

Edited by Iqbal Ahmad,  
John Pichtel and Shamsul Hayat

WILEY-VCH

# Plant-Bacteria Interactions

Strategies and Techniques to Promote Plant Growth



# Contents

## List of Contributors XIII

1	<b>Ecology, Genetic Diversity and Screening Strategies of Plant Growth Promoting Rhizobacteria (PGPR)</b>	1
	<i>Jorge Barriuso, Beatriz Ramos Solano, José A. Lucas, Agustín Probanza Lobo, Ana García-Villaraco, and F.J. Gutiérrez Mañero</i>	
1.1	Introduction	1
1.1.1	Rhizosphere Microbial Ecology	1
1.1.2	Plant Growth Promoting Rhizobacteria (PGPR)	3
1.2	Rhizosphere Microbial Structure	4
1.2.1	Methods to Study the Microbial Structure in the Rhizosphere	4
1.2.2	Ecology and Biodiversity of PGPR Living in the Rhizosphere	5
1.2.2.1	Diazotrophic PGPR	6
1.2.2.2	<i>Bacillus</i>	6
1.2.2.3	<i>Pseudomonas</i>	6
1.2.2.4	Rhizobia	6
1.3	Microbial Activity and Functional Diversity in the Rhizosphere	7
1.3.1	Methods to Study Activity and Functional Diversity in the Rhizosphere	7
1.3.2	Activity and Effect of PGPR in the Rhizosphere	8
1.4	Screening Strategies of PGPR	9
1.5	Conclusions	13
1.6	Prospects	13
	<i>References</i>	13
2	<b>Physicochemical Approaches to Studying Plant Growth Promoting Rhizobacteria</b>	19
	<i>Alexander A. Kamnev</i>	
2.1	Introduction	19
2.2	Application of Vibrational Spectroscopy to Studying Whole Bacterial Cells	20

2.2.1	Methodological Background	20
2.2.2	Vibrational Spectroscopic Studies of <i>A. brasiliense</i> Cells	20
2.2.2.1	Effects of Heavy Metal Stress on <i>A. brasiliense</i>	
	Metabolism	20
2.2.2.2	Differences in Heavy Metal Induced Metabolic Responses in Epiphytic and Endophytic <i>A. brasiliense</i> Strains	21
2.3	Application of Nuclear $\gamma$ -Resonance Spectroscopy to Studying Whole Bacterial Cells	25
2.3.1	Methodological Background	25
2.3.2	Emission Mössbauer Spectroscopic Studies of Cobalt(II) Binding and Transformations in <i>A. brasiliense</i> Cells	26
2.4	Structural Studies of Glutamine Synthetase (GS) from <i>A. brasiliense</i>	29
2.4.1	General Characterization of the Enzyme	29
2.4.2	Circular Dichroism Spectroscopic Studies of the Enzyme Secondary Structure	30
2.4.2.1	Methodology of Circular Dichroism (CD) Spectroscopic Analysis of Protein Secondary Structure	30
2.4.2.2	The Effect of Divalent Cations on the Secondary Structure of GS from <i>A. brasiliense</i>	31
2.4.3	Emission Mössbauer Spectroscopic Analysis of the Structural Organization of the Cation-Binding Sites in the Enzyme Active Centers	32
2.4.3.1	Methodological Outlines and Prerequisites	32
2.4.3.2	Experimental Studies of <i>A. brasiliense</i> GS	33
2.4.3.3	Conclusions and Outlook	35
2.5	General Conclusions and Future Directions of Research	36
	References	37

<b>3</b>	<b>Physiological and Molecular Mechanisms of Plant Growth Promoting Rhizobacteria (PGPR)</b>	<b>41</b>
	<i>Beatrix Ramos Solano, Jorge Barriuso Maicas, and F.J. Gutiérrez Mañero</i>	
3.1	Introduction	41
3.2	PGPR Grouped According to Action Mechanisms	41
3.2.1	PGPR Using Indirect Mechanisms	42
3.2.1.1	Free Nitrogen-Fixing PGPR	42
3.2.1.2	Siderophore-Producing PGPR	44
3.2.1.3	Phosphate-Solubilizing PGPR	45
3.2.2	PGPR Using Direct Mechanisms	45
3.2.2.1	PGPR that Modify Plant Growth Regulator Levels	46
3.2.2.2	PGPR that Induce Systemic Resistance	50
3.3	Conclusions	51
3.4	Future Prospects	51
	References	52

4	<b>A Review on the Taxonomy and Possible Screening Traits of Plant Growth Promoting Rhizobacteria</b>	55
	<i>M. Rodríguez-Díaz, B. Rodelas, C. Pozo, M.V. Martínez-Toledo, and J. González-López</i>	
4.1	Introduction	55
4.2	Taxonomy of PGPR	56
4.3	Symbiotic Plant Growth Promoting Bacteria	63
4.3.1	LNB	63
4.3.1.1	Alphaproteobacteria	63
4.3.1.2	Betaproteobacteria	67
4.3.2	Bacteria Capable of Fixing Dinitrogen in Symbiosis with Plants Other Than Legumes	67
4.3.2.1	Actinobacteria	68
4.3.2.2	Cyanobacteria	68
4.3.2.3	<i>Gluconacetobacter</i>	69
4.4	Asymbiotic Plant Growth Promoting Bacteria	69
4.4.1	Alphaproteobacteria: Genera <i>Acetobacter</i> , <i>Swaminathania</i> and <i>Azospirillum</i>	69
4.4.1.1	<i>Acetobacter</i> and <i>Swaminathania</i>	69
4.4.1.2	<i>Azospirillum</i>	70
4.4.2	Gammaproteobacteria	70
4.4.2.1	Enterobacteria	70
4.4.2.2	<i>Citrobacter</i>	70
4.4.2.3	<i>Enterobacter</i>	70
4.4.2.4	<i>Erwinia</i>	71
4.4.2.5	The <i>Klebsiella</i> Complex	71
4.4.2.6	<i>Kluyvera</i>	71
4.4.2.7	<i>Pantoea</i>	72
4.4.2.8	<i>Serratia</i>	72
4.4.2.9	<i>Pseudomonas</i>	72
4.4.2.10	<i>Azotobacter</i> ( <i>Azomonas</i> , <i>Beijerinckia</i> and <i>Dexia</i> )	72
4.4.3	Firmicutes. Genera <i>Bacillus</i> and <i>Paenibacillus</i>	73
4.4.3.1	<i>Bacillus</i>	73
4.4.3.2	<i>Paenibacillus</i>	73
4.5	Screening Methods of PGPR	74
4.5.1	Culture-Dependent Screening Methods	74
4.5.2	Culture-Independent Screening Methods	75
4.6	Conclusions and Remarks	75
	References	76
5	<b>Diversity and Potential of Nonsymbiotic Diazotrophic Bacteria in Promoting Plant Growth</b>	81
	<i>Farah Ahmad, Iqbal Ahmad, Farrukh Aqil, M.S. Khan, and S. Hayat</i>	
5.1	Introduction	81
5.2	Rhizosphere and Bacterial Diversity	82

5.2.1	Diazotrophic Bacteria	84
5.2.1.1	Symbiotic Diazotrophic Bacteria	85
5.2.1.2	Asymbiotic Diazotrophic Bacteria	86
5.3	Asymbiotic Nitrogen Fixation and Its Significance to Plant Growth	89
5.4	Plant Growth Promoting Mechanisms of Diazotrophic PGPR	90
5.5	Interaction of Diazotrophic PGPR with Other Microorganisms	93
5.5.1	Interaction of Diazotrophic PGPR with Rhizobia	93
5.5.2	Interaction of Diazotrophic PGPR with Arbuscular Mycorrhizae	96
5.6	Other Dimensions of Plant Growth Promoting Activities	97
5.6.1	ACC Deaminase Activity	97
5.6.2	Induced Systemic Resistance (ISR)	98
5.6.3	Improved Stress Tolerance	98
5.6.4	Quorum Sensing	99
5.7	Critical Gaps in PGPR Research and Future Directions	100
	References	102

<b>6</b>	<b>Molecular Mechanisms Underpinning Colonization of a Plant by Plant Growth Promoting Rhizobacteria</b>	<b>111</b>
	<i>Christina D. Moon, Stephen R. Giddens, Xue-Xian Zhang, and Robert W. Jackson</i>	
6.1	Introduction	111
6.2	Identification of Plant-Induced Genes of SBW25 Using IVET	113
6.3	Regulatory Networks Controlling Plant-Induced Genes	119
6.4	Spatial and Temporal Patterns of Plant-Induced Gene Expression	123
6.5	Concluding Remarks and Future Perspectives	126
	References	126
<b>7</b>	<b>Quorum Sensing in Bacteria: Potential in Plant Health Protection</b>	<b>129</b>
	<i>Iqbal Ahmad, Farrukh Aqil, Farah Ahmad, Maryam Zahin, and Javed Musarrat</i>	
7.1	Introduction	129
7.2	AcyL-HSL-Based Regulatory System: The Lux System	130
7.3	QS and Bacterial Traits Underregulation	132
7.4	QS in Certain Phytopathogenic Bacteria	137
7.4.1	<i>E. carotovora</i>	137
7.4.2	<i>R. solanacearum</i>	138
7.4.3	<i>Xanthomonas campestris</i>	138
7.4.4	Other Bacteria	139
7.5	Quorum-Sensing Signal Molecules in Gram-Negative Bacteria	139
7.5.1	Bioassays for the Detection of Signal Molecules	141
7.5.2	Chemical Characterization of Signal Molecules	142
7.6	Interfering Quorum Sensing: A Novel Mechanism for Plant Health Protection	144

7.7	Conclusion	147
	References	148
<b>8</b>	<b><i>Pseudomonas aurantiaca</i> SR1: Plant Growth Promoting Traits, Secondary Metabolites and Crop Inoculation Response</b>	<b>155</b>
	<i>Marisa Rovera, Evelin Carlier, Carolina Pasluosta, Germán Avanzini, Javier Andrés, and Susana Rosas</i>	
8.1	Plant Growth Promoting Rhizobacteria: General Considerations	155
8.2	Secondary Metabolites Produced by <i>Pseudomonas</i>	156
8.3	Coinoculation Greenhouse Assays in Alfalfa ( <i>Medicago sativa</i> L.)	157
8.4	Field Experiments with <i>P. aurantiaca</i> SR1 in Wheat ( <i>Triticum aestivum</i> L.)	158
8.5	Conclusions	161
	References	161
<b>9</b>	<b>Rice–Rhizobia Association: Evolution of an Alternate Niche of Beneficial Plant–Bacteria Association</b>	<b>165</b>
	<i>Ravi P.N. Mishra, Ramesh K. Singh, Hemant K. Jaiswal, Manoj K. Singh, Youssef G. Yanni, and Frank B. Dazzo</i>	
9.1	Introduction	165
9.2	Landmark Discovery of the Natural Rhizobia–Rice Association	166
9.3	Confirmation of Natural Endophytic Association of Rhizobia with Rice	168
9.4	Association of Rhizobia with Other Cereals Like Wheat, Sorghum, Maize and Canola	170
9.5	Mechanism of Interaction of Rhizobia with Rice Plants	171
9.5.1	Mode of Entry and Site of Endophytic Colonization in Rice	171
9.5.2	Systemic Movement of Rhizobial Endophytes from Rice Root to Leaf Tip	176
9.5.3	Genetic Predisposition of Rice–Rhizobia Association	176
9.6	Importance of Endophytic Rhizobia–Rice Association in Agroecosystems	177
9.6.1	Plant Growth Promotion by <i>Rhizobium</i> Endophytes	177
9.6.2	Extensions of Rhizobial Endophyte Effects	180
9.6.2.1	Use of Rhizobial Endophytes from Rice with Certain Maize Genotypes	180
9.6.2.2	Rhizobia–Rice Associations in Different Rice Varieties	180
9.7	Mechanisms of Plant Growth Promotion by Endophytic Rhizobia	182
9.7.1	Stimulation of Root Growth and Nutrient Uptake Efficiency	182
9.7.2	Secretion of Plant Growth Regulators	185
9.7.3	Solubilization of Precipitated Phosphate Complexes by Rhizobial Endophytes	185
9.7.4	Endophytic Nitrogen Fixation	186
9.7.5	Production of Fe-Chelating Siderophores	187
9.7.6	Induction of Systemic Disease Resistance	188

9.8	Summary and Conclusion	188
	References	190
<b>10</b>	<b>Principles, Applications and Future Aspects of Cold-Adapted PGPR</b>	<b>195</b>
	<i>Mahejibin Khan and Reeta Goel</i>	
10.1	Introduction	195
10.2	Cold Adaptation of PGPR Strains	196
10.2.1	Cytoplasmic Membrane Adaptation	197
10.2.2	Carbon Metabolism and Electron Flow	198
10.2.3	Expression of Antifreeze Proteins	199
10.3	Mechanism of Plant Growth Promotion at Low Temperature	201
10.3.1	Phytostimulation	201
10.3.2	Frost Injury Protection	202
10.4	Challenges in Selection and Characterization of PGPR	202
10.5	Challenges in Field Application of PGPRs	202
10.6	Applications of PGPRs	203
10.6.1	Applications of PGPR in Agriculture	203
10.6.2	Application of PGPR in Forestry	204
10.6.3	Environmental Remediation and Heavy Metal Detoxification	207
10.7	Prospects	208
	References	209
<b>11</b>	<b>Rhamnolipid-Producing PGPR and Their Role in Damping-Off Disease Suppression</b>	<b>213</b>
	<i>Alok Sharma</i>	
11.1	Introduction	213
11.2	Biocontrol	214
11.2.1	Antibiotic-Mediated Suppression	214
11.2.2	HCN Production	216
11.2.3	Induced Systemic Resistance	216
11.3	Damping-Off	217
11.3.1	Causal Organisms	217
11.3.2	Control	218
11.4	Rhamnolipids	219
11.4.1	Biosynthesis of Rhamnolipids	222
11.4.2	Genetics of Rhamnolipid Synthesis	222
11.4.3	Regulation	223
11.4.4	Rhamnolipid-Mediated Biocontrol	224
11.4.5	Other Agricultural Applications	226
11.5	Quorum Sensing in the Rhizosphere	226
11.5.1	The Dominant System (las)	226
11.5.2	The rhl System	226
11.6	Conclusions and Future Directions	228
	References	228

12	<b>Practical Applications of Rhizospheric Bacteria in Biodegradation of Polymers from Plastic Wastes</b>	235
	<i>Ravindra Soni, Sarita Kumari, Mohd G.H. Zaidi, Yogesh S. Shouche, and Reeta Goel</i>	
12.1	Introduction	235
12.2	Materials and Methods	236
12.2.1	Chemicals and Media	236
12.2.2	LDPE-g-PMMA	236
12.2.3	LDPE-g-PMH	236
12.2.4	Isolation of Bacteria	236
12.2.5	Screening of Bacterial Isolates to Grow in the Presence of Polymer	237
12.2.6	Optimization of Growth Conditions	237
12.2.7	Biodegradation Studies	237
12.3	Results and Discussion	237
12.3.1	Growth in the Presence of Polymer	238
12.3.2	Biodegradation Studies	238
12.3.2.1	<i>B. cereus</i>	238
12.3.2.2	<i>Bacillus</i> sp.	238
12.3.2.3	<i>B. pumilus</i>	239
12.3.2.4	Bacterial Consortium and LDPE	240
12.3.2.5	FTIR Spectroscopy	241
12.4	Conclusions	242
	References	243
13	<b>Microbial Dynamics in the Mycorrhizosphere with Special Reference to Arbuscular Mycorrhizae</b>	245
	<i>Abdul G. Khan</i>	
13.1	The Soil and the Rhizosphere	245
13.2	Rhizosphere and Microorganisms	245
13.2.1	Glomalian Fungi	245
13.2.2	Arbuscular Mycorrhiza–Rhizobacteria Interactions	247
13.2.3	Plant Growth Promoting Rhizobacteria	249
13.2.4	Co-occurrence of AMF and PGPR/MHB	250
13.3	Conclusion	252
	References	252
14	<b>Salt-Tolerant Rhizobacteria: Plant Growth Promoting Traits and Physiological Characterization Within Ecologically Stressed Environments</b>	257
	<i>Dilfuza Egamberdiyeva and Khandakar R. Islam</i>	
14.1	Introduction	257
14.2	Diversity of Salt-Tolerant Rhizobacteria	259
14.3	Colonization and Survival of Salt-Tolerant Rhizobacteria	261
14.4	Salt and Temperature Tolerance	263

14.5	Physiological Characterization of Rhizobacteria	264
14.6	Plant Growth Stimulation in Arid Soils	268
14.7	Biomechanisms to Enhance Plant Growth	273
14.8	Conclusions	275
14.9	Future Directions	276
	References	276
<b>15</b>	<b>The Use of Rhizospheric Bacteria to Enhance Metal Ion Uptake by Water Hyacinth, <i>Eichhornia crassipe</i> (Mart)</b>	<b>283</b>
	<i>Lai M. So, Alex T. Chow, Kin H. Wong, and Po K. Wong</i>	
15.1	Introduction	283
15.2	Overview of Metal Ion Pollution	284
15.3	Treatment of Metal Ions in Wastewater	285
15.3.1	Conventional Methods	285
15.3.2	Microbial Methods	285
15.3.3	Phytoremediation	286
15.3.3.1	An Overview of Phytoremediation	286
15.3.3.2	Using Water Hyacinth for Wastewater Treatment	287
15.4	Biology of Water Hyacinth	290
15.4.1	Scientific Classification	290
15.4.2	Morphology	291
15.4.3	Ecology	292
15.4.4	Environmental Impact	293
15.4.5	Management of Water Hyacinth	293
15.5	Microbial Enhancement of Metal Ion Removal Capacity of Water Hyacinth	294
15.5.1	Biology of the Rhizosphere	294
15.5.2	Mechanisms of Metal Ion Removal by Plant Roots	295
15.5.3	Effects of Rhizospheric Bacteria on Metal Uptake and Plant Growth	296
15.6	Summary	298
	References	299