

# Contents

**Foreword — V**

**Preface — VII**

**Book overview — XXXIX**

**About the author — XLIII**

## **Chapter 1**

### **Embarking on crop nutrition journey — 1**

- 1.1 Introduction — 1
- 1.2 Soil fertility and soil productivity — 5
  - 1.2.1 Relationship between soil fertility and soil productivity — 5
- 1.3 Crop nutrition — 7
  - 1.3.1 Ingestion (nutrient uptake) — 8
  - 1.3.2 Digestion (nutrient conversion and mobilization) — 9
  - 1.3.3 Assimilation (incorporation into plant biomass) — 9
- 1.4 The role of crop nutrition in modern agriculture — 10
- 1.5 Key concerns with chemical fertilizers — 12
- 1.6 The role of crop nutrition in sustainable agriculture — 13
- 1.7 Sustainable nutrient management practices — 16
  - 1.7.1 Precision agriculture techniques — 16
  - 1.7.2 Improved fertilizer application methods — 17
  - 1.7.3 The 4Rs of nutrient management — 17
  - 1.7.4 Nutrient management plans — 19
- 1.8 Relationship of crop nutrition management with UN SDGs — 20
  - 1.8.1 SDG 2: Zero Hunger — 21
  - 1.8.2 SDG 3: Good Health and Well-being — 21
  - 1.8.3 SDG 6: Clean Water and Sanitation — 21
  - 1.8.4 SDG 12: Responsible Consumption and Production — 21
  - 1.8.5 SDG 13: Climate Action — 22
  - 1.8.6 SDG 15: Life on Land — 22
- 1.9 Climate change — 22
  - 1.9.1 Crop nutrient requirements in changing climates — 23
  - 1.9.2 Strategies for improvement in crop nutrition in changing climates — 23
- 1.10 Food security — 25
  - 1.10.1 The role of crop nutrition in food security — 26
- 1.11 The role of crop nutrition in plants biofortification — 27
- 1.12 General overview of global soils — 28
  - 1.12.1 Pakistani soils — 29

- 1.13 Best management practices for crop nutrition — 31
  - 1.13.1 Soil fertility and health improvement — 31
  - 1.13.2 Soil conservation and sustainability — 32
  - 1.13.3 Nutrient-use efficiency — 32
  - 1.13.4 Reduced cost of production — 32
  - 1.13.5 Crop growth and development — 33
  - 1.13.6 Increase yield per unit area — 33
  - 1.13.7 Reduce food security risks — 33
  - 1.13.8 Combat climate change — 33
  - 1.13.9 Overall sustainability in agriculture — 33
- 1.14 Conclusion — 35
- 1.15 Key messages — 36
- References — 36

**Chapter 2**

**Essentials of crop nutrition and plant nutrient categorization — 39**

- 2.1 Introduction — 39
- 2.2 Crop nutrition — 40
- 2.3 Principles of crop nutrition — 41
- 2.4 Law of diminishing returns — 42
- 2.5 Crop nutrition and law of diminishing returns — 43
- 2.6 Nutrient interactions — 44
- 2.7 Nutrient ratios — 45
- 2.8 Criteria of essentiality of plant nutrients — 46
  - 2.8.1 Additional considerations for essential nutrients — 47
- 2.9 Essential nutrients for plants — 47
- 2.10 The macro- and micronutrients for plant growth and development — 51
  - 2.10.1 Macronutrients for plants — 53
  - 2.10.2 Micronutrients for plants — 53
  - 2.10.3 Key differences in macro- and micronutrients — 53
- 2.11 Beneficial nutrients for plants — 55
- 2.12 The chemical nature of essential elements — 55
- 2.13 Chemical properties of essential elements — 58
- 2.14 Sources of essential elements — 60
- 2.15 Theories of nutrient uptake — 63
- 2.16 Nutrient mobility — 65
  - 2.16.1 Nutrient mobility in soil — 65
  - 2.16.2 Nutrient uptake and mobility in plants — 65
  - 2.16.3 Nutrient deficiency and mobility — 66
- 2.17 Essential elements availability in the form of cations and anions — 67
  - 2.17.1 Cations (positively charged ions) — 67

2.17.2	Anions (negatively charged ions) —	67
2.17.3	Charge on soil —	68
2.17.4	Charge on plant roots —	69
2.18	Root-soil interaction —	70
2.19	Factors influencing nutrient uptake —	71
2.19.1	External factors —	72
2.19.2	Internal factors —	82
2.20	The role of enzymes in crop nutrition —	84
2.21	Nutrients concentration in soils and plants —	88
2.22	Nutrients availability and uptake —	90
2.23	Nutrients uptake (kg/ton) —	92
2.24	Nutrients loss from soil —	93
2.25	Fertilizers (NPK) recommendations —	95
2.26	Deficiency symptoms of essential elements —	96
2.27	Fertilizers as plant food —	100
2.28	Fertilizers reaction in soils —	101
2.29	Conclusion —	105
2.30	Key messages —	106
	References —	106

### Chapter 3

#### The vital role of nitrogen — 108

3.1	Introduction —	108
3.2	Importance of nitrogen —	109
3.3	Nitrogen fixation —	111
3.4	Nitrogen uptake and assimilation —	112
3.5	Factors influencing nitrogen availability —	113
3.5.1	Nitrogen inputs —	114
3.5.2	Soil properties —	114
3.5.3	Environmental factors —	114
3.5.4	Management practices —	115
3.6	Importance of nitrogen for plant health —	115
3.7	Physiological functions of nitrogen in crop plants —	116
3.8	Nitrogen deficiency symptoms in plants —	117
3.9	Nitrogen toxicity in plants —	118
3.9.1	Ammonium toxicity —	119
3.9.2	Nitrate toxicity —	119
3.10	Nitrogenous fertilizers —	120
3.11	Global status of soil nitrogen —	122
3.12	Pakistan's status of soil nitrogen —	124
3.13	Nitrogen requirements for major crops in Pakistan —	125
3.14	Environmental concerns associated with N fertilizers —	126

3.14.1	Water pollution —	127
3.14.2	Eutrophication —	127
3.14.3	Air pollution —	127
3.14.4	Climate change —	128
3.14.5	Soil degradation —	128
3.15	Management strategies to address environmental problems —	129
3.16	Nitrogen cycle —	130
3.17	Sustainable nitrogen management —	131
3.17.1	Improving soil health —	131
3.17.2	Better crop growth and development —	131
3.17.3	Higher crop productivity and profitability —	131
3.17.4	Food security and nutrition —	132
3.17.5	Better environmental health —	132
3.17.6	Alignment with UN SDGs —	132
3.17.7	Strategies for sustainable nitrogen management —	132
3.18	Conclusion —	133
3.19	Key messages —	134
	References —	134

## **Chapter 4**

### **Harnessing phosphorus for plant growth — 137**

4.1	Introduction —	137
4.2	Importance of phosphorus —	138
4.3	The role of phosphorus in plant growth and development —	140
4.4	Physiological functions of phosphorus in plants —	142
4.5	Deficiency symptoms of phosphorus in plants —	143
4.6	Key aspects of phosphorus toxicity in plants —	144
4.7	Management strategies to mitigate phosphorus toxicity problems —	146
4.8	Phosphatic fertilizers —	147
4.9	Phosphorus management in field crop production —	148
4.10	Global status of soil phosphorus —	149
4.11	Pakistan status of soil phosphorus —	150
4.12	Phosphorus management for major crops of Pakistan —	151
4.13	Phosphorus and environmental problems —	152
4.14	Management strategies to address environmental problems —	154
4.15	Phosphorus cycle —	155
4.16	Sustainable phosphorus management —	157
4.16.1	Improving soil health —	157
4.16.2	Better crop growth and development —	158
4.16.3	Higher crop productivity and profitability —	158
4.16.4	Food security and nutrition —	158

4.16.5	Better environmental health —	158
4.16.6	Alignment with UN SDGs —	159
4.17	Strategies for sustainable phosphorus management —	159
4.18	Conclusion —	161
4.19	Key messages —	161
	References —	162

## Chapter 5

### Unlocking potassium's potential — 164

5.1	Introduction —	164
5.2	Importance of potassium —	165
5.3	Potassium importance for crop growth and development —	167
5.4	Physiological functions of potassium in plants —	169
5.5	Symptoms and methods for diagnosing potassium deficiency in crop plants —	170
5.6	Diagnosing potassium deficiency —	171
5.7	Potassium toxicity in soils and plants —	172
5.8	Strategies to mitigate potassium toxicity problems —	173
5.9	Potassium fertilizer sources —	175
5.10	Strategies for effective potassium management —	176
5.11	Global status of soil potassium —	178
5.11.1	Challenges and opportunities —	179
5.12	Pakistan's status of soil potassium —	180
5.12.1	General soil characteristics —	180
5.12.2	Potassium levels in Pakistani soils —	180
5.12.3	Contributing factors to potassium deficiency —	181
5.12.4	Strategies for improving potassium management —	181
5.12.5	Potassium management for major crops —	182
5.13	Environmental issues with potassium fertilizers —	183
5.14	Strategies to mitigate K environmental impacts —	185
5.15	Management strategies for potassium fertilizers —	185
5.16	Potassium cycle —	188
5.17	Sustainable potassium management —	188
5.17.1	Improving soil health —	188
5.17.2	Better crop growth and development —	189
5.17.3	Higher crop productivity and profitability —	189
5.17.4	Food security and nutrition —	189
5.17.5	Better environmental health —	190
5.17.6	Alignment with UN SDGs —	190
5.18	Strategies for sustainable potassium management —	190
5.19	Conclusion —	192

5.20            Key messages — **192**  
                  References — **193**

**Chapter 6**

**Secondary nutrients at a glance (calcium, magnesium, and sulfur) — 195**

6.1            Introduction — **195**  
6.2            Importance of calcium (Ca), magnesium (Mg), and sulfur (S) — **196**  
6.2.1        Importance of secondary nutrients in crop production — **197**  
6.3            Potential toxicity issues associated with these nutrients — **200**  
6.4            Suggestions to overcome the toxicity issues associated with calcium  
                  (Ca), magnesium (Mg), and sulfur (S) — **200**  
6.5            Calcium (Ca) fertilizers — **201**  
6.6            Magnesium (Mg) fertilizers — **202**  
6.7            Sulfur (S) fertilizers — **203**  
6.8            Calcium (Ca), magnesium (Mg), and sulfur (S) fertilizer  
                  management — **204**  
6.8.1        Calcium (Ca) — **205**  
6.8.2        Magnesium (Mg) — **205**  
6.8.3        Sulfur (S) — **206**  
6.9            Improving yield and nutrition with calcium (Ca), magnesium (Mg),  
                  and sulfur (S) — **206**  
6.10          Global status of soil calcium, magnesium, and sulfur — **207**  
6.10.1       Global status of calcium (Ca) — **207**  
6.10.2       Global status of magnesium (Mg) — **207**  
6.10.3       Global status of sulfur (S) — **207**  
6.10.4       Regional variations and trends — **208**  
6.11          Pakistan’s status of soil calcium, magnesium, and sulfur — **208**  
6.11.1       Calcium (Ca) in Pakistan’s soils — **209**  
6.11.2       Magnesium (Mg) in Pakistan’s soils — **209**  
6.11.3       Sulfur (S) in Pakistan’s soils — **209**  
6.11.4       Addressing magnesium and sulfur deficiencies in Pakistan — **209**  
6.12          Management of major crops in Pakistan — **210**  
6.12.1       Wheat — **210**  
6.12.2       Rice — **210**  
6.12.3       Maize — **211**  
6.12.4       Cotton — **211**  
6.12.5       Sugarcane — **211**  
6.13          Uptake of calcium (Ca), magnesium (Mg), and sulfur (S) by crops — **212**  
6.13.1       Calcium uptake — **212**  
6.13.2       Magnesium uptake — **212**  
6.13.3       Sulfur uptake — **213**  
6.14          Implications for secondary nutrient management — **214**

6.14.1	Enhancing soil fertility and structure —	214
6.14.2	Balancing nutrient ratios —	214
6.14.3	Supporting crop protein and oil content —	214
6.14.4	Precision agriculture and targeted applications —	215
6.14.5	Environmental sustainability —	215
6.15	Recommendations for secondary nutrient fertilizers —	215
6.15.1	Balanced fertilization —	216
6.15.2	Organic amendments —	216
6.15.3	Foliar applications —	217
6.16	Detailed fertilizer recommendations for secondary nutrient management —	217
6.16.1	Tailored nutrient management —	217
6.16.2	Integration of organic and inorganic sources —	217
6.16.3	Monitoring and adjustment —	218
6.17	Importance of calcium (Ca) in acidic soils —	219
6.17.1	Soil pH regulation —	219
6.17.2	Nutrient availability —	219
6.17.3	Soil structure and root development —	219
6.17.4	For acidic soils (low pH) —	219
6.18	Importance of sulfur (S) in alkaline soils —	220
6.18.1	Regulation of soil pH —	220
6.18.2	Nutrient availability —	220
6.18.3	Crop health and yield —	220
6.18.4	For alkaline soils (high pH) —	220
6.19	Environmental concerns associated with secondary nutrients —	221
6.19.1	Calcium —	221
6.19.2	Magnesium —	221
6.19.3	Sulfur —	221
6.20	Management strategies to address the environmental problems associated with secondary nutrients —	222
6.20.1	Nutrient management planning —	222
6.20.2	Precision agriculture techniques —	222
6.20.3	Balanced fertilization —	222
6.20.4	Controlled-release fertilizers —	223
6.20.5	Proper irrigation management —	223
6.20.6	Conservation tillage and cover crops —	223
6.20.7	Nutrient cycling and organic matter management —	223
6.20.8	Education and awareness —	223
6.21	Effective management of secondary nutrients —	224
6.22	Sustainable secondary nutrient management (Ca, Mg, and S) —	225
6.22.1	Improving soil health —	226
6.22.2	Better crop growth and development —	226

6.22.3	Higher crop productivity and profitability —	226
6.22.4	Food security and nutrition —	226
6.22.5	Better environmental health —	227
6.22.6	Alignment with UN SDGs —	227
6.23	Strategies for sustainable secondary nutrient management —	227
6.23.1	Use of the 4R principle —	227
6.23.2	Soil testing and monitoring —	228
6.23.3	Use of cover crops and crop rotation —	228
6.23.4	Recycling organic matter —	228
6.23.5	Erosion control practices —	228
6.23.6	Precision agriculture —	228
6.23.7	Integrated nutrient management (INM) —	229
6.24	Conclusion —	229
6.25	Key messages —	230
	References —	231

## **Chapter 7**

### **Micronutrients: small yet crucial — 233**

7.1	Introduction —	233
7.2	Iron (Fe) in agriculture —	234
7.2.1	Importance —	234
7.2.2	Physiological functions in plants —	234
7.2.3	Deficiency symptoms in plants —	235
7.3	Manganese (Mn) in agriculture —	236
7.3.1	Importance —	236
7.3.2	Physiological functions in plants —	237
7.3.3	Deficiency symptoms in plants —	237
7.4	Zinc (Zn) in agriculture —	238
7.4.1	Importance —	238
7.4.2	Physiological functions in plants —	239
7.4.3	Deficiency symptoms in plants —	239
7.5	Copper (Cu) in agriculture —	241
7.5.1	Importance —	241
7.5.2	Physiological functions in plants —	241
7.5.3	Deficiency symptoms in plants —	242
7.6	Molybdenum (Mo) in agriculture —	242
7.6.1	Importance —	242
7.6.2	Physiological functions in plants —	243
7.6.3	Deficiency symptoms in plants —	244
7.7	Boron (B) in agriculture —	245
7.7.1	Importance —	245
7.7.2	Physiological functions in plants —	246



7.7.3	Deficiency symptoms in plants —	<b>246</b>
7.8	Chlorine (Cl) in agriculture —	<b>247</b>
7.8.1	Importance —	<b>247</b>
7.8.2	Physiological functions in plants —	<b>248</b>
7.8.3	Deficiency symptoms in plants —	<b>248</b>
7.9	Nickel (Ni) in agriculture —	<b>249</b>
7.9.1	Importance —	<b>249</b>
7.9.2	Physiological functions in plants —	<b>250</b>
7.9.3	Deficiency symptoms in plants —	<b>250</b>
7.10	Negative effects of micronutrients —	<b>252</b>
7.11	Micronutrient management to mitigate negative effects —	<b>252</b>
7.12	Micronutrient fertilizers —	<b>253</b>
7.12.1	Chelated micronutrient fertilizers —	<b>253</b>
7.12.2	Micronutrient fertilizer mixtures —	<b>253</b>
7.12.3	Micronutrient amendments and supplements —	<b>254</b>
7.12.4	Organic sources —	<b>254</b>
7.13	Global status of soil micronutrients —	<b>255</b>
7.13.1	Iron (Fe) —	<b>255</b>
7.13.2	Manganese (Mn) —	<b>255</b>
7.13.3	Zinc (Zn) —	<b>256</b>
7.13.4	Copper (Cu) —	<b>256</b>
7.13.5	Boron (B) —	<b>256</b>
7.13.6	Molybdenum (Mo) —	<b>256</b>
7.13.7	Chlorine (Cl) —	<b>257</b>
7.14	Pakistan's status of soil micronutrients —	<b>257</b>
7.14.1	Key characteristics of Pakistani soils —	<b>257</b>
7.14.2	Micronutrient status and application —	<b>258</b>
7.14.3	Economic constraints and adoption —	<b>259</b>
7.15	Micronutrient management in crop production —	<b>259</b>
7.16	Micronutrient uptake by crops (kg/ha) —	<b>261</b>
7.17	Micronutrient recommendations for crops —	<b>261</b>
7.18	Effective management of micronutrients for major crops in Pakistan —	<b>262</b>
7.19	Environmental problems with micronutrients —	<b>264</b>
7.19.1	Water contamination —	<b>264</b>
7.19.2	Soil accumulation —	<b>264</b>
7.19.3	Nontarget effects —	<b>264</b>
7.19.4	Nutrient imbalance —	<b>264</b>
7.20	Management strategies for micronutrient environmental concerns —	<b>264</b>
7.20.1	Soil testing and nutrient recommendations —	<b>265</b>
7.20.2	Nutrient management planning —	<b>265</b>

- 7.20.3      Timing and application methods — **265**
- 7.20.4      Balanced fertilization — **265**
- 7.20.5      Environmental stewardship — **265**
- 7.20.6      Education and awareness — **266**
- 7.21        Mismatch of micronutrient deficiency with diseases — **266**
- 7.22        Sustainable micronutrient management — **267**
- 7.22.1      Improving soil health — **268**
- 7.22.2      Better crop growth and development — **268**
- 7.22.3      Higher crop productivity and profitability — **268**
- 7.22.4      Food security and nutrition — **269**
- 7.22.5      Better environmental health — **269**
- 7.22.6      Alignment with UN SDGs — **269**
- 7.23        Strategies for sustainable micronutrient management — **270**
- 7.23.1      Use of the 4R principle — **270**
- 7.23.2      Soil testing and monitoring — **270**
- 7.23.3      Use of cover crops and crop rotation — **270**
- 7.23.4      Recycling organic matter — **270**
- 7.23.5      Erosion control practices — **271**
- 7.23.6      Precision agriculture — **271**
- 7.23.7      Integrated nutrient management (INM) — **271**
- 7.24        Conclusion — **271**
- 7.25        Key messages — **272**
- References — **273**

**Chapter 8**  
**Balancing beneficial elements and heavy metals — 275**

- 8.1        Introduction — **275**
- 8.2        Importance — **276**
- 8.2.1      Silicon (Si) — **276**
- 8.2.2      Sodium (Na) — **276**
- 8.2.3      Cobalt (Co) — **277**
- 8.2.4      Selenium (Se) — **277**
- 8.2.5      Vanadium (V) — **277**
- 8.3        Deficiency symptoms for beneficial elements — **278**
- 8.4        Potential toxicities and strategies to overcome toxicity — **278**
- 8.5        Sources of beneficial elements — **280**
- 8.6        Beneficial element management — **281**
- 8.7        Beneficial element management for some crops — **282**
- 8.8        Environmental problems and strategies to overcome their toxicities — **283**
- 8.9        Sustainable beneficial element management — **284**
- 8.9.1      Improving soil health — **284**

- 8.9.2 Better crop growth and development — 285
- 8.9.3 Higher crop productivity and profitability — 285
- 8.9.4 Food security and nutrition — 285
- 8.10 Better environmental health — 286
- 8.11 Alignment with UN SDGs — 286
- 8.12 Strategies for sustainable beneficial element management — 286
  - 8.12.1 Use of the 4R principle — 286
  - 8.12.2 Soil testing and monitoring — 287
  - 8.12.3 Use of cover crops and crop rotation — 287
  - 8.12.4 Recycling organic matter — 287
  - 8.12.5 Erosion control practices — 287
  - 8.12.6 Precision agriculture — 287
  - 8.12.7 Integrated nutrient management (INM) — 287
- 8.13 Benefits of sustainable beneficial element management — 288
- 8.14 Heavy metals — 288
- 8.15 Heavy metal toxicity — 289
  - 8.15.1 Highly toxic elements (e.g., uranium, plutonium, radium) — 290
  - 8.15.2 Moderately toxic elements (e.g., lead, cadmium, mercury) — 291
  - 8.15.3 Less toxic elements (e.g., gold, silver, platinum) — 291
  - 8.15.4 Varied toxicity (e.g., copper, zinc, nickel) — 291
  - 8.15.5 Context and exposure — 291
- 8.16 The impact of heavy metals on different organisms — 291
  - 8.16.1 Crop health — 291
  - 8.16.2 Human health — 292
  - 8.16.3 Animal health — 292
  - 8.16.4 Birds' health — 292
  - 8.16.5 Fish health — 292
  - 8.16.6 Insects' health — 293
- 8.17 Approaches used in various disciplines to address heavy metal toxicities — 293
  - 8.17.1 Crop production — 293
  - 8.17.2 Human health — 293
  - 8.17.3 Environmental sciences — 294
  - 8.17.4 Animal health — 294
  - 8.17.5 Wildlife and ecosystems — 294
  - 8.17.6 Monitoring and conservation — 295
- 8.18 Sustainable heavy metal management — 295
  - 8.18.1 Improving soil health — 295
  - 8.18.2 Better crop growth and development — 296
  - 8.18.3 Higher crop productivity and profitability — 296
  - 8.18.4 Food security and nutrition — 296
  - 8.18.5 Better environmental health — 297

8.18.6	Alignment with UN SDGs —	<b>297</b>
8.19	Strategies for sustainable heavy metal management —	<b>297</b>
8.20	Conclusion —	<b>298</b>
8.21	Key messages —	<b>299</b>
	References —	<b>300</b>

## **Chapter 9**

### **Mastering fertilizers and their optimal utilization — 302**

9.1	Introduction —	<b>302</b>
9.2	Fertilizers —	<b>303</b>
9.2.1	Straight fertilizers —	<b>303</b>
9.2.2	Double fertilizers —	<b>304</b>
9.2.3	Complex fertilizers (NPK fertilizers) —	<b>304</b>
9.2.4	Secondary nutrient fertilizers —	<b>305</b>
9.2.5	Micronutrient fertilizers —	<b>306</b>
9.2.6	Specialty fertilizers —	<b>306</b>
9.3	Global fertilizers outlook —	<b>307</b>
9.4	The role of chemical fertilizers in modern agriculture —	<b>308</b>
9.4.1	Nutrient availability —	<b>308</b>
9.4.2	Precision and control —	<b>310</b>
9.4.3	Higher yields and improved crop quality —	<b>312</b>
9.4.4	Food security —	<b>313</b>
9.4.5	Fertilizers in green revolution —	<b>315</b>
9.5	Challenges to fertilizers industry —	<b>316</b>
9.5.1	Environmental impact —	<b>317</b>
9.5.2	Economic and supply chain issues —	<b>317</b>
9.5.3	Accessibility and distribution —	<b>318</b>
9.5.4	Regulatory and policy challenges —	<b>318</b>
9.5.5	Sustainability and innovation —	<b>318</b>
9.5.6	Health and safety —	<b>318</b>
9.5.7	Regional and country-specific issues —	<b>319</b>
9.6	Low soil fertility —	<b>320</b>
9.6.1	Natural factors —	<b>320</b>
9.6.2	Human activities —	<b>321</b>
9.6.3	Socioeconomic factors —	<b>321</b>
9.7	Global challenges associated with low soil fertility —	<b>322</b>
9.7.1	Decreased agricultural productivity —	<b>322</b>
9.7.2	Food insecurity —	<b>322</b>
9.7.3	Economic impacts —	<b>323</b>
9.7.4	Environmental degradation —	<b>323</b>
9.7.5	Climate change resilience —	<b>323</b>
9.7.6	Loss of ecosystem services —	<b>323</b>

9.7.7	Human health concerns —	<b>323</b>
9.8	Addressing the global challenges of low soil fertility —	<b>324</b>
9.8.1	Soil testing and monitoring —	<b>325</b>
9.8.2	Nutrient management —	<b>325</b>
9.8.3	Conservation agriculture —	<b>325</b>
9.8.4	Policy and support —	<b>325</b>
9.8.5	Research and innovation —	<b>325</b>
9.9	Challenges of low soil fertility in Pakistan —	<b>325</b>
9.9.1	Reasons for low soil fertility in Pakistan —	<b>326</b>
9.9.2	Factors contribute to high nutrient losses in Pakistan —	<b>327</b>
9.9.3	Factors contribute to pollution problem in Pakistan —	<b>328</b>
9.10	Sustainable nutrient management strategies to control nutrients losses and pollution risks in Pakistan —	<b>329</b>
9.10.1	Precision nutrient management —	<b>330</b>
9.10.2	Conservation practices —	<b>330</b>
9.10.3	Buffer zones and vegetative buffers —	<b>330</b>
9.10.4	Integrated water management —	<b>330</b>
9.10.5	Education and awareness —	<b>330</b>
9.11	Fertilizer recommendations for different crops in Pakistan —	<b>331</b>
9.12	Fertilizer-use efficiency (FUE) —	<b>331</b>
9.12.1	Significance of FUE —	<b>332</b>
9.12.2	Improving FUE —	<b>332</b>
9.12.3	Fertilizer-use efficiency (FUE) in response to method of application —	<b>334</b>
9.12.4	Factors influencing FUE —	<b>335</b>
9.13	Regional variations in fertilizer-use efficiency (FUE) —	<b>336</b>
9.13.1	Reasons for high FUE —	<b>337</b>
9.13.2	Reasons for low FUE —	<b>337</b>
9.14	Low nitrogen-use efficiency —	<b>338</b>
9.15	Low phosphorus-use efficiency —	<b>338</b>
9.16	Low potassium-use efficiency —	<b>339</b>
9.17	Improvement in fertilizer-use efficiency using best management practices —	<b>340</b>
9.17.1	Soil testing and nutrient recommendations —	<b>341</b>
9.17.2	Balanced fertilizer application —	<b>341</b>
9.17.3	Precision nutrient management —	<b>341</b>
9.17.4	Integrated nutrient management —	<b>342</b>
9.17.5	Education and extension services —	<b>342</b>
9.18	Influence of cultural practices on rate of fertilizer application —	<b>342</b>
9.18.1	Timing of fertilizer application —	<b>342</b>
9.18.2	Placement of fertilizers —	<b>342</b>
9.18.3	Crop rotation and intercropping —	<b>343</b>

9.18.4	Tillage practices —	<b>343</b>
9.18.5	Mulching and cover cropping —	<b>343</b>
9.18.6	Irrigation management —	<b>343</b>
9.18.7	Soil pH management —	<b>343</b>
9.18.8	Nutrient cycling and organic matter management —	<b>344</b>
9.18.9	Weeds and insect pests management —	<b>344</b>
9.18.10	Crop genetics (varieties vs. hybrids) —	<b>344</b>
9.18.11	Integrated nutrient management (INM) —	<b>345</b>
9.19	Methods of fertilizer application —	<b>345</b>
9.19.1	Broadcasting —	<b>345</b>
9.19.2	Banding —	<b>346</b>
9.19.3	Foliar application —	<b>346</b>
9.19.4	Seed coating —	<b>346</b>
9.19.5	Injection or fertigation —	<b>346</b>
9.20	Foliar nutrition —	<b>347</b>
9.20.1	Important points to be consider regarding foliar nutrition in field crops —	<b>347</b>
9.20.2	Drawbacks associated with foliar nutrition —	<b>348</b>
9.21	Fertigation —	<b>349</b>
9.21.1	Details about fertigation in field crops —	<b>349</b>
9.21.2	Drawbacks associated with fertigation —	<b>350</b>
9.22	Effective fertilizer management —	<b>351</b>
9.22.1	Soil testing and nutrient management planning —	<b>353</b>
9.22.2	Balanced fertilization —	<b>353</b>
9.22.3	Optimal application rates and timing —	<b>353</b>
9.22.4	Site-specific nutrient management —	<b>353</b>
9.22.5	Use of slow-release and controlled-release fertilizers —	<b>353</b>
9.22.6	Integrated nutrient management —	<b>354</b>
9.22.7	Fertigation and irrigation management —	<b>354</b>
9.22.8	Farmer education and awareness —	<b>354</b>
9.22.9	Environmental stewardship —	<b>354</b>
9.23	Controlled-release fertilizers —	<b>354</b>
9.23.1	Key features of controlled-release fertilizers —	<b>355</b>
9.23.2	Benefits of controlled-release fertilizers —	<b>355</b>
9.23.3	Mechanisms of controlled-release —	<b>356</b>
9.23.4	Challenges and considerations —	<b>356</b>
9.24	Balanced nutrition for field crops —	<b>357</b>
9.24.1	Approaches for balanced nutrition of crops —	<b>358</b>
9.24.2	Importance of balanced fertilization —	<b>358</b>
9.24.3	Practical implementation of balanced fertilization —	<b>359</b>
9.24.4	Benefits of balanced fertilization —	<b>359</b>
9.25	The 4Rs of nutrient management in field crops —	<b>360</b>

- 9.26 Precision plant nutrition or variable-rate technology (VRT) — 361
  - 9.26.1 Advantages of precision plant nutrition — 361
  - 9.26.2 Disadvantages of precision plant nutrition — 362
- 9.27 Management of fertilizers for sustainable agriculture and global food security — 363
  - 9.27.1 Key components of fertilizer management — 363
  - 9.27.2 Benefits of proper fertilizer management — 364
  - 9.27.3 Strategies for effective fertilizer management — 365
- 9.28 Effective fertilizer management: a holistic approach — 365
  - 9.28.1 Key components of effective fertilizer management — 366
  - 9.28.2 Benefits of effective fertilizer management — 366
  - 9.28.3 Strategies for implementing effective fertilizer management — 367
- 9.29 Fertilizer calculations — 368
  - 9.29.1 Basic formula for fertilizer calculations — 368
  - 9.29.2 Steps for fertilizer calculations — 368
  - 9.29.3 Examples — 368
  - 9.29.4 Fertilizer calculation from combined DAP and urea — 369
- 9.30 Conversion factors for nutrients in fertilizers — 371
- 9.31 Economic analysis of fertilizers application in field experiments — 373
  - 9.31.1 Example of economic analysis — 375
  - 9.31.2 Analyzing economic indicators: CBR vs. ROI — 376
- 9.32 Partial factor productivity (PFP) — 377
- 9.33 Agronomic efficiency (AE) — 378
- 9.34 Case studies from Peshawar, Khyber Pakhtunkhwa (Pakistan) — 381
  - 9.34.1 Nitrogen fertilizers experiment — 381
  - 9.34.2 Phosphorus fertilizer experiment — 382
- 9.35 The role of chemical and synthetic fertilizers in UN SDGs — 382
  - 9.35.1 Improving soil fertility and soil health — 382
  - 9.35.2 Enhancing crop productivity and profitability — 383
  - 9.35.3 Ensuring food security and nutrition — 383
  - 9.35.4 Promoting environmental quality — 383
  - 9.35.5 Supporting sustainable agriculture and UN SDGs — 384
- 9.36 Conclusion — 385
- 9.37 Key messages — 385
  - References — 386

**Chapter 10**

**Enriching soils with amendments and organic fertilization — 389**

- 10.1 Introduction — 389
- 10.2 Soil amendments — 390
- 10.3 The role of soil amendments — 390
  - 10.3.1 Improving crop productivity — 390

10.3.2	Enhancing growers' profitability —	<b>392</b>
10.3.3	Ensuring food security —	<b>392</b>
10.3.4	Promoting soil health —	<b>392</b>
10.3.5	Mitigating environmental impacts —	<b>392</b>
10.3.6	Global warming and climate change —	<b>393</b>
10.4	Soil amendments for alkaline soils —	<b>393</b>
10.5	Soil amendments for acidic soils —	<b>393</b>
10.6	Soil amendments' disadvantages —	<b>394</b>
10.7	Organic fertilizers —	<b>394</b>
10.8	Some common organic sources —	<b>396</b>
10.8.1	Animal manures – rich sources of nutrients —	<b>396</b>
10.8.2	Plant residues – recycling crop nutrients —	<b>397</b>
10.8.3	Compost and vermicompost – the power of decomposition —	<b>397</b>
10.8.4	Biochar and ash – carbon-based soil enhancers —	<b>397</b>
10.9	The role of organic fertilizers —	<b>397</b>
10.9.1	Improving crop productivity —	<b>398</b>
10.9.2	Improving fertilizer-use efficiency —	<b>398</b>
10.9.3	Enhancing water-use efficiency —	<b>398</b>
10.9.4	Enhancing growers' profitability —	<b>398</b>
10.9.5	Ensuring food security —	<b>399</b>
10.9.6	Promoting soil health —	<b>399</b>
10.9.7	Mitigating environmental impacts —	<b>399</b>
10.9.8	Addressing global warming and climate change —	<b>399</b>
10.10	Soil organic matter and their impact on nitrogen fertility —	<b>399</b>
10.11	Disadvantages of organic fertilizers —	<b>400</b>
10.11.1	Nutrient variability —	<b>400</b>
10.11.2	Slow release of nutrients —	<b>400</b>
10.11.3	Bulkiness and handling —	<b>401</b>
10.11.4	Potential contaminants —	<b>401</b>
10.12	Compost versus vermicompost —	<b>401</b>
10.12.1	Compost —	<b>401</b>
10.12.2	Vermicompost —	<b>401</b>
10.12.3	The role of compost and vermicompost —	<b>402</b>
10.13	Compost versus biochar —	<b>402</b>
10.13.1	Composition —	<b>402</b>
10.13.2	Production process —	<b>403</b>
10.13.3	Effects on soil —	<b>403</b>
10.13.4	Application and benefits —	<b>403</b>
10.13.5	The role of compost and biochar —	<b>404</b>
10.13.6	Disadvantages of compost and biochar —	<b>405</b>
10.14	Compost, biochar, and ash composition —	<b>406</b>
10.14.1	Differences in compost, biochar, and ash —	<b>407</b>



- 10.15 Ash versus biochar — 407
  - 10.15.1 Composition — 408
  - 10.15.2 Production process — 409
  - 10.15.3 Properties — 409
  - 10.15.4 Effects on soil — 409
  - 10.15.5 Environmental impact — 409
  - 10.15.6 The role of ash and biochar — 410
  - 10.15.7 Disadvantages of ash and biochar — 411
- 10.16 Use of biochar in alkaline and acidic soils — 412
  - 10.16.1 Biochar in alkaline soils — 412
  - 10.16.2 Biochar in acidic soils — 413
- 10.17 Use of ash in alkaline and acidic soils — 414
  - 10.17.1 Ash in alkaline soils — 414
  - 10.17.2 Ash in acidic soils — 415
- 10.18 The role of organic sources and soil amendments under saline soil — 415
  - 10.18.1 Ash in saline soils — 416
  - 10.18.2 Biochar in saline soils — 416
  - 10.18.3 Compost in saline soils — 416
  - 10.18.4 Other soil amendments in saline soils — 417
- 10.19 The role of soil amendments and organic fertilizers in combating soil pollution — 417
  - 10.19.1 Types of soil pollutants — 418
  - 10.19.2 Problems associated with soil pollution — 418
- 10.20 Role of organic manures in soil reclamation — 419
  - 10.20.1 Biochar in soil reclamation — 419
  - 10.20.2 Ash in soil reclamation — 420
  - 10.20.3 Compost in soil reclamation — 420
  - 10.20.4 Other soil amendments in soil reclamation — 421
- 10.21 The role of green manuring in improving soil fertility and health — 421
  - 10.21.1 Green manuring — 421
  - 10.21.2 Benefits of green manuring for soil fertility and health — 422
  - 10.21.3 The role of green manuring in INM and ISFM — 422
- 10.22 The role of intercropping and crop rotation in increasing soil fertility and productivity — 424
  - 10.22.1 Intercropping — 424
  - 10.22.2 Crop rotation — 425
  - 10.22.3 Role of intercropping and crop rotation with legume crops — 425
- 10.23 NPK concentration and C:N ratios of different animal manure sources — 426
- 10.24 NPK concentration and C:N ratios of different plant residues — 427

10.25	Case studies: nutrient management in cereal-based systems in Khyber Pakhtunkhwa (Pakistan) —	<b>428</b>
10.26	Soil organic carbon: importance and implications for desertification, climate change, food security, and human health —	<b>429</b>
10.26.1	Importance in combating soil desertification —	<b>429</b>
10.26.2	Role in combating climate change —	<b>429</b>
10.26.3	Impact on food security —	<b>430</b>
10.26.4	Healthy soils, healthy life —	<b>430</b>
10.27	Black soils —	<b>431</b>
10.27.1	Soil organic carbon (SOC) in black soils —	<b>431</b>
10.27.2	Global significance of black soils —	<b>432</b>
10.28	Organic and inorganic soils —	<b>433</b>
10.28.1	Composition —	<b>433</b>
10.28.2	Formation —	<b>433</b>
10.28.3	Characteristics —	<b>433</b>
10.28.4	Distribution of organic soils —	<b>434</b>
10.29	Black soils and organic soils —	<b>434</b>
10.29.1	Composition —	<b>434</b>
10.29.2	Formation —	<b>435</b>
10.29.3	Geographical distribution —	<b>435</b>
10.29.4	Characteristics —	<b>435</b>
10.30	Integrated approaches and best management practices of organic sources —	<b>436</b>
10.31	Challenges and future perspectives —	<b>437</b>
10.32	Soil organic sources and amendments: UN SDGs —	<b>438</b>
10.32.1	Improving soil fertility and soil health —	<b>438</b>
10.32.2	Boosting crop productivity and profitability —	<b>438</b>
10.32.3	Ensuring food security and nutrition —	<b>439</b>
10.32.4	Promoting environmental quality —	<b>439</b>
10.32.5	Supporting sustainable agriculture and UN-SDGs —	<b>439</b>
10.33	Conclusion —	<b>440</b>
10.34	Key messages —	<b>441</b>
	References —	<b>441</b>

**Chapter 11**

**Harnessing the power of beneficial microbes and biofertilizers — 444**

11.1	Introduction —	<b>444</b>
11.2	Understanding beneficial microbes —	<b>445</b>
11.3	Types of beneficial microbes —	<b>445</b>
11.3.1	Nitrogen-fixing bacteria —	<b>445</b>
11.3.2	Phosphate-solubilizing bacteria —	<b>446</b>
11.3.3	Zinc-solubilizing bacteria —	<b>446</b>

11.3.4	Plant growth-promoting rhizobacteria (PGPR) — <b>447</b>
11.3.5	Mycorrhizal fungi — <b>447</b>
11.3.6	Trichoderma fungi — <b>447</b>
11.4	Beneficial microbes' role in agricultural systems — <b>447</b>
11.4.1	Nutrient cycling — <b>447</b>
11.4.2	Disease suppression — <b>448</b>
11.4.3	Soil structure improvement — <b>448</b>
11.4.4	Enhancing plant resilience — <b>448</b>
11.5	Defining biofertilizers and beneficial microbes — <b>448</b>
11.6	Role of beneficial microbes and biofertilizers — <b>449</b>
11.6.1	Improving crop productivity — <b>449</b>
11.6.2	Enhancing growers' profitability — <b>449</b>
11.6.3	Ensuring food security — <b>450</b>
11.6.4	Promoting soil health — <b>450</b>
11.6.5	Mitigating environmental impacts — <b>450</b>
11.6.6	Global warming and climate change — <b>450</b>
11.7	Modes of action of beneficial microbes — <b>451</b>
11.7.1	Enhancing nutrient availability — <b>452</b>
11.7.2	Production of growth-promoting substances — <b>452</b>
11.8	Beneficial microbes' interactions with plants and soil — <b>454</b>
11.8.1	Root colonization — <b>454</b>
11.8.2	Nutrient availability — <b>454</b>
11.8.3	Plant growth promotion — <b>454</b>
11.8.4	Disease suppression — <b>455</b>
11.8.5	Abiotic stress tolerance — <b>455</b>
11.8.6	Soil health improvement — <b>455</b>
11.8.7	Signal exchange — <b>455</b>
11.9	The role of beneficial microorganisms (BMOs) in plant growth and health — <b>456</b>
11.9.1	Production of growth-promoting substances — <b>456</b>
11.9.2	Biocontrol of pathogens — <b>456</b>
11.9.3	Modulation of plant immune responses — <b>457</b>
11.9.4	Improvement of soil health — <b>457</b>
11.9.5	Case studies and applications — <b>457</b>
11.10	Beneficial microbes functions — <b>458</b>
11.10.1	Production of growth-promoting substances — <b>458</b>
11.10.2	Biocontrol of pathogens — <b>458</b>
11.10.3	Modulation of plant immune responses — <b>458</b>
11.11	Benefits of biofertilizers in agriculture — <b>459</b>
11.11.1	Improving soil fertility — <b>459</b>
11.11.2	Enhancing nutrient uptake efficiency — <b>459</b>
11.11.3	Reducing the need for synthetic fertilizers — <b>459</b>

11.11.4	Promotion of sustainable farming practices —	<b>460</b>
11.11.5	Positive impact on crop yield, quality, and disease resistance —	<b>460</b>
11.12	Types of biofertilizers —	<b>460</b>
11.12.1	Nitrogen-fixing biofertilizers —	<b>461</b>
11.12.2	Phosphate-solubilizing biofertilizers —	<b>461</b>
11.12.3	Plant growth-promoting rhizobacteria (PGPR) biofertilizers —	<b>461</b>
11.12.4	Mycorrhizal biofertilizers —	<b>461</b>
11.12.5	Other microbial formulations —	<b>463</b>
11.13	Application methods of biofertilizers —	<b>463</b>
11.13.1	Seed treatment —	<b>463</b>
11.13.2	Soil application —	<b>464</b>
11.13.3	Foliar spray —	<b>464</b>
11.13.4	Drip irrigation —	<b>465</b>
11.14	Factors influencing efficacy of biofertilizers —	<b>465</b>
11.14.1	Proper handling —	<b>466</b>
11.14.2	Compatibility with chemical inputs —	<b>466</b>
11.14.3	Soil conditions —	<b>466</b>
11.14.4	Nutrient availability —	<b>466</b>
11.15	Practical aspects of biofertilizer application —	<b>467</b>
11.15.1	Quality control —	<b>467</b>
11.15.2	Proper storage —	<b>467</b>
11.15.3	Shelf life —	<b>467</b>
11.15.4	Application timing —	<b>467</b>
11.15.5	Compatibility with chemical inputs —	<b>467</b>
11.16	Challenges associated with the use of biofertilizers and ongoing research —	<b>468</b>
11.16.1	Viability and shelf life —	<b>468</b>
11.16.2	Application timing and dosage —	<b>468</b>
11.16.3	Commercial scale production —	<b>468</b>
11.16.4	Standardized quality control and improved formulation techniques —	<b>468</b>
11.17	Combining biofertilizers with other agricultural practices —	<b>469</b>
11.17.1	Organic farming —	<b>469</b>
11.17.2	Precision agriculture —	<b>470</b>
11.18	Case study —	<b>472</b>
11.19	Biofertilizers and beneficial microbes role in UN-SDGs —	<b>472</b>
11.19.1	Improving soil fertility and soil health —	<b>473</b>
11.19.2	Enhancing crop productivity and profitability —	<b>473</b>
11.19.3	Ensuring food security and nutrition —	<b>473</b>
11.19.4	Promoting environmental quality —	<b>474</b>
11.19.5	Supporting sustainable agriculture and UN-SDGs —	<b>474</b>
11.20	Conclusion —	<b>475</b>

11.21	Key messages — 475
	References — 476

## Chapter 12

### Nanofertilizers: shaping the future of field crop production — 479

12.1	Introduction — 479
12.2	Definition and overview of nanofertilizers — 480
12.3	Brief history and development — 480
12.4	Importance and potential applications in agriculture — 480
12.5	Advantages of nanofertilizers — 481
12.5.1	Improved nutrient efficiency — 482
12.5.2	Increased crop productivity — 482
12.5.3	Reduced environmental impacts — 482
12.5.4	Precision agriculture — 482
12.5.5	Sustainable agriculture — 482
12.6	Types of nanofertilizers — 483
12.6.1	Metal-based nanofertilizers — 483
12.6.2	Metal oxide nanofertilizers — 483
12.6.3	Carbon-based nanofertilizers — 483
12.6.4	Polymer-based nanofertilizers — 483
12.7	Nanoparticles used in nanofertilizers — 484
12.8	Different formulations and compositions of nanofertilizers — 484
12.8.1	Nanoparticles embedded in carriers — 484
12.8.2	Nanoparticles coated on carriers — 484
12.8.3	Nanoparticles incorporated in polymer matrices — 485
12.8.4	Nanoparticles encapsulated in microspheres — 485
12.9	Unique characteristics and properties of nanofertilizers — 485
12.9.1	High surface-area-to-volume ratio — 485
12.9.2	Controlled-release and slow-release properties — 485
12.9.3	Enhanced nutrient uptake and utilization — 485
12.9.4	Targeted delivery and specificity — 486
12.9.5	Synergistic effects — 486
12.10	Mechanisms and benefits of nanofertilizers — 486
12.10.1	Uptake and delivery mechanisms of nanofertilizers in plants — 486
12.10.2	Enhanced nutrient absorption and utilization efficiency — 486
12.10.3	Increased crop yield and quality — 487
12.10.4	Improved soil fertility and nutrient availability — 487
12.10.5	Reduced environmental impacts and resource use — 487
12.11	Synthesis and manufacturing of nanofertilizers — 488
12.11.1	Methods and techniques for synthesizing nanofertilizers — 488
12.11.2	Controllable synthesis approaches for desired properties — 488
12.12	Scale-up production and commercialization considerations — 489

12.12.1	Manufacturing efficiency —	<b>489</b>
12.12.2	Quality control —	<b>489</b>
12.12.3	Economic viability —	<b>489</b>
12.13	Safety and regulatory aspects of nanofertilizers —	<b>490</b>
12.13.1	Toxicity assessment —	<b>490</b>
12.13.2	Environmental impact —	<b>490</b>
12.13.3	Regulation and standards —	<b>490</b>
12.14	Application methods of nanofertilizers —	<b>490</b>
12.14.1	Soil application techniques —	<b>491</b>
12.14.2	Seed coating and treatment methods —	<b>491</b>
12.14.3	Foliar spray and root drenching approaches —	<b>492</b>
12.14.4	Integration with irrigation systems and fertigation —	<b>492</b>
12.15	Challenges and limitations of nanofertilizers —	<b>492</b>
12.15.1	Environmental concerns and potential risks —	<b>492</b>
12.15.2	Long-term effects on soil health and ecosystems —	<b>493</b>
12.15.3	Economic feasibility and cost-effectiveness —	<b>493</b>
12.15.4	Perception, acceptance, and adoption by farmers —	<b>493</b>
12.16	Current research and future perspectives —	<b>493</b>
12.16.1	Ongoing research in nanofertilizer development and applications —	<b>494</b>
12.16.2	Innovative approaches and emerging trends —	<b>494</b>
12.16.3	Potential synergies with other agricultural practices —	<b>494</b>
12.16.4	Future prospects and implications for sustainable agriculture —	<b>495</b>
12.17	Case studies and success stories —	<b>495</b>
12.17.1	Rice production in Vietnam —	<b>495</b>
12.17.2	Tomato cultivation in Spain —	<b>496</b>
12.17.3	Wheat farming in India —	<b>496</b>
12.18	Benefits and outcomes —	<b>496</b>
12.18.1	Increased yield —	<b>496</b>
12.18.2	Enhanced nutrient-use efficiency —	<b>496</b>
12.18.3	Reduced environmental impact —	<b>497</b>
12.19	Recommendations for safe and effective use of nanofertilizers —	<b>497</b>
12.19.1	Regulatory oversight —	<b>497</b>
12.19.2	Standardization and certification —	<b>497</b>
12.19.3	Risk assessment and environmental monitoring —	<b>497</b>
12.19.4	Education and awareness —	<b>498</b>
12.20	Guidelines for application rates and timing —	<b>498</b>
12.20.1	Crop-specific recommendations —	<b>498</b>
12.20.2	Nutrient balance —	<b>498</b>
12.20.3	Soil and environmental factors —	<b>498</b>
12.21	Precautionary measures for handling and storage —	<b>499</b>
12.21.1	Personal protective equipment (PPE) —	<b>499</b>
12.21.2	Proper storage conditions —	<b>499</b>

- 12.21.3 Labeling and documentation — **499**
- 12.22 Monitoring and evaluation strategies — **499**
- 12.22.1 Field trials and experimental design — **499**
- 12.22.2 Nutrient uptake and plant performance — **499**
- 12.22.3 Environmental monitoring — **500**
- 12.23 Awareness and education — **500**
- 12.23.1 Training programs and workshops — **500**
- 12.23.2 Information dissemination — **500**
- 12.23.3 Policy development and regulation — **500**
- 12.24 Future directions and potential impact on sustainable agriculture — **501**
- 12.24.1 Improving soil fertility and soil health — **501**
- 12.24.2 Enhancing crop productivity and profitability — **501**
- 12.24.3 Ensuring food security and nutrition — **502**
- 12.24.4 Promoting environmental quality — **502**
- 12.24.5 Supporting sustainable agriculture and UN SDGs — **502**
- 12.25 Conclusion — **503**
- 12.26 Key messages — **504**
- References — **504**

**Chapter 13**

**Harmonizing nutrient management through integrated approaches — 506**

- 13.1 Introduction — **506**
- 13.2 Integrated nutrient management (INM) — **507**
- 13.3 Understanding INM — **508**
- 13.3.1 Organic and inorganic nutrient sources — **508**
- 13.3.2 Nutrient budgeting and optimization — **508**
- 13.3.3 Timing and method of nutrient application — **509**
- 13.3.4 Balanced nutrition — **509**
- 13.3.5 Soil health and sustainability — **509**
- 13.3.6 Integration with other sustainable practices — **509**
- 13.4 Key components of INM approach — **509**
- 13.4.1 Soil testing and nutrient analysis — **509**
- 13.4.2 Nutrient budgeting and optimization — **510**
- 13.4.3 Organic and inorganic nutrient sources — **510**
- 13.4.4 Timing and method of nutrient application — **511**
- 13.5 Case studies — **511**
- 13.5.1 Integrated nitrogen management in rice: wheat system in Malakand (Khyber Pakhtunkhwa) — **511**
- 13.5.2 Impact of integrated use of biofertilizers, organic, and inorganic phosphorus sources on wheat-maize cropping system — **513**
- 13.6 Balanced nutrition for higher quality crops — **514**
- 13.6.1 Understanding the concept of balanced nutrition — **515**

13.6.2	Macronutrients and micronutrients —	<b>515</b>
13.6.3	Optimal nutrient ratios for different crops —	<b>515</b>
13.7	Optimal NPK ratios in agriculture —	<b>516</b>
13.7.1	Understanding NPK ratios —	<b>516</b>
13.7.2	The 1:1:1 ratio (balanced ratio) —	<b>517</b>
13.7.3	The 2:2:1 ratio (higher nitrogen and phosphorus) —	<b>517</b>
13.7.4	The 2:1:1 ratio (higher nitrogen) —	<b>517</b>
13.7.5	The 1:2:1 ratio (higher phosphorus) —	<b>518</b>
13.7.6	The 2:1:2 ratio (balanced with emphasis on nitrogen and potassium) —	<b>518</b>
13.8	Factors influencing optimal NPK ratios —	<b>519</b>
13.8.1	Soil type and fertility —	<b>519</b>
13.8.2	Crop type and growth stage —	<b>519</b>
13.8.3	Climate and weather conditions —	<b>519</b>
13.8.4	Agricultural practices —	<b>519</b>
13.8.5	Regional considerations —	<b>520</b>
13.9	Balancing of essential nutrients for field crops —	<b>520</b>
13.9.1	Nitrogen (N), phosphorus (P), and potassium (K) —	<b>520</b>
13.9.2	Secondary nutrients: calcium (Ca), magnesium (Mg), and sulfur (S) —	<b>521</b>
13.9.3	Micronutrients: iron (Fe), zinc (Zn), manganese (Mn), and others —	<b>521</b>
13.10	Importance of balanced nutrient ratios for specific crops —	<b>522</b>
13.10.1	Nutrient requirements during different growth stages —	<b>522</b>
13.10.2	Impact on plant physiology and metabolism —	<b>522</b>
13.11	Techniques and tools for assessing nutrient imbalances and deficiencies —	<b>523</b>
13.11.1	Leaf tissue analysis —	<b>523</b>
13.11.2	Soil nutrient testing —	<b>523</b>
13.11.3	Visual symptoms and diagnostic tools —	<b>524</b>
13.11.4	Field experiments —	<b>524</b>
13.12	Biofortification —	<b>525</b>
13.12.1	Definition and significance —	<b>525</b>
13.12.2	Approaches of biofortification —	<b>525</b>
13.12.3	Implications for improving human nutrition and addressing micronutrient deficiencies —	<b>526</b>
13.13	Case studies on crop biofortification —	<b>526</b>
13.13.1	Enhancing zinc biofortification in wheat through the integration of zinc, compost, and zinc-solubilizing bacteria in a wheat-maize cropping system in Peshawar (Khyber Pakhtunkhwa) —	<b>527</b>
13.13.2	Biofortified rice varieties with enhanced iron and zinc content —	<b>527</b>



- 13.13.3 Phosphorus and zinc fertilization improve zinc biofortification in grains and straw of coarse vs. fine rice genotypes at Malakand (Khyber Pakhtunkhwa) — **527**
- 13.13.4 Biofortified wheat with increased levels of essential micronutrients — **528**
- 13.14 Role of INM and balanced nutrition practices — **528**
- 13.14.1 Impact of INM on production costs and growers' income — **528**
- 13.14.2 Reduction in fertilizer usage and associated expenses through INM practices — **529**
- 13.14.3 Enhanced crop quality and market value resulting in increased income for growers — **529**
- 13.14.4 Economic analysis of the financial benefits of adopting INM and balanced nutrition — **530**
- 13.15 Linkages of INM with sustainable crop production — **531**
- 13.15.1 Integration of INM and balanced nutrition with other sustainable practices — **531**
- 13.15.2 Synergies between INM and precision agriculture, organic farming, and conservation agriculture — **531**
- 13.15.3 Contribution to soil health, environmental sustainability, and ecosystem services — **532**
- 13.15.4 Implications for sustainable agriculture and human health — **533**
- 13.16 Integrated nutrient management (INM): UN-SDGs — **534**
- 13.16.1 Improving soil fertility and soil health — **534**
- 13.16.2 Enhancing crop productivity and profitability — **534**
- 13.16.3 Ensuring food security and nutrition — **535**
- 13.16.4 Promoting environmental quality — **535**
- 13.16.5 Supporting sustainable agriculture and UN-SDGs — **535**
- 13.17 Conclusion — **536**
- 13.18 Key messages — **537**
- References — **537**

**Chapter 14**

**Managing global soil threats through effective crop nutrition — 541**

- 14.1 Introduction — **541**
- 14.2 Understanding global soil threats — **541**
- 14.2.1 Soil erosion — **542**
- 14.2.2 Soil salinization — **542**
- 14.2.3 Soil acidification — **542**
- 14.2.4 Soil compaction — **542**
- 14.2.5 Soil contamination — **542**
- 14.2.6 Nutrient depletion — **543**
- 14.2.7 Loss of soil organic matter — **543**

14.2.8	Desertification —	543
14.2.9	Soil sealing —	543
14.2.10	Soil biodiversity loss —	543
14.2.11	Soil waterlogging —	543
14.2.12	Climate change impacts —	544
14.2.13	Deforestation and land use changes —	544
14.3	Impact of soil threats on agriculture —	544
14.3.1	Soil erosion —	544
14.3.2	Soil salinization —	545
14.3.3	Soil acidification —	546
14.3.4	Soil compaction —	546
14.3.5	Soil contamination —	547
14.3.6	Nutrient depletion —	547
14.3.7	Loss of soil organic matter —	548
14.3.8	Desertification —	548
14.3.9	Soil sealing —	549
14.3.10	Soil biodiversity loss —	550
14.3.11	Soil waterlogging —	550
14.3.12	Climate change impacts —	551
14.3.13	Deforestation and land use changes —	551
14.4	Soil threats: challenges to soil health and sustainability —	552
14.4.1	Soil erosion —	552
14.4.2	Soil salinization —	552
14.4.3	Soil acidification —	553
14.4.4	Soil compaction —	553
14.4.5	Soil contamination —	553
14.4.6	Nutrient depletion —	553
14.4.7	Loss of soil organic matter —	554
14.4.8	Desertification —	554
14.4.9	Soil sealing —	554
14.4.10	Soil biodiversity loss —	554
14.4.11	Soil waterlogging —	555
14.4.12	Climate change impacts —	555
14.4.13	Deforestation and land use changes —	555
14.5	Soil threats and climate change —	556
14.5.1	Soil erosion —	556
14.5.2	Soil salinization —	556
14.5.3	Soil acidification —	556
14.5.4	Soil compaction —	556
14.5.5	Soil contamination —	557
14.5.6	Nutrient depletion —	557
14.5.7	Loss of soil organic matter —	557

14.5.8	Desertification — <b>557</b>
14.5.9	Soil sealing — <b>557</b>
14.5.10	Soil biodiversity loss — <b>558</b>
14.5.11	Soil waterlogging — <b>558</b>
14.5.12	Climate change impacts — <b>558</b>
14.5.13	Deforestation and land use changes — <b>558</b>
14.6	Sustainable management practices to control soil threats — <b>559</b>
14.6.1	Soil erosion — <b>559</b>
14.6.2	Soil salinization — <b>559</b>
14.6.3	Soil acidification — <b>559</b>
14.6.4	Soil compaction — <b>560</b>
14.6.5	Soil contamination — <b>560</b>
14.6.6	Nutrient depletion — <b>560</b>
14.6.7	Loss of soil organic matter — <b>560</b>
14.6.8	Desertification — <b>560</b>
14.6.9	Soil sealing — <b>561</b>
14.6.10	Soil biodiversity loss — <b>561</b>
14.6.11	Soil waterlogging — <b>561</b>
14.6.12	Climate change impacts — <b>561</b>
14.6.13	Deforestation and land use changes — <b>562</b>
14.7	Soil threats management: the role of crop nutrition — <b>562</b>
14.8	Global strategies for nutrient management under soil threats — <b>563</b>
14.8.1	Soil amendments — <b>563</b>
14.8.2	Tailored fertilization — <b>564</b>
14.8.3	Biological solutions — <b>565</b>
14.8.4	Integrated management practices — <b>566</b>
14.8.5	Innovative technologies — <b>568</b>
14.9	Case studies and regional approaches to control soil threats — <b>569</b>
14.9.1	Controlling soil erosion with integrated nutrient management (INM) and integrated soil fertility management (ISFM) — <b>569</b>
14.9.2	Salinity management in arid regions: techniques like salt-tolerant crops, efficient irrigation practices, and gypsum application are vital in regions such as the Middle East and North Africa — <b>571</b>
14.9.3	Acidity management in tropical soils: liming, organic amendments, and acid-tolerant crops are effective in Latin America and Southeast Asia — <b>576</b>
14.9.4	Controlling soil compaction with integrated nutrient management (INM) and integrated soil fertility management (ISFM) — <b>579</b>
14.9.5	Global strategies for soil pollution control: innovations and case studies — <b>581</b>
14.9.6	Controlling nutrient depletion with integrated nutrient management (INM) and integrated soil fertility management (ISFM) — <b>582</b>

- 14.9.7 Enhancing soil organic matter: strategies to preserve and restore global soil health — **584**
- 14.9.8 Controlling soil desertification with integrated nutrient management (INM) and integrated soil fertility management (ISFM) — **586**
- 14.9.9 Controlling soil sealing with integrated nutrient management (INM) and integrated soil fertility management (ISFM) — **588**
- 14.9.10 Enhancing soil biodiversity through integrated nutrient management and integrated soil fertility management — **590**
- 14.9.11 Controlling soil waterlogging with integrated nutrient management (INM) and integrated soil fertility management (ISFM) — **594**
- 14.9.12 Controlling climate change impact on soil degradation with integrated nutrient management (INM) and integrated soil fertility management (ISFM) — **596**
- 14.9.13 Controlling deforestation and land use change impacts on soil degradation with integrated nutrient management (INM) and integrated soil fertility management (ISFM) — **597**
- 14.10 Integrated soil fertility management (ISFM) — **599**
  - 14.10.1 Significance of ISFM — **599**
  - 14.10.2 Principles of ISFM — **600**
  - 14.10.3 Contributions of ISFM — **607**
  - 14.10.4 A success story: integrated soil fertility management (ISFM) in Pakistan — **607**
- 14.11 Soil conservation — **609**
  - 14.11.1 Significance of soil conservation on a global scale — **609**
  - 14.11.2 Different soil conservation practices — **610**
  - 14.11.3 Examples of soil conservation worldwide — **610**
- 14.12 Future directions and research needs — **611**
  - 14.12.1 Innovative soil amendments — **611**
  - 14.12.2 Climate-resilient practices — **612**
  - 14.12.3 Farmer education and training — **612**
  - 14.12.4 Policy support — **612**
- 14.13 Conclusion — **613**
- 14.14 Key messages — **613**
  - References — **614**

**Chapter 15**

**Agriculture and Sustainable Development Goals: the role of crop nutrition in achieving global targets — 617**

- 15.1 Introduction — **617**
- 15.2 Goal and importance of 17 UN SDGs — **618**
  - 15.2.1 SDG 1: No Poverty — **618**
  - 15.2.2 SDG 2: Zero Hunger — **618**

15.2.3	SDG 3: Good Health and Well-being — <b>619</b>
15.2.4	SDG 4: Quality Education — <b>619</b>
15.2.5	SDG 5: Gender Equality — <b>619</b>
15.2.6	SDG 6: Clean Water and Sanitation — <b>619</b>
15.2.7	SDG 7: Affordable and Clean Energy — <b>619</b>
15.2.8	SDG 8: Decent Work and Economic Growth — <b>620</b>
15.2.9	SDG 9: Industry, Innovation, and Infrastructure — <b>620</b>
15.2.10	SDG 10: Reduced Inequality — <b>620</b>
15.2.11	SDG 11: Sustainable Cities and Communities — <b>620</b>
15.2.12	SDG 12: Responsible Consumption and Production — <b>620</b>
15.2.13	SDG 13: Climate Action — <b>621</b>
15.2.14	SDG 14: Life Below Water — <b>621</b>
15.2.15	SDG 15: Life on Land — <b>621</b>
15.2.16	SDG 16: Peace, Justice, and Strong Institutions — <b>621</b>
15.2.17	SDG 17: Partnerships for the Goals — <b>621</b>
15.3	Scope of Sustainable Development Goals (SDGs) — <b>622</b>
15.3.1	Addressing global challenges — <b>622</b>
15.3.2	Promoting inclusivity — <b>623</b>
15.3.3	Environmental sustainability — <b>623</b>
15.3.4	Economic prosperity — <b>623</b>
15.3.5	Health and well-being — <b>623</b>
15.3.6	Global partnerships — <b>623</b>
15.3.7	Long-term development — <b>624</b>
15.4	Key SDGs related to agriculture: role of integrated nutrient management and integrated soil fertility management — <b>624</b>
15.4.1	SDG 1: No Poverty — <b>625</b>
15.4.2	SDG 2: Zero Hunger — <b>625</b>
15.4.3	SDG 3: Good Health and Well-being — <b>625</b>
15.4.4	SDG 6: Clean Water and Sanitation — <b>625</b>
15.4.5	SDG 13: Climate Action — <b>626</b>
15.4.6	SDG 15: Life on Land — <b>626</b>
15.5	Role of crop nutrition to achieve SDGs — <b>626</b>
15.5.1	SDG 1 – No poverty: end poverty in all its forms everywhere — <b>627</b>
15.5.2	SDG 2 – zero hunger: end hunger, achieve food security and improved nutrition, and promote sustainable agriculture — <b>628</b>
15.5.3	SDG 3 – good health and well-being: ensure healthy lives and promote well-being for all at all ages — <b>629</b>
15.5.4	SDG 6 – clean water and sanitation: ensure availability and sustainable management of water and sanitation for all — <b>630</b>
15.5.5	SDG 13 – climate action: take urgent action to combat climate change and its impacts — <b>631</b>

15.5.6	SDG 15 – Life on Land: protect, restore, and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss —	632
15.6	Conclusion —	633
15.7	Key messages —	633
	References —	635

Glossary — 637

Index — 663