



UNIVERSITI PUTRA MALAYSIA

**FERTILIZER MANAGEMENT AND NUTRIENT USE BY SAGO PALM
(*METROXYLON SAGU*) ON PEAT AND MINERAL SOILS**

ADEBIYI OJO TIMOTHY VINCENT

FP 2003 27

**FERTILIZER MANAGEMENT AND NUTRIENT USE BY SAGO PALM
(*METROXYLON SAGU*) ON PEAT AND MINERAL SOILS**

By

ADEBIYI OJO TIMOTHY VINCENT

**Thesis Submitted to the School of Graduate Studies, Universiti Putra
Malaysia, in Fulfillment of the Requirement for the Degree of Doctor of
Philosophy**

February 2003



DEDICATION

This thesis is dedicated to:

Datuk Seri Dr Mahathir Mohamad, the Prime Minister of Malaysia, for his leadership quality and for being a visionary and realist to the core. He exemplified a leader with human heart and fear of GOD and he loves the well being of Malaysians. His government “good policies” stimulated a robust economy and create considerable middle class Malaysians.

The Prime Minister’s political teammates especially the Deputy Prime Minister of Malaysia, Datuk Seri Abdullah Badawi, who through their continued support and loyalty to the country made the Prime Minister’s visions to be achievable.

The Malaysians; despite their religio-cultural diversities prefer to harmonize their differences in the spirit of “Malaysia Boleh” to evolve a powerful and an economic vibrant nation.

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirement for the degree of Doctor of Philosophy

**FERTILIZER MANAGEMENT AND NUTRIENT USE BY SAGO PALM
(METROXYLON SAGU) ON PEAT AND MINERAL SOILS**

By

ADEBIYI OJO TIMOTHY VINCENT

February 2003

Chairperson: Professor Zaharah Abd Rahman, Ph.D.

Faculty: Agriculture

Earlier research on the use of fertilizer nitrogen (N), phosphorus (P) and potassium (K) to enhance the growth performance of Sago Palms (*Metroxylon sp.*) on peat could not produce any positive result despite peat being reported to be nutrient deficient. This study was carried out with the main aim of evaluating the N, P and K fertilizer use by young sago palms grown on peat and mineral soils.

The nutrient sorption study on mineral and peat soils showed that both soils interacted weakly with ammonium and potassium ions respectively. The potential buffering capacity (b-value) of the peat for ammonium and potassium ions is 6.61 and 34.09 respectively while the respective b-value of the mineral soil for the ions is 1.62 and 6.23. The mineral soil showed strong affinity for phosphate ion (P-sorption index: 1442.2; b-value for the first slope: 962.8) while

the peat soil exhibited no interaction with the ion (b-value: -0.46). Evidences from the controlled experiments showed that the poor sorption ability of peat for ammonium, potassium and phosphate ions enhances the nutrient leaching and diffusion movements within the peat medium.

Results from Experiment 5.1 in which the effect of soil type applied with three rates of N, P or K showed that soil type has significant effect on P uptake and the subsequent palm performance. The poor sorption ability of peat for phosphate ion caused P-toxicity in the palms while the palms grown on the mineral soil are not affected. For the palms grown on the mineral soil, leaflets P concentrations with the increasing rate of P applied are 0.112, 0.118 and 0.133% (Std. error: 0.004) and the corresponding dry matter yields are 339.3, 374.6 and 431.1 g/plant (Std. error: 55.1). For the palms grown on the peat soil, leaflets P concentrations are 0.237, 0.340 and 0.403% (Std. error: 0.095) and the corresponding dry matter yields are 123.9, 41.2 and 36.3 g/plant (Std. error: 22.6). Effect of P-toxicity on peat was shown by significant decline in plant height, girth size and dry matter yield with the increasing rates of P applied. It is evident in both experiments that high rate of P application was too excessive for sago palms growing in potted peat soil; a rate as low as 0.1 g P/plant at a time was adequate.

Abstrak tesis dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

**PENGURUSAN BAJA DAN KEGUNAAN NUTRIEN OLEH POKOK SAGU
(METROXYLON SAGU) DI TANAH GAMBUT DAN MINERAL**

Oleh

ADEBIYI OJO TIMOTHY VINCENT

Februari 2003

Pengerusi: Profesor Zaharah Abd Rahman, Ph.D.

Fakulti: Pertanian

Kajian terdahulu mengenai penggunaan baja nitrogen (N), fosforus (P) dan kalium (K) untuk meningkatkan pertumbuhan pokok sagu (*Metroxylon sp.*) di tanah gambut tidak menunjukkan sebarang keputusan yang positif, sungguhpun tanah gambut dilaporkan kekurangan nutrien. Kajian ini dijalankan dengan objektif utama menilai penggunaan baja N, P dan K oleh pokok sagu muda yang ditanam di tanah gambut dan tanah mineral.

Kajian serapan nutrien oleh tanah mineral dan tanah gambut menunjukkan bahawa kedua-dua jenis tanah berinteraksi lemah dengan ion ammonium dan ion kalium. Kapasiti keupayaan penampakan (nilai-b) bagi ion ammonium dan ion kalium bagi tanah gambut ialah 6.61 dan 34.09, manakala keupayaan penampakan (nilai-b) bagi tanah mineral untuk ion-ion tersebut ialah 1.62 dan 6.23. Tanah mineral menunjukkan afiniti kuat terhadap ion fosfat (Indeks

serapan-P: 1442.2; nilai-b untuk kecondongan pertama: 962.8) sementara tanah gambut pula menunjukkan tiada interaksi dengan ion tersebut (nilai-b: -0.46). Bukti dari eksperimen kawalan menunjukkan keupayaan serapan lemah terhadap ion ammonia, kalium dan fosfat oleh tanah gambut, dan dengan itu meningkatkan proses larutresap dan menyebarkan-nya didalam medium tanah gambut.

Keputusan dari kajian kesan jenis tanah yang diberikan tiga kadar N, P dan K menunjukkan kesan yang bermakna terhadap pengambilan P dan seterusnya pertumbuhan pokok. Keupayaan serapan unsur P yang lemah oleh tanah gambut menyebabkan ketoksikan-P di dalam pokok, manakala tumbuhan di tanah mineral tidak mengalami sebarang kesan. Untuk pokok yang ditanam pada tanah mineral, kepekatan P dalam daun meningkat dengan bertambahnya kadar P iaitu 0.112, 0.118 dan 0.133% dan hasil berat kering yang sejajar, iaitu 339.3, 374.6 dan 431.1 g/pokok. Bagi pokok yang ditanam di tanah gambut, kepekatan ion P dalam daun ialah 0.237, 0.340 dan 0.403% dan berat kering pokok yang sejajar ialah 123.9, 41.2 dan 36.3 g/pokok. Kesan ketoksikan P pada tanah gambut telah menyebabkan penurunan yang bererti bagi ketinggian pokok, saiz lilitan batang dan hasil berat kering dengan meningkatnya kadar baja P yang diberi. Ini telah membuktikan bahawa kadar pemberian P yang tinggi adalah terlalu tinggi untuk tanaman sago yang ditanam pada tanah gambut dalam pasu. Kadar serendah 0.1 g P/pokok pada satu-satu masa adalah mencukupi.

ACKNOWLEDGEMENTS

I wish to sincerely thank Prof. Dr. Zaharah Abdul Rahman for giving me the opportunity to do my Ph.D. research under her supervision. I appreciate the care and the contributions towards the success of the programme.

Also, I wish to express my thankfulness to the other members of my supervisory committee, Assoc. Prof. Dr. Ahmad Husni Mohd Hanif and Assoc. Prof. Dr. Anuar Abdul Rahim, for their support and contributions.

I am indebted to the Universiti Putra Malaysia for granting admission and facilities and awarding a fellowship. I also thank the Sponsor of the Project for providing the Research Grant.

I wish to express my heartfelt thankfulness to Dr. Nteranya Sanginga (IITA, Ibadan, Nigeria) without whom it is unlikely for me to go this far. I thank him for his strong recommendation and goodwill. I also wish to express my heartfelt thankfulness to Dr. Bernard Vanlauwe (IITA, Ibadan, Nigeria) for his recommendation and goodwill.

My sincere thankfulness also goes to Dr. G.O. Adeoye (Faculty of Agriculture, University of Ibadan, Nigeria) for his goodwill and recommendation.



I am eternally grateful to Dr. Marie Kristen Van der Meersch (formerly of IITA, Ibadan, Nigeria) who supported me financially during my Undergraduate years. I am also grateful to Dr. Sally Liya for her goodwill and encouragement and for the financial supports given to me.

I thank Assoc. Prof. Dr. Raha Abdul Rahim (Microbial Molecular Biology Laboratory, Department of Biotechnology, Faculty of Food Science and Biotechnology) for allowing me access to her laboratory. I am also grateful to her assistant, Pn. Ernie Eileen Rizlan Ross.

I thank my friend, Mr. Linton Britten, for his numerous assistance and companionship.

I am grateful to Pn. Zabedah Timirin, Mr. Abdul Rahim bin Utar, Mr. Jamil Bin Omar, Pn. Faridah bt. Aman, Mr. Zainudin bin Mohd. Ali, and Pn. Fouzaiah bt. Sulaiman of the Department of Land Management and the entire staff in the departmental office, who one way or the other assisted me during the programme. I also thank Mr. Mohd Shahril bin Ab Rahman of Ladang 2 and the entire staff of Faculty of Agriculture and of School of Graduate Studies.

I am indebted to my friends, Mr. Patrick Olusoga and Mr. Samuel Ojo (IITA, Ibadan), for standing by me and my family, for their words of encouragement and prayers.



TABLE OF CONTENTS

		Page
DEDICATION		2
ABSTRACT.....		3
ABSTRAK.....		5
ACKNOWLEDGEMENTS.....		7
APPROVAL.....		9
DECLARATION.....		11
TABLE OF CONTENTS.....		12
LIST OF TABLES.....		16
LIST OF FIGURES.....		22
CHAPTER		
1	INTRODUCTION	25
2	LITERATURE REVIEW	29
2.1	Sago Palms Cultivation in Malaysia	29
2.1.1	The Sago Palm	29
2.1.2	Renewed Interest in Sago Cultivation	31
2.1.3	Geographical Distribution of Sago Palms	33
2.1.4	Soil Type of Sago Areas	33
2.1.5	Sago Performances	34
2.1.6	Common Features of Sago-Growing Areas	34
2.1.7	Previous Fertilizer Trials	35
2.2	Peat Lands of Malaysia	36
2.2.1	Geographical Distribution	36
2.2.2	Peat Soils and Peat Lands: Their Properties and Classification	36
2.2.3	Nutritional Status of Peat Lands	39
2.3	Fertilizer Use	39
2.3.1	The Necessity for Using Fertilizers	39
2.3.2	Concept in Fertilizer Use	40
2.3.3	Soil Nutrient Availability Indexes	41
2.3.4	Assessment of Soils Fertilizer Requirements	44
2.3.5	Nutrient-Use Efficiency	47
2.3.6	Fate of Applied Fertilizer Nutrients	49
3	MATERIALS	50
3.1	Soils Collection, Preparation and Characterizations	50
3.1.1	Sites of Collection	50
3.1.2	Soil Preparation	50

3.1.3	Physico-Chemical Characterization	51
3.2	Preliminary Growing of Sago Seedlings inside Screen House	58
3.3	Preparation of ³² P-Labeled SSP from Phosphate Rock	60
3.4	Preparation of Micro-Nutrient Solution	61
4	NUTRIENT SORPTION STUDIES	62
4.1	Introduction	62
4.2	Literature Review	62
4.3	Materials and Method	65
4.3.1	Experiment 4.1: Rate of Nutrient Sorption	65
4.3.2	Experiment 4.2: Nutrient Sorption Isotherms	66
4.3.3	Determinations and Measurements	67
4.4	Results	69
4.4.1	Rate of Nutrient Sorption	69
4.4.2	Nutrient Sorption Isotherms	71
4.4.3	Langmuir's Plots	78
4.5	Discussion	81
4.6	Conclusion	85
5	EFFECT OF SOIL TYPE ON SAGO PALM PERFORMANCE WITH DIFFERENT RATES OF NITROGEN, PHOSPHORUS AND POTASSIUM IN FREELY DRAINED SYSTEM	86
5.1	Introduction	86
5.2	Literature Review	86
5.3	Materials and Method	88
5.3.1	Experiment 5.1: Non-Isotopic Studies	88
5.3.2	Experiment 5.2: Isotopic Studies	94
5.4	Results	99
5.4.1	Nutrient Concentration in Palm Tissues	99
5.4.2	Palm Height and Girth size	104
5.4.3	Dry Matter Yield	107
5.4.4	Nutrient Yield in Palm Tissue	110
5.4.5	Isotopic Studies	114
5.5	Discussion	117
5.5.1	General Observation on Sago Palms Performance	117
5.5.2	Phosphorus Nutrition	119
5.5.3	Nitrogen Nutrition	127
5.5.4	Potassium Nutrition	131
5.6	Conclusion	134
6	EFFECTS OF FERTILIZER RATE AND DEPTH OF WATER TABLE ON NUTRIENT TRANSPORT AND PERFORMANCE OF SAGO PALM GROWN ON PEAT SOIL	137
6.1	Introduction	137
6.2	Literature Review	138

6.3	Materials and Method	148
6.3.1	Experiment 6.1	148
6.3.2	Experiment 6.2	153
6.3.3	Experiment 6.3	155
6.3.4	Experiment 6.4	156
6.4	Results	158
6.4.1	Experiment 6.1 – Water Data	158
6.4.2	Experiment 6.2	168
6.4.3	Experiment 6.3	186
6.4.4	Experiment 6.4	196
6.5	Discussion	210
6.5.1	Fertilizer Nutrients Transport in Peat Soil	210
6.5.2	Effects of Fertilizer Rate and the Depth of Water Table on the Solution Concentration of Nutrients	217
6.5.3	Nutrient Uptake by the Growing Sago Palms	226
6.5.4	Effects of N Rate and Depth of Water Table on Sago Palm Performance and the N Use Efficiency	237
6.5.5	Effects of P Rate and Depth of Water Table on Sago Palm Performance and the P Use Efficiency	243
6.5.6	Effect of K Rate on Tissue Concentration of K and Sago Palm Performance	250
6.6	Conclusion	251
7	GENERAL DISCUSSION	259
7.1	Soil-Nutrient Interaction	259
7.1.1	Results from the Nutrient Sorption Study	260
7.1.2	General Implications of the Poor Soil-Nutrient Interaction	261
7.2	Effect of Fertilizer Rate on Sago Performance and the Nutrient yield	268
7.2.1	Effect of N Rate	268
7.2.2	Effect of K Rate	270
7.2.3	Effect of P Rate	270
7.3	Effect of Depth of Water Table on Sago Performance	273
7.4	Constraints to the Use of N, P and K Fertilizers for Sago Production on Peat Land	274
7.5	Fertility Status of Peat Lands, Problems with its Assessment and Nutrient Supplying Characteristics of Peat Lands	281
7.5.1	Technical Errors Associated with the Use of Conventional Indexes of Fertility for Wetlands	284
7.5.2	Evidences that Show Fertility Status of Peat Lands was Being Grossly Underrated	287
7.5.3	Nutrient Transport Within Peat Land System	294

7.5.4	Assessment of Nutrient Supply Characteristics of Peat Land	297
7.5.5	Parameters Affecting Nutrient Movement in the Rhizosphere	300
7.5.6	Parameters Affecting Nutrient Absorption by Plant Roots	303
	Conclusion	305
8	GENERAL CONCLUSION AND SUMMARY	311
	REFERENCES	320
	VITA	330

LIST OF TABLES

Table	Page	
2.1	Distribution of peat land areas by states in Malaysia	36
3.1	Soil physical and chemical characterization	59
3.2	Chemical properties of peat soil – proportion of the total in available form	60
4.1	Rate studies- concentration used and times of equilibration	66
4.2	Sorption isotherm studies- concentrations used and period for equilibration	67
4.3	Adsorption maxima (K_2) and binding energy constants (K_1) described by linear Langmuir plots shown in Figure 4.6 for ammonium, phosphate and potassium interactions with the mineral and peat soils	80
4.4	Comparison of the soils potential buffering capacities (PBC) for the nutrients (slopes from Figures 4.2 - 4.5)	83
4.5	Values of labile nutrient estimated with Q/I curves compared with the corresponding values obtained with the normal extraction methods (according to Sparks and Huang, 1982)	84
5.1	Fertilizers application and timing	91
5.2	The effects of soil type and fertilizer rate on nitrogen concentration of palm tissues	100
5.3	The effects of soil type and fertilizer rate on phosphorus concentration of palm tissues	102
5.4	The effects of soil type and fertilizer rate on potassium concentration of palm tissues	103
5.5	The effects of soil type and fertilizer rate on palm height	105
5.6	The effects of soil type and fertilizer rate on girth size at harvest	107
5.7	The effects of nitrogen rate and soil type on palm dry matter yield	108

		17
5.8	The effects of phosphorus rate and soil type on palm dry matter yield	109
5.9	The effects of potassium rate and soil type on palm dry matter yield	110
5.10	The effects of soil type and fertilizer rate on total nitrogen yield in above soil surface portions of sago palm	111
5.11	The effects of soil type and fertilizer rate on total phosphorus yield in above soil surface portions of sago palm	112
5.12	The effects of soil type and fertilizer rate on the total potassium yield in above soil surface portions of sago palm	114
5.13	Dry weight and nitrogen content of the palms used for ¹⁵ N studies	115
5.14	¹⁵ N Studies – Effect of soil type on nitrogen derived from fertilizer, fertilizer N-yield and fertilizer N-use efficiency in palm parts	116
5.15	Height, base circumference, dry weight and phosphorus content of the palms used for ³² P studies	117
5.16	³² P Studies – Effect of soil type on phosphorus derived from fertilizer, fertilizer P-yield and fertilizer P-use efficiency in palm parts	117
6.1	Fertilization schedule used in Experiment 6.1. The values given for each nutrient are its equivalent amounts in the respective fertilizer used per bag of soil	150
6.2	Fertilization schedule used in Experiment 6.2. The value given for each rate is the equivalent amount of nutrient in the respective fertilizer used expressed in grams nutrient per bag of soil	153
6.3	The total amount of labeled nitrogen added and the respective average percent N15 atom excess for each rate	154
6.4	Fertilization schedule used in Experiment 6.3. The value given for each rate is the equivalent amount of nutrient in the respective fertilizer used expressed in grams nutrient per bag of soil	155

6.5	Fertilization schedule used in Experiment 6.4. The amount of each nutrient given is the rate expressed in grams per bag of soil. P32-labelled Single Super-Phosphate was administered on 27 th October to all treatments	157
6.6	Concentration of ammonium ion in soil water at 10, 25 and 40 cm water table. $\Delta 1$, $\Delta 2$ and $\Delta 3$ are differences between sampling times	159
6.7	Concentration of nitrate ion in soil water at 10, 25 and 40 cm water table. $\Delta 1$, $\Delta 2$ and $\Delta 3$ are differences between sampling times	161
6.8	Concentration of phosphate ion in soil water at 10, 25 and 40 cm water table. $\Delta 1$, $\Delta 2$ and $\Delta 3$ are differences between sampling times	163
6.9	Concentration of potassium ion in soil water at 10, 25 and 40 cm water table. $\Delta 1$, $\Delta 2$ and $\Delta 3$ are differences between sampling times	165
6.10	Electrical conductivity of soil water at 10, 25 and 40 cm water table. $\Delta 1$, $\Delta 2$ and $\Delta 3$ are differences between sampling times	167
6.11	Effect of N rate on the apparent amount of ammonium and nitrate ions released from urea (or taken up by palms). Amount of each nutrient is expressed in concentration unit	172
6.12	Effect of N rate on nitrogen concentration of palm parts at different depth of water table	175
6.13	Effect of N rate on palm height at different depths of water table	176
6.14	Effect of N rate on girth size and average counts of live frond at harvest under different depths of water table	177
6.15	Effect of N rate on the dry matter yield of palm parts with respect to the depth of water table	179
6.16	Summary of the overall effect of N rate	179
6.17	Summary of the overall effect of water depth	180
6.18	Effect of N rate on nitrogen yield of palm parts at different depths of water table	181

6.19	Effect of N rate on nitrogen derived from ¹⁵ N-labeled fertilizer in palm parts at different depths of water table	182
6.20	Effect of N rate on ¹⁵ N-labeled nitrogen fertilizer yield in palm parts at different depths of water table	183
6.21	Effect of N rate on ¹⁵ N-labeled fertilizer nitrogen recovered in palm parts at different depths of water table (palm portion above soil surface only)	184
6.22	The overall effect of N rate on nitrogen yield and recovery in the above soil surface portion of sago palms. Comparison of ¹⁵ N-isotopic with non-isotopic studies	185
6.23	The overall effect of water depth on ¹⁵ N-labeled fertilizer nitrogen yield and recovery in the above soil surface portion of sago palms	185
6.24	Effect of P rate on the apparent amount of phosphate ion released and taken up by palm. Amount of phosphate ion is expressed in the unit of concentration	189
6.25	Effect of P rate on phosphorus concentration of palm parts at different depths of water table	191
6.26	Effect of P rate on palm height, girth size and average counts of live frond at harvest under different depths of water table	192
6.27	Effect of P rate on the dry matter yield of palm parts under different depths of water table	194
6.28	Effect of P rate on phosphorus yield of palm parts under different depths of water table	195
6.29	Summary of the overall effect of P rate applied	196
6.30	Summary of the overall effect of water depth	196
6.31	Effects of fertilizer rate and palm uptake on changes observed in nutrient concentration in soil water	200
6.32	Effect of fertilizer rate on phosphorus concentration of palm parts	203
6.33	Effect of fertilizer rate on potassium concentration of palm parts	203

		20
6.34	Effect of fertilizer rate on palm height, girth size and average counts of live and dead frond at harvest	204
6.35	Effect of fertilizer rate on dry matter yield	205
6.36	Effect of fertilizer rate on phosphorus yield of palm parts	206
6.37	Effect of fertilizer rate on potassium yield of palm parts	206
6.38	Effect of fertilizer rate on phosphorus derived from ³² P-labeled fertilizer in palm parts	207
6.39	Effect of fertilizer rate on ³² P-labeled fertilizer P yield in palm parts	208
6.40	Effect of fertilizer rate on ³² P-labeled fertilizer phosphorus recovered in palm parts	209
6.41	Effect of P rate on phosphorus yield and %recovery in the above soil surface portion of sago palms. Comparison of isotopic and non-isotopic studies	209
6.42	Diffusion coefficients for diffusion of ions in solution and soils	228
6.43	Possible mechanism of P influx into sago roots with respect to the observed solution concentration range – Experiment 6.2	232
6.44	Possible mechanism of P influx into sago roots with respect to the observed solution concentration range – Experiment 6.3	232
6.45	Possible mechanism of influx of each nutrient into sago roots with respect to the observed solution concentration – Experiment 6.4	233
7.1	³² P-isotopic studies: Comparison of the effects of soil type, constrained condition and P-rate on the recovery of the ³² P-labeled P applied	265
7.2	¹⁵ N-isotopic studies: Comparison of the effects of soil type, constrained condition* and N-rate on the recovery of the ¹⁵ N-labeled N applied	269
7.3	Average monthly rainfall (mm) at Jenderata Estate U.P. (20 years). Source: Kanapathy, 1984	276

7.4	Nutrient solution concentration of peat soil when extracted with water and 0.01M CaCl ₂ solution	280
7.5	Properties of the surface layer (0-25 cm) of the main sago-growing soils in Mukah and Oya-Dalat areas (Tie et al., 1991)	287
7.6	Amounts of fertilizers added per year (PORIM recommendation for use for oil palm production on peat land)	300
7.7	Some features of peat land that affect its fertility status and the processes that enhance nutrient release and accessibility to plant	306
7.8	Nitrogen forms and sources in peat land, modes of its release and factors affecting its quantity, availability and transport to plant roots	308
7.9	Phosphorus forms and sources in peat land, modes of its release and factors affecting its quantity, availability and transport to plant roots	309
7.10	Potassium forms and sources in peat land, modes of its release and factors affecting its quantity, availability and transport to plant roots	310

LIST OF FIGURES

Figure		Page
2.1	Sago palms- <i>Metroxylon sp.</i>	30
4.1	Kinetic of disappearance of (a) ammonium-, (b) phosphate-, and (c) potassium ions with mineral and peat soils. C_0 is the initial concentration of each ion in the equilibrating solution	70
4.2	Ammonium sorption studies on the mineral and peat soils- ammonium concentration of equilibrated solution (N_e) plotted against (a) ammonium concentration of solution added and (b) rate of ammonium added in nitrogen per kilogram soil; (c) sorption isotherms (N_s is the amount of ammonium adsorbed or desorbed)	73
4.3	Phosphate sorption studies on the mineral and peat soils- phosphate concentration of equilibrated solution (P_e) plotted against (a) phosphate concentration of solution added and (b) rate of phosphate added in phosphorus per kilogram soil; (c) sorption isotherms (P_s is the amount phosphate adsorbed or desorbed)	75
4.4	Potassium sorption studies on the mineral and peat soils- potassium concentration of equilibrated solution (K_e) plotted against (a) potassium concentration of solution added and (b) rate of potassium added in potassium per kilogram soil; (c) sorption isotherms (K_s is the amount of potassium adsorbed or desorbed)	77
4.5	Quantity-Intensity (Q/I) plots for potassium	78
4.6	Sorption data for the mineral and peat soils fitted into Langmuir equation- (a) ammonium, (b) phosphate, and (c) potassium	79
5.1	Total dry matter yield in relation to phosphorus concentration in leaflets and rachis of sago palm grown on peat soil	124
6.1	Processes of nutrient transformation within peat soil	138
6.2	Setup of the experiment with the polybags containing peat soil fitted into plastic buckets. Four holes were drilled around each bucket to mark the depth of water table from soil surface	149

6.3	Concentration dynamics of ammonium in soil water as affected by the rate of N and palms uptake at different depths of water table. Each error bar is twice the standard error of least square means	169
6.4	Concentration dynamics of nitrate in soil water as affected by the rate of N and palms uptake at different depths of water table. Each error bar is twice the standard error of least square means	170
6.5	Combined effect of P rate and palm uptake on dynamics of phosphorus concentration in soil water at different depths of water table. Each error bar is twice the standard error of least square means	187
6.6	Combined effect of nitrogen rate and palm uptake on ammonium concentration in soil water. Error bar is twice the standard error of least square means	197
6.7	Combined effect of nitrogen rate and palm uptake on nitrate concentration in soil water. Error bar is twice the standard error of least square means	197
6.8	Combined effect of phosphorus rate and palm uptake on phosphate concentration in soil water. Error bar is twice the standard error of least square means	198
6.9	Combined effect of potassium rate and palm uptake on potassium concentration in soil water. Error bar is twice the standard error of least square means	198
6.10	Effect of rate of nitrogen and the depth of water table on nitrate and ammonium concentrations (means for samplings at 2 nd , 6 th , 10 th , and 14 th weeks)	220
6.11	Effect of rate of potassium and the depth of water table on potassium concentration	224
6.12	Effect of potassium concentration on the electrical conductivity of soil water at different sampling times	225
6.13	The effect of palm performance on the ammonium concentration in soil water. Comparison among replicates that received the same rate of N	235

6.14	Comparison of phosphate concentration in soil water among replicates that received the same rate of N and P and the subsequent dry matter yield	236
6.15	Effect of P concentration in leaflets on total dry matter yield (Experiment 6.2)	239
6.16	The relationship between P concentration in leaflets and N use efficiencies of sago palms	240
6.17	The effect of increasing concentration of phosphorus in palm tissue on the dry matter yields (Experiment 6.3)	247
6.18	Effect of increasing phosphorus concentration in palm tissue on the dry matter yield (Experiment 6.4)	248
6.19	Effect of increasing potassium concentration in palm tissue on the dry matter yield	251
7.1	The effect of P-rate on sago palm performances (palm height, number of fronds and leaflets) on peat soil	271
7.2	The effect of P-rate on sago palm performances on the mineral soil	271
7.3	Response curves with respect to tissue P concentrations. "Critical" tissue P concentration for the respective tissue is assumed to be that at which highest yield was obtained with the mineral soil	272
7.4	Wetland compared with upland (hypothetical)	285
7.5	Vertical section of hypothetical hydromorphic soils of sago areas. Arrows showing the directions of nutrient mobility by diffusion	289
7.6	Yellowing of leaflets of sago plants in the constrained experiment	299