BRIEF CONTENTS

COMPARTMENTS

- Membrane Structure and Membranous
 Organelles 2
- 2 The Cell Wall 45
- 3 Membrane Transport 111
- 4 Protein Sorting and Vesicle Traffic 151
- 5 The Cytoskeleton 191

CELL REPRODUCTION

- 6 Nucleic Acids 240
- 7 Amino Acids 289
- 8 Lipids 337
- 9 Genome Structure and Organization 401
- 10 Protein Synthesis, Folding, and Degradation 438
- 11 Cell Division 476

ENERGY FLOW

12	Photosynthesis 508
13	Carbohydrate Metabolism 567
14	Respiration and Photorespiration 610

METABOLIC AND DEVELOPMENTAL INTEGRATION

- 15 Long-Distance Transport 658
 16 Nitrogen and Sulfur 711
 17 Biosynthesis of Hormones 769
 18 Signal Transduction 834
 19 Molecular Regulation of Reproductive Development 872
- 20 Senescence and Cell Death 925
 - PLANT ENVIRONMENT AND AGRICULTURE
- 21 Responses to Plant Pathogens 984
- 22 Responses to Abiotic Stress 1051
- 23 Mineral Nutrient Acquisition, Transport,and Utilization 1101
- 24 Natural Products 1132

z The Cell Wa

abroduction 4

CONTENTS

The Editors xi List of Contributors xii Preface xv About the Companion Website xvi

COMPARTMENTS

1 Membrane Structure and Membranous Organelles 2

Introduction 2

- **1.1** Common properties and inheritance of cell membranes 2
- **1.2** The fluid-mosaic membrane model 4
- 1.3 Plasma membrane 10
- 1.4 Endoplasmic reticulum 13
- 1.5 Golgi apparatus 18
- 1.6 Exocytosis and endocytosis 23
- 1.7 Vacuoles 27
- 1.8 The nucleus 28
- 1.9 Peroxisomes 31
- 1.10 Plastids 32
- 1.11 Mitochondria 39

Summary 44

2 The Cell Wall 45

Introduction 45

- 2.1 Sugars are building blocks of the cell wall 45
- 2.2 Macromolecules of the cell wall 51
- 2.3 Cell wall architecture 73
- 2.4 Cell wall biosynthesis and assembly 80
- 2.5 Growth and cell walls 90
- 2.6 Cell differentiation 99
- 2.7 Cell walls as sources of food, feed, fiber, and fuel, and their genetic improvement 108

Summary 110

3 Membrane Transport III

Introduction 111

- 3.1 Overview of plant membrane transport systems 111
- 3.2 Pumps 120
- 3.3 Ion channels 128
- 3.4 Cotransporters 142

3.5 Water transport through aquaporins 146 Summary 148

4 Protein Sorting and Vesicle Traffic 151

Introduction 151

- 4.1 The cellular machinery of protein sorting 151
- **4.2** Targeting proteins to the plastids 153
- 4.3 Targeting proteins to mitochondria 157
- 4.4 Targeting proteins to peroxisomes 159
- 4.5 Transport in and out of the nucleus 160
- **4.6** ER is the secretory pathway port of entry and a protein nursery 161
- **4.7** Protein traffic and sorting in the secretory pathway: the ER 175
- **4.8** Protein traffic and sorting in the secretory pathway: the Golgi apparatus and beyond 182

4.9 Endocytosis and endosomal compartments 188 Summary 189

5 The Cytoskeleton 191

Introduction 191

- 5.1 Introduction to the cytoskeleton 191
- 5.2 Actin and tubulin gene families 194
- 5.3 Characteristics of actin filaments and microtubules 196
- 5.4 Cytoskeletal accessory proteins 202
- 5.5 Observing the cytoskeleton: Statics and dynamics 207
- **5.6** Role of actin filaments in directed intracellular movement 210
- 5.7 Cortical microtubules and expansion 216
- 5.8 The cytoskeleton and signal transduction 219
- 5.9 Mitosis and cytokinesis 222
- Summary 238

CELL REPRODUCTION

6 Nucleic Acids 240

Introduction 240

- Composition of nucleic acids and synthesis 6.1 of nucleotides 240
- Replication of nuclear DNA 245 6.2
- DNA repair 250 6.3
- DNA recombination 255 6.4
- Organellar DNA 260 6.5
- DNA transcription 268 6.6
- Characteristics and functions of RNA 270 6.7

6.8 RNA processing 278

Summary 288

7 Amino Acids 289

Introduction 289

- Amino acid biosynthesis in plants: research 7.1 and prospects 289
- 7.2 Assimilation of inorganic nitrogen into N-transport amino acids 292
- 7.3 Aromatic amino acids 302
- Aspartate-derived amino acids 318 7.4
- Branched-chain amino acids 326 7.5
- Glutamate-derived amino acids 330 7.6

7.7 Histidine 333

Summary 336

8 Lipids 337

Introduction 337

- 8.1 Structure and function of lipids 337
- 8.2 Fatty acid biosynthesis 344
- 8.3 Acetyl-CoA carboxylase 348
- 8.4 Fatty acid synthase 350
- 8.5 Desaturation and elongation of C₁₆ and C₁₀ fatty acids 352
- 8.6 Synthesis of unusual fatty acids 360
- 8.7 Synthesis of membrane lipids 365
- 8.8 Function of membrane lipids 373 8.9 Synthesis and function of extracellular
- lipids 382
- 8.10 Synthesis and catabolism of storage lipids 389
- 8.11 Genetic engineering of lipids 395
- Summary 400

9 Genome Structure and Organization 401

Introduction 401

- 9.1 Genome structure: a 21st-century perspective 401
- 9.2 Genome organization 404
- 9.3 Transposable elements 416
- 9.4 Gene expression 422
- 9.5 Chromatin and the epigenetic regulation of gene expression 430

Summary 436

10 Protein Synthesis, Folding, and **Degradation** 438

Introduction 438

- **10.1** Organellar compartmentalization of protein synthesis 438
- 10.2 From RNA to protein 439
- Mechanisms of plant viral translation 447 10.3
- 10.4 Protein synthesis in plastids 450
- 10.5 Post-translational modification of proteins 457
- 10.6 Protein degradation 463

Summary 475

11 Cell Division 476

Introduction 476

- Animal and plant cell cycles 476 11.1
- 11.2 Historical perspective on cell cycle research 477
- Mechanisms of cell cycle control 482 11.3
- The cell cycle in action 488 11.4

11.5 Cell cycle control during development 497 Summary 506



12 Photosynthesis 508

Introduction 508

- Overview of photosynthesis 508 12.1
- Light absorption and energy conversion 511 12.2
- 12.3 Photosystem structure and function 519
- Electron transport pathways in chloroplast 12.4 membranes 529
- 12.5 ATP synthesis in chloroplasts 537
- Organization and regulation of photosynthetic 12.6 complexes 540
- Carbon reactions: the Calvin–Benson cycle 542 12.7

12.8 Rubisco 548

12.9 Regulation of the Calvin–Benson cycle by light 551 **12.10** Variations in mechanisms of CO_2 fixation 557 Summary 565

13 Carbohydrate Metabolism 567

Introduction 567

- 13.1 The concept of metabolite pools 570
- **13.2** The hexose phosphate pool: a major crossroads in plant metabolism 571
- 13.3 Sucrose biosynthesis 573
- 13.4 Sucrose metabolism 577
- 13.5 Starch biosynthesis 580
- **13.6** Partitioning of photoassimilates between sucrose and starch 587
- 13.7 Starch degradation 593
- **13.8** The pentose phosphate/triose phosphate pool 597
- 13.9 Energy and reducing power for biosynthesis 601
- 13.10 Sugar-regulated gene expression 606

Summary 608

14 Respiration and Photorespiration 610

Introduction 610

- 14.1 Overview of respiration 610
- 14.2 Citric acid cycle 613
- 14.3 Plant mitochondrial electron transport 620
- **14.4** Plant mitochondrial ATP synthesis 632
- 14.5 Regulation of the citric acid cycle and the cytochrome pathway 634
- **14.6** Integration of the cytochrome pathway and nonphosphorylating pathways 635
- 14.7 Interactions between mitochondria and other cellular compartments 639
- 14.8 Biochemical basis of photorespiration 646
- 14.9 The photorespiratory pathway 648
- **14.10** Role of photorespiration in plants 652 Summary 655



METABOLIC AND DEVELOPMENTAL INTEGRATION

15 Long-Distance Transport 658

Introduction 658

15.1 Selection pressures and long-distance transport systems 658

- 15.2 Cell biology of transport modules 664
- **15.3** Short-distance transport events between xylem and nonvascular cells 668
- **15.4** Short-distance transport events between phloem and nonvascular cells 673
- 15.5 Whole-plant organization of xylem transport 691
- 15.6 Whole-plant organization of phloem transport 696
- **15.7** Communication and regulation controlling phloem transport events 705

Summary 710

16 Nitrogen and Sulfur 711

Introduction 711

- **16.1** Overview of nitrogen in the biosphere and in plants 711
- 16.2 Overview of biological nitrogen fixation 715
- **16.3** Enzymology of nitrogen fixation 715
- 16.4 Symbiotic nitrogen fixation 718
- 16.5 Ammonia uptake and transport 735
- 16.6 Nitrate uptake and transport 735
- 16.7 Nitrate reduction 739
- 16.8 Nitrite reduction 744
- **16.9** Nitrate signaling 745
- 16.10 Interaction between nitrate assimilation and carbon metabolism 745
- 16.11 Overview of sulfur in the biosphere and plants 746
- 16.12 Sulfur chemistry and function 747
- 16.13 Sulfate uptake and transport 750
- 16.14 The reductive sulfate assimilation pathway 752
- 16.15 Cysteine synthesis 755
- **16.16** Synthesis and function of glutathione and its derivatives 758
- 16.17 Sulfated compounds 763
- 16.18 Regulation of sulfate assimilation and interaction with nitrogen and carbon metabolism 764

Summary 767

17 Biosynthesis of Hormones 769

Intro	duction 769	
17.1	Gibberellins 769	
17.2	Abscisic acid 777	
17.3	Cytokinins 785	
17.4	Auxins 795	
17.5	Ethylene 806	
17.6	Brassinosteroids 810	
17.7	Polyamines 818	
17.8	Jasmonic acid 821	

17.9 Salicylic acid 826

vii

17.10 Strigolactones 830 Summary 833

18 Signal Transduction 834

Introduction 834

- **18.1** Characteristics of signal perception, transduction, and integration in plants 834
- 18.2 Overview of signal perception at the plasma membrane 838
- 18.3 Intracellular signal transduction, amplification, and integration via second messengers and MAPK cascades 843
- 18.4 Ethylene signal transduction 847
- **18.5** Cytokinin signal transduction 850
- **18.6** Integration of auxin signaling and transport 852
- **18.7** Signal transduction from phytochromes 857
- 18.8 Gibberellin signal transduction and its integration with phytochrome signaling during seedling development 861
- **18.9** Integration of light, ABA, and CO₂ signals in the regulation of stomatal aperture 866
- 18.10 Prospects 870

Summary 870

19 Molecular Regulation of Reproductive Development 872

Introduction 872

- **19.1** The transition from vegetative to reproductive development 872
- 19.2 The molecular basis of flower development 881
- 19.3 The formation of male gametes 889
- 19.4 The formation of female gametes 897
- **19.5** Pollination and fertilization 902
- 19.6 The molecular basis of self-incompatibility 908

19.7 Seed development 913

Summary 923

20 Senescence and Cell Death 925

Introduction 925

- 20.1 Types of cell death 925
- 20.2 PCD during seed development and germination 930
- **20.3** Cell death during the development of secretory bodies, defensive structures and organ shapes 932
- 20.4 PCD during reproductive development 937
- **20.5** Senescence and PCD in the terminal development of leaves and other lateral organs 940
- 20.6 Pigment metabolism in senescence 948

- **20.7** Macromolecule breakdown and salvage of nutrients in senescence 951
- **20.8** Energy and oxidative metabolism during senescence 957
- **20.9** Environmental influences on senescence and cell death I: Abiotic interactions 961
- **20.10** Environmental influences on senescence and cell death II: PCD responses to pathogen attack 964
- **20.11** Plant hormones in senescence and defense-related PCD 974

Summary 982



21 Responses to Plant Pathogens 984

Introduction 984

- 21.1 Pathogens, pests, and disease 984
- 21.2 An overview of immunity and defense 985
- **21.3** How pathogens and pests cause disease 989
- 21.4 Preformed defenses 1009
- **21.5** Induced defense 1012
- **21.6** Effector-triggered immunity, a second level of induced defense 1022
- **21.7** Other sources of genetic variation for resistance 1032
- 21.8 Local and systemic defense signaling 1033
- **21.9** Plant gene silencing confers virus resistance, tolerance, and attenuation 1042
- **21.10** Control of plant pathogens by genetic engineering 1044

Summary 1050

22 Responses to Abiotic Stress 1051

Introduction 1051

- 22.1 Plant responses to abiotic stress 1051
- **22.2** Physiological and cellular responses to water deficit 1054
- **22.3** Gene expression and signal transduction in response to dehydration 1061
- 22.4 Freezing and chilling stress 1068
- 22.5 Flooding and oxygen deficit 1076
- 22.6 Oxidative stress 1085
- 22.7 Heat stress 1094
- **22.8** Crosstalk in stress responses 1097 Summary 1099

23 Mineral Nutrient Acquisition, Transport, and Utilization 1101

Introduction 1101

- 23.1 Overview of essential mineral elements 1102
- 23.2 Mechanisms and regulation of plant K⁺ transport 1103
- 23.3 Phosphorus nutrition and transport 1113
- **23.4** The molecular physiology of micronutrient acquisition 1118
- **23.5** Plant responses to mineral toxicity 1127

Summary 1131

24 Natural Products 1132

Introduction 1132

- 24.1 Terpenoids 1133
- 24.2 Biosynthesis of the basic five-carbon unit 1135
- 24.3 Repetitive additions of C_5 units 1138
- 24.4 Formation of parent carbon skeletons 1141
- 24.5 Modification of terpenoid skeletons 1143

- **24.6** Metabolic engineering of terpenoid production 1145
- 24.7 Cyanogenic glycosides 1146
- **24.8** Cyanogenic glycoside biosynthesis 1152
- 24.9 Functions of cyanogenic glycosides 1157
- 24.10 Glucosinolates 1158
- 24.11 Alkaloids 1159
- 24.12 Alkaloid biosynthesis 1164
- **24.13** Biotechnological application of alkaloid biosynthesis research 1171
- 24.14 Phenolic compounds 1178
- 24.15 Phenolic biosynthesis 1185
- 24.16 The phenylpropanoid-acetate pathway 1188
- 24.17 The phenylpropanoid pathway 1195

24.18 Universal features of phenolic biosynthesis 1202

24.19 Evolution of secondary pathways 1205

Summary 1206

Further reading 1207 *Index* 1222

18.9 Integration of lightr Adjammer 100 Jargunds maller and the set of the second stormatal apertifice describer startif.
18.10 Prospects 870 447 noticuber startif.
18.10 Prospects 870 547 gailangia startif.
20.10 Molecular Regulation of maiodation of maiodation of the second startific sta