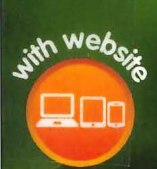
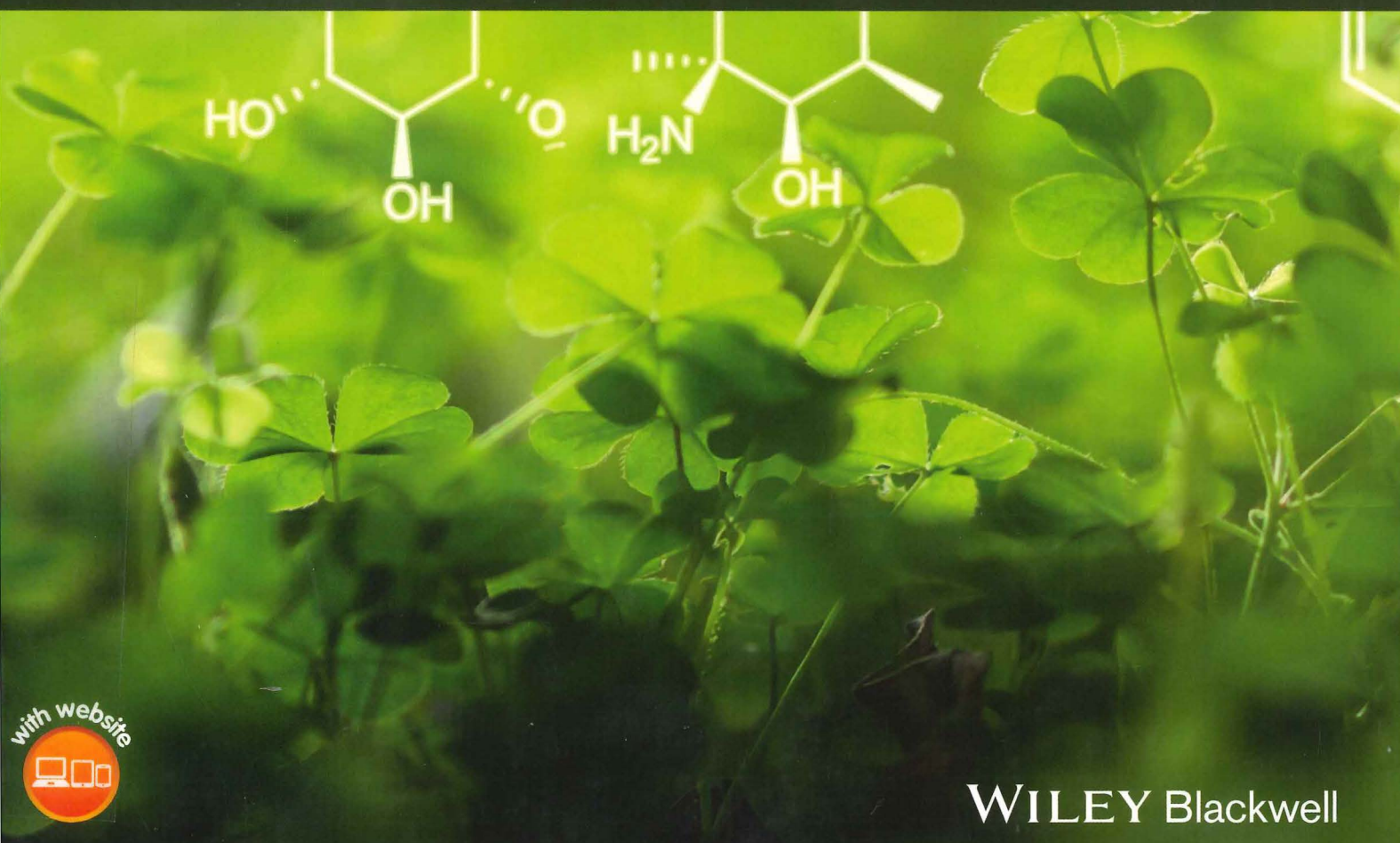




GEORGE ACQUAAH

PRINCIPLES OF PLANT GENETICS AND BREEDING

THIRD EDITION



WILEY Blackwell

Principles of Plant Genetics and Breeding

b16623629
012555162
122610030

Third Edition

George Acquaah

Bowie State University, Room 315 C, Computer Science Building, Bowie, MD, US,



WILEY Blackwell

Contents

Preface xxi

Acknowledgments xxiii

Industry highlights boxes xxv

Industry highlights boxes: Authors xxvii

Section 1 Overview and historical perspectives 1

1 Introduction 3

- 1.1 What is plant breeding? 3
- 1.2 The goals of plant breeding 4
- 1.3 The concept of genetic manipulation of plant attributes 4
- 1.4 Why breed plants? 4
- 1.5 Overview of the basic steps in plant breeding 6
- 1.6 How have plant breeding objectives changed over the years? 7
- 1.7 The art and science of plant breeding 8
- 1.8 Training of plant breeders 10
- 1.9 The plant breeding industry 11
- 1.10 Duration and cost of plant breeding programs 19
- 1.11 The future of plant breeding in society 20
- 1.12 The organization of the book 21

2 History of plant breeding 23

- 2.1 Origins of agriculture and plant breeding 23
- 2.2 The “unknown breeder” 24
- 2.3 Plant manipulation efforts by the early civilizations 24
- 2.4 Early pioneers of the theories and practices of modern plant breeding 24
- 2.5 Later pioneers and trailblazers 26
- 2.6 History of plant breeding technologies/techniques 28
- 2.7 Genome-wide approaches to crop improvement 30
- 2.8 Bioinformatics and OMICs technologies in crop improvement 30
- 2.9 Summary of changes in plant breeding over the last half century 31
- 2.10 Achievements of modern plant breeders 32

Section 2 Population and quantitative genetic principles 35

3 Introduction to concepts of population genetics 37

- 3.1 Concepts of a population and gene pool 37
- 3.2 Issues arising from Hardy-Weinberg equilibrium 40
- 3.3 Factors affecting changes in gene frequency 41
- 3.4 Frequency dependent selection 41
- 3.5 Summary of key plant breeding applications 42
- 3.6 Modes of selection 42
- 3.7 Effect of mating system on selection 43
- 3.8 Concept of inbreeding 44
- 3.9 Inbreeding and its implications in plant breeding 44
- 3.10 Concept of population improvement 46
- 3.11 Types 46

- 4 Introduction to quantitative genetics 49
 - 4.1 What is quantitative genetics? 49
 - 4.2 Quantitative traits 50
 - 4.3 The genetic architecture of quantitative traits 68
 - 4.4 Systems genetics 69
 - 4.5 Predicting breeding value 70
 - 4.6 Genomic selection (genome-wide selection) 70
 - 4.7 Mapping quantitative traits 70
- Section 3 Reproductive systems 73
- 5 Introduction to reproduction 75
 - 5.1 Importance of mode of reproduction to plant breeding 75
 - 5.2 Overview of reproductive options in plants 76
 - 5.3 Types of reproduction 76
 - 5.4 Sexual reproduction 76
 - 5.5 What is autogamy? 80
 - 5.6 Genotype conversion programs 91
 - 5.7 Artificial pollination control techniques 91
 - 5.8 What is allogamy? 91
 - 5.9 Mendelian concepts relating to the reproductive system 93
 - 5.10 Complex inheritance 95
- 6 Hybridization 99
 - 6.1 Concept of gene transfer and hybridization 99
 - 6.2 Applications of crossing in plant breeding 100
 - 6.3 Artificial hybridization 100
 - 6.4 Artificial pollination control techniques 101
 - 6.5 Flower and flowering issues in hybridization 101
 - 6.6 Emasculation 102
 - 6.7 Pollination 103
 - 6.8 Number of F_1 crosses to make 103
 - 6.9 Genetic issues in hybridization 104
 - 6.10 Types of populations generated through hybridization 105
 - 6.11 Wide crosses 107
 - 6.12 Issue of reproductive isolation barriers 116
 - 6.13 Overcoming challenges of reproductive barriers 116
 - 6.14 Bridge crosses 118
- 7 Clonal propagation and *in vitro* culture 121
 - 7.1 What is a clone? 121
 - 7.2 Clones, inbred lines, and pure lines 121
 - 7.3 Categories of clonally propagated species based on economic use 122
 - 7.4 Categories of clonally propagated species for breeding purposes 122
 - 7.5 Types of clonal propagation 122
 - 7.6 Importance of clonal propagation in plant breeding 123
 - 7.7 Breeding implications of clonal propagation 123
 - 7.8 Genetic Issues in Clonal Breeding 124
 - 7.9 Breeding approaches used in clonal species 124
 - 7.10 Natural propagation 126
 - 7.11 *In vitro* culture 126
 - 7.12 Micropropagation 126
 - 7.13 Concept of totipotency 138
 - 7.14 Somaclonal variation 138
 - 7.15 Apomixis 139

- 7.16 Other tissue culture applications 141
 - 7.17 Production of haploids 142
 - 7.18 Germplasm preservation 144
- Section 4 Germplasm for breeding 147
- 8 Variation: types, origin, and scale 149
 - 8.1 Classifying plants 149
 - 8.2 Rules of classification of plants 150
 - 8.3 Operational classification systems 151
 - 8.4 Types of variation among plants 154
 - 8.5 Origins of genetic variability 155
 - 8.6 Biotechnology for creating genetic variability 157
 - 8.7 Scale of variability 158
 - 9 Plant domestication 161
 - 9.1 The concept of evolution 161
 - 9.2 What is domestication? 162
 - 9.3 Evolution versus domestication 162
 - 9.4 Conscious selection versus unconscious selection 163
 - 9.5 Patterns of plant domestication 163
 - 9.6 Centers of plant domestication 163
 - 9.7 Roll call of domesticated plants 165
 - 9.8 Changes accompanying domestication 165
 - 9.9 Genetic bottleneck 166
 - 9.10 Tempo of domestication 170
 - 9.11 Genetic architecture and domestication 171
 - 9.12 Models of domestication 171
 - 9.13 Modern breeding is a continuation of the domestication process 171
 - 10 Plant genetic resources 175
 - 10.1 Importance of germplasm to plant breeding 175
 - 10.2 Centers of diversity in plant breeding 176
 - 10.3 Sources of germplasm for plant breeding 176
 - 10.4 Concept of genetic vulnerability 178
 - 10.5 What plant breeders can do to address crop vulnerability 179
 - 10.6 Wild (exotic) germplasm in plant breeding 179
 - 10.7 Plant genetic resources conservation 180
 - 10.8 Nature of cultivated plant genetic resources 182
 - 10.9 Approaches to germplasm conservation 182
 - 10.10 Germplasm collection 196
 - 10.11 Types of plant germplasm collections 196
 - 10.12 Managing plant genetic resources 197
 - 10.13 Issue of redundancy and the concept of core subsets 198
 - 10.14 Germplasm storage technologies 198
 - 10.15 Using genetic resources 199
 - 10.16 Plant explorations and introductions and their impact on agriculture 200
 - 10.17 International conservation efforts 201
 - 10.18 An example of a national germplasm conservation system 201
 - 10.19 Who owns biodiversity? 202
 - 10.20 Understanding the genetic architecture of germplasm for crop improvement 205
- Section 5 Breeding objectives 209
- 11 Yield and morphological traits 211
 - 11.1 Physiological traits 211

- 11.2 What is yield? 212
- 11.3 Biological versus economic yield 212
- 11.4 The ideotype concept 213
- 11.5 Improving the efficiency of dry matter partitioning 222
- 11.6 Harvest index as a selection criterion for yield 223
- 11.7 Selecting for yield *per se* 223
- 11.8 Biological pathway to economic yield 223
- 11.9 The concept of yield potential 224
- 11.10 The concept of yield plateau 224
- 11.11 Yield stability 224
- 11.12 Lodging resistance 225
- 11.13 Shattering resistance 225
- 11.14 Reduced plant height 226
- 11.15 Breeding determinacy 227
- 11.16 Photoperiod response 227
- 11.17 Early maturity 228

- 12 Quality traits 231
 - 12.1 Concept of quality 231
 - 12.2 Nutritional quality of food crops 231
 - 12.3 Brief history of breeding for improved nutritional quality of crops 232
 - 12.4 Breeding for improved protein content 236
 - 12.5 Improving protein content by genetic engineering 236
 - 12.6 Breeding improved oil quality 238
 - 12.7 Breeding low phytate cultivar 239
 - 12.8 Breeding end-use quality 239
 - 12.9 Breeding seedlessness 240
 - 12.10 Breeding for industrial uses 241
 - 12.11 Breeding plants for novel traits 242
 - 12.12 Breeding for enhanced bioavailable micronutrients 242

- 13 Environmental stress factors and plant breeding 245
 - 13.1 Environmental stress factors in crop production 245
 - 13.2 Climate change and plant breeding 246
 - 13.3 Crop production environment and stress 247
 - 13.4 Abiotic environmental stress factors 248
 - 13.5 Biotic environmental stress factors 248
 - 13.6 Effects of combined stresses 249
 - 13.7 Impact of environmental stress factors in crop production 250

- 14 Breeding for resistance to diseases and insect pests 253
 - 14.1 Selected definitions 253
 - 14.2 Groups of pathogens and pests targeted by plant breeders 254
 - 14.3 Biological and economic effects of plant pathogens and pests 254
 - 14.4 Overview of the methods of control of plant pathogens and pests 255
 - 14.5 Concepts of resistance in breeding 255
 - 14.6 Concepts of pathogen and host 255
 - 14.7 Mechanisms of defense in plants against pathogens and pests 257
 - 14.8 Types of genetic host resistance and their breeding approaches 259
 - 14.9 Resistance breeding strategies 266
 - 14.10 Challenges of breeding for pest resistance 267
 - 14.11 Role of wild germplasm in disease and pest resistance breeding 268
 - 14.12 Screening techniques in disease and pest resistance breeding 268

- 14.13 Applications of biotechnology in pest resistance breeding 268
- 14.14 Epidemics and plant breeding 270

- 15 Breeding for resistance to abiotic stresses 273
 - 15.1 Importance of breeding for resistance to abiotic stresses 273
 - 15.2 Resistance to abiotic stress and yield potential 274
 - 15.3 Types of abiotic environmental stresses 274
 - 15.4 Tolerance to stress or resistance to stress? 280
 - 15.5 Screening for stress resistance 281
 - 15.6 Drought stress 281
 - 15.7 Breeding drought resistance 282
 - 15.8 Approaches for breeding drought resistance 285
 - 15.9 Cold stress 285
 - 15.10 Mechanisms of resistance to low temperature 286
 - 15.11 Selection for low-temperature tolerance 287
 - 15.12 Breeding for tolerance to low-temperature stress 287
 - 15.13 Salinity stress 287
 - 15.14 Heat stress 288
 - 15.15 Mineral toxicity stress 289
 - 15.16 Mineral deficiency stress 290
 - 15.17 Oxidative stress 290
 - 15.18 Flood stress (waterlogging) 291

- Section 6 Selection methods 295
- 16 Breeding self-pollinated species 297
 - 16.1 Types of cultivars 297
 - 16.2 Genetic structure of cultivars and its implications 298
 - 16.3 Types of self-pollinated cultivars 299
 - 16.4 Common plant breeding notations 299
 - 16.5 Mass selection 300
 - 16.6 Pure-line selection 308
 - 16.7 Pedigree selection 310
 - 16.8 Bulk population breeding 314
 - 16.9 Single-seed descent 317
 - 16.10 Backcross breeding 318
 - 16.11 Special backcross procedures 322
 - 16.12 Multiline breeding and cultivar blends 323
 - 16.13 Composites 324
 - 16.14 Recurrent selection 325

- 17 Breeding cross-pollinated species 329
 - 17.1 The concept of population improvement 329
 - 17.2 Concept of recurrent selection 330
 - 17.3 Genetic basis of recurrent selection 331
 - 17.4 Types of recurrent selection 331
 - 17.5 Intrapopulation improvement methods 331
 - 17.6 Optimizing gain from selection in population improvement 339
 - 17.7 Development of synthetic cultivars 339
 - 17.8 Backcross breeding 343

- 18 Breeding hybrid cultivars 345
 - 18.1 What is a hybrid cultivar? 345
 - 18.2 Brief historical perspective 345

- 18.3 The concepts of hybrid vigor and inbreeding depression 346
 - 18.4 Genetic basis of heterosis 347
 - 18.5 Biometrics of heterosis 348
 - 18.6 Concept of heterotic relationship 349
 - 18.7 Types of hybrids 351
 - 18.8 Germplasm procurement and development for hybrid production 351
 - 18.9 Selection of parents (inbred lines) 353
 - 18.10 Field establishment 354
 - 18.11 Maintenance 354
 - 18.12 Harvesting and processing 355
 - 18.13 Hybrid seed production of maize 355
 - 18.14 Hybrids in horticulture 356
 - 18.15 Exploiting hybrid vigor in asexually reproducing species 356
 - 18.16 Prerequisites for successful commercial hybrid seed production 356
- 19 Breeding clonally propagated species 359
- 19.1 Clones, inbred lines, and pure lines 359
 - 19.2 Categories of clonally propagated species for breeding purposes 360
 - 19.3 Breeding implications of clonal propagation 360
 - 19.4 Genetic issues in clonal breeding 360
 - 19.5 Breeding approaches used in clonal crops 361
 - 19.6 Advantages and limitations of clonal propagation 371
 - 19.7 Breeding apomictic cultivars 372
 - 19.8 *In vitro* selection 372
- Section 7 Technologies for linking genes to traits 375
- 20 Molecular markers 377
- 20.1 The concept of genetic markers 377
 - 20.2 Use of genetic markers in plant breeding 378
 - 20.3 Concept of polymorphism and the origin of molecular markers 378
 - 20.4 Brief history of molecular markers 379
 - 20.5 Classification of molecular markers 380
 - 20.6 Enzyme-based markers 380
 - 20.7 Hybridization-based markers 381
 - 20.8 PCR-based markers 382
 - 20.9 PCR-based markers from RFLPs 390
 - 20.10 DNA sequence-based markers 390
 - 20.11 Comparison of selected molecular markers 391
 - 20.12 Desirable properties of a molecular marker system 391
 - 20.13 Ready-made markers for marker assisted selection 391
- 21 Mapping of genes 395
- 21.1 Why map genes? 395
 - 21.2 Types of gene maps 395
 - 21.3 Principles of linkage mapping 396
 - 21.4 Mapping populations 396
 - 21.5 Identification of polymorphic markers 398
 - 21.6 Linkage analysis of markers 398
 - 21.7 Rendering linkage maps 398
 - 21.8 Mapping quantitative trait loci (QTL) 399
 - 21.9 High-resolution QTL mapping 403
 - 21.10 Bulk segregant analysis (BSA) 404
 - 21.11 The value of multiple parent populations in mapping 404
 - 21.12 Creating MAGIC and NAM populations for QTL mapping 405

- 21.13 Comparative genome mapping 406
- 21.14 Synteny 406

- 22 DNA sequencing and OMICs technologies 409
 - 22.1 What is DNA sequencing? 409
 - 22.2 Types of sequencing technologies 410
 - 22.3 Next-generation sequencing (NGS) workflow 410
 - 22.4 Genotyping by sequencing 412
 - 22.5 What are the “OMICs” technologies in plant breeding? 414
 - 22.6 Genomics 415
 - 22.7 Transcriptomics 416
 - 22.8 Proteomics 417
 - 22.9 Metabolomics 418
 - 22.10 Phenomics 433

- Section 8 Applications of genetic markers in breeding 437
- 23 Marker-assisted selection 439
 - 23.1 The concept of molecular breeding 439
 - 23.2 Choosing molecular markers for MAS 440
 - 23.3 Advantages of MAS over conventional breeding protocols 440
 - 23.4 The MAS schemes 440
 - 23.5 Limitations of MAS 446
 - 23.6 Enhancing the potential of MAS in breeding 447

- 24 Genomic selection and genome-wide association studies 451
 - 24.1 Making the case for genomic selection 451
 - 24.2 What is genomic selection? 452
 - 24.3 Genome-wide association studies 453
 - 24.4 MAS, MABC, and GS compared 454
 - 24.5 Haplotypes 454
 - 24.6 Linkage disequilibrium mapping (association mapping) 460

- Section 9 Mutations and ploidy in plant breeding 465
- 25 Mutagenesis in plant breeding 467
 - 25.1 Brief historical perspectives 467
 - 25.2 Types of mutations 468
 - 25.3 Mutagenic agents 471
 - 25.4 Types of tissues used for mutagenesis 472
 - 25.5 Factors affecting the success of mutagenesis 472
 - 25.6 Mutation breeding of seed-bearing plants 472
 - 25.7 Mutation breeding of clonally propagated species 474
 - 25.8 Mutations from tissue culture systems 475
 - 25.9 Using induced mutants 475
 - 25.10 Limitations of mutagenesis as a plant breeding technique 475
 - 25.11 Selected significant successes of mutation breeding 475
 - 25.12 Molecular techniques for enhancing efficiency of induced mutagenesis 476
 - 25.13 Horticultural applications of mutagenesis 478
 - 25.14 General effects of mutagenesis 478
 - 25.15 Key successes of induced mutagenesis 479

- 26 Ploidy in plant breeding 481
 - 26.1 Terminology 481
 - 26.2 Variations in chromosome number 482
 - 26.3 General effects of polyploidy of plants 482

- 26.4 Origin of polyploids 483
 - 26.5 Autoploidy 484
 - 26.6 Breeding autoploids 487
 - 26.7 Natural allopolyploids 487
 - 26.8 Aneuploidy 489
 - 26.9 General importance of polyploidy in plant improvement 491
 - 26.10 Inducing polyploids 492
 - 26.11 Use of $2n$ gametes for introgression breeding 492
 - 26.12 Haploidy 492
 - 26.13 Anther culture 500
 - 26.14 Doubled haploids 501
- Section 10 Genetic molecular modifications in plant breeding 509
- 27 Breeding genetically modified crops 511
 - 27.1 What is biotechnology? 511
 - 27.2 Antisense technology 512
 - 27.3 Restriction enzymes 513
 - 27.4 Vectors 513
 - 27.5 Categories of vectors by functions 514
 - 27.6 Cloning 515
 - 27.7 Breeding genetically modified (GM) cultivars 515
 - 27.8 Engineering pest resistance 517
 - 27.9 Trends in adoption of GM cultivars 519
 - 28 Genome editing and other modification technologies 521
 - 28.1 General steps in genome editing 521
 - 28.2 Types of editing systems 522
 - 28.3 Zinc finger nucleases (ZFNs) 523
 - 28.4 Transcription activator-like effector nucleases (TALENs) 524
 - 28.5 Clustered regularly interspaced short palindromic repeats (CRISPR-Cas9) 524
 - 28.6 Comparison of gene editing systems 525
 - 28.7 RNA interference (RNAi) 526
 - 28.8 Oligonucleotide-directed mutagenesis 527
 - 29 Paradigm shifts in plant breeding and other non-GM technologies 531
 - 29.1 The way breeders manipulate the plant genome 531
 - 29.2 Paradigm shifts in plant breeding 532
 - 29.3 Cisgenesis 533
 - 29.4 Intragenesis 534
 - 29.5 Reverse breeding 534
 - 29.6 Grafting non-GM scion on GM rootstock 535
 - 29.7 Agroinfiltration 535
 - 29.8 Epigenetics 536
 - 29.9 RNA-directed DNA methylation 537
 - 29.10 DNA barcoding 538
 - 29.11 Techniques for shortening the plant generation cycle for faster breeding 539
- Section 11 Computer-aided applications in plant breeding 543
- 30 Bioinformatics, big data analytics, and computer simulations in plant breeding 545
 - 30.1 What is bioinformatics? 545
 - 30.2 Subdivisions of bioinformatics 546
 - 30.3 Workflow for bioinformatics projects 546
 - 30.4 General goals of bioinformatics 546
 - 30.5 Data for bioinformatics 547

- 30.6 Data sources and how they are utilized in bioinformatics 547
 - 30.7 Types of bioinformatics databases 547
 - 30.8 Data management and integration 548
 - 30.9 Data mining 549
 - 30.10 Applications of bioinformatics in plant breeding 549
 - 30.11 What is big data? 570
 - 30.12 Big data workflow in plant breeding 570
 - 30.13 Plant breeding applications 570
 - 30.14 What is a computer simulation or model? 572
 - 30.15 Applications of computer simulation in plant breeding 573
 - 30.16 Ideotype breeding 573
 - 30.17 Simulation models in plant breeding 574
- Section 12 Variety release process in plant breeding 577
- 31 Performance evaluation for crop cultivar release 579
 - 31.1 Purpose of performance trials 579
 - 31.2 Kinds of field trials 579
 - 31.3 Designing field trials 581
 - 31.4 The role of the environment in field trials 581
 - 31.5 Genotype \times environment interaction (GEI) 582
 - 31.6 Models of G \times E interaction 584
 - 31.7 Measurement of GEI using ANOVA 585
 - 31.8 Importance and Applications of GEI in Plant Breeding 586
 - 31.9 Stability analysis models 587
 - 31.10 Adaptation 590
 - 31.11 Field plot technique in plant breeding 591
 - 31.12 Field plot designs 592
 - 31.13 Materials, equipment, and machinery for field evaluation of genotypes 594
 - 32 Seed certification and commercial seed release 597
 - 32.1 The role of improved seed in agriculture 597
 - 32.2 Role of the private sector in the seed industry 598
 - 32.3 General steps of operation of the seed industry 599
 - 32.4 The cultivar release process 600
 - 32.5 Multiplication of pedigree seed 600
 - 32.6 Concept of seed certification 601
 - 32.7 The seed certification process 602
 - 32.8 Seed testing 602
 - 32.9 Tagging commercial seed 603
 - 32.10 International role in seed certification 604
 - 32.11 Production of conventional seed 610
 - 32.12 Production of hybrid seed 611
 - 32.13 Crop registration 611
 - 32.14 Variety protection 612
 - 33 Regulatory and Legal Issues 615
 - 33.1 The concept of intellectual property 615
 - 33.2 Patents 616
 - 33.3 Patents in plant breeding and biotechnology: unique issues and challenges 618
 - 33.4 Protecting plant varieties 620
 - 33.5 The concept of substantial equivalence in regulation of biotechnology 622
 - 33.6 The issue of "novel traits" 623
 - 33.7 The concept of the precautionary principle 623
 - 33.8 Regulation and the issue of public trust 624

- 33.9 Biosafety regulation at the international level 624
 - 33.10 Labeling of biotechnology products 625
 - 33.11 Economic impact of labeling and regulations 626
 - 33.12 Legal risks that accompany adoption of GM crops 626
 - 33.13 Overview of the regulation of the biotechnology industry in the US 627
 - 33.14 The concept of biopiracy 628
 - 33.15 The impact of IPRs on plant breeding 629
- Section 13 Societal issues in plant breeding 633
- 34 Value-driven concepts and social concerns 635
 - 34.1 Concepts of ethics, morals, and values 635
 - 34.2 Evolution of social debates on science-based issues 636
 - 34.3 Ethics in plant breeding 636
 - 34.4 Risk analysis of biotechnology 637
 - 34.5 Genetic use restriction technologies 637
 - 34.6 Public perceptions and fears about biotechnology 639
 - 34.7 Some concerns of plant breeders 641
 - 34.8 GM foods and the issue of food allergy 641
 - 34.9 The concept of organic plant breeding 642
 - 34.10 Principles of organic plant breeding 642
 - 34.11 Acceptable organic plant breeding techniques 643
 - 34.12 Making agricultural biotechnology more acceptable to society 643
 - 34.13 The “halo effect” of GM crops in the field 643
 - 34.14 The rise of minor pests in GM fields 643
 - 34.15 Who owns biodiversity? 644
 - 35 International plant breeding efforts 647
 - 35.1 International crop research centers 647
 - 35.2 The CGIAR centers and their mission 649
 - 35.3 Brief overview of plant breeding in developed countries 651
 - 35.4 Plant breeding efforts in Sub-Saharan Africa 651
 - 35.5 Biotechnology efforts in developing countries 652
 - 35.6 Participatory plant breeding (PPB) 654
 - 35.7 Conventional plant breeding versus decentralized-participatory plant breeding 659
 - 35.8 The Green Revolution 660
 - 35.9 The Green Revolution and the impact of international breeding efforts 664
- Section 14 Breeding selected crops 667
- 36 Breeding wheat 669
 - 36.1 Economic importance 669
 - 36.2 Origin and history 669
 - 36.3 Adaptation 670
 - 36.4 History of breeding in the US 670
 - 36.5 Commercial wheat classes 670
 - 36.6 Germplasm resources 671
 - 36.7 Cytogenetics 671
 - 36.8 Genetics 671
 - 36.9 General botany 672
 - 36.10 Reproductive biology 672
 - 36.11 Common breeding methods 673
 - 36.12 Establishing a breeding nursery 673
 - 36.13 Artificial pollination for hybridization 674
 - 36.14 Natural pollination 674

- 36.15 Seed development 674
- 36.16 Breeding objectives 674
- 37 Breeding corn 679
 - 37.1 Economic importance 679
 - 37.2 Origin and general history 679
 - 37.3 Adaptation 679
 - 37.4 History of corn breeding in the United States 680
 - 37.5 Types of corn 685
 - 37.6 Germplasm resources 686
 - 37.7 Cytogenetics 686
 - 37.8 Genetics 686
 - 37.9 General botany 687
 - 37.10 Reproductive biology 688
 - 37.11 Genetic consequences of reproductive biology 688
 - 37.12 Common breeding approaches 688
 - 37.13 Establishing a breeding nursery 689
 - 37.14 Other nurseries 689
 - 37.15 Special environment 689
 - 37.16 Artificial pollination for hybridization 689
 - 37.17 Natural pollination for hybridization 690
 - 37.18 Common breeding objectives 690
- 38 Breeding rice 695
 - 38.1 Economic importance 695
 - 38.2 Origin and history 695
 - 38.3 Adaptation 696
 - 38.4 Commercial classes 696
 - 38.5 Germplasm resources 697
 - 38.6 Cytogenetics 702
 - 38.7 Genetics 702
 - 38.8 General botany 703
 - 38.9 Reproductive biology 703
 - 38.10 Common breeding methods 703
 - 38.11 Establishing a breeding nursery 703
 - 38.12 Common breeding objectives 704
- 39 Breeding sorghum 707
 - 39.1 Economic importance 707
 - 39.2 Origin 707
 - 39.3 History of breeding in the US 707
 - 39.4 Genetic resources 708
 - 39.5 Cytogenetics 708
 - 39.6 Genetics 708
 - 39.7 General botany 708
 - 39.8 Sorghum races 709
 - 39.9 Grain sorghum groups 709
 - 39.10 Reproductive biology 709
 - 39.11 Pollination 709
 - 39.12 Common breeding methods 709
 - 39.13 Establishing a breeding nursery 714
 - 39.14 Artificial pollination 714
 - 39.15 Natural pollination 715

- 39.16 Seed development 715
- 39.17 Harvesting 715
- 39.18 Common breeding objectives 715

- 40 Breeding soybean 719
 - 40.1 Economic importance 719
 - 40.2 History and origin 719
 - 40.3 History of breeding 720
 - 40.4 Genetic resources 720
 - 40.5 Cytogenetics 720
 - 40.6 Genetics 720
 - 40.7 General botany 720
 - 40.8 Cultivars 720
 - 40.9 Reproductive biology 721
 - 40.10 Common breeding methods 721
 - 40.11 Establishing a field nursery 721
 - 40.12 Artificial hybridization 721
 - 40.13 Natural hybridization 722
 - 40.14 Seed development 722
 - 40.15 Harvesting 722
 - 40.16 Breeding objectives 722

- 41 Breeding peanut 729
 - 41.1 Economic importance 729
 - 41.2 Origin and history 729
 - 41.3 Market types 729
 - 41.4 Genetic resources 730
 - 41.5 Cytogenetics 730
 - 41.6 General botany 730
 - 41.7 Reproductive biology 730
 - 41.8 Common breeding methods 731
 - 41.9 Establishing a breeding nursery 731
 - 41.10 Artificial pollination 731
 - 41.11 Common breeding objectives 731

- 42 Breeding potato 737
 - 42.1 Economic importance 737
 - 42.2 Origin and history 737
 - 42.3 Adaptation 738
 - 42.4 Genetic resources 738
 - 42.5 Cytogenetics 738
 - 42.6 Genetics 738
 - 42.7 General botany 738
 - 42.8 Cultivars 738
 - 42.9 Reproductive biology 739
 - 42.10 Common breeding methods 739
 - 42.11 Establishing a breeding nursery 743
 - 42.12 Artificial pollination for hybridization 744
 - 42.13 Natural pollination 744
 - 42.14 Seed development 744
 - 42.15 Breeding objectives 744

- 43 Breeding cotton 747
 - 43.1 Economic importance 747
 - 43.2 Origin and history 747
 - 43.3 Germplasm resources 748
 - 43.4 Cytogenetics 748
 - 43.5 Genetics 748
 - 43.6 Cultivars 748
 - 43.7 American upland cotton 749
 - 43.8 General botany 749
 - 43.9 Reproductive biology 753
 - 43.10 Common breeding methods 753
 - 43.11 Establishing a breeding nursery 753
 - 43.12 Artificial crossing 753
 - 43.13 Natural pollination 754
 - 43.14 Seed development 754
 - 43.15 Breeding objectives 754

- 44 Breeding tomato 757
 - 44.1 Economic importance 757
 - 44.2 Origin and history 757
 - 44.3 Commercial market classes 757
 - 44.4 Tomato types 758
 - 44.5 Germplasm 758
 - 44.6 Cytogenetics 758
 - 44.7 Genetics 758
 - 44.8 General botany 759
 - 44.9 Brief history of tomato breeding 759
 - 44.10 Breeding objectives 759
 - 44.11 Common breeding methods 764

- Supplementary 1: Plant cellular organization and genetic structure: an overview 767
- Supplementary 2: Common statistical methods in plant breeding 781
- Glossary of terms 803
- Index 807