PRINCIPLES OF PLANT NUTRITION

Principles of Plant Nutrition

5th Edition

Edited by

Konrad Mengel

Justus Liebig University, Giessen, Germany

and

Ernest A. Kirkby

School of Biology, University Leeds, U.K.

with the support of

Harald Kosegarten

Justus Liebig University, Giessen, Germany

and

Thomas Appel

University of Applied Sciences, Bingen, Germany



A C.I.P. Catalogue record for this book is available from the Library of Congress.
ISBN 978-1-4020-0008-9 ISBN 978-94-010-1009-2 (eBook) DOI 10.1007/978-94-010-1009-2
Printed on acid-free paper
All Rights Reserved © 2001Springer Science+Business Media Dordrecht Originally published by Kluwer Academic Publishers in 2001 No part of the material protected by this copyright notice may be reproduced or utilized in any form or by any means, electronic or mechanical, including photocopying, recording or by any information storage and retrieval system, without written permission from the copyright owner.

TABLE OF CONTENTS

Chapter 1 Plant Nutrients		
1.1	Definition and Classification	1
1.2	General Functions	4
1.3	Mineral Concentrations in Plant Material	9
Chapt The So	er 2 oil as a Plant Nutrient Medium	15
2.1	Important Physico-Chemical Properties	15
2.1.1	General	15
2.1.1	Cation adsorption and exchange	15
2.1.2	The Gapon equation	22
2.1.3	Anion adsorption	23
2.1.5	Water adsorption	26
2.1.5	Colloidal systems	27
2.1.0	Important Soil Characteristics	29
2.2.1	Soil texture and clay minerals	29
2.2.2	Soil organic matter	34
2.2.3	Soil structure	38
2.2.4	Soil water	41
2.2.5	Soil atmosphere	45
2.2.6	Soil pH	51
2.2.7	Salt affected Soils	62
2.3	Factors Relating to Nutrient Availability	64
2.3.1	General	64
2.3.2	Interception and contact exchange	65
2.3.3	Mass-flow and diffusion	66
2.3.4	Soil solution	71
2.3.5	Intensity, quantity and buffer power	74
2.3.6	Root growth and morphology	78
2.3.7	The rhizosphere and root exudation	84
2.3.8	Mycorrhiza	88
2.4	Determination of Nutrient Availablity	92
2.4.1	General	92
2.4.2	Soil sampling and interpretation of soil tests	93
2.4.3	Estimation of cations	94
2.4.4	Estimation of phosphates	95
2.4.5	Tracer techniques	96

2.4.6	Electro-ultrafiltration technique (EUF technique)	98
2.4.7	Estimation of available nitrogen	100
2.4.8	Leaf analysis, plant analysis and tissue analysis	103
2.4.9	Microbiological methods	110
Chapt		111
Nutrie	ent Uptake and Assimilation	111
3.1	Ion Uptake and Ionic Status of Plants	111
3.1.1	General	111
3.1.2	The plant cell	112
3.1.3	Membranes	114
3.1.4	Ion pumps, electrochemical potentials, and ion channels	118
3.1.5	Mechanisms of membrane transport	126
3.1.6	Compartmentation of ions in plant cells	128
3.1.7	Cation/anion balance and ion antagonism	130
3.1.8	Relationship between uptake rate and the ion concentration	
	in the nutrient solution	135
3.2	Photosynthesis and CO ₂ Assimilation	136
3.2.1	General	136
3.2.2	Light absorption and electron flow	137
3.2.3	Photophosphorylation	145
3.2.4	CO ₂ assimilation and the Calvin cycle	147
3.2.5	Photorespiration and the glycollate pathway	150
3.2.6	C ₄ pathway	153
3.2.7	Crassulacean acid metabolism	160
3.3	Nitrogen and Sulphur Assimilation	161
3.3.1	General	161
3.3.2	Nitrate and nitrite reduction	162
3.3.3	Nitrogen fixation	168
3.3.4	Ammonia assimilation	173
3.3.5	Amino acids and amides	175
3.3.6	Sulphur assimilation	177
Chapt Plant	er 4 Water relationships	181
- MIII	The Commonspo	101
4.1	Basic Processes in Plant Water Relationships	181
4.1.1	General	181
4.1.2	Water potential	181
4.1.3	Osmosis	185
4.1.4	Bulk flow of water	189
4.2	Water Balance	189

4.2.1	General	189	
4.2.2	Soil-plant-water relationships	190	
4.2.3	Water and solute uptake by roots and their centripetal movement	191	
4.2.4	Water release into the xylem vessels	196	
4.2.5	Root pressure	199	
4.2.6	Transpiration and water movement in the xylem	199	
4.2.7	Stomatal opening and closure	203	
4.3	Long Distance Transport of Mineral Nutrients	206	
4.3.1	General	206	
4.3.2	Xylem transport	207	
4.3.3	•		
4.5.5	phloem and xylem transport	210	
4.3.4	Redistribution of mineral nutrients in the phloem	214	
4.4.	Physiological Aspects of Drought Stress	215	
4.4.1	General	215	
4.4.2	Interdependence of the parameter of leaf water potential	218	
4.4.3	Physiological processes and parameters affected		
т.т.Э	by drought stress in plants	218	
4.5	Practical Aspects of Drought Stress	229	
4.5.1	Water potential values and irrigation	229	
4.5.2	Transpiraion and crop yeald	230	
4.6	Salinity	232	
4.6.1	General	232	
4.6.2	Water and salt stress effects of salinity in crop plants	234	
4.6.3	Salt tolerance	237	
4.6.4	Crop production	240	
Chapt Plant	er 5 Growth and Crop Production	243	
<i>-</i> 1	District 10 and 10 about the solution of the	243	
5.1	Physiological Source and Sink relationships	243	
5.1.1	General	27.	
5.1.2	Assimilate production and cellular partitoning	243	
5 1 2	in the physiological source	243	
5.1.3	Assimilate transport and phloem loading in the physiological source	250	
5.1.4	Phloem tissue	253	
5.1.5	Mechanism of phloem transport	253	
5.1.6	Phloem unloading and assimilate movement	25/	
517	into the physiological sink	254 256	
5.1.7	Storage processes in physiological sinks	259	
5.1.8	Assimilate partitioning between physiological source and sink		
5.2	Essential Growth Stages and Yield Components	263	
5.2.1	General Phytohography	263 265	
5.2.2	Phytohormones	203	

5.2.3	Growth rate and nutrient supply	276
5.2.4	Grain crops	278
5.2.5	Root crops	286
5.2.6	Fruit crops	291
5.2.7	Growth regulators	293
5.3	Nutrition and Yield Response	296
5.3.1	General	296
5.3.2	Net assimilatio rate and leaf area index	297
5.3.3	Carbon dioxide assimialtion, CO ₂ concentration, and light intensity	300
5.3.4	Yield curves	305
5.3.5	Modelling soil/plant relationships and crop production processes	312
5.4	Nutrition and Plant Quality	317
5.4.1	General	317
5.4.2	Root crops	318
5.4.3	Grain crops	320
5.4.4	Oil crops	324
5.4.5	Forage crops	325
5.4.6	Vegetables and fruits	329
Chapt Fertili	er 6 zer Application	337
6.1		
0.1	Nutrient Cycling	337
6.1.1	Nutrient Cycling General	337 337
	General	
6.1.1	General Nutrient removal by crops	337
6.1.1 6.1.2	General	337 339
6.1.1 6.1.2 6.1.3	General Nutrient removal by crops Nutrient removol by leaching	337 339 342
6.1.1 6.1.2 6.1.3 6.1.4	General Nutrient removal by crops Nutrient removol by leaching Volatilization and denitrification Erosion	337 339 342 347
6.1.1 6.1.2 6.1.3 6.1.4 6.1.5	General Nutrient removal by crops Nutrient removol by leaching Volatilization and denitrification	337 339 342 347 351
6.1.1 6.1.2 6.1.3 6.1.4 6.1.5 6.1.6	General Nutrient removal by crops Nutrient removol by leaching Volatilization and denitrification Erosion Nutrient supply by precipitation and atmosphere	337 339 342 347 351 352
6.1.1 6.1.2 6.1.3 6.1.4 6.1.5 6.1.6 6.2	General Nutrient removal by crops Nutrient removal by leaching Volatilization and denitrification Erosion Nutrient supply by precipitation and atmosphere Mineral Fertilizers, Manures and Fertilization Techniques	337 339 342 347 351 352 354
6.1.1 6.1.2 6.1.3 6.1.4 6.1.5 6.1.6 6.2 6.2.1	General Nutrient removal by crops Nutrient removal by leaching Volatilization and denitrification Erosion Nutrient supply by precipitation and atmosphere Mineral Fertilizers, Manures and Fertilization Techniques Mineral fertilizers	337 339 342 347 351 352 354 354
6.1.1 6.1.2 6.1.3 6.1.4 6.1.5 6.1.6 6.2 6.2.1 6.2.2	General Nutrient removal by crops Nutrient removal by leaching Volatilization and denitrification Erosion Nutrient supply by precipitation and atmosphere Mineral Fertilizers, Manures and Fertilization Techniques Mineral fertilizers Organic manures and crop residues	337 339 342 347 351 352 354 354 355
6.1.1 6.1.2 6.1.3 6.1.4 6.1.5 6.1.6 6.2 6.2.1 6.2.2 6.2.3	General Nutrient removal by crops Nutrient removal by leaching Volatilization and denitrification Erosion Nutrient supply by precipitation and atmosphere Mineral Fertilizers, Manures and Fertilization Techniques Mineral fertilizers Organic manures and crop residues Liquid fertilizers	337 339 342 347 351 352 354 354 355 362
6.1.1 6.1.2 6.1.3 6.1.4 6.1.5 6.1.6 6.2 6.2.1 6.2.2 6.2.3 6.2.4 6.2.5 6.2.6	General Nutrient removal by crops Nutrient removal by leaching Volatilization and denitrification Erosion Nutrient supply by precipitation and atmosphere Mineral Fertilizers, Manures and Fertilization Techniques Mineral fertilizers Organic manures and crop residues Liquid fertilizers Controlled-release fertilizers	337 339 342 347 351 352 354 355 362 364 366 367
6.1.1 6.1.2 6.1.3 6.1.4 6.1.5 6.1.6 6.2 6.2.1 6.2.2 6.2.3 6.2.4 6.2.5 6.2.6 6.2.7	General Nutrient removal by crops Nutrient removal by leaching Volatilization and denitrification Erosion Nutrient supply by precipitation and atmosphere Mineral Fertilizers, Manures and Fertilization Techniques Mineral fertilizers Organic manures and crop residues Liquid fertilizers Controlled-release fertilizers Techniques of application Foliar application Nutrient ratios and recommendations	337 339 342 347 351 352 354 355 362 364 366 367 369
6.1.1 6.1.2 6.1.3 6.1.4 6.1.5 6.1.6 6.2 6.2.1 6.2.2 6.2.3 6.2.4 6.2.5 6.2.6 6.2.7 6.2.8	General Nutrient removal by crops Nutrient removal by leaching Volatilization and denitrification Erosion Nutrient supply by precipitation and atmosphere Mineral Fertilizers, Manures and Fertilization Techniques Mineral fertilizers Organic manures and crop residues Liquid fertilizers Controlled-release fertilizers Techniques of application Foliar application	337 339 342 347 351 352 354 355 362 364 366 367
6.1.1 6.1.2 6.1.3 6.1.4 6.1.5 6.1.6 6.2 6.2.1 6.2.2 6.2.3 6.2.4 6.2.5 6.2.6 6.2.7 6.2.8 6.3	General Nutrient removal by crops Nutrient removal by leaching Volatilization and denitrification Erosion Nutrient supply by precipitation and atmosphere Mineral Fertilizers, Manures and Fertilization Techniques Mineral fertilizers Organic manures and crop residues Liquid fertilizers Controlled-release fertilizers Techniques of application Foliar application Nutrient ratios and recommendations Hydroponics soilless cultivation and fertigation General Aspects of Fertilizer Application	337 339 342 347 351 352 354 355 362 364 366 367 369
6.1.1 6.1.2 6.1.3 6.1.4 6.1.5 6.1.6 6.2 6.2.1 6.2.2 6.2.3 6.2.4 6.2.5 6.2.6 6.2.7 6.2.8 6.3 6.3.1	General Nutrient removal by crops Nutrient removal by leaching Volatilization and denitrification Erosion Nutrient supply by precipitation and atmosphere Mineral Fertilizers, Manures and Fertilization Techniques Mineral fertilizers Organic manures and crop residues Liquid fertilizers Controlled-release fertilizers Techniques of application Foliar application Nutrient ratios and recommendations Hydroponics soilless cultivation and fertigation General Aspects of Fertilizer Application Fertilizer use and agricultural production	337 339 342 347 351 352 354 355 362 364 366 367 369 373 378
6.1.1 6.1.2 6.1.3 6.1.4 6.1.5 6.1.6 6.2 6.2.1 6.2.2 6.2.3 6.2.4 6.2.5 6.2.6 6.2.7 6.2.8 6.3	General Nutrient removal by crops Nutrient removal by leaching Volatilization and denitrification Erosion Nutrient supply by precipitation and atmosphere Mineral Fertilizers, Manures and Fertilization Techniques Mineral fertilizers Organic manures and crop residues Liquid fertilizers Controlled-release fertilizers Techniques of application Foliar application Nutrient ratios and recommendations Hydroponics soilless cultivation and fertigation General Aspects of Fertilizer Application	337 339 342 347 351 352 354 355 362 364 366 367 369 373 378

Chapt Nitrog		397
7.1	Nitrogen in the Soil and its Availability	397
7.1.1	General aspects	397
7.1.2	Biological nitrogen fixation	397
7.1.3	The agronomic importance of biological dinitrogen fixation	406
7.1.4	Ammonification and nitrification	408
7.1.5	Nitrification inhibitors	414
7.1.6	Ammonium fixation	416
7.1.7	Nitrogen of the soil solution	418
7.2	Nitrogen in Physiology	418
7.2.1	General	418
7.2.2	Uptake	419
7.2.3	Nitrogen fractions	424
7.2.4	Translocation	425
7.2.5	Nitrogen deficiency symptoms	426
7.3	Nitrogen Fertilizer Application and Crop Production	427
7.3.1	General	427
7.3.2	Response to nitrogen application	427
7.3.3	Nitrogen fertilizer application rates	430
7.3.4	Nitrogen fertilizers	431
Chapt Sulph		435
Sulpii		
8.1	Soil Sulphur	435
8.2	Sulphur in Physiology	438
8.2.1	Uptake and translocation	438
8.2.2	Metabolic functions of sulphur	439
8.2.3	Sulphur deficiency and toxicity	447
8.3	Sulphur in Crop Nutrition	448
8.3.1	Sulphur balance	448
8.3.2	Sulphur application	450
Chap	ter 9	
	phorus	453
9.1	Soil Phosphorus	453
9.1.1	Phosphorus fractions and phosphate minerals	453
9.1.2	Phosphorus in solution and plant root interactions	460
9.2	Phosphorus in Physioloy	464
9.2.1	Absorption and translocation	464

9.2.2	Phosphate fractions and metabolic functions	465
9.2.3	Phosphorus deficiency	469
9.3	Phosphorus in Crop Nutrition	470
9.3.1	Phosphorus availability and crop requirements	470
9.3.2	Phosphate fertilizers	473
9.3.3	Phosphate application	477
Chapte		
Potassi	um	481
10.1	Soil Potassium	481
10.1.1	Potassium minerals and potassium release	481
10.1.2	Potassium fixation	484
10.1.3	Potassium adsorption and mobility	485
10.1.4	Potassium fractions	486
10.2	Potassium in Physiology	489
10.2.1	Uptake and translocation	489
10.2.2	Meristematic growth	493
10.2.3	Water regime	494
10.2.4	Photosynthesis and translocation of photosynthates	496
10.2.5	Enzyme activation	498
10.2.6	Replacement of potassium by sodium	501
10.2.7	Potassium deficiency	503
10.3	Potassium in Crop Nutrition	504
10.3.1	Crop requirements and response	504
10.3.2	Deficient soils and fixation	507
10.3.3	Disease	508
10.3.4	Fertilizers and application	509
Chapte	r 11	
Calciu		513
11.1	Soil Calcium	513
11.1.1	Occurence in soils, weathering and leaching	513
11.1.2	Ecological aspects	517
11.2	Calcium in Physiology	519
11.2.1	Uptake and translocation	519
11.2.2	Calcium forms and contents	523
11.2.3	Biochemical functions	527
11.2.4	Calcium deficiency and disorders	531
11.2.5	Strontium	533
11.3	Liming and Calcium in Crop Nutrition	533
11.3.1	The pH effect and the calcium effect	533

11.3.2 11.3.3	Liming materials Lime application and reaction in the soil	537 538
Chapter Magnes		541
12.1 12.2 12.2.1 12.2.2 12.2.3 12.3 12.3	Soil Magnesium Magnesium in Physiology Uptake and translocation Biochemical functions Magnesium deficiency Magnesium in Crop Nutrition Crop requirements and critical levels Magnesium fertilizers	541 542 542 544 546 548 548 551
Chapte Iron	r 13	553
13.1 13.2 13.2.1 13.2.2 13.3 13.3.1 13.3.2 13.3.3	Soil Iron Iron in Physiology Uptake and translocation Biochemical functions Iron in Crop Nutrition Iron availability Lime induced chlorosis Iron application	553 556 556 560 565 565 566 570
Chapte Manga		573
14.1 14.2 14.2.1 14.2.2 14.2.3 14.3	Soil Manganese Manganese in Physiology Uptake and translocation Biochemical functions Deficiency and toxicity Manganese in Crop Nutrition	573 576 576 577 578 581

Chapter 15 Zinc 583		
15.1	Soil Zinc	585
15.2	Zinc in Physiology	586
15.2.1	Uptake and translocation	586
15.2.2	Biochemical functions	588
15.2.3	Zinc deficiency	591
15.2.4	Zinc toxicity and tolerance	592
15.3	Zinc in Crop Nutrition	593
15.3.1	Crop requirement and availability	593
15.3.2	Zinc application	596
Chante	n 16	
Chapte Copper		599
16.1	Sell Connection	500
16.1 16.2	Soil Copper	599
16.2.1	Copper in Physiology Uptake and translocation	601 601
16.2.1	Biochemical functions	602
16.2.3	Copper deficiency and toxicity	605
16.3	Copper in Crop Nutrition	607
16.3.1	Crop requirement and availability	607
16.3.2	Copper application	608
Chapte		(10
Molybo	lenum	613
17.1	Soil Molybdenum	613
17.2	Molybdenum in Physiology	614
17.3	Molybdenum in Crop Nutrition	618
Chapte	r 18	
Boron		621
18.1	Soil Boron	621
18.2	Boron in Physiology	624
18.2.1	Uptake and translocation	624
18.2.2	General aspects of boron in physiology and metabolism	627
18.2.3	Cell walls	627
18.2.4	Membrane function	628
18.2.5	Other aspects of B in biochemistry and nutrition	629

		xiii
18.2.6	Boron deficiency	631
18.3	Boron in Crop Nutrition	633
18.3.1	Availability and boron application	633
18.3.2	Crop requirement	635
18.3.3	Boron toxicity	637
Chapte	er 19	
-	er Elements of Importance	639
19.1	Chlorine	639
19.2	Silicon	643
19.3	Cobalt	649
19.4	Vanadium	654
Chapte	er 20	
Elemen	nts with More Toxic Effects	657
20.1	Iodine	657
20.2	Bromine	658
20.3	Fluorine	658
20.4	Aluminium	659
20.5	Nickel	662
20.6	Chromium	664
20.7	Selenium	665
20.8	Lead	668
20.9	Cadmium and Further Heavy Metals	670
Genera	al Readings	675
Refere	nces	695
Index		807