Grayling, A. and Hanke, D.E. 1992. Cytokinins in exudates from leaves and roots of red Perilla. Phytochemistry. 31: 1863-1868.
250. Hammond, K.E., Evans, D.E. and Hodson, M.J. 1995. Aluminium/Silicon interactions in barley (Hordeum vulgare L.) seedlings. Plant Soil. 173: 89-95.
251. Hara, T., Gu, M.H. and Koyama, H. 1999. Ameliorative effect of silicon on aluminium injury in the rice plant. Soil Sci. Plant Nutr. 45: 929-936.
252. Hodson, M.J. and Sangster, A.G. 1993. The interaction between silicon and aluminium in sorghum (Hordeum bicolor L.): growth analysis and X-ray microanalysis. Ann. Bot. 72:
253. Hodson, M.J. and Wilkins, D.A. 1991. Localization of aluminium in the roots of Norway spruce (Picea abies L.) inoculated with Paxillus involutus Fr. New Phytol. 118: 273-278
254. Horst, W.J.. Asher, C.J., Cakmak, I., Szulkiewicz, P. and Wissemeir, A. H. 1991. Short-term responses of soybean roots to aluminium. Plant-Soil Interactions at low pH. (Ed. By R. J Wright. V.C. Baligar, & R.P. Murram), pp. 733-739. Kluwar Academic Publishers, Dordrecht. Horst. W.J., Puschel, A.K. and Schmol, N. 1997. Induction of callose formation is a sensitive marker for genotypic aluminium sensitivity in maize. J. Plant Physiol. 192: 23-30.
255. Hue, N.V., Craddock, G.R. and Adams, F. 1986. Effect of organic acids on alumium toxicity in subsoils. Soil Sci. Soc. Am. J. 50: 28-34.
256. Ikegawa, H.. Yamamoto, Y. and Matsumoto, H. 1998. Cell death caused by a combination of aluminium and iron in cultured tobacco cells. Physiol. Plant. 104: 474-478.
257. Jackson, M. 1997. Hormones from roots as signals for the roots of stressed plants. Trends plant sci. 2: 22-28.
258. Jena, K.K. and Kochert, G. 1991. Restriction fragment length polymorphism analysis of CCDD genome species of the genus Oryza sativa L. Plant Mol. Biol. 16: 831-839
259. Kass, oc of armer, mesqueene cale and are guan in 959) Springer-Verlag, Berlin, Germany.
260. Keser, M., Neubauer. B.F., tolerance of sugar-beet chivan a een Veil, Da mia struttered ad omi u
261. Kinraide. T.B, Ryan, P.R. and Kochian, L.V. 1992. Interactive effects of Al®, H and other cations on root elongation considered in terms of cell-surface electrical potential. Plant Physiol. 99: 1461-1468
262. Kochaian, L.V. 1995. Cellular mechanisms of aluminium toxicity and resistance in plants. Ann. Rev. Plant Physiol. Plant Mol. Biol. 46:237-260.

263. Larsen, P.B., Kochian, L.V. and Howell, S.H. 1997. Aluminium inhibits both shoot development and root growth in als, an Al-sensitive Arabdiopsis mutant. Plant Physiol. 114: 1210-1214
264. Lazof, D.B. and Holland, M.J. 1999. Evaluation of the alumiunium-induced root growth inhibition in isolation from low pH effects in Glycine max, Pisum sativum and Phaseolus vulgaris. Aust. J. Plant Physiol. 26: 147-157.
265. Lee, J., Pritchard, M.W., Sedcole, J.R. and Robertson, M. R. 1984. Aluminium and ammonium ion effects on the depletion of potassium from hydroponic solutions by Trifolium repens L. cv. Grasslands Huia. J. plant Nutr. 7: 1635-1650.
266. Lindberg. S. 1990. Aluminium interactions with K+ (8Rb) and 25Ca2+ fluxes in three cultivars of sugar beet (Beeta vulagris). Physiol. Plant. 79: 275-286.
267. Maehly, A.C. and Chance, B. 1954. The assay of catalase and peroxidases in Methods of Biochemical Analysis, Vol. 1, 357. (D.Glick, Ed, pp, 357, Interscience Publishers, New York Marienfeld, S., Nicole, S., Michael, K., Schroder, W.H., Kuhn, A.J. and Horst, W.J. 2000 Localization of aluminium in root tips of Zea mays and Vicia faba. J. Plant Physiol. 156 666-671.
268. Matsumoto, H., Morimura, S. and Takahashi, E. 1977. Less involvement of pectin in the precipitation of aluminium in pea root. Plant Cell Physiol. 18: 325-335
269. Mattioni, C. Gabbrielli, R., Vangronsveld, J. and Clijsters, H. 1997. Nickel and Cadmium toxicity and enzymatic activity in Ni-tolerant and non-tolerant populations of Silene italica Pers. J. Plant Physiol. 150: 173-177.
270. McCormick, L.H and Bordon, F.Y. 1972. Phosphate fixation by aluminium in plant roots. Soil Sci. Soc. Am. Proc. 36: 779-802
271. Miyasaka, S.C., Buta, J.G., Howell, R.K and Foy, C.D. 1991. Mechanism of aluminium tolerance in snap beans. Root exudation of citric acid. Plant Physiol. 96: 737-43
272. Moustakas, M. and Ouzounidou, G. 1995. Aluminium effects on photosynthesis and elemental uptake in an aluminium-tolerant and non-tolerant wheat cultivar. J. Plant Nutr. 18: 669-
273. Ohki, K. 1987. Aluminium stress on sorghum growth and nutrient relationship. Plant Soil. 98: 195-202.
274. Ownby. J. D. 1993. Mechanisms if reaction of hematoxylin with aluminium-treated wheat roots. Physiol. Plant. 87: 371-380.
275. Ownby, J.D. and Hruschka, W.R. 1991. Quantitative changes in cytoplasmic and microsomal proteins associated with aluminium toxicity in two cultivars of winter wheat Plant Cell Environ. 14: 303-309.
276. Pellet, D.M., Grunes, D.L. and Kochin, L.V. 1995. Organic acid exudation as an aluminium tolerance mechanism in maize (Zea mays L.). Planta. 196: 788-795.
277. Rahman, M.T., kawamura, K., Koyama, H. and Hara, T. 1998. Varietal differences in the growth of rice plants in response to aluminium and silicon. Soil. Sci. Nutr. 44: 423-431.
278. Richard. G., Federolf, G. and Habermann, E. 1985. The interaction of aluminium and other metal ions with calcium-calmodulin-dependent phosphodiesterase. Arch. Toxicol. 57: 257-259.
279. Rincon, M. and Gonzales, R. A. 1992. Aluminium partitioning in intact roots of aluminium-tolerant and aluminium-sensitive wheat cultivars. Plant Physiol. 99: 1021-1028.

280. Salt, D.E. and Wagner, G.J. 1993. Cadmium transport across tonoplast of vesicles from Oat roots: Evidence for a Cd'/H antiport activity. J. Biol. Chem. 268: 12297-12302.
281. Shure, M.,Wessler, S. and Federoff, N. 1983. Molecular identification of the Waxy locus in maize. Cell. 35: 225-233.
282. Siegel, N. and Haug, A. 1983b. Calmodulin-dependent formation of membrane potential in barley root plasma memrane vesicles: A biochemical model of aluminium toxicity in plants. Physiol. Planta. 59: 285-291.
283. Simpson, J. R., Pinkerton, A. and Lazdovokis, J. 1977. Effects of sub soil calcium on the root growth
284. Tan, K. and Keltjens, W.G. 1995. Analysis of acid-soil stress in sorghum genotypes with emphasis on aluminium and magnesium interactions. Plant Soil. 171: 147-150.
285. Tanaka, K. and Sugahara, K. 1980. Role of superoxide dismutase indefense against SO and an increase in SOD activity with SO fumigation. Plant Cell Physiol. 21: 601-611.
286. Taylor. G.J. 1988. The physiology of aluminium phytotoxicity. In H Siegel, ed, Metal ions in biological systems; aluminium and its role in Biology, vol. 24, Marcel-Dekker, NewY ork. pp. 123-163.
287. Tester, M. 1990. Plant ion channels: Whole cell and single-channel studies. New Phytol. 114: 305-340
288. Thornton. F. C., Schaedle. M. and Raynal, D. J. 1987. Effects of aluminium on red spruce seedlings in solution culture. Environ. Exp. Bot. 27: 489-498.
289. Van Assche. F., Cardinaeles, C. and clijsters, H. 1988. Induction of enzyme capacity in plants as a result of heavy metal toxicity: Dose-response relationships in Phaseolus vulagris L., treated with zinc and cadmium. Environ. Pollut. 52: 103-115.
290. Van. H.L... Kuraishi, S. and Sakuraj, N. 1994. Aluminium-induced rapid root inhibition and changes in
291. Wagatsuma, T. M., Kaneko, M. and Hayasaka, Y. 1987. Destruction process of plant root cells by aluminium. Soil Sci. Plant Nutr. 33: 161-175.
292. Weckz. J. E. J. and Clijsters, H. M. M. 1996. Oxidative damage and defense mechanisms in primary leaves of Phaseolus vulgaris as a result of root assimilation of toxic amounts of copper. Physiol. plant. 96: 500-512.
293. Welsh, J. and McClelland, M. 1990. Fingerprinting of genomes using PCR with arbitrary primers. Nucleic Acid. Res. 18: 7213-7218.
294. Williams, J., Kubelik, G.K. Livak, A.R., Rafalski, J.A. and Tingey, S.A. 1990. DNA Polymorphisms acids Res. 18: 6531-6535. amplified by arbitrary primers are useful as genetic markers. Nucleic acides Res. 18: 6531-6535.
295. Wissemeier, A. H., Koltz, F. and Horst, W. J. 1987. Aluminium induced callose synthesis in roots of soybean (Glycine max L.). J. Plant Physiol. 129: 487-492.
296. Woolhouse, H. W. 1969. Differences in the properties of the acid phosphate in plant roots and their significance in the evolution of edaphic ecotypes. In: Ecological aspects of the mineral nutrition of plants. Ed. Robinson, I. H., Blackwell Scientific Publications, Oxford 357-380.
297. Yoshida, S., Forno, D.A. and Cock, J.H. 1976. Routine procedure for growing rice plants in culture solution. Pp 61-66. In IRRI (Ed,) Laboratory Manual for physiological studies of Rice. IRRI, LosBanos, Philippines.

298. Zhao, X. J.. Sucoff, E. and Stadelmann, E. J. 1987. $Al^{2+}$ and $Ca^{2+}$ alteration of membrane permeability of Quercus rubra root cortex cells. Plant Physiol. 83: 159-162.

Balaji Meriga

# Aluminium Toxicity in Rice Cultivars and Some Ameliorative Methods

Rice is a staple food crop for more than half of the global population. Its yields are limited by many factors including Aluminium (Al) toxicity. Al is a major abiotic stress factor affecting crop productivity, especially in acidic soils where soluble forms of aluminium becomes toxic to plants. Despite its importance, the physiological, biochemical, and molecular mechanisms of Al toxicity and tolerance in rice remain incompletely understood. This book is a comprehensive exploration into the intricate responses of rice seedlings to aluminium stress, with focus on cultivar-specific differences in tolerance and injury.

The investigations presented herein were undertaken to decipher how different rice cultivars-VIK, IR-8, IR-64, PB, and SUR-respond to varying concentrations and durations of aluminium exposure. Particular focus was given to changes in growth parameters, aluminium accumulation, cellular and histological alterations, membrane lipid peroxidation, antioxidant enzyme responses, metabolic adaptations, and molecular markers associated with tolerance.

The findings reveal that Al stress significantly hinders growth, root-shoot development, and nutrient uptake, particularly under lower pH conditions and in younger seedlings. However, PB and SUR cultivars demonstrated marked resilience, evident from their minimal growth inhibition, reduced oxidative damage, and efficient antioxidant responses. Histological studies revealed effective compartmentalization of aluminium in tolerant cultivars, minimizing injury to root tissues. Elevated activity of key enzymes in the pentose phosphate pathway and TCA cycle, alongside enhanced exudation of citric acid, reflect metabolic adjustments in PB and SUR. Moreover, protein profiling and DNA analysis identified potential molecular markers and stress-inducible components associated with tolerance.

This book not only enriches our understanding of aluminium-induced stress responses but also underscores potential physiological and molecular markers that could be leveraged in rice breeding programs for developing Al-tolerant cultivars. The insights presented here aim to contribute towards sustainable agricultural practices and improved food security in regions with acidic soils.

We hope that researchers, students, plant physiologists, agronomists, and molecular biologists will find this work a valuable resource in the field of plant stress physiology and crop improvement.

DeepScience

9 789371 858793