

Reactive Oxygen, Nitrogen and Sulfur Species in Plants

Reactive Oxygen, Nitrogen and Sulfur Species in Plants

Production, Metabolism, Signaling and Defense Mechanisms

Volume 1

Edited by

Mirza Hasanuzzaman Sher-e-Bangla Agricultural University Dhaka Bangladesh

Vasileios Fotopoulos Cyprus University of Technology Lemesos Cyprus

Kamrun Nahar Sher-e-Bangla Agricultural University Dhaka Bangladesh

Masayuki Fujita Kagawa University Japan



This edition first published 2019 © 2019 John Wiley & Sons Ltd

All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording or otherwise, except as permitted by law. Advice on how to obtain permission to reuse material from this title is available at http://www.wiley.com/go/permissions.

The right of Mirza Hasanuzzaman, Vasileios Fotopoulos, Kamrun Nahar, Masayuki Fujita to be identified as the authors of this editorial material in this work has been asserted in accordance with law.

Registered Offices

John Wiley & Sons, Inc., 111 River Street, Hoboken, NJ 07030, USA John Wiley & Sons Ltd, The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SO, UK

Editorial Office

The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, UK

For details of our global editorial offices, customer services, and more information about Wiley products visit us at www.wiley.com.

Wiley also publishes its books in a variety of electronic formats and by print-on-demand. Some content that appears in standard print versions of this book may not be available in other formats.

Limit of Liability/Disclaimer of Warranty

While the publisher and authors have used their best efforts in preparing this work, they make no representations or warranties with respect to the accuracy or completeness of the contents of this work and specifically disclaim all warranties, including without limitation any implied warranties of merchantability or fitness for a particular purpose. No warranty may be created or extended by sales representatives, written sales materials or promotional statements for this work. The fact that an organization, website, or product is referred to in this work as a citation and/or potential source of further information does not mean that the publisher and authors endorse the information or services the organization, website, or product may provide or recommendations it may make. This work is sold with the understanding that the publisher is not engaged in rendering professional services. The advice and strategies contained herein may not be suitable for your situation. You should consult with a specialist where appropriate. Further, readers should be aware that websites listed in this work may have changed or disappeared between when this work was written and when it is read. Neither the publisher nor authors shall be liable for any loss of profit or any other commercial damages, including but not limited to special, incidental, consequential, or other damages.

Library of Congress Cataloging-in-Publication Data

Names: Hasanuzzaman, Mirza, editor.

Title: Reactive oxygen, nitrogen and sulfur species in plants: production, metabolism, signaling and defense mechanisms / edited by Mirza Hasanuzzaman, Sher-e-Bangla Agricultural University, Dhaka, Bangladesh, Vasileios Fotopoulos, Cyprus University of Technology, Lemesos, Cyprus, Kamrun Nahar, Sher-e-Bangla Agricultural University, Dhaka, Bangladesh, Masayuki Fujita, Kagawa University, Japan.

Description: Hoboken, NJ : Wiley-Blackwell, [2019] | Two volumes in one. | Includes bibliographical references and index. |

Identifiers: LCCN 2019000084 (print) | LCCN 2019000951 (ebook) | ISBN 9781119468660 (Adobe PDF) | ISBN 9781119468646 (ePub) | ISBN 9781119468691 (hardcover)

Subjects: LCSH: Plants–Effect of stress on–Molecular aspects. | Plant cellular signal transduction. | Oxidative stress.

Classification: LCC QK725 (ebook) | LCC QK725 .R4295 2019 (print) | DDC 571.7/42–dc23 LC record available at https://lccn.loc.gov/2019000084

Cover Design: Wiley

 $Cover\ Image: @\ molekuul_be/Shutterstock, @\ molekuul_be/Shutterstock, @\ oticki/Shutterstock, @\ extender_01/Shutterstock, @\ Anton-Burakov/Shutterstock$

Set in 10/12pt Warnock by SPi Global, Pondicherry, India

Contents

About the Editors xix List of Contributors xxiii Preface xxxiii

Section I Reactive Oxygen Species Metabolism and Antioxidant Defense 1

1	Regulated Suicide for Survival: Toward Programmed Cell Death During
	Reactive Species Mediated-Oxidative Stress of Plant Cells 3
	Dibyendu Talukdar
1.1	Introduction 3
1.2	PCD: Versatile But Programmed in Functional Plant Biology 4
1.2.1	Experimental Evidence of PCD in Plant System 5
1.3	PCD through ROS Network in Plant Cell 7
1.3.1	Cellular Organelles: Hub of PCD Components 7
1.3.1.1	PCD: The Chloroplastic Connection 8
1.3.1.2	PCD: The Mitochondrial Drive 10
1.3.1.3	PCD: The Vacuolar Mediation 11
1.3.2	Inter-Organelle Cross Talk in PCD Programming 12
1.4	Mechanisms of ROS-Mediated PCD in Plant Cell 14
1.4.1	ROS-Mediated Disruption of Antioxidant System en Route to PCD 14
1.4.2	ROS-Mediated Disruption of Oxidative Metabolism en Route to PCD 15
1.4.3	ROS-Induced Electrolyte Leakage in PCD Programming 16
1.4.4	ROS-Induced Release of Cytochrome c en Route to PCD 17
1.4.5	Caspase Like Cascade and Its Cross-Talk with Cytochrome c,
	and Nuclease in Plant PCD 19
1.4.6	ROS to PCD: Cross-Talk via Proteasome Complex 21
1.5	ROS Signaling Network in Regulating Plant PCD 22
1.5.1	Cross Talk Between ROS and RNS Toward PCD 23
1.5.2	Interactive Hormone Signaling Toward PCD via ROS 25
1.5.3	MAP Kinase Cascade in ROS-Driven PCD Events 28
1.5.4	Lipid Signaling and PCD 30
1.6	Future Prospects 31
	References 32

2	Iron and Its Catalytic Properties on Radical Generation: Role of Chelators on the Labile Iron Pool (LIP) 39 Elizabeth Robello, Andrea Galatro, and Susana Puntarulo
2.1	Introduction 39
2.2	Iron-Dependent Oxidative Metabolism 40
2.3	Role of Chelators on Fe-Dependent Oxidant Production 40
2.4	Cellular Fe Distribution in Plants and Animals 41
2.5	
2.6	Experimental Alternatives Related to the Operational Definition of LIP 44 LIP Changes Under Stress Situations in Plants and Animals 47
2.7	Conclusions 48
2.7	Acknowledgments 50
	References 50
	References 30
3	Superoxide Dismutases (SODs) and Their Role in Regulating Abiotic Stress
	induced Oxidative Stress in Plants 53
	Panchanand Mishra and Pallavi Sharma
3.1	Introduction 53
3.2	Generation of Reactive Oxygen Species (ROS) and Their Effects in Plants
	Experiencing Abiotic Stress 55
3.2.1	ROS Generation in Plants 56
3.2.2	Abiotic Stress Induced ROS Generation in Plants 58
3.2.3	ROS Induced Oxidative Damage in Plants 59
3.2.4	ROS Detoxification System in Plants 60
3.3	Superoxide Dismutase (SOD) Isoenzymes in Plants 61
3.3.1	Copper Zinc SODs (Cu-ZnSOD) 61
3.3.2	Iron Superoxide Dismutase (FeSOD) and Manganese Superoxide
	Dismutase (MnSOD) 64
3.3.3	Cambialistic Superoxide Dismutase (Fe/MnSOD) 66
3.4	Regulation, Expression and Interaction Network of Superoxide
	Dismutase Isozymes 67
3.5	SOD Mediated Improvement in Abiotic Stress Tolerance in Plants 71
3.6	Concluding Remarks and Future Prospects 76
	Acknowledgments 76
	References 77
4	The Role of Ascorbate-Glutathione Pathway in Reactive Oxygen Species
•	Balance Under Abiotic Stresses 89
	Liudmyla O. Sakhno, Alla I. Yemets, and Yaroslav B. Blume
4.1	Introduction 89
4.2	Water Availability 90
4.2.1	Drought 90
4.2.2	Flooding 93
4.3	Salinity 94
4.4	Extreme Temperatures 97
4.4.1	Chilling 97
4.4.2	Heat 98
4.5	Insolation 99
4.5.1	High Insolation 99

4.6 4.6.1	Cd 100 Pb 100 Cu 101 Cr 101 Nanoparticles 101 Combination of Stresses 102 Conclusion 104
	Acknowledgment 105 References 105
5	Oxidative Stress and Antioxidant Defense Under Combined Waterlogging and Salinity Stresses 113 Savita Duhan, Anita Kumari, Manohar Lal, and Sunita Sheokand
5.1	Introduction 113
5.2	Reactive Oxygen Species (ROS) and Oxidative Stress 115
5.3	Effects of Oxidative Stress 117
5.3.1	Lipid Peroxidation 117
5.3.2	Membrane Injury 118
5.3.3	Ion Homeostasis and ROS Metabolism 119
5.3.4	Antioxidative Defense System 119
5.4	Enzymatic Components 120
5.4.1	Superoxide Dismutase (SOD) 120
5.4.2	Catalase (CAT) 121
5.4.3	Ascorbate Peroxidase (APX) 122
5.4.4	Peroxidases (POX) 124
5.4.5	Glutathione Reductase (GR) 125
5.4.6	Dehydroascorbate Reductase (DHAR) 126
5.4.7	Monodehydroascorbate Reductase (MDHAR) 126
5.5	Non-enzymatic Components 127
5.5.1	Ascorbate Content 127
5.5.2	Glutathione Content 129
5.6	Aerenchyma Formation and Root Modifications 130
5.7	Conclusions and Future Projections 132
	References 133
6	Role of Polyamines in Protecting Plants from Oxidative Stress 143 Pooja, Vinod Goyal, Sarita Devi, and Renu Munjal
6.1	Introduction 143
6.2	Discovery of Polyamines 143
6.2.1	Biosynthesis, Catabolism and Biosynthetic Inhibitor of Polyamines 144
6.2.2	Role of Polyamines in Protecting Plants from Oxidative Stress 146
6.3	Important Physiological Effects of Polyamines in Plants 147
6.3.1	Interaction of Polyamines with ROS 147
6.3.2	Cell Proliferation 147
6.3.3	Stress Response 148

viii	Contents	
	6.3.4 6.4 6.4.1 6.5 6.6 6.7	Gene Expression 148 Role of Polyamines in Combating Oxidative Stress 149 Polyamines and Detoxification of ROS 151 Polyamine and H_2O_2 152 Exogenous Polyamine 152 Conclusion and Future Prospective 152 Abbreviations 153 References 154
	7	Role of Glutathione in Plant Abiotic Stress Tolerance 159
		Aditya Banerjee and Aryadeep Roychoudhury
	7.1	Introduction 159
	7.2	GSH Metabolism in Plants 159
	7.3	GSH Confers Protection during Abiotic Stress 160 GSH: Variable Redox States 160
	7.3.1 7.3.2	The AsA-GSH Cycle (AGC) 161
	7.3.2	GSH as an Antioxidant 162
	7.3.3 7.3.4	Glutathione S-Transferases (GSTs) Protect against Abiotic Stress 162
	7.3.4	GSH Regulation of Transcription and Nitric Oxide Signaling
	7.5.5	during Stress 163
	7.4	GSH Regulates Abiotic Stress Tolerance 163
	7.4.1	Exogenous Application of GSH 163
	7.4.2	Genetic Engineering Approach 163
	7.4.3	The Sub-cellular Distribution of GSH in Response to Abiotic Stresses 164
	7.4.3.1	
	7.4.3.2	Nuclei 167
	7.4.3.3	Chloroplasts and Peroxisomes 167
	7.5	Conclusion and Future Perspectives 167
		Acknowledgments 168
		References 168
	8	Molecular Approaches in Enhancing Antioxidant Defense in Plants 173 Kanika Khanna, Neha Handa, Poonam Yadav, Vandana Gautam, Vinod Kumar, Puja Ohri, and Renu Bhardwaj
	8.1	Introduction 173
	8.2	Plant Responses to Environmental Stresses 175
	8.3	Approaches for Stress Tolerance 177
	8.4	Genetic Engineering for Environmental Stresses 180
	8.4.1	Genomics 180
	8.4.2	Proteomics 181
	8.4.3	Metabolomics 184
	8.5	Conclusion and Future Prospects 185 References 185
	_	
	9	Omics in Oxidative Stress Tolerance in Crops 195
	0.1	Ceyhun Kayıhan and Füsun Eyidoğan
	9.1	Introduction 195
	9.2	Genomics 196

9.2.1	Structural Genomics 196
	Genome Sequencing 196
	Molecular Markers 197
9.3	Transcriptomics 197
9.3.1	Hybridization-Based Approaches 198
9.3.1.1	Suppression Subtractive Hybridization (SSH) 198
9.3.1.2	Microarrays 198
9.3.2	Sequencing-Based Approaches 199
9.3.2.1	Serial Analysis of Gene Expression (SAGE) 199
9.3.2.2	RNA-Sequencing 199
9.3.3	Plant Transcriptomics Applications 199
9.3.3.1	Salt Tolerance 199
9.3.3.2	Drought Tolerance 201
9.3.3.3	Cold Tolerance 201
9.3.3.4	Nutrient Deficiency and Toxicity 202
9.4	Proteomics 203
9.4.1	Plant Proteomics Applications 204
	Salt Tolerance 205
9.4.1.2	Drought Tolerance 206
	Cold Tolerance 207
	Nutrient Deficiency 208
9.5	Metabolomics 209
	Plant Metabolomics Applications 209
	Salt Tolerance 210
	Drought Tolerance 211
9.5.1.3	Low-Oxygen Tolerance 212
	Cold Tolerance 212
	Nutrient Deficiency and Toxicity 212
	Oxidative Stress 213
9.6	Conclusions and Outlook 213
9.0	References 214
	References 217
10	Polo of Poactive Ovugan Species Signaling in Plant Growth
10	Role of Reactive Oxygen Species Signaling in Plant Growth and Development 225
	Neveen B. Talaat
10.1	
10.1	Introduction 225
10.2	ROS Generation 227
10.3	Deleterious Effects of Different Types of ROS on Plant Cells 229
10.4	ROS Detoxification 230
10.5	Regulation of Antioxidant Genes Expression by Different Types of ROS 231
10.5.1	Singlet Oxygen (O_2^{-1}) 231
10.5.2	Superoxide Radical (O ₂ •-) 232
10.5.3	Hydrogen Peroxide (H ₂ O ₂) 233
10.6	ROS and Redox Signaling 234
10.7	ROS as Long Distance Signal and ROS Waves 236
10.8	ROS Signaling with Hormonal Signaling Networks 237
10.8.1	Abscisic Acid (ABA) 237
10.8.2	Ethylene (ET) 238

x	Contents	
	10.8.3	Auxin 238
		Gibberellins (GAs) 239
	10.8.5	
		Jasmonic Acid (JA) 241
	10.8.7	
	10.9	Processes Regulated by ROS 242
	10.9.1	·
		Cell Death 247
	10.9.3	Acclimation to Stressful Conditions 250
		Conclusion and Perspectives 252
		Abbreviations 253
		References 253
	11	Oxidative Stress and Antioxidant Defense in Germinating Seeds:
		A Q&A Session 267
		Andrea Pagano, Chiara Forti, Carla Gualtieri, Alma Balestrazzi, and Anca Macovei
	11.1	Introduction 267
	11.2	
		Where Does ROS Act at a Molecular Level? 269
		ROS vs. Lipids 270
		ROS vs. Proteins 270
	11.3.3	
	11.4	
		Passive Mechanisms 272
		Active Mechanisms 273
		DDR and ROS in Seeds 274
	11.5	4
	11.6	How Does the Crosstalk Between ROS and Phytohormones Influences Seed Germination? 276
	11.7	
		and Seed Longevity? 278
	11.7.1	· · · · · · · · · · · · · · · · · · ·
	11.7.2	ROS vs. Seed Longevity 279
	11.8	Concluding Remarks 280
		References 280
	12	Oxidative Stress and Antioxidant Defense in Plants Under Salinity 291
		Pedro García-Caparrós, Mirza Hasanuzzaman, and María Teresa Lao
	12.1	Introduction 291
	12.2	Types of ROS and Damages 292
	12.3	Sites of ROS Production 293
	12.3.1	Chloroplast 293
	12.3.2	Peroxisomes 293
	12.3.3	Mitochondria 294
	12.3.4	Apoplast 294
	12.4	Antioxidant Machinery 294
	12.4.1	Enzymatic Antioxidants 294

12.4.1.1	Superoxide Dismutase 294
12.4.1.2	Catalase 296
12.4.1.3	Ascorbate Peroxidise 296
12.4.1.4	Guaiacol Peroxidise 296
12.4.1.5	Glutathione Reductase 297
12.4.1.6	Monodehydroascorbate Reductase 297
12.4.1.7	Dehydroascorbate Reductase 298
12.4.2	Non-enzymatic Antioxidants 298
12.4.2.1	Ascorbic Acid 298
12.4.2.2	Glutathione 298
12.4.2.3	Tocopherol 300
12.4.2.4	Carotenoids 300
12.4.2.5	Flavonoids 301
12.5	Conclusion and Future Perspectives 301
	References 302
13	ROS Modulation in Crop Plants Under Drought Stress 311
	Giti Verma, Dipali Srivastava, Poonam Tiwari, and Debasis Chakrabart
13.1	Introduction 311
13.2	ROS Generation: An Overview 312
13.2.1	Singlet Oxygen (¹ O ₂) 313
13.2.2	Superoxide Radical $(O_2^{\bullet-})$ 313
13.2.3	Hydrogen Peroxide (H ₂ O ₂) 313
13.2.4	Hydroxyl Radical (OH*) 314
13.3	Site of ROS Production in Plants 314
13.4	Enhanced ROS Production in Drought 315
13.5	ROS Scavenging Mechanism 316
13.6	ROS Scavenging Enzymes During Drought Stress 318
13.6.1	Superoxide Dismutase (SOD) 318
13.6.2	Catalase (CAT) 318
13.6.3	Ascorbate Peroxidase (APX) 319
13.6.4	Glutathione Peroxidase (GPX) 319
13.6.5	Monodehydroascorbate Reductase (MDHAR) 319
13.6.6	Dehydroascorbate Reductase (DHAR) 319
13.6.7	Glutathione Reductase (GR) 320
13.7	Non-Enzymatic ROS Scavenging Under Drought Stress 320
13.7.1	Ascorbic Acid, AsA 320
13.7.2	Tocopherols 320
13.7.3	Glutathione 321
13.7.4	Thioredoxin 321
13.7.5	Peroxiredoxins 321
13.7.6	Glutaredoxin 322
13.8	ROS Signaling Under Drought Stress 322
13.8.1	Hormones and ROS Interaction 322
13.8.1.1	Auxin 322
13.8.1.2	Abscisic Acid 323
13.8.1.3	Brassinosteroids 323

13.8.1.4	Gibberellic Acid 324
13.8.1.5	Jasmonic Acid (JA) 324
13.8.2	ROS and Calcium Signaling 324
13.9	Concluding Remark and Future Perspective 326
	Acknowledgment 327
	References 327
14	Oxidative Stress and Antioxidant Defense in Plants Under High
	Temperature 337
	Pooja and Renu Munjal
14.1	Introduction 337
14.2	HT Stress Induced by Oxidative Stress in Major Food Crops 338
14.3	Antioxidant Defense System Under HT Stress 338
14.3.1	Enzymatic Antioxidant Defense 338
14.3.2	Non Enzymatic Antioxidant Defense 340
14.3.2.1	Carotenoids 340
14.3.2.2	Anthocyanin 340
14.3.2.3	Glultathione 341
14.3.2.4	Osmolytes 341
14.3.2.5	Plant Hormones 342
14.3.2.6	Nitrous Oxide 343
14.3.2.7	Ascorbic Acid (AsA) 344
14.3.2.8	Polyamines 344
14.3.2.9	Selenium 344
14.4	Transgenic Plants a New Approach to Induce Oxidative Stress
	Tolerance 345
14.5	Conclusion and Future Prospective 345
	Abbreviations 345
	References 346
15	Oxidative Stress and Antioxidant Defense in Plants Exposed to Metal/
	Metalloid Toxicity 353
	Muhammad Arif Ali, Shah Fahad, Idrees Haider, Niaz Ahmed, Shakeel Ahmad,
151	Sajjad Hussain, and Muhammad Arshad
15.1	Introduction to Oxidative Stress in Plants 353
15.1.1	Lipids Damages Due to Oxidative Stress 354
15.1.2	Protein Damages Due to Oxidative Stress 356
15.1.3	DNA Damages Due to Oxidative Stress 356
15.2	Metal and Metalloid Toxicity and Oxidative Stress 356
15.3	Production of Antioxidants Due to Metal Toxicity 360
15.4 15.4.1	Mechanism of Antioxidant Defense System in Plants 360
	Non-enzymatic Antioxidant Defense System 361 Ascorbate (AsA) 361
15.4.1.1 15.4.1.2	Glutathione 362
15.4.1.2	Tocopherols 362
15.4.1.4	Carotenoids 362
15.4.1.5	Phenolic Compounds 362
19.4.1.9	Thenone Compounds 302

15.4.2 15.4.2.1 15.4.2.2 15.4.2.3 15.4.2.4	Enzymatic Antioxidant Defense System 363 Superoxide Dismutase (SOD) 363 Catalase (CAT) 363 Guaiacol Peroxidase (GPX) 363 Enzymes of Ascorbate Glutathione (AsA-GSH) Cycle 364 References 365					
16	Oxidative Stress and Antioxidant Defense in Plants Exposed to Ultraviolet					
	Radiation 371					
	Jainendra Pathak, Rajneesh, Haseen Ahmed, Deepak K. Singh,					
	Prashant R. Singh, Deepak Kumar, Vinod K. Kannaujiya,					
	Shailendra P. Singh, and Rajeshwar P. Sinha					
16.1	Introduction 371					
16.2	Effects of UV Radiation on Plants 373					
16.3	UV-B Perception 376					
16.4	UV-B-induced Signal Transduction and Photomorphogenesis 378					
16.5	UV-Induced Oxidative Stress 381					
16.6	ROS Signaling in Plants Under Oxidative Stress 383					
16.7	ROS Produced in Plants Under Oxidative Stress 387					
16.7.1	Singlet Oxygen (¹ O ₂) 387					
16.7.2	Superoxide Radicals $(O_2^{\bullet-})$ 387					
16.7.3	Hydrogen Peroxide (H ₂ O ₂) 387					
16.7.4	Hydroxyl Radicals (OH*) 388					
16.8	Lipid Peroxidation (LPO) 388					
16.9	Effect of UV on DNA 389					
16.10	ROS and Proteins 390					
16.11	Effect of UV on Photosynthesis 391					
16.11.1	Effect of UV on Ribulose-1,5-bisphosphate Carboxylase/Oxygenase 392					
16.12	Localization of the Oxidative Scavenging Pathways in Plants Cells 393					
16.13	Metabolism of ROS 394					
16.14 16.14.1	Enzymatic Defense 394 Superoxide Dismutase (SOD) 395					
16.14.1	Superoxide Dismutase (SOD) 395 Hydrogen Peroxide (H_2O_2) 395					
16.14.3	Ascorbate Peroxidase (APX) 396					
16.14.4	Peroxidase (POD) 396					
16.14.5	Catalase (CATs) 397					
16.15	Non-enzymatic Antioxidants 398					
16.16	Conclusions and Future Perspectives 400					
	Acknowledgements 401					
	Conflict of Interest 401					
	References 401					
17	Methods/Protocols for Determination of Oxidative Stress in Crop Plants 421					
	Baskar Venkidasamy, Mahima Karthikeyan, and Sathishkumar Ramalingam					
17.1	Introduction 421					
17.2	ROS Determination in Plants 423					
17.3	Estimation of Biochemical Components 423					

xiv	Contents				
	17.3.1	Total Chlorophyll Estimation 423			
	17.3.2	Estimation of Anthocyanin 423			
	17.3.3	Estimation of Malondialdehyde (MDA) 424			
	17.3.4	Estimation of Proline 424			
	17.3.4.1	Isatin Paper Assay 424			
	17.3.4.2	Colorimetric Assay 425			
	17.3.4.3	Quantification of Proline using HPLC 425			
	17.3.5	Estimation of Glycine Betaine 425			
	17.4	Assays for Measurement of Total Antioxidants in Plants 426			
	17.4.1	Estimation of Non-enzymatic Antioxidants 426			
	17.4.1.1	Estimation of Ascorbic Acid 426			
	17.4.1.2	Estimation of Tocopherol 426			
		Estimation of Reduced Glutathione 426			
	17.4.1.4	Estimation of Total Phenolics and Flavonoids 426			
	17.4.1.5	Antioxidant Capacity Using DPPH Assay 427			
	17.4.1.6	Ferric Reducing/Antioxidant Assay (FRAP) 427			
	17.4.2 Antioxidant Enzyme Assays 427				
	17.4.2.1 Preparation of Plant Extract for Antioxidant Enzyme Assays 427				
	17.4.2.2 Estimation of Superoxide Dismutase (SOD) 428				
17.4.2.3 Estimation of Catalase (CAT) 428					
17.4.2.4 Estimation of Ascorbate Peroxidase (APX) 428					
17.4.2.5 Estimation of Glutathione Reductase (GR) 428					
	17.4.2.6 Estimation of Monodehydroascorbate Reductase (MDHAR) 429				
	17.4.2.7	,			
	17.5	Direct Methods 429			
	17.5.1	Estimation of H_2O_2 429			
	17.5.2	Direct Detection of ROS by Electron Paramagnetic Resonance (EPR) 429			
	17.5.3	Histochemical Staining Methods 430			
	17.5.3.1	Estimation of Total ROS Using DCFDA 430			
	17.5.3.2	Estimation of Superoxide Anion by NBT Staining 430			
	17.5.3.3	Detection of Singlet Oxygen 430			
	17.5.3.4	Estimation of H ₂ O ₂ by DAB Staining 431			
	17.6	Role of Plants Hormones During Biotic and Abiotic Stress 431			
	17.7	Estimation of Phytohormones by HPLC-MS/MS 432			
	17.8 Concluding Perspectives 432				
		Acknowledgments 433 Conflict of Interest 433			
		References 433			
		References 455			
	18 Does Seed Priming Play a Role in Regulating Reactive Oxygen Species Und				
		Saline Conditions? 437			
	18.1	Mohamed Magdy F. Mansour, Esmat Farouk Ali, and Karima Hamid A. Salama Introduction 437			
	18.2	Reactive Oxygen Species (ROS) 440			
	18.2.1	Sites of ROS Synthesis 441			
	18.2.2	Damaging Effects of ROS 443			
	18.2.3	Beneficial Effects of ROS 444			

18.2.3 18.3

Seed Priming 446

18.3.2 18.3.3 18.3.4 18.3.5 18.3.6	Priming Techniques and Agents 447 Hydro-priming 447 Osmo-Priming 449 Halo-Priming 451 Hormonal Priming 453 Chemical Priming 456 Bio-priming 459
18.3.8 18.4 18.4.1	Nutrient Priming 460 Changes Induced During Seed Priming 462 Physiological Changes 462 Biochemical and Molecular Changes 465
19	Computer-Assisted Image Analysis of the Distribution and Intensity of Reactive Oxygen Species Accumulation in Plant Leaves 489 Joanna Sekulska-Nalewajko, Jarosław Gocławski, and Elżbieta Kuźniak
19.1 19.2	Introduction 489 Plant Material and Histochemical ROS Detection 491
19.3	Image Measurement System Framework 492
19.4	Image Segmentation 493
19.5	Classification of ROS Regions 495
19.6 19.7	The Detection of ROS with WRF Classifier 501 Comparison of ROS Regions Segmentation Results and Accuracy 504
19.7	Conclusions 509
2710	References 510
	Section II Reactive Nitrogen Species Metabolism and Signalling 515
20	Role of Nitric Oxide in Physiological and Stress Responses of Plants Under Darkness 517
20.1	Péter Poór, Zalán Czékus, and Attila Ördög Introduction 517
20.2	NO Synthesis and Regulation by Dark 517
20.3	Seedling Growth and Development in the Dark 520
20.4	Dark-Induced Senescence 521
20.5 20.6	Dark-Induced Stomatal Closure and Stress Responses 522 Conclusion and Perspectives 524
20.0	Acknowledgments 525 References 525
21	Nitric Oxide and Phytohormones Cross-Talk During Abiotic Stresses Responses in Plants 533 Tariq Shah, Sumbal Wahid, Muhammad Ilyas, and Mirza Hasanuzzaman
21.1	Introduction 533
21.2	NO-Phytohormone Cross Talk Under Drought Stress 534

kvi Content

xvi	Contents	•					
	21.3	NO-phytohormone Cross Talk Under Heavy Metals Stress 538					
	21.4	NO-phytohormone Cross Talk Under Salinity Stress 540					
	21.5	NO-phytohormone Cross Talk Under Temperature Stress 541					
	21.6	NO-phytohormone Cross Talk Under Other Abiotic Stresses 543					
	21.7	Conclusion and Future Perspectives 545 References 545					
	22	The Role of Nitric Oxide in the Antioxidant Defense of Plants Exposed to UV-B Radiation 555					
		Raúl Cassia, Melina Amenta, María Belén Fernández, Macarena Nocioni, and Valeria Dávila					
	22.1	Introduction: What Is UV-B and How Much UV-B Is Reaching					
	22.1	the Earth? 555					
	22.2	UV-B Is a Stressor and a Signal 556					
	22.3	How Does UV-B Produce ROS? 556					
	22.4	Endogenous Nitric Oxide Is a Component of the UV-B Response in Plants 557					
	22.5	Genes Participating on the UV-B Response Are Regulated by NO 558					
	22.6	Are the Nitric Oxide and the UV-B Receptor UVR8 Work Coordinately in the Response of <i>Arabidopsis</i> to UV-B? 558					
	22.7	Nitric Oxide Positively Influences the Stability of UVR8 561					
	22.8	A Comprehensive Model of NO Role in the Antioxidant Response of Plants to UV-B 563					
	22.9	Other Components of the Aantioxidant System: GSH as a Redox Buffer. GSNO as NO Reservoir SNO and S-Nitrosylation 564					
	22.10	Different Effects of NO in the Regulation of the Antioxidant System 564					
	22.11	Conclusion and Perspectives 566					
		Acknowledgments 567					
		References 567					
	23	Reactive Oxygen Species and Nitric Oxide Production, Regulation and Function During Defense Response 573 Eliana Molina-Moya, Laura C. Terrón-Camero, Leyre Pescador-Azofra, Luisa M. Sandalio, and María C. Romero-Puertas					
	23.1	Introduction 573					
	23.2	ROS and NO Metabolism in Plants 574					
	23.3	ROS and NO Production and Regulation During Basal Resistance: PTI					
	20.0	Response 575					
	23.4	ROS and NO Production and Regulation During Incompatible Interaction: Hypersensitive Response (HR) 577					
	23.5	ROS and NO Function During Plant Immunity 579					
	23.6	Conclusions 582					
		Acknowledgments 582					
		References 582					

24	4 Role of Nitric Oxide in Growth Regulation and Re-orientation				
	of Pollen Tubes 591				
	Tariq Shah, Mehmood Ali Noor, and Mirza Hasanuzzaman				
24.1	Introduction 591				
24.2	Role of NO in Sexual Reproduction 592				
24.3	NO Signaling: Multitasking in Plants 594				
24.4	NO; an Effective Weapon for Plant Defense 597				
24.5	Search for NO-Sensing Molecules in Plants 598				
24.6	Conclusions 601				
	References 602				
25	Nitric Oxide (NO)-Mediated Plant Stress Signaling 609				
	L.V. Dubovskaya and Y.S. Bakakina				
25.1	Introduction 609				
25.2	Molecular Mechanisms of NO Signaling 611				
25.2.1	cGMP-Mediated NO Signaling 611				
25.2.2	Interplays Between NO, cADPR and Ca ²⁺ 612				
25.2.3	cGMP-Independent NO-Signaling 613				
25.3	NO and Abiotic/Biotic Stress Signaling 615				
25.3.1	NO and Abiotic Stresses 615				
25.3.2	NO and Biotic Stress Responses 617				
25.3.3	NO and Oxidative Burst 618				
25.4	Conclusion 619				
	References 620				
26	S-Nitrosoglutathione (GSNO) and Plant Stress Responses 627				
	Anjali Khajuria, Shagun Bali, Priyanka Sharma, Ravinderjit Kaur,				
	Shivam Jasrotia, Poonam Saini, Puja Ohri, and Renu Bhardwaj				
26.1	Introduction 627				
26.2	Synthesis of S-Nitrosoglutathione 628				
26.2.1	Biological Mechanism of GSNO Synthesis 628				
26.2.1.1	Routes for GSNO Formation 628				
26.3	Catabolism of GSNO 630				
26.4	Role of GSNO in Plants 630				
26.5	Cross-Stalk with Other Molecules 631				
26.5.1	Auxin 632				
26.5.2	Gibberellins 634				
26.5.3	Cytokinins 634				
26.5.4	NO and Other Signaling Molecules 635				
26.6	GSNO During Stress in Plants 636				
26.7	Conclusion 638				
	References 638				

About the Editors



Dr. Mirza Hasanuzzaman is Professor of Agronomy at Sher-e-Bangla Agricultural University in Dhaka. He received his PhD on "Plant Stress Physiology and Antioxidant Metabolism" from Ehime University, Japan with a scholarship from the Japanese government. Later, he completed his postdoctoral research at the Center of Molecular Biosciences, University of the Ryukyus, Japan, as a recipient of the Japan Society for the Promotion of Science (JSPS) postdoctoral fellowship. He was also the recipient of the Australian Government's Endeavor Research Fellowship for postdoctoral research as an Adjunct Senior Researcher at the University of Tasmania, Australia. Dr. Hasanuzzaman's current work is focused on the physiological and molecular mechanisms of environmenstress tolerance (salinity, drought, flood, and heavy metals/metalloids). Dr. Hasanuzzaman has published over 100 articles in peer-reviewed journals. He has edited six books and written 30 book chapters on important aspects of plant physiology, plant stress tolerance, and crop production. According to Scopus, Dr. Hasanuzzaman's publications have received over 3000 citations with an h-index of 30 and an i10-index of 55. He is an editor and reviewer for more than 50 peer-reviewed international journals and was a recipient of the "Publons Peer Review Award 2017 and 2018." He has been honored by different authorities for to his outstanding performance in different fields like research and education, and he has received the World Academy of Science Young Scientist Award (2014). He has presented 25 papers, abstracts, and posters at international conferences in several countries (USA, UK, Germany, Australia, Japan, Austria,

Sweden, Russia, etc.). Dr. Hasanuzzaman is a member of 40 professional societies and is the acting Publication Secretary of the Bangladesh Society of Agronomy and the Bangladesh JSPS Alumni Association. He is a fellow of The Linnean Society of London.



Dr. Vasileios Fotopoulos is Associate Professor in Structural and Functional Plant Biology and head of the CUT Plant Stress Physiology Group established in 2008 (HYPERLINK "http://www.plant-stress.weebly.com"www.plant-stress.weebly.com). His main scientific research focuses on the study of nitro-oxidative signaling cascades involved in the plant's response to stress factors, while emphasis is being given in the development of chemical treatment technologies towards the amelioration of abiotic stress factors and promotion of plant growth. To date, Dr. Fotopoulos is the author of 62 scientific papers published in peer-reviewed journals (h-index=23; Source: Scopus), as well as 7 book chapters. He currently serves as Associate Editor in BMC Plant Biology, Gene and five other journals. He has also been assigned to evaluate competitive research proposals from different countries (France, Belgium, Poland, Chile, Latvia, Greece, Italy, Portugal, Israel, Qatar, Austria, Cyprus, Denmark), EU proposals (EUROSTARS), while he is an active Review Panel Member for COST Actions (EU) in the field of 'Natural Sciences'. Finally, he has acted as examiner of MSc theses/PhD dissertations from Italy, South Africa and The Netherlands.



Dr. Kamrun Nahar is Associate Professor, Department of Agricultural Botany at Sher-e-Bangla Agricultural University, Dhaka, Bangladesh. She obtained BSc Ag (Hons.) and MS in Agricultural Botany from Sher-e-Bangla Agricultural University, Dhaka, Bangladesh. She persued her second MS degree in 2013 from Kagawa University, Japan. She also received her PhD Degree on "Environmental Stress Physiology of Plants" in 2016 from the United Graduate School of Agricultural Sciences, Ehime University, Japan with a Japanese Government (MEXT) Scholarship. She started her career as a Lecturer in the Department of Agricultural Botany, Sher-e-Bangla Agricultural University in February 2010, was promoted to Assistant Professor in 2012 and to Associate Professor in 2017. Dr. Nahar has been involved in research with field crops emphasizing stress physiology since 2006. She has completed several research works and is also continuing a research project funded by Sher-e-Bangla Agricultural University Research System and Ministry of Science and Technology (Bangladesh). She is supervising MS students. Dr. Nahar published number of articles in peer-reviewed journals and books of reputed publishers. She has published 50 articles and chapters related to plant physiology and environmental stresses with Springer, Elsevier, CRC Press, Wiley, etc. Her publications reached about 2000 citations with h-index: 22 (according to Scopus). She is involved in editorial activities and reviewer of international journals. She is an active member of about 20 professional societies.



Dr. Masayuki Fujita is Professor in the Laboratory of Plant Stress Responses, Faculty of Agriculture, Kagawa University, Kagawa, Japan. He received his BSc in Chemistry from Shizuoka University, Shizuoka, and M Ag and PhD in plant biochemistry from Nagoya University, Nagoya, Japan. His research interests include physiological, biochemical, and molecular biological responses based on secondary metabolism in plants under various abiotic and biotic stresses; phytoalexin, cytochrome P450, glutathione S-transferase, and phytochelatin; and redox reaction and antioxidants. In the last decade his works have focused on oxidative stress and antioxidant defense in plants under environmental stress. His group investigates the role of different exogenous protectants in enhancing antioxidant defense and methylglyoxal detoxification systems in plants. He has supervised 4 MS students and 13 PhD students as main supervisor. He has about 150 publications in journal and books and has edited 10 books.

List of Contributors

Shakeel Ahmad

Department of Agronomy
Faculty of Agricultural Sciences and
Technology
Bahauddin Zakariya University
Multan
Punjab

Haseen Ahmed

Pakistan

Laboratory of Photobiology and Molecular Microbiology Center of Advanced Study in Botany Institute of Science Banaras Hindu University Varanasi Uttar Pradesh India

Niaz Ahmed

Department of Soil Science
Faculty of Agricultural Sciences and
Technology
Bahauddin Zakariya University
Multan
Punjab
Pakistan

Melina Amenta

Laboratorio de Bioquímica Vegetal y Microbiana Facultad de Cs. Agrarias Universidad Nacional de Mar del Plata Balcarce Argentina

Mehmood Ali Noor

Institute of Crop Science
Key Laboratory of Crop Physiology and
Ecology
Chinese Academy of Agricultural
Sciences
Beijing
China

Muhammad Arif Ali

Department of Soil Science
Faculty of Agricultural Sciences and
Technology
Bahauddin Zakariya University
Multan
Punjab
Pakistan

Muhammad Arshad

Institute of Environmental Sciences and Engineering
School of Civil and Environmental
Engineering
National University of Sciences and
Technology
Islamabad
Islamabad Capital Territory
Pakistan

Y.S. Bakakina

Institute of Biophysics and Cell Engineering of the National Academy of Sciences of Belarus

Minsk Belarus

Alma Balestrazzi

Department of Biology and Biotechnology 'L. Spallanzani' University of Pavia

Pavia Italy

Shagun Bali

Department of Botanical and **Environmental Sciences** Guru Nanak Dev University Amritsar Puniab India

and Institute of Food Biotechnology and Genomics

National Academy of Sciences of Ukraine

Kyiv Ukraine

Aditya Banerjee

Department of Biotechnology St. Xavier's College (Autonomous) Kolkata West Bengal India

María Belén Fernández

Instituto de Investigaciones Biológicas Facultad de Ciencias Exactas y Naturales Universidad Nacional de Mar del Plata-Consejo Nacional de Investigaciones Científicas y Técnicas Mar del Plata Argentina

Renu Bhardwaj

Department of Botanical and **Environmental Sciences** Guru Nanak Dev University

Amritsar Puniab India and Institute of Food Biotechnology and Genomics National Academy of Sciences of Ukraine Kviv

Yaroslav B. Blume

Ukraine

Institute of Food Biotechnology and Genomics National Academy of Sciences of Ukraine Kviv Ukraine

Raúl Cassia

Instituto de Investigaciones Biológicas Facultad de Ciencias Exactas y Naturales Universidad Nacional de Mar del Plata-Consejo Nacional de Investigaciones Científicas y Técnicas Mar del Plata Argentina

Debasis Chakrabarty

Genetics and Molecular Biology Division CSIR - National Botanical Research Institute Lucknow Uttar Pradesh India

Zalán Czékus

Department of Plant Biology University of Szeged Szeged Hungary and Doctoral School in Biology Faculty of Science and Informatics University of Szeged Szeged Hungary

Valeria Dávila

Laboratorio de Zoonosis Parasitarias Facultad de Ciencias Exactas v Naturales Universidad Nacional de Mar del Plata Mar del Plata Argentina

Sarita Devi

Department of Botany and Plant Physiology CCS Haryana Agricultural University Hisar Harvana India

L.V. Dubovskaya

Institute of Biophysics and Cell Engineering of the National Academy of Sciences of Belarus Minsk Belarus

Savita Duhan

Department of Botany and Plant Physiology CCS Haryana Agricultural University Hisar Harvana India

Füsun Eyidoğan

Department of Elementary Education **Baskent University** Ankara Turkey

Shah Fahad

Department of Agriculture The University of Swabi Swabi Khyber Pakhtunkhwa Pakistan

Esmat Farouk Ali

Department of Horticulture (Floriculture)

Faculty of Agriculture Assuit University Assuit Egypt

Chiara Forti

Department of Biology and Biotechnology 'L. Spallanzani' University of Pavia Pavia Italy

Andrea Galatro

Universidad Nacional de La Plata. La Plata Argentina and CONICET-Universidad Nacional de La Instituto de Fisiología Vegetal (INFIVE) La Plata Argentina

Pedro García-Caparrós

Department of Agronomy University of Almeria Agrifood Campus of International Excellence ceiA3 Almería La Cañada de San Urbano Spain

Vandana Gautam

Department of Botanical and **Environmental Sciences** Guru Nanak Dev University Amritsar Puniab India

Jarosław Gocławski

Institute of Applied Computer Science Lodz University of Technology Lodz Poland

Vinod Goyal

Department of Botany and Plant

Physiology

CCS Haryana Agricultural University

Hisar Haryana India

Carla Gualtieri

Department of Biology and Biotechnology 'L. Spallanzani'

University of Pavia

Pavia Italy

Idrees Haider

Department of Soil Science

Faculty of Agricultural Sciences and

Technology

Bahauddin Zakariya University

Multan Punjab Pakistan

Neha Handa

Department of Botanical and **Environmental Sciences** Guru Nanak Dev University

Amritsar Punjab India

Mirza Hasanuzzaman

Department of Agronomy Faculty of Agriculture Sher-e-Bangla Agricultural University Dhaka Bangladesh

Sajjad Hussain

Department of Horticulture

Faculty of Agricultural Sciences and

Technology

Bahauddin Zakariya University

Multan Punjab Pakistan

Muhammad Ilyas

Department of Agronomy

Faculty of Crop Production Sciences University of Agriculture Peshawar

Peshawar

Khyber Pakhtunkhwa

Pakistan

Shivam Jasrotia

Department of Zoology Guru Nanak Dev University

Amritsar Puniab India and

Institute of Food Biotechnology and

Genomics

National Academy of Sciences of Ukraine

Kviv Ukraine

Vinod K. Kannaujiya

Department of Botany

MMV

Banaras Hindu University

Varanasi Uttar Pradesh India

Mahima Karthikeyan

Department of Biotechnology Bharathiar University Coimbatore

Tamil Nadu India

Ravinderjit Kaur

Department of Zoology Guru Nanak Dev University

Amritsar Punjab India and

Institute of Food Biotechnology and

Genomics

National Academy of Sciences of

Ukraine

Kviv Ukraine

Ceyhun Kayıhan

Department of Molecular Biology and Genetics **Baskent University** Ankara Turkey

Anjali Khajuria

Department of Zoology Guru Nanak Dev University Amritsar Punjab India and Institute of Food Biotechnology and Genomics National Academy of Sciences of Ukraine Kviv Ukraine

Kanika Khanna

Department of Botanical and **Environmental Sciences** Guru Nanak Dev University Amritsar Punjab India

Deepak Kumar

Laboratory of Photobiology and Molecular Microbiology Center of Advanced Study in Botany Institute of Science Banaras Hindu University Varanasi Uttar Pradesh India

Vinod Kumar

Department of Botany **DAV University** Jalandhar, Punjab India

Anita Kumari

Department of Botany and Plant Physiology CCS Harvana Agricultural University Hisar Haryana, India

Elżbieta Kuźniak

Department of Plant Physiology and Biochemistry Faculty of Biology and Environmental Protection University of Lodz Lodz Poland

Manohar Lal

Department of Botany and Plant Physiology CCS Haryana Agricultural University Hisar Haryana India

María Teresa Lao

Department of Agronomy University of Almeria Agrifood Campus of International Excellence ceiA3 Almería La Cañada de San Urbano Spain

Anca Macovei

Department of Biology and Biotechnology 'L. Spallanzani' University of Pavia Pavia Italy

Mohamed Magdy F. Mansour

Department of Botany Faculty of Science Ain Shams University Cairo Egypt

Panchanand Mishra

Centre for Education

Central University of Jharkhand

Ranchi Iharkhand India and

Department of Botany Simdega College Simdege

Iharkhand India

Eliana Molina-Moya

Department of Biochemistry and Cellular and Molecular Biology of Plants Estación Experimental del Zaidín

(CSIC) Granada Spain

Renu Munjal

Department of Botany and Plant Physiology

CCS Haryana Agricultural University

Hisar Haryana India

Macarena Nocioni

Instituto de Investigaciones Biológicas Facultad de Ciencias Exactas y Naturales Universidad Nacional de Mar del Plata-Consejo Nacional de Investigaciones Científicas y Técnicas Mar del Plata

Argentina

Puja Ohri

Department of Zoology Guru Nanak Dev University

Amritsar Puniab India

Attila Ördög

Department of Plant Biology University of Szeged

Szeged Hungary

Jainendra Pathak

Laboratory of Photobiology and

Molecular Microbiology

Center of Advanced Study in Botany Institute of Science

Banaras Hindu University Varanasi Uttar Pradesh

India

Andrea Pagano

Department of Biology and Biotechnology 'L. Spallanzani' University of Pavia

Pavia

Italy

Levre Pescador-Azofra

Department of Biochemistry and Cellular and Molecular Biology of Plants Estación Experimental del Zaidín (CSIC)

Granada Spain

Pooja

Department of Botany and Plant Physiology CCS Haryana Agricultural University Hisar Haryana India

Péter Poór

Department of Plant Biology University of Szeged Szeged Hungary

Susana Puntarulo

Facultad de Farmacia y Bioquímica Fisicoquímica Universidad de Buenos Aires **Buenos Aires** Argentina