

Contents

Preface *XI*

List of Contributors *XIII*

1	Nitric Oxide: Chemistry, Biosynthesis, and Physiological Role	1
	<i>Shamsul Hayat, Syed Aiman Hasan, Masaki Mori, Qazi Fariduddin, and Aqil Ahmad</i>	
1.1	Introduction	1
1.2	Nitric Oxide Chemistry	2
1.3	Biosynthesis of Nitric Oxide	3
1.4	Physiological Role of Nitric Oxide	5
1.4.1	Effect of Nitric Oxide on Seed Dormancy	5
1.4.2	Effect of Nitric Oxide on Growth	6
1.4.3	Effect of Nitric Oxide on Senescence	6
1.4.4	Effect of Nitric Oxide on Nitrate Reductase Activity	7
1.4.5	Effect of Nitric Oxide on Respiration	7
1.4.6	Effect of Nitric Oxide on Stomatal Movement	7
1.4.7	Effect of Nitric Oxide on Chlorophyll Content	7
1.4.8	Effect of Nitric Oxide on Photosynthesis	8
1.4.9	Effect of Nitric Oxide on Antioxidant System	8
1.4.10	Effect of Nitric Oxide on Programmed Cell Death	9
1.5	Nitric Oxide and Cross Talk with Classical Plant Hormones	10
1.5.1	Auxins and Nitric Oxide	10
1.5.2	Abscisic Acid and Nitric Oxide	11
1.5.3	Cytokinins, Gibberellins, and Nitric Oxide	11
1.5.4	Ethylene and Nitric Oxide	12
	References	12
2	Electron Paramagnetic Resonance as a Tool to Study Nitric Oxide Generation in Plants	17
	<i>Susana Puntarulo, Sebastián Jasid, Alejandro D. Boveris, and Marcela Simontacchi</i>	
2.1	Introduction	17

2.1.1	Chemistry of Nitrogen-Active Species	17
2.1.2	Biological Effects of NO	18
2.2	Methods of NO Detection	19
2.2.1	Determination of NO by Specific Electrodes	19
2.2.2	Determination of NO by Spectrophotometric and Fluorometric Methods	19
2.2.3	Determination of NO by Electron Paramagnetic Resonance	20
2.2.3.1	Specific Experimental Advances	20
2.3	Use of EPR Methodology for Assaying Enzyme Activities	22
2.3.1	NOS-Like Dependent NO Generation	24
2.3.2	Nitrate Reductase-Dependent NO Generation	24
2.4	Application of EPR Methods to Assess NO Generation During Plant Development	26
2.5	Conclusions	27
	References	27
3	Calcium, NO, and cGMP Signaling in Plant Cell Polarity	31
	<i>Ana Margarida Prado, José A. Feijó, and David Marshall Porterfield</i>	
3.1	Introduction	31
3.2	Cell Polarity and Plant Gametophyte Development	33
3.3	Calcium Signaling in Pollen and Fern Spores	34
3.4	NO/cGMP Signaling in Pollen and Fern Spores	35
3.5	NO/cGMP in Pollen-Pistil Interactions	38
3.6	Ovule Targeting and NO/cGMP	39
3.7	Ca ²⁺ /NO/cGMP Connection?	42
3.8	Closing Perspectives	46
	References	48
4	Nitric Oxide and Abiotic Stress in Higher Plants	51
	<i>Francisco J. Corpas, José M. Palma, Marina Leterrier, Luis A. del Río, and Juan B. Barroso</i>	
4.1	Introduction	51
4.2	Nitric Oxide and Related Molecules	52
4.2.1	Chemistry of Nitric Oxide in Plant Cells	52
4.2.2	Reactive Nitrogen Species	52
4.3	Cellular Targets of NO	54
4.3.1	Nitrosylated Metals	54
4.3.2	Protein S-Nitrosylation	55
4.3.3	Protein Tyrosine Nitration	55
4.3.4	Nitrolipids	55
4.3.5	Nucleic Acid Nitration	56
4.3.6	NO and Gene Regulation	56
4.4	Functions of NO in Plant Abiotic Stress	57
4.4.1	Salinity	57

4.4.2	Ultraviolet Radiation	58
4.4.3	Ozone	58
4.4.4	Mechanical Wounding	59
4.4.5	Toxic Metals (Cadmium and Aluminum)	59
4.5	Concluding Remarks	60
	References	61
5	Polyamines and Cytokinin: Is Nitric Oxide Biosynthesis the Key to Overlapping Functions?	65
	<i>Rinukshi Wimalasekera and Günther F.E. Scherer</i>	
5.1	Introduction	65
5.2	Cytokinin- and Polyamine-Induced NO Biosynthesis	66
5.3	Tissue Distribution of Zeatin-Induced and PA-Induced NO Formation	67
5.4	Nitric Oxide, Cytokinin, and Polyamines in Plant Growth and Development and in Abiotic and Biotic Stresses	68
5.4.1	Embryogenesis	68
5.4.2	Flowering	69
5.4.3	Senescence	69
5.4.4	Programmed Cell Death	69
5.4.5	Abiotic Stresses	70
5.4.6	Biotic Stresses	71
	References	73
6	Role of Nitric Oxide in Programmed Cell Death	77
	<i>Michela Zottini, Alex Costa, Roberto De Michele, and Fiorella Lo Schiavo</i>	
6.1	Programmed Cell Death in Plants	77
6.1.1	PCD Hallmarks and Regulation	78
6.2	NO as a Signaling Molecule	79
6.2.1	NO Is Able to Induce or Inhibit PCD	79
6.2.2	Nitric Oxide and PCD in Hypersensitive Response	80
6.2.3	Signaling Component in SA-Induced NO Production	80
6.3	Role of Mitochondria in NO-Induced PCD	84
6.4	Conclusions	85
	References	85
7	Nitrate Reductase-Deficient Plants: A Model to Study Nitric Oxide Production and Signaling in Plant Defense Response to Pathogen Attack	89
	<i>Ione Salgado, Halley Caixeta de Oliveira, and Marcia Regina Braga</i>	
7.1	Introduction	89
7.2	Physicochemical Basis of NO Signaling	91
7.3	Defense Responses Mediated by NO	92
7.3.1	Accumulation of Defensive Compounds	92

7.3.2	Hypersensitive Response	93
7.3.3	Systemic Responses	94
7.3.4	Stomatal Closure	94
7.4	Substrates for NO Production During Plant-Pathogen Interactions	95
7.4.1	Production of NO from L-Arginine	95
7.4.2	Production of NO from Nitrite	95
7.5	The Role of Nitrate Reductase in NO Production During Plant-Pathogen Interactions	97
	References	98
8	Effective Plant Protection Weapons Against Pathogens Require "NO Bullets"	103
	<i>Luzia V. Modolo</i>	
8.1	Introduction	103
8.2	Nitric Oxide and Reactive Oxygen Species in the Hypersensitive Response	104
8.3	Nitric Oxide and Phytoalexin Production	107
8.4	Nitric Oxide and the Salicylic Acid Signaling Pathway	108
8.5	Nitric Oxide and the Jasmonic Acid Signaling Pathway	109
8.6	Nitric Oxide and Gene Regulation	109
8.7	Nitric Oxide and Protein Regulation	110
8.8	Concluding Remarks	111
	References	111
9	The Role of Nitric Oxide as a Bioactive Signaling Molecule in Plants Under Abiotic Stress	115
	<i>Gang-Ping Hao and Jian-Hua Zhang</i>	
9.1	Introduction	116
9.2	Biosynthesis of Nitric Oxide Under Abiotic Stress	116
9.2.1	NO Generated from NOS-Like Activity Under Abiotic Stress	116
9.2.2	NO Generated from NR Under Abiotic Stress	120
9.3	NO Signaling Functions in Abiotic Stress Responses	121
9.3.1	Function of NO Under Drought Stress	122
9.3.2	Function of NO Under Salt Stress	123
9.3.3	Function of NO Under Ultraviolet Radiation	125
9.3.4	Function of NO Under Heat and Low Temperature	126
9.3.5	Function of NO Under Heavy Metal Stress	126
9.3.6	Function of NO Under Other Abiotic Stresses	127
9.4	NO Signal Transduction in Plants Under Abiotic Stress	128
9.4.1	cGMP-Dependent Signaling	128
9.4.2	Downstream Signaling for NO Action	129
9.5	Interactions of NO Signaling with Other Signaling Molecules in Plant Response to Abiotic Stress	131
	References	135

10	Interplay Between Nitric Oxide and Other Signals Involved in Plant Resistance to Pathogens	139
	<i>Jolanta Floryszak-Wieczorek and Magdalena Arasimowicz-Jelonek</i>	
10.1	Introduction	139
10.2	NO Burst	140
10.3	Cooperation of NO with H ₂ O ₂ in Triggering Programmed Cell Death	142
10.4	Cross Talk of NO with Salicylic Acid, Jasmonic Acid, and Ethylene	145
10.5	The Role of NO in the Micro- and Macroscale of Plant Communication	146
10.5.1	NO Cell Signaling Domain	147
10.5.2	NO in Short-Distance Communication	147
10.5.3	NO from Cross- to Long-Distance Communication	148
10.6	Does NO Participate in Stressful Memory of the Plant?	149
10.7	NO and Plant Recovery from Stress	151
10.8	NO in the Offensive Strategy of the Pathogen	154
10.9	Concluding Remarks	155
	References	155
11	Nitric Oxide Signaling by Plant-Associated Bacteria	161
	<i>Michael F. Cohen, Lorenzo Lamattina, and Hideo Yamasaki</i>	
11.1	Introduction	161
11.2	Production of Nitric Oxide by Bacteria	162
11.2.1	Nitrification	162
11.2.2	Denitrification	163
11.2.3	Nitric Oxide Synthase	164
11.3	Regulatory Roles for Nitric Oxide in Bacteria	164
11.3.1	Metabolic Regulation	164
11.3.2	Regulation of Biofilm Formation	165
11.3.3	Stimulation of Oxidative and Nitrosative Defenses	165
11.4	Bacterial Nitric Oxide in Plant-Bacteria Interactions	166
11.4.1	Production of NO in Response to Plant Products	166
11.4.2	Plant Responses to Bacterial NO: The <i>Azospirillum</i> -Tomato Interaction	166
11.4.3	Perspectives	169
	References	169
12	Nitric Oxide Synthase-Like Protein in Pea (<i>Pisum sativum</i> L.)	173
	<i>Mui-Yun Wong, Jengsheng Huang, Eric L. Davis, Serenella Sukno, and Yee-How Tan</i>	
12.1	Introduction	173
12.2	Physiological and Immunoblot Analyses of NOS-Like Protein of Pea	174
12.3	Isolation and Characterization of an NOS-Like Protein of Pea	177

12.4	Molecular Cloning and Analyses of an NOS-Like Gene of Pea	181
12.5	Correlation Study of NOS-Like Gene Expression and NOS Activity in Compatible and Incompatible Pea-Bacteria Interactions	184
	References	185
13	Posttranslational Modifications of Proteins by Nitric Oxide: A New Tool of Metabolome Regulation	189
	<i>Jasmeet Kaur Abat and Renu Deswal</i>	189
13.1	Introduction	189
13.2	S-Nitrosylation	190
13.2.1	S-Nitrosylation and Ethylene Biosynthesis	191
13.2.2	S-Nitrosylation and Photosynthesis	192
13.2.3	S-Nitrosylation and Glycolysis	194
13.2.4	S-Nitrosylation and Biotic/Abiotic Stresses	195
13.3	Tyrosine Nitration	197
13.4	Binding to Metal Centers	198
13.5	Conclusions and Prospects	198
	References	200
	Index	203