EVALUATION OF PIGEON PEA [*CAJANUS CAJAN* (L.)] VARIETIES AND PHOSPHORUS FERTILISATION ON DROUGHT TOLERANCE MECHANISMS, GRAIN YIELD AND NUTRITIONAL VALUE UNDER NO-TILL IN A SMALLHOLDER FARMING SYSTEM OF SOUTH AFRICA

By

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THESIS

Submitted in Fulfilment of the requirements for the degree of

DOCTOR OF PHILOSOPHY IN AGRICULTURE (PLANT PRODUCTION)

In the

FACULTY OF SCIENCE AND AGRICULTURE

(School of Agricultural and Environment Sciences)

At the

UNIVERSITY OF LIMPOPO

SUPERVISOR : PROF KK AYISI

2023

DECLARATION

I, Sanari Chalin Malele declare that **the thesis** hereby submitted to the University of Limpopo, for the degree of DOCTOR OF PHILOSOPHY IN AGRICULTURE (PLANT PRODUCTION) has not previously been submitted by me for a degree at this or any other university; that it is my work in design and in execution, and that all material contained herein has been duly acknowledged

Malele SC   Date

ACKNOWLEDGEMENTS

Firstly, I would like to thank the Almighty God for His Grace and unconditional love, thank you for protecting me and my family during my studies. I will not be able to finish without YOU, my LORD. My sincere gratitude and appreciation to my supervisor, Prof. Ayisi K.K., for his patience, guidance, and encouragement, which kept me throughout my journey. Thank you for taking me as your student, and I am grateful for the knowledge that I gained from you. During my studies, I lost my co-supervisor, Dr. Mofokeng Alina (ARC-GCI). I hope you have rested in perfect peace. I would like to thank you for believing in me and also for the opportunity and support that you gave me during my studies. I would like to thank Dr. Munjonji Lawrence, Mashao Frederick (RVSC-VLIR), and Dr. Mathobo R (LDARD), for the comments, advice, guidance, and support that I have received from you. Itemeleng Ba- Makhutjwe primary cooperative (Ofcolaco) and Mohlala farm (Zoeknog), thank you for allowing me to conduct the research trials on your farm and taking care of the research trials.

I would like to take this opportunity to thank my former Deputy Director from the Limpopo Department of Agriculture and Rural Development (LDARD)-Maruleng local Agricultural office, Mrs. Dipela Anna Morotha, for allowing me to further my studies and also to work on research activities in LDARD-Maruleng. May the Good Lord Almighty shower you with blessings. Dr. Ndou Dimakatso, I thank you for your encouragement, motivation, and moral support.

My gratitude goes to Ms. Khoza Joysephine and Lehutjo Carol for all the administrative work, logistic arrangements, and support that I have received during my studies. Mr. Mabitsela Nkabisheng and the research technical team, thank you for the research trials establishment, data collection, and traveling from Polokwane to Zoeknog was not easy, but you have never complained. I would like to thank Mr. Zwane Pumulane for assisting me with the study area maps. A special thank you goes to Sesi Florah (RVSC-VLIR) and Maite (Kleentech), for allowing me to stay at VLIR accommodation during my studies, To my fellow PhD students, Dr. Mogale Queen, thank you for the assistance, moral support, fruitful advice, comments, and consistent encouragement. If it was not for you, I wouldn't have managed to complete my studies. May the Mighty God grant you what your heart desire. Dr. Motshega Lesego, for the consistent support that you gave me, even though sometimes I felt like I would shatter into pieces, you kept on giving me the support that I needed the most. Dr. Mokoka Vincent, thank you for the moral support and for ensuring that we share information and challenges. To my colleagues (Mhlanga PB, Baloyi KD, Raseasala MJ, Mokgope PK, Maponya TP, and Lebea TJ), thank you for the support that I have received during my studies. I would like to appreciate Mr. Mphokane MM for assisting me with the experimental site at Zoeknog, the survey in Mpumalanga, and all the traveling that you did to ensure that I complete my studies.

I have no words to express my gratitude to my husband, Diboneng Ridwel Malele, for your love and consistent support. You have never complained about my studies, traveling (data collection, writing retreat, and training), housework, or taking care of the children. I will always cherish the love that you have shown during my journey. To my brothers and sisters, especially my big brother Eliazara Moriri, thank you for your prayers and encouragement. Thabo Moriri, for taking care of O’mphile when I was at the university. Martha, Kedibone, and Kgaudi thank you so much for the love and support that you gave O’mphile when I was away during my studies. During my journey, I have also lost my aunt Mmamphiri Agnes Mohuba, my Niece Kgolofelo Hope Rangongo and my brother-in-law Norman Malele, I hope you are very proud of what I have achieved.

To my two daughters, Thato Theola and O’mphile Tshiamo, for your patience and understanding especially when I was away to fulfill my studies. Hoping that the PhD study will encourage both of you to reach your goals in life.

Finally, I would like to acknowledge the Risk and Vulnerability Science Centre (RVSC) at the University of Limpopo for support of the study and the Department of Science and Innovation (DSI) through the National Research Foundation (NRF) for funding the study.

DEDICATION

This PhD study is dedicated to my late mother in heaven Sophy Mmantabe Moriri, you wanted the best for me and you worked very hard for what I am today, and will be forever grateful. I hope you are dancing with the angels in heaven, ‘’Alleluya!! Thank YOU Jesus”, because I have fulfilled your wish. Now you can rest in peace, my lovely mother.

And also to my two daughters, Thato Theola and Omphile Tshiamo I have no regrets to call you my Angel and Bella.

TABLE OF CONTENTS

DECLARATION ii

ACKNOWLEDGEMENTS iii

DEDICATION v

LIST OF TABLES xiv

LIST OF FIGURES xvi

LIST OF ACRONYMS AND ABBREVIATIONS xx

LIST OF MANUSCRIPTS IN PREPARATION xxi

THESIS STRUCTURE xxiii

THESIS ABSTRACT xxv

CHAPTER 1: : GENERAL INTRODUCTION 1

1.1 Problem statement 3

1.2 Motivation for the study 4

1.3 Aim of the study 5

1.4 Hypotheses 6

CHAPTER 2: LITERATURE REVIEW 7

2.1 Introduction 7

2.2 Pigeon pea distribution, taxonomy, and origin 7

2.3 Utilisation of pigeon pea 8

2.3.1 Fodder: 8

2.3.2 Conservation: 9

2.3.3 Human consumption: 9

2.3.4 Nutritional value 10

2.3.5 Medicinal value: 10

2.3.6 Litter and firewood: 11

2.4 Economic potential of pigeon pea production 11

2.5 Pigeon pea genotypes and maturity durations 12
2.6 Environmental factors affecting legumes production 14
2.6.1 Water: 14
2.6.2 Temperature: 15
2.6.3 Photoperiod: 15
2.6.4 Soils: 16
2.7 Impact of climate change on pigeon pea production 17
2.8 Physiological processes of pigeon pea and other leguminous crops 17
2.9 Phosphorus input in smallholder farmer fields 18
2.10 Response of legume crops to p fertilizer application 19
2.11 Biological Nitrogen Fixation (BNF) in legumes 21
2.13 Effect of tillage systems on legumes production 22
2.14 Pigeon peas production in cropping systems 22
2.15 Phosphorus fertilizer application and genotype on nutritional value of pigeon pea 24
2.16 Concluding remarks 24
Chapter 3: 26
Chapter 3a: THE STATUS OF PIGEON PEAS [CAJANUS CAJAN (L.) MILLSPAUGH] PRODUCTION IN LIMPOPO AND MPUMALANGA PROVINCES OF SOUTH AFRICA: FARMER PRACTICES, UTILIZATION, AND POTENTIAL MARKETS 26
Abstract 26
3.1 Introduction 27
3.2 Material and methods 29
3.2.2 Procedure for sampling and administration of questionnaires 30
3.3 Results 34
3.3.1 Farmers’ category in pigeon peas production 34
3.3.2 Land size allocation for pigeon peas production 34

3.3.3 Pigeon peas production sites 35

3.3.4 Pigeon peas variety used by farmers 36

3.3.5 Pigeon peas seed source for farmers 37

3.3.8 Weed control methods used by pigeon peas farmers 39

3.3.9 Pigeon pea farmers' use of soil fertility improvement 40

3.3.10 Farmers' preferences for pigeon pea products 41

3.3.12 Utilization of pigeon pea processed products 41

3.3.13 The utilization of pigeon peas 42

3.3.14 Access to pigeon pea agro-processing information 43

3.3.15 Farmers' source of information 43

3.3.16 Socio-economic characteristics of pigeon pea farmers 44

3.4 Discussion 47

3.4.12 Pigeon pea status in the two Provinces at the moment 47

3.4.13 Pigeon pea production practices: 48

3.4.14 Farmers' knowledge of pigeon pea utilization 50

3.5 Conclusion 52

CHAPTER 3.B: PIGEON PEA [CAJANUS CAJAN (L.) Millsp.] RISKS MANAGEMENT STRATEGIES FOR SMALLHOLDER FARMERS IN SOUTH AFRICA 55

Abstract 55

3.1b Introduction 56

3.2b Material and methods 58

3.3b Results 58

3.3.3 Natural factors affecting pigeon production 62

3.4B Discusion 68

3.5B Conclusion 73

Chapter 4: RESPONSE OF PIGEON PEA [CAJANUS CAJAN (L.) Millspaugh] BIOMASS PRODUCTION, PHOSPHORUS YIELD,

PHOSPHOROUS RECOVERY EFFICIENCY, AND GRAIN YIELD TO PHOSPHORUS FERTILIZATION UNDER RAINFED NO-TILL SMALLHOLDER FARMING SYSTEM 76

Abstract 76

4.1 Introduction 77

4.2 Material and Methods 79

4.2.1 Study area 79

4.2.2 Field management 80

4.2.3 Experimental layout 81

4.2.4 Soil sampling procedures 82

4.2.5 Plant sampling procedures 83

4.2.6 Determination of stem diameter 83

4.2.7 Plant height 84

4.2.8 Chlorophyll content of leaves 84

4.2.9 Determination of P yield in plant tissue 84

4.2.10 Phenological variables 85

4.2.11 Grain yield and yield components 85

4.2.12 Statistical analysis and interpretation of data 86

4.3 Results 86

4.3.1 Rainfall, evapotranspiration, and temperatures during the growing seasons 86

4.3.2 Pigeon pea shoot biomass production 88

4.3.3 Pigeon pea stem growth (mm) 91

4.3.4 Plant height in pigeon peas 93

4.3.5 Chlorophyll concentration in pigeon peas 95

4.3.6 Phosphorus yield in pigeon pea plant tissue 98

4.3.7 PRE in Pigeon pea (%) 99

4.3.8 Phenological variables response to treatments 101

4.3.9 Grain yield production of the pigeon pea variety 103
4.3.10 Yield components 104
4.3.11 Harvest index 107
4.3.12 Correlations between pigeon pea grain yield and yield components 109
4.4 Discussion 114
4.4.1 Effect of variety on biomass production 114
4.4.2 Effects of P fertilizer application and their interaction with shoot biomass production 115
4.4.3 Pigeon pea variety effect on stem diameter 115
4.4.4 Effects of different pigeon pea varieties on plant height 116
4.4.5 Effect of P fertilizer application on pigeon pea plant height 117
4.4.6 Chlorophyll content in pigeon pea varieties. 117
4.4.7 Effect of P on chlorophyll content 118
4.4.8 Phosphorus yield in plant tissue is influenced by variety. 118
4.4.9 Phosphorus fertilizer application rates effects on plant tissue P yield 119
4.4.10 Varietal effect on PRE 120
4.4.11 Phosphorus fertilizer application affects phosphorous recovery efficiency 120
4.4.12 Effect of variety on pigeon pea phenological variables 121
4.4.13 Varietal response to grain yield production 122
4.4.14 The impact of P fertilizer application on grain yield 123
4.4.15 Grain yield components as influenced by a variety 124
4.4.16 The effect of the harvest index on pigeon pea varieties 124
4.4.17 Effect of P fertilizer on harvest index 125
4.4.18 Correlations between pigeon pea grain production, phenotypic and yield component variables 126
4.5 Conclusion 126

Chapter 5: DROUGHT TOLERANCE ATTRIBUTES FOR PIGEON PEA [CAJANUS CAJAN (L.) Millspaugh] VARIETIES AND P-FERTILIZERS THROUGH ROOTS BIOMASS PRODUCTION, STOMATAL CONDUCTANCE, AND WATER USE EFFICIENCY IN DIVERSE AGRO-ECOLOGICAL ZONES 129

Abstract 129

5.1 Introduction 130

5.2 Materials and methods 133

5.2.1 Study Area 133

5.2.2 Roots biomass production 133

5.2.3 Determination of pigeon pea root length 133

5.2.4 Determination of the root-shoot ratio 134

5.2.5 Measurements of leaf gaseous exchange 134

5.2.6. Determination of Water-use efficiency (WUE) 134

5.2.7 Gravimetric moisture content (%) 135

5.2.8 Statistical analysis and interpretation 135

5.3 Results 136

5.3.1 Rainfall, evapotranspiration, averaged maximum and minimum temperatures (°C) 136

5.1.2 Pigeon pea root biomass production (kg ha^{-1}) 138

5.1.3 Pigeon pea root growth 141

5.1.4 Root-shoot ratios 143

5.3.5 Effect of gravimetric soil moisture content 147

5.3.6 Effect on leaf gaseous exchange parameters 151

5.3.7 Intrinsic and instantaneous WUE of pigeon peas 161

5.3.8 The interaction effect of pigeon pea variety and P fertilizer application on intrinsic and instantaneous WUE 163

5.3.9 Relationship between leaf transpiration and stomatal conductance, photosynthesis rate, and intercellular CO_2 concentration. 165

5.4 Discussion 167

5.4.1 Influence of pigeon pea variety on root biomass, and root length........... 167

5.4.2 Effect of P fertilizer application rates and growth stages (P x DAP) on root biomass and length of pigeon peas 168

5.4.3 Influence of pigeon pea variety on the root-shoot ratio (RSR) 168

5.4.4 Phosphorus fertilizer effects and growth periods on the root-shoot ratio 169

5.4.5 Varietal effect on gravimetric soil moisture content................................ 169

5.4.6 The interaction effect of P fertilizer and growth stages in gravimetric soil moisture.. 170

5.4.7 Varietal effects on leaf gas exchange 170

5.4.8 Phosphorus fertilizer application and interaction of V x P effects on leaf gaseous exchange.. 174

5.4.9 intrinsic WUE 175

5.4.10 Instantaneous WUE 175

5.4.11 The interaction effects of V x P on intrinsic and instantaneous WUE............... 176

5.5 Conclusion.. 176

Chapter 6: NITROGEN and PHOSPHORUS YIELD, NUTRITIVE VALUE, AND RESIDUAL SOIL NUTRIENTS OF PIGEON PEA [CAJANUS CAJAN (L.) MILLSPAUGH] AS INFLUENCED BY VARIETY AND Phosphorus APPLICATION UNDER NO-TILL SYSTEM AND DRYLAND CONDITIONS . 178

Abstract 178

6.1 Introduction... 178

6.2 Material and methods 180

6.2.1 Study area 180

6.2.2 Determination of N yield in plant tissue... 180

6.2.3 Determination of P and nutritive value in grains..................................... 181

6.2.4 Mineral and trace elements determination in pigeon pea grains............. 181

6.2.5 Soil sampling for chemical analyses at harvest 182

6.2.6 Data analysis and interpretation 182

6.3 Results.. 183

6.3.1 Accumulation of N in pigeon pea plant tissue 183

6.3.2 Phosphorus yield in pigeon pea grains 185

6.3.3 Nutritive value of pigeon pea grains... 186

6.3.4 Mineral elements in pigeon pea grain as a result of a variety 193

6.3.5 Effects of variety, P fertilizer application rates, and V x P interaction on residual soil nutrients content after crop harvest.. 196

6.3.6 Minerals and trace elements after crop harvest 197

6.4 Discussion 200

6.4.1 Nitrogen yield in plant tissue 200

6.4.2 Phosphorus yield in grains... 200

6.4.3 Nutritive value on pigeon pea grains... 201

6.4.4 Minerals and microelements in pigeon pea grains.................................. 202

6.4.5 Residual soil nutrients after experimentation 202

6.5 Conclusion.. 203

Chapter 7: GENERAL CONCLUSIONS AND RECOMMENDATIONS.......... 205

REFERENCES 211

Appendices 232

LIST OF TABLES

Table 2.1 Pigeon pea maturity duration 13

Table 3.1 Geographical coordinates, altitude, daily mean temperatures, and mean annual rainfall of the six municipalities of the two Provinces of South Africa. 32

Table 3.2 Frequency and percentage of socio-economic characteristics in pigeon pea production and their relationship with other variables 46

Table 3.3 Socio-demographic characteristics of six municipalities in six municipalities of South Africa 61

Table 4.1 The factorial arrangements of treatment combinations. 81

Table 4.2 Initial soil physical and chemical properties at the two experimental sites 83

Table 4.3 Monthly maximum and minimum temperature (°C) collected during the two growing seasons (November 2019 to July 2021) at Ofcolaco and Zoeknog...............88

Table 4.4 Stem diameter (mm) of pigeon pea influenced by varieties and growth stages during 2019/20 and 2020/ growing seasons at Ofcolaco and Zoeknog 93

Table 4.5 Plant height (cm) of pigeon pea varieties at growth periods during 2019/20 and 2020/21 growing seasons at Ofcolaco and Zoeknog..............................94

Table 4.6 Chlorophyll content (µmolm^{-2}) influenced by growth stages during the regrowth stages at Ofcolaco and Zoeknog. 97

Table 4.7 Pigeon pea variety response to phenological parameters during the 2019/20 and 2020/21 growing seasons at Ofcolaco and Zoeknog. 102

Table 4.8 Grain yield components of pigeon pea varieties at Ofcolaco during the first and second harvest at Ofcolaco and Zoeknog. 107

Table 4.9: Pigeon pea harvest index (%) during the first and second harvest periods at Ofcolaco and Zoeknog. 108

Table 4.10 Correlations between grain yield and yield variables of pigeon peas during the first harvest at Ofcolaco. 111

Table 4.11 Correlations between grain yield and yield variables of pigeon peas during the second harvest period at Ofcolaco. 112

Table 4.12 Correlations between grain yield and yield variables of pigeon peas during the first harvest period at Zoeknog. 113

Table 5.1: Monthly maximum and minimum temperatures collected during growing seasons at Ofcolaco and Zoeknog..138

Table 5.2: Root-shoot ratio at different growth stages during 2019/20 and 2020/21 growing seasons at Ofcolaco and Zoeknog..145
Table 5.3: Interaction effects of P-fertilizer x sampling dates on gravimetric soil moisture (%) during the regrowth periods at Ofcolaco and Zoeknog 150
Table 5.4: Interaction effect of V x P on photosynthetic rate (A), transpiration rate (E), Stomatal conductance (gs), and intercellular CO2 concentration during the regrowth periods at Ofcolaco 159
Table 5.5: Interaction effect of V x P on photosynthetic rate (A), transpiration rate (E), Stomatal conductance (gs), and intercellular CO2 concentration during the regrowth periods at Zoeknog. 160
Table 5.6: Intrinsic (µmol mol^{-1}) and instantaneous (µmol mmol-1) water use efficiency (WUE) of pigeon pea varieties during the regrowth period at Ofcolaco and Zoeknog 161
Table 5.7: Interaction effect of pigeon pea variety and P fertilizer application (V x P) on intrinsic (µmol $mmol^{-1}$) and instantaneous WUE (µmol $mmol^{-1}$) during the regrowth periods at Ofcolaco and Zoeknog. 165
Table 6.1 Interaction effects of V x P on the nutritional composition of pigeon pea at Ofcolaco..192
Table 6.2 Interaction effects of V x P on the nutritional composition of pigeon pea at Zoeknog..192
Table 6.3 Minerals and trace elements influenced by variety in pigeon pea grains on a dry weight basis during first and second harvest at Ofcolaco 194
Table 6.4 Minerals and trace elements influenced by variety in pigeon pea grains during the first harvest at Zoeknog..195
Table 6.5 Residual soil nutrients during the second harvest at Ofcolaco..................198
Table 6.6 Residual soil nutrients during the second harvest at Zoeknog..................199

LIST OF FIGURES

Figure 3.1: Map showing Limpopo and Mpumalanga Provinces within the district municipalities and villages and different climatic zones. 30

Figure 3.2: Farmer category and production area of pigeon peas production in six municipalities of the two Provinces of South Africa during the 2020/21 growing season. 34

Figure 3.3: Farmers' allocation of land area for pigeon peas production in six municipalities during the 2020/21 growing seasons in the two Provinces of South Africa. 35

Figure 3.4: Pigeon peas production sites in various municipalities in the two Provinces of South Africa during the 2020/21 growing seasons. 36

Figure 3.5: Pigeon peas variety used by farmers during the 2020/21 growing periods in six municipalities in the two Provinces of South Africa. 36

Figure 3.6: Farmers' source of pigeon peas seeds in all six municipalities in the two Provinces of South Africa. 37

Figure 3.7: Pigeon peas grain yield produced by farmers in various municipalities of South Africa's two Provinces during the 2020/21 growing season. 38

Figure 3.8: Cropping systems used by farmers in six municipalities in South Africa's two Provinces. 39

Figure 3.9: Pest control methods used by pigeon pea farmers during the 2020/21 and 2020/22 growing periods in six municipalities in the two Provinces of South Africa. 40

Figure 3.10: Illustration of farmers' fertilizer choices in producing pigeon peas in six municipalities across two South African Provinces. 40

Figure 3.11: Pigeon pea preparations used by farmers in six municipalities across two South African Provinces. 41

Figure 3.12: Farmers' processed products of pigeon pea in all municipalities of the two Provinces of South Africa. 42

Figure 3.13: Farmers' choice of pigeon pea utilization in all six municipalities in the two Provinces of South Africa 43

Figure 3.14: Risk and vulnerability factors affecting pigeon pea farmers in all municipalities. 59

Figure 3.15: Effect of climate extremes on pigeon pea production in six municipalities in six municipalities of South Africa. 62
Figure 3.16: Sources of water used for irrigating pigeon pea products in six municipalities of the two Provinces of South Africa. 63
Figure 3.17: Pigeon pea grain yields between 2012 and 2020 by gender in six municipalities of the two Provinces of South Africa. 63
Figure 3.18: Pigeon pea production constraints by gender in six municipalities of the two Provinces of South Africa. 64
Figure 3.19: Farmers' constraints in pigeon pea production in six municipalities of the two Provinces of South Africa. 65
Figure 3.20: Pigeon pea traits by gender in six municipalities in the two Provinces of South Africa. 66
Figure 3.21: Weed control methods used by gender in six municipalities of the two Provinces of South Africa. 67
Figure 3.22: Farmers' use of tillage systems in pigeon production during the 2020/21 growing season in six municipalities in the two Provinces of South Africa. 67
Figure 4.1: A map of the study area at Ofcolaco and Zoeknog during the 2019/2020 and 2020/2021 growing seasons 81
Figure 4.2: Weather data recorded during 2019/20 and 2020/21 growing seasons at Ofcolaco and Zoeknog experimental trials (ETO= evapotranspiration). 87
Figure 4.3: Shoot biomass (kg ha^{-1}) influenced by variety at different sampling dates (V x DAP) during 2019/20 and 2020/21 growing seasons at Ofcolaco and Zoeknog. (Vertical bar represents LSD value) 90
Figure 4.4: Shoot biomass production (kg ha^{-1}) as influenced by P fertilizer application and different days after planting at Ofcolaco and Zoeknog (Vertical bar represents LSD value) 91
Figure 4.5: Influence of pigeon variety on stem diameter (mm) at Ofcolaco and Zoeknog. (Different letters mean significant differences whereas similar letters mean no significant differences). 92
Figure 4.6: Chlorophyll content (µmolm^{-2}) of pigeon pea varieties during 2019/20 and 2020/21 growing seasons at Ofcolaco and Zoeknog (Different letters mean significant differences whereas similar letters mean no significant differences). 95

Figure 4.7: Phosphorous application effect on the chlorophyll content of pigeon pea varieties at Ofcolaco and Zoeknog. (Vertical bars represent LSD value). 98
Figure 4.8: Pigeon pea varieties P yield (kg ha^{-1}) at Ofcolaco and Zoeknog as influenced by sampling dates. 99
Figure 4.9: Phosphorus recovery efficiency (%) influenced by pigeon pea variety at two sampling dates during the 2019/20 and 2020/ growing seasons at Ofcolaco and Zoeknog (Different letters mean significant differences whereas similar letters mean no significant differences). 100
Figure 4.10: Phosphorus fertilizer application rates affecting pigeon pea PRE in different sampling periods during the 2019/20 and 2020/ growing seasons at Ofcolaco and Zoeknog. (Different letters mean significant differences whereas similar letters mean no significant differences). 101
Figure 4.11: The effect of variety on grain yield production (kg ha^{-1}) during the 2019/20 and 2020/21 harvest periods at Ofcolaco and Zoeknog (Different letters mean significant differences whereas similar letters mean no significant differences). 104
Figure 4.12: Harvest index (%) of pigeon pea as influenced by P fertilizer application rates during harvest periods at Ofcolaco and Zoeknog (Different letters mean significant differences whereas similar letters mean no significant differences). 109
Figure 5.1: Weather data recorded during 2019/20 and 2020/21 growing seasons at Ofcolaco and Zoeknog experimental trials (ETO= evapotranspiration). 137
Figure 5.2: Root biomass (kg ha^{-1}) of pigeon pea at different growth stages during 2019/ 2020 and 2020/2021 growing seasons at Ofcolaco and Zoeknog. 139
Figure 5.3: Root biomass (kg ha^{-1}) influenced by P fertilizer application at different growth stages during the 2019/2020 and 2020/2021 growing seasons at Ofcolaco and Zoeknog (Vertical bars represent LSD value)...140
Figure 5.4: Root length (cm) at different growth stages during 2019/20 and 2020/21 growing seasons growing periods at Ofcolaco and Zoeknog (Vertical bars represent LSD value)..142
Figure 5.5: Effect of P fertilizer application and growth periods on pigeon pea root length (cm) during 2019/20 and 2020/21 growing seasons at Ofcolaco and Zoeknog 143

Figure 5.6: Effect of root-shoot ratio of pigeon pea influenced by P fertilizer over a growth period during 2019/20 and 2020/21 growing seasons at Ofcolaco and Zoeknog. 147
Figure 5.7: Gravimetric moisture(%) influence by pigeon pea variety at Ofcolaco and Zoeknog during the two growing seasons (Different letters mean significant differences whereas similar letters mean no significant differences). 148
Figure 5.8: Gravimetric soil moisture (%) influenced by sampling stages during the regrowth periods at Ofcolaco and Zoeknog 149
Figure 5.9: Mean of photosynthetic rate (A), transpiration (E), intercellular carbon concentration (ci), and stomatal conductance (gs) during the regrowth periods at Ofcolaco and Zoeknog (Different letters mean significant differences whereas similar letters mean no significant differences). 153
Figure 5.10: The relationship between (A) photosynthetic, (E) transpiration rates, and intercellular carbon concentration (ci) and stomatal conductance (gs) with growth periods during the regrowth periods at Ofcolaco and Zoeknog. 157
Figure 5.11: The relationship between intrinsic and instantaneous water use efficiency (WUE) growth stages during the regrowth stages at Ofcolaco and Zoeknog. 163
Figure 5.12: Relationship between transpiration and stomatal conductance, photosynthetic rates, and internal CO_2 concentrations during regrowth stages at Ofcolaco and Zoeknog. 166
Figure 6.1: Nitrogen yield (kg ha^{-1}) in pigeon pea plant tissues influenced by sampling dates at Ofcolaco and Zoeknog (Different letters mean significant differences whereas similar letters mean no significant differences). 184
Figure 6.2: Plant nitrogen yield (kg ha^{-1})as influenced by the P fertilizer application and sampling date at Ofcolaco and Zoeknog (Vertical bars represent LSD value). 185
Figure 6.3 Phosphorus yield (kg ha^{-1}) in grains of pigeon pea varieties influenced by harvest periods at Ofcolaco and Zoeknog (Different letters mean significant differences whereas similar letters mean no significant differences). 186

LIST OF ACRONYMS AND ABBREVIATIONS

A	= Photosynthetic rate
ANOVA	= Analysis of variance
AOAC	= Association of Official Analytical Chemists
Ca	=Calcium
ADF	= Acid detergent fiber;
NDF	= Neutral detergent fiber
Ci	=Sub-stomatal CO_2 concentration
CO_2	=Carbon dioxide
Cu	=Copper
CV	=Coefficient variation
cm	=Centimetres
DAP	= Days after planting
E	=Transpiration rate
Fe	=Iron
g	=gram
LSD	=Least significant difference
l	=litre
gs	=Stomatal conductance
ha^{-1}	=Per hectare
K	=Potassium
kg	=Kilogram
kg ha^{-1}	=Kilogram per hectare

mg	=Milligram
Mg	=Magnesium
%	= Percentage
<	= Less than
±	= Standard deviation
mm	=Millimetre
$mmolm^{-1}S^{-1}$	= Mille mole per square meter per second
$Molm^{-2}S^{-1}$	=Mole per square meter per second
$\mu Molmolm^{-2}\ S^{-1}$	= Micromole per square metre per second
CO2	=Carbon dioxide
ns	= Not significant
SD	= Standard deviation
Tx	=Maximum temperature
Tn	= Minimum temperature
WUE	=Water Use Efficiency
P	=Phosphorus
N	=Nitrogen
Na	= Sodium
Zn	=Zinc

LIST OF MANUSCRIPTS IN PREPARATION

The following articles are in preparation for the thesis:

Moriri, SC., Ayisi K.K., and Mofokeng A. Farmers' production status, utilization, awareness and market opportunities of pigeon pea (*Cajanus cajan*) production in South Africa.

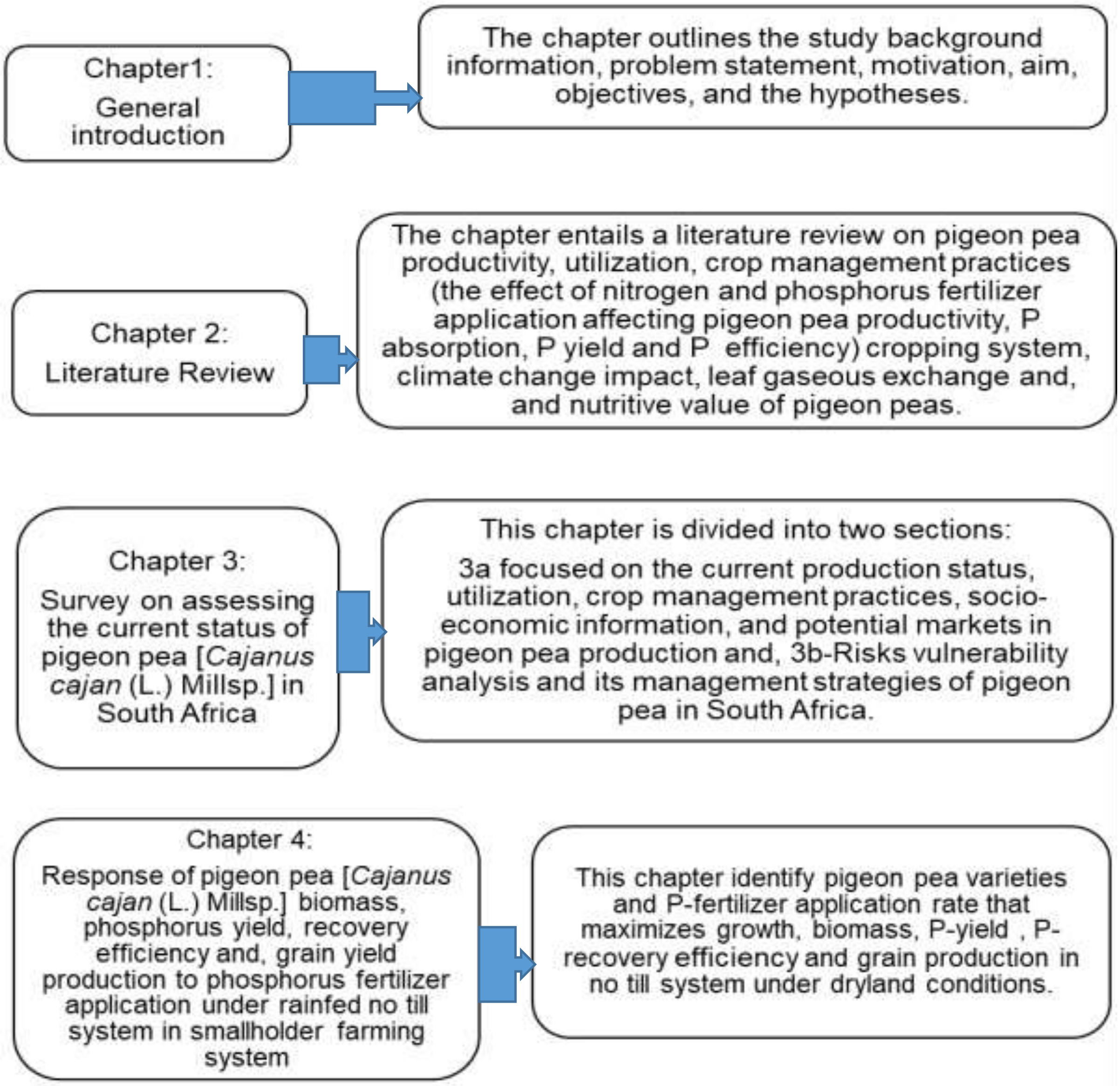
Moriri, SC., Ayisi K.K., and Mofokeng A. Strategies of risk management for smallholder farmers in South Africa: a case study on pigeon pea (*Cajanus cajan*) production.

Moriri, SC., Ayisi K.K., and Mofokeng A. Response of pigeon pea (*Cajanus cajan*) on biomass production, P-uptake, phosphorus use efficiency and grain yield production to phosphorus application under a rainfed no-till system in smallholder farming system

Moriri, SC., Ayisi K.K., and Mofokeng A. Drought tolerance mechanism of pigeon pea [*Cajanus cajan* (l.) Millsp.] varieties and P-fertilizers through water use efficiency, stomatal conductance, and roots biomass production in diverse agro-ecological zones

Moriri, SC., Ayisi K.K., and Mofokeng A. Nitrogen yield, residual soil nutrients and nutritional value of Pigeon pea *(Cajanus cajan)* varieties influenced by phosphorus fertilizer application rates in a no-till system under dryland conditions

THESIS STRUCTURE



Chapter 5:

Influence of pigeon pea [*Cajanus cajan* (L.) Millsp.] varieties and P fertilizer application on drought mechanisms through water use efficiency, stomatal conductance and root biomass in diverse agro ecological zones

This chapter identifies pigeon pea varieties that are tolerant to drought conditions, efficient water utilization, root growth, root biomass production and leaf gaseous exchange influenced by variety and P – fertilizer application rates.

Chapter 6:

Effect of pigeon pea varieties and P fertilizers application on nitrogen, phosphorus accumulation in grains, nutritive valuer, minerals and trace elements in grain and the residual soil nutrients under dryland conditions

In order to improve crop food security and nutrition status in smallholder farming systems through the use of pigeon pea varieties and application of P fertilizersoil fertility enhancement and nutrient use efficiently.

Chapter 7:

General conclusions and recommendations

Provide a summary of the study findings by addressing all objectives, recommendations based on the study findings and suggested future research studies

THESIS ABSTRACT

The first study comprised a survey on pigeon peas to determine the crop's current status in six local municipalities within the two Provinces. The survey study was divided into two sections. The first section found that the crop is produced on less than 1 ha of land, mostly by old, female, and subsistence farmers, mainly for home consumption. Out of 114 farmers interviewed, 11 were smallholder farmers, 103 subsistence, and no commercial farmers were recorded. Grain yield ranged from 10 to 20 kg ha^{-1} and fewer farmers produced more than 200 kg ha^{-1}. About 66% of farmers used unknown pigeon pea varieties. The crop is mostly produced in an intercrop system with maize and mangoes without fertilizer applications. Only 3% of male farmers used pigeon pea for fodder. About 78% used pigeon peas for income generation and mainly were male farmers. Majority of farmers confirmed that markets are available both locally and internationally. The second section revealed that low production yields were caused primarily by drought, high temperatures, poor agronomic practices, the use of unimproved seeds, and the outbreak of insect pests and disease.

The second study was carried out in smallholder farmers' fields at two locations in Limpopo and Mpumalanga, namely, Ofcolaco and Zoeknog respectively from December 2019 to July 2021 to assess the growth and yield of pigeon pea. The trials were laid out at the two experimental sites as a randomized complete block design (RCBD) in 4 × 2 factorial arrangements with three replications. The two treatment factors were four pigeon pea varieties, namely Komboa; Tumia; Ilonga 14-M2; local landrace, and two levels of P-fertilizers at 0 kg ha^{-1} and 60 kg ha^{-1}. Shoot biomass ranged from 5375 to 10149 kg ha^{-1} for all varieties and sampling dates at both locations. Application of P-fertilizer and growth stages (P X DAP) significantly influenced shoot biomass at 180 DAP only at Ofcolaco. Interaction of V x P did not show significant variations in shoot biomass at both locations. At Ofcolaco, P yield in plant tissue ranged from 11.11 to 23.89 kg ha^{-1} and 15.11 to 41.47 kg ha^{-1} at 120 and 470 DAP, respectively, whereas at Zoeknog, the range was from 16.73 to 31.09kg ha^{-1} and 22.68 to 52.0 kg ha^{-1} at 120 and 470 DAP, respectively. PRE was reduced by the application of P-fertilizer at 60 kg ha^{-1}. The Ilonga 14-M2 variety and the local landrace produced the lowest grain yield ranging from 618 kg ha^{-1} to 922 kg ha^{-1}.

Komboa produced the highest grain yield of 1136 kg ha^{-1} and 1431kg ha^{-1} during the first harvest at Ofcolaco and Zoeknog, respectively. The study revealed that unfertilized plants had a higher HI of 30.64% relative to fertilized plants which attained 27.23% during the first harvest only at Ofcolaco.

The third study objective was to identify pigeon pea varieties under P fertilization that are tolerant to drought conditions through root biomass production, stomatal conductance, and water use efficiency (WUE). Across all sampling dates, Ilonga 14-M2 produced the highest root biomass of 3185 and 3867 kg ha^{-1} at Ofcolaco and Zoeknog, respectively. Significant variations in P-fertilizer application were observed from 150 to 500 DAP at Ofcolaco and Zoeknog only at 500 DAP. Photosynthetic rates ranged from 26.39 to 39.06 (µmol $m^{-2}s^{-1}$) across varieties. Application of P-fertilizer at 60 kg ha^{-1} influenced the opening of the stomata for Komboa and controlled in Ilonga 14-M2. Komboa resulted in higher $_{intrinsic}$-WUE due to higher photosynthesis rates over stomatal conductance. Ilonga 14-M2 had the highest $_{instantaneous}$-WUE, low photosynthetic and transpiration rates, and able to control their stomatal conductance The interaction effect of V x P in $_{instantaneous}$ -WUE was significant and not significant for $_{intrinsic}$ WUE.

The fourth study objective was to assess the effect of pigeon pea variety and P-fertilizer application on the nutritional composition of pigeon pea grain. Protein content ranking was 33.30, 32.81, 23.25%, and 20.84% for Ilonga 14-M2, Tumia, Komboa, and the local varieties, respectively at Zoeknog. P-fertilizer application did not change the nutritive value and mineral elements of pigeon pea grains. Minerals, trace elements, and residual soil nutrients did not differ significantly among varieties, P-fertilizer application, and interactions at both locations. In conclusion, Ilonga 14-M4 proved to be a promising variety for drought tolerance, soil fertility enhancement, high protein content, and satisfactory grain yield even under suboptimal rainfall growing seasons. Komboa variety is recommended for farmers in grain production. Whereas Tumia is a dual-purpose variety The application of P-fertilizer at 60 kg ha^{-1} enhanced pigeon pea's drought tolerance and productivity but this was found to be dependent on several factors which extend to growth stage, variety, locality, climatic conditions, soil type, and agronomic management practices.

Keywords: drought, leaf gaseous exchange, grain yield, P-fertilizer, P yield, PRE, proteins, varieties, biomass, residual soil nutrients, WUE

Chapter 1: GENERAL INTRODUCTION

1.1 Background of the study

Pigeon pea [*Cajanus cajan* (L.) Millspaugh] is a multipurpose and drought-tolerant leguminous crop that provides food, fodder, and wood for smallholder farmers in Southern Africa (Matthews and Saxena, 2001a). India and Myanmar are regarded as the major pigeon pea producers with 83% in the world whereas Malawi, Tanzania, Kenya, and Uganda are considered the major producers in Africa (FAOSTAT, 2015). In South Africa, the crop is not yet considered a major field crop and it is mainly grown by smallholder farmers in homestead gardens either as a single plant or as hedges in or around the home gardens in Limpopo, Mpumalanga, and KwaZulu-Natal (DAFF, 2009). Although pigeon pea is a multi-purpose species (Odeny, 2007), in South Africa the crop remains one of the underutilized and neglected legume crops. The present study is aimed at promoting pigeon pea utilization through varietal use and P fertilizer application under no-till in smallholder farming systems.

The majority of smallholder farmers in Southern Africa still grow unimproved pigeon pea seeds from landraces that are poor in germination and lack genetic vigor, and the consequences are reduced yields of poor quality grain (Saxena *et al*., 2020). The unavailability of improved pigeon pea varieties of good quality grain and high yielding traits is still a major challenge in the smallholder farming system in South Africa. The maturity period of pigeon peas is an important factor that determines the adaptation of the crop to various agro-climatic zones and cropping systems (Matthews *et al.,*2001a and 2001 b). According to Mergeai *et al*. (2001), late-maturing pigeon pea genotypes and mostly landraces produce low yields ranging from 300 to 500 kg ha^{-1} and these varieties are mostly intercropped with maize, sorghum, and millet. Pigeon peas are known to be drought-tolerant species (Odeny 2007). However, some pigeon pea genotypes are sensitive to photoperiod (Gwata and Shimelis, 2013), high temperatures (Choudhary *et al*. 2011), and are susceptible to pests (Matthews *et al.,* (2001a). Although improved pigeon pea varieties demonstrated high yield potential in the tropics (Hardev *et al*., 2016), their performance in smallholder farming systems under no-till conditions in South Africa's diverse agro-ecological zones has not yet been tested.

Climate change is one of the major factors that is negatively impacting dryland crop production in South Africa as a result of recent changes in rainfall patterns and temperatures. Water use efficiency (WUE) is an important physiological trait in legume production and this is controlled by plant stomatal activities (Munjonji *et al*., 2018). Pigeon peas are known to be drought-tolerant species due to their deep root systems that allow the plant to utilize water sources in deep soil layers (Subbarao *et al.,* 2000). The crop has a greater ability to withstand drought than all other legume crops due to its osmotic leave adjustment (Odeny, 2007). Although pigeon peas are known to be drought-tolerant, information on the WUE of pigeon pea varieties' responses to P fertilizer application under no-till in smallholder farming systems in diverse agro-ecological zones of South Africa is not yet documented. Such information is important to address this limitation for optimum yields of pigeon peas under smallholder farming conditions.

Pigeon pea is one of the leguminous crops with protein content and is nutritionally well-balanced. Several scientists found different values of protein content in pigeon pea matured grain and these were: Saxena *et al*., (2010) 18.8%; Makelo, (2011) 18–26%; and Dabhi *et al*., (2019) 26%. Pigeon pea is an important food legume that can be grown to eliminate protein malnutrition in Southern Africa. Regrettably, the unavailability of improved pigeon pea seeds of good quality and high-yielding traits is still a major challenge in the smallholder farming system. Several authors also reported that the poor nutritive value of pigeon pea grain is the result of climate change, low soil nutrients, and other environmental factors (Saxena *et al*., 2010) which vary within pigeon pea genotypes (Fujita *et al*., 2004). Hence, the demand for nutritional foods is increasing due to an increasing population and expensive meat proteins, which are unaffordable to the majority of the rural populace in South Africa. Information on the nutritional quality of grain produced by the crop is influenced by variety and P fertilizer application under no-till in smallholder farming systems is still scanty. However, improved pigeon pea varieties are known to have the high yielding potential of good quality grains and need to be documented under prevailing climatic conditions in South Africa. The use of improved pigeon pea varieties and P fertilizer application will also help in the reduction of food and nutrition insecurity in rural farming systems.

Most soils in dryland farming areas of South Africa are low in nitrogen (N), phosphorus (P), and organic matter content due to continuous maize cultivation with little or no fertilizer application. Pigeon pea is primarily grown without the use of fertilizer. However, the crop can fix up to 235 kg ha^{-1} (Odeny, 2007; Dasbak and Asiegbu, 2009). Hence, most soil nutrient improvement practice in the system is through the use of inorganic fertilizers, which are not affordable to many smallholder farmers due to escalating prices of inorganic fertilizers. The majority of South African smallholder farmers are resource-constrained, and incorporating N-fixing legumes like pigeon peas into their farming systems could be a solution to the low N problem. Boateng and Owusu-Bennoah (2021) stressed that leguminous crops require P in relatively adequate amounts for growth and N_2 fixation. Recent information on pigeon peas revealed that low application of P fertilizers decreases nitrogenase activity and ATP concentration in nodules, thus decreasing the ability of the plant to fix nitrogen (N_2) (Boateng and Owusu-Bennoah, 2021). Although pigeon pea has proven to fix a substantial amount of N through symbiotic nitrogen fixation, their N-fixing ability is influenced by the crop variety used and P-fertilizer application. Therefore, the current study objective is to investigate whether pigeon pea variety and P-fertilizer application have an influence on P-uptake, N-uptake, residual soil nutrient content, and nutritional composition of pigeon pea grains in a no-till system under a smallholder farming system in South Africa.

1.1 PROBLEM STATEMENT

Although pigeon pea [*Cajanus cajan* (L.) Millspaugh] is a multi-purpose leguminous drought-tolerant species (Odeny, 2007), it still remains one of the most underutilized and little-researched crops in South Africa. The majority of smallholder farmers in South Africa still grow the traditional unimproved pigeon pea landraces, which comprised a mixture of genotypes. In addition, the crop is mostly grown in poor nutrient-depleted soils caused by inappropriate conventional soil preparation methods (Kumar *et al*., 2015), and continuous maize cropping with little or no fertilizer inputs (Kgonyane *et al*., 2013). This results in yield variation of low-quality grains across farmers' fields. Even though some studies on pigeon pea have been carried out in South Africa, none have documented the physiological mechanisms regulating the crops' water use and drought tolerance mechanism as well as the grain yield and nutritional quality constraints resulting from climate-induced drought in the crop (Nndwambi *et al*., 2016; Gwata and Shimelis, 2013). Information on pigeon pea water use efficiency (WUE), P and N-uptake efficiency, and biological nitrogen fixation (BNF) in relation to grain yield and nutrient content under a no-till system in South Africa are yet to be documented. The information generated on these parameters of pigeon peas is critical if the crop is to be sustainably produced and to increase its utilization under a changing climate in South Africa.

1.2 MOTIVATION FOR THE STUDY

Pigeon pea is a drought-tolerant crop that prevails in many tropical and subtropical countries of the world (Matthews and Saxena, 2000). In Limpopo Province, drought, the use of poor quality and unimproved seeds for planting as well as poor soil fertility are some of the important factors affecting the productivity of the crop and its competitiveness in the dryland farming system. The use of improved pigeon pea seeds together with P-fertilizer application is suboptimal in smallholder dryland farming due to the unavailability of the seeds and high prices of inorganic fertilizers which are not affordable to the majority of smallholder farmers. Pigeon pea varieties are known to be drought-tolerant and can withdraw deep, inaccessible water and nutrients from the soil profile with their deep root systems, which helps the crop to survive during drought periods (Subbarao *et al*., 2000; Odeny, 2007).

The crop is mostly planted in poor soils, which are predominantly sandy with low P status. P-fertilizer application and management in low soil P status are critical in improving pigeon pea productivity because it has been shown to affect the crop's biological nitrogen-fixing ability (Stephen *et al*., 2014). Pigeon pea can fix up to 235 kg ha^{-1} of nitrogen under non-limiting P conditions and produce more nitrogen from crop biomass than other leguminous crops (Egbe and Anyam, 2011). Other legume crops such as cowpea were reported to fix N from the atmosphere ranging between 11.86 to 50 kg ha^{-1} and the amount of N fixed differs with variety, maturity durations, and nutrient uptake (Abaidoo *et al*., 2016). Biological fixation of N will help to reduce farmers' reliance on chemical fertilizers as the prices of fertilizers are ever-increasing. Currently, the P requirements of pigeon pea varieties and the consequent benefits have not yet been fully explored in South Africa. Understanding the response of pigeon pea varieties to P fertilizer application, as well as the effects on N-uptake, P-uptake, and residual soil nutrient content under various agro-climatic conditions is critical if the crop is to be widely promoted among smallholder farmers.

Pigeon pea can utilize iron-bound soil P efficiently (Subbarao *et al*., 2000). However, drought stress has been reported to reduce P availability, uptake, and the efficiency of P utilization by obstructing different physiological phenomena (Garg, 2003). Very little information is available regarding the effect of drought mechanisms on the nutrient relations of pigeon pea varieties under a no-till system. The introduction of improved pigeon pea varieties in smallholder farming systems that are adaptable to local environmental conditions is important for attaining optimum yields in drier areas where the crop is mostly grown.

The demand for nutritional foods is increasing due to an increasing population and expensive meat proteins, which are not affordable to the majority of poor smallholder farmers in South Africa. The crop is known to be rich in proteins, crude fiber, starch, fat, trace elements, and minerals compared to other leguminous crops (Saxena *et al*., 2010). The incorporation of pigeon peas into the smallholder farming system, using improved seed varieties with adequate P-fertilizer application under no-till in a dryland system, has the potential to improve soil fertility, growth, yield, and produce nutritious grains. This will contribute to the reduction of food and nutrition insecurity in rural areas of South Africa. In addition, improved pigeon pea seed varieties have a high yielding potential of good quality grain that needs to be documented.

1.3 AIM OF THE STUDY

The overall goal of the study was to assess the drought tolerance mechanisms, grain yield, and nutritional composition of pigeon pea varieties in response to P-fertilizers under a smallholder no-till system through a survey and field experimentation. The specific objectives were to:

i. Assess the status of pigeon pea production by smallholder farmers in Limpopo and Mpumalanga Provinces of South Africa concerning production practices, utilization, as well as potential market channels for the crop.

ii. Determine the effect of pigeon pea variety and P-fertilizer application on the crop's biomass production, P-uptake, phosphorus use efficiency (PUE), and grain yield.
iii. Evaluate pigeon varieties and P-fertilizer application for drought tolerance through WUE, stomatal conductance, and root biomass production of pigeon peas.
iv. Investigate the effect of pigeon pea variety and P-fertilizer application on N-uptake, residual soil nutrient content, nutrient use efficiency (NUE), and biological nitrogen fixation (BNF) abilities.
v. Assess the effect of pigeon pea variety and P-fertilizer application on the nutritional composition of pigeon pea grain.

1.4 HYPOTHESES

i. Farmers' production practices, utilization, and potential markets are comparable among smallholder farmers in Limpopo and Mpumalanga Provinces.
ii. Pigeon pea variety and P-fertilizer application do not influence pigeon pea biomass production, P- uptake, PUE, and grain yield.
iii. Pigeon pea variety and P-fertilizer application have no effects on drought tolerance mechanism through WUE, stomatal conductance, and root biomass production of pigeon pea.
iv. Pigeon pea variety and P-fertilizer application have no influence on N - uptake, soil nutrient content, NUE, and BNF abilities.
v. Pigeon pea variety and P-fertilizer application do not affect the nutritional composition of pigeon pea grain.

Chapter 2: LITERATURE REVIEW

2.1 INTRODUCTION

The literature review in this chapter highlights the following: the utilization of pigeon pea as a fodder crop; conservation crop for improved soil fertility; food for human consumption; litter and firewood; nutritive and medicinal value for increased food and nutrition security, and economic potential. The chapter further assesses the impact of environmental factors such as rainfall (drought, heat stress, flood) and temperatures due to climate change on pigeon pea growth and grain yield production. The crop's response to moisture stress, leaf gaseous exchange, and water use efficiency. The effects of pigeon pea genotypes are influenced by nitrogen and P fertilizer application; the nutritional composition of pigeon pea; and the improvement of soil fertility through residual soil nutrients.

2.2 PIGEON PEA DISTRIBUTION, TAXONOMY, AND ORIGIN

Pigeon pea is regarded as an important grain legume crop in the Tropics and Subtropics. Globally, the crop is cultivated on about 4.23 million ha with an average annual production of 2.96 million tonnes (Fatokimi and Tanimonure, 2021). According to FAO (2016 & 2017), the crop occupies about 5.377,970ha in Asia, Africa, and America. According to FAOSTAT (2017), India produces about 3 million tonnes of pigeon pea annually and it is regarded as the largest producer of pigeon pea with 4.600,000ha, followed by Southern and Eastern Africa (500.000ha), Myanmar (251.700ha), South America (52.000ha) and Nepal (25.000ha). Various authors reported that Kenya and Uganda account for 4% of the world's production, while the Caribbean, Central, and South America produce 2% of the total pigeon pea in the world (FAOSTAT, 2017; Fatokimi and Tanimonure, 2021). Pigeon pea in South Africa is not yet regarded as an important field crop and its production is mainly by subsistence farmers who contribute 120-150 tonnes (Matthews and Saxena, 2001). In Sub-Saharan Africa (SSA), pigeon pea is widely grown by subsistence farmers in Kenya, Uganda, Tanzania, Malawi, and Mozambique, and produced mainly for local and international markets (Odeny, 2007)

Pigeon pea [*Cajanus cajan* (L.) Millspaugh] belongs to the genus *Cajanus*, subtribe *Cajaninae*, tribe Phaseoleae, and family Fabaceae. The plant is also known as red gram, Congo pea, arhar, gungo pea, no-eye pea, or gandul. In South Africa, it is commonly known as Lothlodi, Ndozi, Duifert, Udaali, and Dithlodi (DAFF, 2009). According to Lakshmi *et al.* (2000), the pigeon pea has many wild relatives belonging to six genera, including *Cajanus, Dunbaria, Flemingia Paracalyx, Rhynchosia,* and *Eriosema*.

Pigeon pea originated in India due to its range of genetic diversity (Mohar *et al*., 2014). Other authors also considered eastern Africa to be the center of origin of the plant because it is found in the wild form (DAFF, 2009) and has concluded that India is the primary center of origin of pigeon pea whereas Africa is the secondary center of origin. Currently, the crop is cultivated in many countries in the tropics and subtropics. The production areas of pigeon peas in South Africa are mainly Limpopo, Mpumalanga, and Kwazulu-Natal (Matthews and Saxena, 2001a).

2.3 UTILISATION OF PIGEON PEA

Pigeon pea is known as a multipurpose leguminous crop and it is an important source of food in Africa. The crop is not regarded as a field crop in South Africa, and it is grown either as a single plant or as a hedge in or around homesteads, mainly in Kwazulu-Natal, Limpopo, and Mpumalanga Provinces (DAFF, 2009; Matthews *et al.*, 2001a). According to Matthews and Saxena (2000), pigeon pea was introduced by migrant workers from Mozambique and Malawi in Mpumalanga Province for its use as a green vegetable or for making soup with or without meat. Though pigeon pea is primarily grown for its edible seeds, it is also used as fodder, fuelwood, windbreak, fencing, roofing, and basket making in other areas (Upadhyaya, 2006; Edje, 2014).

2.3.1 *Fodder*:

Pigeon peas in smallholder farmers' fields have numerous uses in livestock feeding. The plant parts, such as the leaves and pods, are valuable, palatable, and protein-rich fodder. Studies conducted by Joshi *et al*. (2001) reported that pigeon pea processed seed by-products and the whole seeds are mainly used as livestock feed. They concluded that it is important to select high-yielding pigeon pea cultivars of high forage yield and high proteins. A study conducted in Hawaii reported that pigeon pea seeds mixed with maize seeds were found to be nutritious and successful for poultry feeding (Orwa *et al*., 2009; Joshi *et al*., 2001). They also revealed that bees feeding on pigeon pea flowers were shown to produce honey with a distinctive color (greenish) in the comb. A study conducted on pigeon pea as a supplement for lactating dairy cow-fed corn-based diets show that pigeon pea improved the protein diet of lactating cows but did not influence milk production (Carriher *et al*., 2010). Introducing pigeon pea varieties with high biomass production could be used as supplementary feed during the dry winter seasons in Limpopo and Mpumalanga Provinces.

2.3.2 Conservation:

Cajanus cajan has an important role in conservation agriculture as it is known to provide several benefits to the soil where it is grown. It is an important leguminous crop that fixes nitrogen (N) through the biological nitrogen fixation (BNF) process. Egbe and Anyam (2011) studied N fixation in pigeon peas and found that the crop can fix up to 235 kg N ha^{-1} and also produce more N per unit area from the biomass than other legumes. The same author also reported that pigeon pea N fixation differs amongst pigeon pea genotypes and is influenced by growth durations. Biological N fixation is important in cropping systems such as intercropping, crop rotation, agroforestry, green manuring, etc. Findings from a study by Egbe (2007) stressed that BNF is important where N fertilizer applications are limited in the soil and organic matter status is very low. Pigeon pea is capable of bringing minerals from deep soil horizons to the soil surface (Egbe and Anyam 2011), thereby improving soil fertility and quality when they are used in various cropping systems.

2.3.3 Human consumption:

The leguminous crop is primarily used as a vegetable, and the pods are consumed when they are still green, immature, or dry (DAFF, 2009). In most cases, the edible parts for human consumption are pods and seeds, mainly in their fresh, shelled, dried, and processed form. In some areas, the seeds are canned and consumed as green pigeon peas or frozen veggies (Matthews *et al*., 2001a). Studies conducted by scientists found that immature seeds of pigeon peas are more nutritious than dry seeds (Saxena *et al*., 2010). More information was also recorded by Matthews and

Saxena (2001), stressing that pigeon pea grains are also cooked without removing the seed coat and that the challenge is that it takes 3 to 4 hours longer to cook when the seed coat is not removed. Slow cooking whole pigeon pea grains is recommended by several authors because the seed coats are rich in fiber than most legume seed coats with low digestibility (Fasoyiro et al., 2005). Pigeon pea is prepared in several ways, namely as soup by cooking dry seeds and fresh green pods, as a flour and dhal stew (Majili *et al*., 2020).

2.3.4 Nutritional value

Pigeon pea is an important food legume that can be grown to eliminate protein malnutrition in smallholder farming systems. Legumes are regarded as an economical dietary source of good quality protein and are higher in protein than most other plant foods (FAO, 2016). According to Duhan *et al*. (2002), legumes contain relatively low quantities of the essential amino acid methionine, and it is also known as a good source of vitamin B and carbohydrates. Numerous studies have revealed that pigeon peas are rich in starch, protein, calcium, manganese, crude fiber, fat, trace elements, and minerals (Morake *et al*., 2002; Saxena *et al*., 2010). Some studies also revealed that pigeon pea contains a protein range of 19–23%, fat 1-2%, carbohydrate 45–55%, fiber 1-5%, and energy between 16–18% (Saxena *et al*., 2010), however, the recent information show that pigeon pea proteins ranged from 17 to 25% (Kachere *et al*., 2019). Makelo (2011) studied the nutritional value of pigeon peas and reported that they contain more minerals, ten times more fat, five times more vitamin A, and three times more vitamin C than ordinary peas and other food legumes such as cowpeas and chickpeas. The same researcher reported that the protein content in pigeon pea grains ranged between 18 to 26% and that the wild type has a protein content of 30% and above.

2.3.5 Medicinal value:

Pigeon pea plant parts are vital and are used for medicinal purposes, mainly for the remedy of health problems. Several scientists have revealed that pigeon pea flowers are mainly used for treating human diseases such as bronchitis, coughs, respiratory infections, sore throats, and pneumonia (Saxena *et al*., 2010). Other researchers also indicated that pigeon pea grains and seeds are also used for skin, liver, lung, and kidney treatments (Matthews and Saxena, 2001). According to Saxena *et al*. (2010), pigeon pea fresh seeds are also used for treating urinary systems in males. The authors further stressed that pigeon pea immature seeds are recommended for kidney problem treatment. Farmers in Benin grow pigeon peas for their stems and leaves to treat malaria, dizziness, measles, and eye infection (Ayenan *et al*., 2017). More studies are still needed in South Africa to find out which pigeon pea genotypes have higher medicinal values.

2.3.6 Litter and firewood:

Long-duration pigeon pea is a deciduous plant, shedding its leaves in the dry season and accumulating litter on the soil surface twice as much as the short-duration type (Edje, 2014). A study was done on appropriate technologies to replenish soil fertility in Southern Africa and estimated that pigeon pea leaf drops contributed up to 40 kg ha^{-1} of nitrogen to the soil surface (Mafongoya *et al*., 2006). The quality of firewood production in pigeon peas was reported to be high in energy yield with a rate of 4350K-cal kg^{-1} (Yude *et al*., 1993). A study in Swaziland on pigeon pea seed yield, litter, and fuelwood production under an intercropping system revealed that sole pigeon pea produced higher litter biomass of 3,752 kg ha^{-1} and 17,734 kg ha^{-1} firewood than in maize/pigeon pea intercrop and sole maize (Edje, 2014). Firewood is the first solid form of biofuel and an energy source in rural areas for cooking and heating (Orr *et al*., 2013). Makhado *et al.* (2014) also stressed that 60% of the inhabitants in Limpopo Province, South Africa (SA), are still using firewood as the main source of energy. Saxena *et al.* (2010), reported in a study that pigeon peas produced 9 to 10t ha^{-1} of dry firewood.

2.4 ECONOMIC POTENTIAL OF PIGEON PEA PRODUCTION

Pigeon pea market revenue is expected to grow at a rapid growth rate in the near future if the crop's yields and quality are improved. The market revenue growth of pigeon peas is accelerated by numerous factors, including high nutritional value, soil fertility improvement, medicinal value, and livestock fodder (Mponda *et al*., 2013). Other authors indicated that farmers who practiced intercropping of maize and pigeon peas made 81% more profit than farmers who produced maize and pigeon pea in monocropping (Dania *et al*., 2014). However, the authors also noticed that the profit in the intercropping system by farmers was because of production cost reductions such as fertilizers, labor for weeding, etc. Alabi and Esobhawan (2006), conducted a study and found that the cost of fertilizer was reduced in intercropping of maize and okra due to the ability of the companion crop to reduce the impact of rainfall and soil erosion, thereby reducing soil nutrient depletion. Dania *et al*. (2014) revealed that labor costs were reduced as a result of the pigeon pea's ability to suppress weeds and that it was higher in intercropping systems than in monocropping systems.

The demand for processed pigeon pea products in the local, regional, and international markets in Asia, North America, and Europe exceeds the supply by 30% (Odeny, 2007). According to Mponda *et al*., (2013), there is a strong and unfulfilled demand for pigeon peas in Southern Tanzania for processing into dhal (dehulling of seeds for making soup) in India. In South Africa, the demand for the crop as green and mature pods is higher and the supply is very low. Matthews *et al.* (2001a) indicated that most of the suppliers are household producers and they produce the crop seasonally. The same author also stressed that the demand for oil dhal is high in Kwa-Zulu Natal and it is imported at R5000/tonne. The study indicates that markets for pigeon peas in various forms (green mature pods, dry seeds, and processed) are available for smallholder farmers in all spheres. However, the study conducted by Mponda *et a*l. (2013) also reported that pigeon pea economies showed a viable enterprise but the crop's profit margin was found to be low due to the low selling price and productivity per unit area   The value chain analysis of pigeon pea shows that there is a strong demand in Tanzania (Mponda *et al.*, 2013) and this could be met by increasing production area through more efficient productivity. Therefore, the use of high-yielding pigeon pea seed varieties and the application of fertilizers could help in increasing pigeon pea production thereby increasing the supply of the crop for processing purposes. In addition, Improved production practices will help smallholder farmers to increase pigeon pea production yields and thereby increasing their net profits.

2.5 PIGEON PEA GENOTYPES AND MATURITY DURATIONS

Pigeon pea can be classified as cultivars, varieties, genotypes, and landraces. Landraces are defined as traditional or local varieties with a mixture of genotypes and a highly diverse population (Saxena *et al.*, 2020). The majority of smallholder farmers in Southern Africa are still planting pigeon peas using landraces or traditional seeds, which take time to mature with no or insufficient fertilizers, and this results in low crop productivity. Maturity duration in pigeon peas is an important factor that determines the adaptation of varieties to different agro-climatic areas and cropping systems (Matthews and Saxena, 2000). Pigeon pea duration in the field is reported to be controlled by temperature and sensitivity to photoperiod (Gwata and Shimelis, 2013). According to Matthews *et al.* (2001a), pigeon peas are classified into three major duration groups, as outlined in table 1 below:

Table 2.1 Pigeon pea maturity duration

Maturity Duration type	Number of days to Maturity
1. Extra –short-duration (ESD)	Less than 100
2. Short- duration (SD)	100-150
3. Medium-duration (MD)	151-180
4. Long-duration (LD)	More than 180

Source: Matthews, C., K.B. Saxena, and S.N., Silim. 2001a. Evaluation of short, medium, and long-duration pigeon pea cultivars in Mpumalanga, South Africa.

Several scientists revealed that planting ESD pigeon peas under optimal population and low yield conditions increased yield and biomass production (Dahiya et al., 2002). According to Kimani (2001), the short-duration type (SD) is less sensitive to photoperiod and can flower and mature during the short summer season. The SD pigeon pea type can also be grown in frost-free areas (Matthews and Saxena, 2000) because it is insensitive to photoperiod. Though the pigeon peas are adaptable to the local conditions in Limpopo and Mpumalanga Provinces of SA, the short-durations pigeon pea type is susceptible to pests, which require appropriate production inputs with high maintenance (Joshi *et al*., 2001).

The medium-duration (MD) pigeon pea varieties are mostly planted in mixed cropping in warm temperatures areas. Other scientists have indicated that MD pigeon peas are photoperiod sensitive and also flower when days are short (Matthews and Saxena, 2000). A study conducted by Snapp (2003), has shown that the MD pigeon pea cultivars have shown good adaptation across different agro-ecological zones and also perform better in 1600 to 1500 altitudes with mean temperatures of 23°C to 25˚C. According to Matthews and Saxena (2000), the long-duration (LD) pigeon pea types are photoperiod sensitive and flower in short days. This means that planting dates will differ from one locality to another due to prevailing climate conditions. The crop initiates flowers and matures after 180 DAP. The production of LD varieties also varied on temperatures or day length and if the temperatures are not favorable the crop will not flower when it has reached 12 months (Jones, 2002).

2.6 ENVIRONMENTAL FACTORS AFFECTING LEGUMES PRODUCTION

2.6.1 Water:

Drought is one of the most important environmental constraints limiting crop productivity in Southern Africa. However, according to Odeny, (2007), pigeon pea has proven to have the ability to better withstand severe drought conditions relative to other legumes due to their deep roots and osmotic adjustment in the leaves. Pigeon pea is a deep-rooted leguminous crop known to be drought-tolerant and survives well in harsh climatic conditions (Singh *et al*., 2008 & 2020). In South Africa, pigeon peas are mostly grown under rainfed conditions. In Limpopo Province, where rainfall is erratic and very low ranging from 350mm to 600mm annum^{-1}, water is always a very scarce resource for smallholder farmers resulting in low pigeon pea production.

Pigeon pea short, medium, and long-duration varieties increase grain yield and biomass production when adequate water is received during flowering and reproductive stages (Matthews and Saxena, 2001). However, Choudhary *et al.* (2011) also have found that excessive moisture in pigeon pea production is detrimental because it promotes crop growth and increases the incidence of P*hytophthora* and *Alternaria* blight.

Water availability in crops is important because it influences growth at all growth stages (vegetative and reproductive stages). According to a study reported by DAFF (2019), several crops grow well in an environment with rainfall ranging from 400 to 750mm annum^{-1} in South Africa. The same author also stressed that crops prefer moist soil conditions for the first two months and drier conditions during flowering and harvesting. Water deficit negatively affects pigeon production and the extent of damage depends on the stage of crop development during which the stress occurs (Chaudhary *et al*., 2011). Pigeon pea is mostly produced in dryland in South Africa and hence, the growth and grain yield performance are directly dependent on the availability of rain during the summer season. It is therefore important that farmers apply irrigation when the crop experiences extreme drought stress, especially during the flowering and pod filling stage.

Drought is becoming a common occurrence in many parts of Africa due to climate change and hence, dryland production is expanding. Pigeon pea, with its drought tolerance abilities (Odeny, 2007) is found to be important for managing food security and the nutritional situation in Africa (FAOSTAT, 2008). This is because pigeon pea is often the only crop that can give some yield during dry spells when other grain legumes and cereals wilt and dry up due to moisture stress.

2.6.2 Temperature:

Pigeon pea grows in a variety of agro-ecological zones, and is well adapted to semi-arid climate conditions in Southern Africa. Other scientists have described pigeon peas as hardy, warm season, drought-tolerant, widely adaptable, and tolerant to high temperatures of up to 35˚C (Vittal *et al*., 2004). The same author also indicated that pigeon peas can be grown between 14˚N and 28˚N latitude, with temperatures ranging from 26˚C to 30˚C in raining season and 17˚C to 22°C during the post-rainy season. According to the study conducted by Silim *et al.* (2001), pigeon peas are sensitive to low radiation and cloudy weather during the flowering and pod development stages which leads to poor pod formation. Choudhary *et al*. (2011) stressed that pigeon peas are sensitive to low temperatures which can lead to the conversion of intracellular water into ice and consequently shrinking cells, wilting, and causing the death of plants.

2.6.3 Photoperiod:

Pigeon pea is known to be a thermos and photo-sensitive crop. It grows in a variety of agro-ecological zones and is well adapted to semi-arid climate conditions. Crop development is affected by temperature, day length, and other factors that cause yield reduction in crops. Choudhary *et al*. (2011) indicated that pigeon pea is mostly grown in areas where day length varies from 11 to 14 hours and large temperature differences are experienced, due to variations in altitude and latitude. According to Silim *et al*. (2001), the majority of pigeon pea varieties are found to be sensitive to photoperiod and temperatures especially when they are grown in high latitude areas. Previous studies reported that photoperiodicity and excessive soil moisture stress which coincides with reproductive growth caused a reduction in pigeon pea yield

(Choudhary *et al*., 2011). Low radiation and cloudy weather have also been reported to cause poor pod formation (Gwata and Shimelis, 2013). The medium-duration pigeon pea varieties are photoperiod sensitive and they also flower when days are short (Matthews and Saxena, 2000). In South Africa, the temperature in the winter months is generally low with occasional frost negatively affecting pigeon pea productivity (Gwata and Shimelis, 2013). The authors further concluded that late-maturing pigeon pea varieties are sensitive to day length and resulted in delays in flowering and maturity which leads to increased susceptibility to a terminal drought that frequently occurs in most areas in South Africa. According to Carrybery *et al*. (2001) flowering in short-duration pigeon pea cultivars was delayed by up to 100 days when the day length in the photoperiod-inductive phase exceeded a critical value. This also affected the medium and late-maturing varieties and delayed flowering by 150 days in response to the photoperiod. Silim *et al*. (2001) reported that pigeon pea plant height, biomass, phenology, and grain yield are highly affected by photoperiod and temperatures.

2.6.4 Soils:

Pigeon pea is reported to be sensitive to water-logging soils which affect plant growth by reducing the oxygen diffusion rate between soil and atmosphere and by changing the physical and chemical properties of soil (Choudhary *et al*., 2011). The same scientist concluded that the risk of crop failure or yield reduction due to water logging is quite high in extra early and early-duration varieties because they have less time to recover from this stress as compared to the long-duration types. The crop does not grow well in acidic soil with problems of aluminum and manganese toxicity. According to Choudhary *et al*. (2011), acidic and saline soils reduces the availability of soil nutrients and it severely affects plant growth. The high salt content in soils may affect soil microbial activity through direct toxicity and osmotic stress (Zahran, 1999) and also affect N_2 fixation (Rao *et al*., 2002). Pigeon pea grows well in all types of well-drained soils with soil pH ranging from 5.0 to 7.0 (DAFF, 2009). Other scientists have stated that pigeon pea plants can tolerate soil salinity and alkalinity but not excessive soil acidity of pH Below 5.0 (Matthews and Saxena, 2001).

2.7 IMPACT OF CLIMATE CHANGE ON PIGEON PEA PRODUCTION

Climate change is defined as a weather pattern leading to changes in climate and an increase in temperatures, erratic rainfalls, floods, and a rise in sea level (Levin *et al.*, 2022). The change in climatic conditions has a major impact on rainfed crops including pigeon peas (Basu and Bandyopadhyay, 2009). Southern Africa is a semi-arid region and it is characterized by low and erratic rainfall. According to Madegwa *et al*. (2016), frequent droughts are the effects of climate change hence food security is also threatened. Drought stress is one of the major abiotic stresses in food production. Pigeon pea is grown under rain-fed conditions and gives reasonable yields under drought conditions in Southern and Eastern Africa (Matthews 2001; Saxena *et al*., 2010). According to Odeny (2007), pigeon peas can better withstand severe drought relative to other legumes due to their deep root system and osmotic adjustment in the leaves. Studies have revealed that genotypes with deeper rooting systems have greater tolerance to water deficit than in crops such as cowpea (Munjonji *et al*., 2018) chickpea (Mafakheri *et al*., 2010), and pigeon pea (Odeny, 2007; Singh *et al*., 2020). The deep roots system of pigeon peas allows the plant to utilize water sources in deep soil layers (Odeny, 2007) during water stress and withstand drought better than most legume crops due to its osmotic leave adjustment (Odeny, 2007). Pigeon pea can thus be used as a possible solution to combat climate change due to their drought-tolerant nature.

2.8 PHYSIOLOGICAL PROCESSES OF PIGEON PEA AND OTHER LEGUMINOUS CROPS

Drought stress influences several changes in physiological, biochemical, and molecular components of photosynthesis (Prasad *et al*., 2008). Drought induces photosynthesis either through regulations by stomatal closure or decreasing flow of CO_2 into mesophyll tissue (Flexas *et al*., 2004). In some studies, metabolic changes decline in ribulose 1,5- bisphosphate carboxylase/oxygenase protein content (Bota *et al*., 2004), decline in photosynthesis (Cornic, 2000), metabolic impairment caused by tissue dehydration (Siddique *et al*., 2001), impairment of ATP synthesis, and decreased inorganic P. Impaired mitosis, cell elongation, and expansion result in reduced plant height, leaf area and growth of legume crops under drought (Hussain *et al*., 2008).

Water use efficiency (WUE) is the physiological mechanism that enables plants to withstand low soil moisture content and perform satisfactorily under water stress. Damour *et al*. (2010) also explained that stomata play a key role in plant adaptation to changing environmental conditions as they control both water losses and CO_2 uptake. Recent studies found that deep-rooted pigeon peas controlled their stomatal conductance relative to shallow-rooted finger millet (Singh *et al*., 2020). The same scientist reported that intercropping of pigeon pea/ finger millet was more effective and the stomatal conductance remained at 60mmol m^{-2} S^{-1}. Stomatal conductance showed the highest value and gradually decreased with a decrease in the leaf water potential of grain legumes (Reynolds-Henne *et al*., 2010). The water holding capacity of soil also influences stomatal behavior. According to the findings of Gunderson *et al*. (2002) photosynthesis and stomata conductance changes with time and are sensitive to environmental variation.

Genotypes of plants behave differently in stomatal control under drought conditions with some having a higher stomatal conductance than non-stressed plants (Pimentel and Silva, 1999). According to Munjonji *et al*. (2018), the stomatal behavior of cowpea genotypes grown under varying moisture levels showed that cowpea genotypes varied in stomatal conductance under drought conditions and the variation is more severe at the vegetative growth stage. Water stress was found to reduce the stomatal conductance of bean genotypes due to drought conditions and certain bean genotypes maintained higher stomatal conductance levels in the morning (09:00), when the vapor pressure deficit is the lowest during the day than at 12:00 middays (Pimentel and Silva, 1999).

2.9 PHOSPHORUS INPUT IN SMALLHOLDER FARMER FIELDS

In South Africa, most soils for agricultural purposes are generally poor and characterized by low cation capacity, pH, organic matter content, and available soil nutrients. The majority of South African soils are characterized by low phosphorus (P) concentration (Whitbreat *et al*., 2004), especially in areas of high rainfall (Gichangi, 2007). A study conducted in South Africa on P availability in phosphate-fixing soils using goat manure (Gichangi, 2007) has revealed that the unavailability or low soil P is a major constraint resulting in low agricultural production as a result of strong sorption of P in relatively rainfall areas. According to Gichangi (2007), a sufficient supply of P to plants is essential for the formation of seed and root development with assistance in the maturing of crops. According to Kgonyane *et al*. (2013) studied the availability of soil P in Limpopo Province, South Africa. The author reported that Phaudi, Perskebult, and Bokgaga in Limpopo Province, recorded low P content of 3.0, 3.0, and 1 mg kg^{-1}, respectively. Furthermore, the same scientist explained that P depletion in soils was caused by continuous cultivation with little or no fertilizer application by smallholder farmers. Recent studies conducted in Nigeria also reported that Ekpoma soils which are classified as Ultisol were found to be generally low in P content (Stephen *et al*. 2014).

Phosphorus is an essential macronutrient element in plants as it is part of Adenosine Triphosphate (ATP), DNA, RNA, and plays a major role in energy storage and transfer (Stephen *et al*., 2014). The same literature indicated that P plays an important role in the growth, nodulation, nitrogenase activities, and seed yield in pigeon peas. Grain legumes require P in large quantities because it is essential during photosynthesis for energy transfer, root development, increased plant growth, N fixation through nodulation, and N- uptake (Reamaekers, 2001). However, other scientists have stressed that crop requires an adequate amount of P for optimum production during early growth stages (Grant *et al*., 2001). Previous studies by Hussain *et al*., (2020) have detected that a low P supply decreases nitrogenize activity and ATP concentration in nodules thereby decreasing the ability of the plant to fix Nitrogen (N). According to Igwe *et al*. (2010), most of the soils P are not available for growing crops due to the fixation of iron (Fe) and aluminum (Al) oxides which are present in highly weathered soils. Hence, the additional application of P as fertilizers is essential to improving crop productivity. Stephen *et al*. (2014) also advised that it is important to apply P fertilizers to improve the growth and yield of pigeon peas in such an environment.

2.10 RESPONSE OF LEGUME CROPS TO P FERTILIZER APPLICATION

Phosphorus plays a major role in many processes such as storage and transfer of energy, stimulation of root growth, flowering, fruiting and seed formation, nodule development, and N_2 fixation (Gichangi, 2007). The application of P in legume crops can increase plant leaf area, biomass, grain yield, number and weight of nodules, and residual soil nutrients (Stephen *et al*., 2014). According to Pramanic *et al*., (2009), the application of small quantities of P at the rate of 36 kg ha^{-1} showed an increase in pigeon pea growth, yield, and nodulation.

Stephen *et al.* (2014) studied the residual effect of P fertilizer on the yield of pigeon peas in Ultisol, Nigeria. The scientists demonstrated that high application of P 75 kg ha^{-1} increased nodules count and weight by 52.9 and 54.7% respectively compared to the control (0 and 25 kg P ha^{-1}). The same authors also revealed that high application of P 75 kg ha^{-1} increased pigeon pea biomass and nodule index whereas 25 kg P ha^{-1} has recorded the highest grain yield. Stephen *et al*., (2014) concluded that the application of P fertilizer at the rate of 25-75 kg increased nodulation and nutrient uptake of pigeon pea in degraded soils. Other studies have reported that the application of 26.4 kg P ha^{-1} significantly improved seed yield, nodulation, and nitrogenase activity in peas (Babu *et al.*2014) revealing that the N_2 fixation process in legumes is sensitive to P deficiency and leads to reduced nodule mass.

Recent studies in South Africa have demonstrated a positive response of P application to the growth and grain yield of pigeon peas in intercropping systems. Nndwambi *et al*. (2016) reported that the application of P fertilizer at 45 kg ha^{-1} resulted in a grain yield increase of 37.1% higher than the grain yield of intercropped pigeon pea.

The response of pigeon peas to a small quantity of P also depends on the soil P status and some cultivars are tolerant to P deficiency (Fujita *et al*., 2004). Several researchers have observed that pigeon pea varies in P-utilisation efficiency and it also differs amongst pigeon pea cultivars (Fujita *et al*., 2004). The same researchers have also found that pigeon pea cultivars can absorb more P from the soil under limiting conditions and were found to have a high yield through effective translocation of the absorbed P to the leaves. P uptake by legume crops such as cowpeas also varies due to the growth duration of pigeon pea (Asiwe *et al.*, 2021)

Researchers have shown that pigeon pea is one of the few crop species that can utilize bound P efficiently and able to produce under P-limiting conditions (Odeny, 2007). Works done by numerous scientists indicated that pigeon pea responds positively to P application (Stephen *et al*., 2014; Nndwambi *et al*., 2016). The application of P fertilizer can overcome the deficiency in soils that do not strongly adsorb P (Giller, 2001). A study in Malawi demonstrated that low legume yields were associated with the minimal use of P fertilizers in smallholder farmers' fields (Mwalwanda *et al*., 2003).

2.11 BIOLOGICAL NITROGEN FIXATION (BNF) IN LEGUMES

Biological N_2 fixation is defined as the reduction of atmospheric dinitrogen N_2 to ammonia (NH_3), catalyzed by the enzyme nitrogenase (Tairo and Ndakidemi, 2013; Li *et al*., 2021). Pigeon pea is one of the legumes with the ability to fix N and is crucial for increasing plant growth since most smallholder farmers cannot afford sufficient N fertilizer. In a land-based system, N is continually cycled between the atmospheres where it exists in an unreactive state as gaseous N_2 and the soil (Herridge *et al*., 2013). The same study also indicates that about 150 to 200 million tons of N annually as fertilizers are added to the world's agricultural soils. Research work indicated that crops also process N into soil organic matter each year, and remove N in harvested products and those lost through erosion, denitrification, ammonia volatilization, and leaching. The crop can fix up to 235 kg N ha^{-1} (Subbarao *et al*., 2000) and produces more N^{-1} unit area from biomass compared to other legumes. The crop's ability to fix atmospheric N into the soil is crucial for the nutrition of associated cereals by improving the amount of food that farmers can produce with or without sufficient fertilizers (Odeny, 2007). Olujobi and Oyun (2012) studied N transfer from pigeon pea to maize in a pigeon pea/maize intercrop and revealed that there was a transfer of N from pigeon pea to maize when both crops were intercropped through root-to-root interaction (below-ground process).

Several scientists have found that BNF from nodules is very important for the growth and yield of legumes (Dinh *et al*., 2013) and is known to reduce soil fertility problems (Kahindi *et al*., 2004). Other authors also reported that pigeon peas can fix up to 235 kg N ha^{-1} (Subbarao, *et al*., 2000) and produce more N $unit^{-1}$ area from biomass than many other legumes (Egbe and Anyam, 2011). According to the study conducted by Herridge *et al*. (2008 & 2013) legumes can fix about 40 million tonnes of N annually. Other researchers have recorded that soya beans produced the highest N fixation which contribute to 180 kg N ha^{-1} under a well-irrigated plot and the water-limited crops such as lentils and Mung beans have fixed the lowest amount of N of 58 and 34 kg ha^{-1}, respectively (Unkovich *et al*., 2010).

According to the study done by Mapfumo *et al*. (1999), SD pigeon pea fixes from 6 to 43 kg N ha^{-1} whereas the LD pigeon pea genotype was found to fix between 18 and 183 kg N ha^{-1}. The legumes are known to produce residues with high N content that remain in the soil after the crop is harvested (Herridge *et al*., 2013). The same scientists reported that mineral N released from the residues was decomposed and utilized by the following crop. According to the research findings, the fixed N is crucial for the nutrition of other cereal crops in rotational and intercropping with pigeon peas to increase crop productivity, irrespective of the farmer's ability to apply sufficient N fertilizers.

2.13 EFFECT OF TILLAGE SYSTEMS ON LEGUMES PRODUCTION

The conventional tillage system has led to a decline in soil organic matter due to water runoff, and soil erosion which led to physical, chemical, and biological soil degradation (Benites *et al.,* 2003). Conservation tillage is important in dry areas where crop residues are essential to achieve sustainable yields (Busari *et al.,* 2015). A study conducted in India by Kumar *et al*. (2015) observed that tillage practices did not significantly increase the number of pigeon peas pods plant^{-1}, seeds pod^{-1}, and grains plant^{-1}. The authors further recorded a high biological yield of pigeon peas under minimum tillage over conventional tillage. Though, the study also detected that in the intercropping system, the productivity was higher in conventional tillage than in minimum tillage. According to Herridge *et al.* (2013) cereal under no-till requires additional N fertilizer to supplement the reduced soil nitrate. However, for legumes, the lower nitrate levels were demonstrated to increase N_2 fixation activity. The same author indicated that improved soil water and reduced soil nitrate, increased chickpeas shoot dry matter and grain yield, % Ndfa and total N fixed were observed.

2.14 PIGEON PEAS PRODUCTION IN CROPPING SYSTEMS

There is an urgent need to develop a resilient agroecosystem capable of helping smallholder farmers to adapt to climate change, mainly drought. The results of the study conducted revealed that cropping systems by intercropping grain with tree legumes may improve crop productivity and resilience to adverse weather conditions (Renwick *et al*., 2020). Pigeon peas can be incorporated into several cropping systems which extend to intercropping, agroforestry, and crop rotation.

Agroforestry is a dynamic and sustainable land management system of growing agricultural crops with woody perennials. Perennial or long-duration pigeon peas types have not received attention in South Africa as a multi-purpose species for Agroforestry systems. Pigeon peas in smallholder farming systems are mostly planted as intercrop, rotation with cereals. Renwick *et al.* (2020), studied Maize/ pigeon peas intercropping in Tanzania, and found that intercropping system outperformed monocropping in grain yield and protein content and also showed tolerance in drought conditions. The same scientists also observed a steady increase in the quantity of N transferred from pigeon peas plants to maize due to N flux in cereal/legume intercropping. In a study conducted by Makumba *et al*. (2009) demonstrated that yields of maize from maize/pigeon/gliricidia intercropped results were similar to maize yield in moderately fertilized sole maize. Several authors also observed the same trend and recorded a 32% maize yield increase when maize was planted in association with pigeon peas (Sogbedji *et al*., 2006). Similar results were documented by numerous scientists that legumes grown in intercrop or rotation with cereals often increase the yield of a subsequent cereal crop grown on the same soil (Rusinamhodzi *et al*., 2011). The findings of the study conducted by Nndwambi *et al.* (2016) contradict the results reported by Ansari *et al*. (2015) recorded lower pigeon peas yields in intercropping were caused by competition for resources.

Studies reviewed by Snapp *et al*., (2003) indicated that maize/pigeon peas intercropped or in the rotation increased maize yields by 0.3 to 1.6 t ha^{-1}. However, time is an important factor in pigeon peas/maize intercropping (Chamago, 2001) results are evident after 2 to 3 years. The study conducted in Swaziland, (Edje, 2014) demonstrated that maize and pigeon peas should be grown in association with maize at the recommended plant density and spacing of 40 000 pigeon peas ha^{-1}in intercropping system.

The study conducted in Mpumalanga on pigeon peas/maize intercropping (Matthews *et al*., 2001b) showed that intercropping increased land-use efficiency and were higher in LD/MD pigeon peas varieties types than in SD types due to high competition between crops. The same researchers have also reported that yield reduction of both maize and pigeon peas under intercropping was observed where maize was intercropped with pigeon pea SD varieties and was more severely affected than the long-duration cultivars. Similar studies conducted in Zimbabwe on maize/legume intercropping under a no-till system (Rusinamhodzi *et al*., 2011) found that LD pigeon peas varieties coincide with the free-roaming livestock, though farmers plant their crop close to their homestead. The same author concluded that maize/grain legume intercropping reduces the risk of total crop failure, but it improves crop productivity by ensuring food security in vulnerable production systems. The success of the maize/pigeon peas intercropping systems should be strengthened by strong extension support and strong market linkages.

2.15 PHOSPHORUS FERTILIZER APPLICATION AND GENOTYPE ON NUTRITIONAL VALUE OF PIGEON PEA

Babu *et al.* (2014) found that a high protein yield in pigeon peas was recorded with the P application of 30 kg ha^{-1}. Aher *et al*. 2015 studied the sources and level of P on the yield and quality of pigeon pea. The same author observed an increase in protein content range from 17.7 to 20.52% when 75 and 100 kg P_2O_5 ha^{-1} were applied. Other studies were conducted on the growth, yield, and quality of pigeon peas as influenced by different P levels and liquid bio-fertilizers (Ade *et al*., 2018). The author noticed that when 40 and 50 kg of P were applied, pigeon pea growth and yield were increased. Yin *et al*. (2016) stressed that excessive P application rates reduced seed quality, increased protein concentration and the oil levels decreased with an increase in P application. Abbasi *et al*. (2012) reported that P application increased the concentration of both protein oil in soybeans.

Studies on genotypic variability of pigeon pea in the distribution of photosynthetic carbon at low P level in Nigeria (Fujita *et al*., 2004). The author revealed that the sugar and starch concentration of pigeon peas in the upper stem declined at low P soils in ICPH 8 and ICPL 87 cultivars, whereas in sensitive cultivars such as UPAS120, carbohydrate concentration increased marginally in roots. This indicates that low application of P in pigeon peas decreases starch accumulation in biomass than in the roots and results in low biomass production (Fujita *et al*., 2004). Numerous authors in Southern Africa also stressed that the protein content and other nutritional values of pigeon peas grains are influenced by genotype performance (Morake *et al*., 2002; Makelo, 2011). Saxena *et al.* (2010), emphasized that low pigeon pea yields with poor nutritive value were caused by climate change, locality, low soil nutrients, and other environmental factors. The same author also observed significant differences in pigeon peas' protein content across locations and months.

2.16 CONCLUDING REMARKS

Climate change and weather variability already affect farming conditions across Southern Africa leading to the vulnerability of farmers, agricultural production, and food security. Pigeon peas are a climate-smart legume crop with numerous uses and benefits for smallholder farmers and consumers. However, pigeon peas have been neglected and received less attention by researchers, compared to other legumes such as dry beans, groundnuts, soya beans, etc. According to the literature, pigeon peas have a high protein content ranging from 18 to 26% and are also a good source of minerals like potassium, phosphorus, calcium, magnesium, sodium, and zinc. the demand for nutritional foods is increasing due to an increasing population and expensive meat proteins, which are not affordable to the majority of smallholder farmers in South Africa. This high-protein vegetable can be used to eliminate protein malnutrition in smallholder farming systems. Legumes are regarded as an economical dietary source of good quality protein and are higher in protein than most other plant foods. However, low pigeon peas productivity in smallholder farmers' fields was recorded

Chapter 3:

CHAPTER 3A: THE STATUS OF PIGEON PEAS [*CAJANUS CAJAN (L.) MILLSPAUGH]* PRODUCTION IN LIMPOPO AND MPUMALANGA PROVINCES OF SOUTH AFRICA: FARMER PRACTICES, UTILIZATION, AND POTENTIAL MARKETS

Abstract

Despite the fact that pigeon peas are an ancient crop, only a few farmers in South Africa still plant it. Therefore, the study's objectives were to assess farmers' production status, utilization, awareness, and socioeconomic factors in pigeon peas. Both quantitative and qualitative methods were in the two Provinces of South Africa during the 2020/21 crop season to collect information. To gather information, 114 farmers were questioned individually at their farms using a snowball sampling method. Quantitative data was collected and numerically recorded in an excel spreadsheet before statistical analysis with SAS. Qualitative data was collected through a participant-observation method to collect detailed and accurate information using content analysis. Likelihood ratio chi-square was used to detect relationships between pigeon peas and various measured parameters.

The study indicates that commercial farmers are not involved in pigeon peas production in all six municipalities. Out of 114 farmers interviewed,11 were smallholder farmers and 103 were subsistence farmers in all six municipalities. The majority of farmers produced pigeon peas under 1 ha of land. Significant variation between municipalities on pigeon peas variety use was recorded. The study recorded that 78% of farmers used unknown varieties in all municipalities which resulted in low grain yields. More farmers used the crop as grains and only a few farmers used the crop as fodder and medicinal. Grain yield production ranged from 10–20 kg ha^{-1} in all six municipalities. A high proportion of farmers (93%) grow pigeon peas using intercropping system and only 8% of farmers produced in sole cropping. The study revealed that few farmers utilized commercial fertilizers to improve soil fertility. Pigeon peas were mostly used by male farmers for income generation and by female farmers mainly for domestic consumption. Currently, production levels of pigeon peas are still relatively low. The majority of farmers are still producing the crop in backyard gardens, mostly by subsistence farmers. Low yields were mainly contributed to poor quality seeds and poor agronomic practices. There was also a lack of information on production, marketing, and processing for all farmers across gender and age. In order to alleviate malnutrition and food insecurity in South Africa, attention should be directed to the allocation of production resources, infrastructure assistance, availability of improved seed types, provision of knowledge, and new technology transfer.

Keywords: pigeon peas, smallholder farmers, production practices, utilization, and information

3.1 INTRODUCTION

Pigeon peas (*Cajanus cajan* [L] Millsp) are a leguminous crop in South Africa and are not yet regarded as a major grain legume crop. In Limpopo, Mpumalanga, and KwaZulu-Natal, it is usually grown by subsistence farmers as a single plant or as hedges in or around their backyard gardens (DAFF, 2009). The crop is known as red gram, Congo peas, arhar, gungo peas, no-eye peas, or gandul. It is also known as Lothlodi, Ndozi, Duifert, Udaali, and Dithlodi in South Africa (DAFF, 2009). Migrant workers from Mozambique and Malawi introduced the crop to Mpumalanga Province, as well as Indian immigrants to coastal Kwazulu-Natal Province (Matthews and Saxena, 2001b). However, the majority of smallholder farmers in South Africa are not aware of its potential as a food crop and the market demand that exists locally and internationally for the Indian and Asian populations.

Pigeon peas are used as a subsistence, food security, and income crop by many smallholder farmers in distant rural locations. The crop plays a dual role, including being a good source of feed for livestock. The crop provides protein-rich food, with protein levels in seeds ranging from 19 to 26% (Saxena *et al*., 2010), and 17 – 25% (Kachere *et al*., 2019). Furthermore, the crop's roots, leaves, and flowers have healing potential. Smallholder farmers used the crop to treat diseases like the liver, skin, lungs, and kidneys. Pigeon pea stems and twigs are utilized as fences and firewood (Matthews and Saxena, 2000; Orr *et al*., 2013). Despite its numerous uses in the food, feed, and medicinal industries as well as local, national, and international markets, the crop has received less research and development support in South Africa.

Pigeon peas are typically grown in dryland environments by smallholder farmers with little resources, with or without fertilizer applications. Pigeon peas are mostly used in crop rotation and intercropping systems, mainly for crop diversification (Rusinamhodzi *et al*., 2011). Many studies have been undertaken to promote the use of pigeon peas in intercropping to increase crop yield (Nndwambi *et al*., 2016) and improve crop productivity. Some scientists have advocated the choice of intercrop combination and selection of pigeon peas cultivars that are suitable for a farmer's field conditions (Saxena *et al*., 2018). Pigeon peas have been shown to improve soil fertility and structure through biological nitrogen fixation (Stephen *et al*., 2014), organic matter accumulation, and plant nutrient recycling.

Pigeon peas are an important legume crop in Sub-Saharan Africa (SSA) and Asia. The crop is still considered a minor crop in South Africa, with more emphasis placed on high-value crops such as vegetables, fruits, and cereal crops. Numerous efforts were done to introduce improved pigeon peas varieties in South Africa's Mpumalanga and Limpopo Provinces (Matthews *et al*., 2001a). However, smallholder farmers continue to use landrace pigeon peas varieties, which are associated with low grain yields of poor quality and susceptibility to pests and diseases (Matthews *et al*, 2001a). Southern Africa's average overall grain yield is quite low. According to Saxena (2008), an estimated 866.2 and 736.2 kg ha^{-1} pigeon pea grain yield from landraces were recorded respectively, compared to 2500 kg ha^{-1} from improved pigeon peas varieties. More efforts should be made to promote new and improved varieties in order to increase production yields in the smallholder farming system.

Despite the fact that pigeon peas are a multi-purpose legume species (Odeny, 2007), information on recent pigeon peas improvements in South Africa is still lacking. Pigeon peas are major actors in the food supply, including researchers, scientists, government extension agencies, non-governmental organizations, and commercial corporations, continue to underutilize and ignore the crop. Understanding farmers' and markets' preferred pigeon peas features, as well as prioritizing their production constraints, is critical for increased pigeon peas productivity in South Africa. As a result, it is critical to involve farmers in variety selection (Saxena *et al*., 2018), encourage participation in the technology evaluation process, and provide infrastructure support from all stakeholders for improved pigeon peas production to achieve high levels of adoption of new innovations. As a result, the present study assessed the current status of pigeon peas production, utilization, and potential markets, as well as evaluated farmers' knowledge, and socioeconomic attributes in pigeon peas production in the two agro-climatic conditions in South Africa.

3.2 MATERIAL AND METHODS

3.2.1 Study sites

The study was conducted in Limpopo and Mpumalanga Provinces of South Africa in six municipalities, mostly where pigeon peas are predominant during the 2020/21 growing season. The study targeted only pigeon peas growers with 1 or more plants. Pigeon peas farmers from various villages within the municipalities were interviewed. The municipalities sampled in the survey in Limpopo Province were Collins Chabane and Malamulele municipalities, represented by Vhembe district, Giyani, Maruleng, and Tzaneen. In Mpumalanga Province, the targeted municipality was Bushbuckridge in the Ehlanzeni District (Table 3.1 and Figure 3.1).

Rainfall in Limpopo Province ranges from 200 mm in very dry areas to 1500 mm/annum in high rainfall areas (ARC, ISCW). Maximum temperatures during summer are very high, up to 40°C in January. The rainiest months are October to March, and winters are dry and warm with average maximum temperatures of 25°C. The lowest temperatures are in July, with occasional frost. In Mpumalanga Province, summer rainfall is high, which ranges from 500 to 1800 mm/annum. Winters are very cold with frequent frost in most areas, and the average annual minimum and maximum temperatures are 8°C and 22°C, respectively.

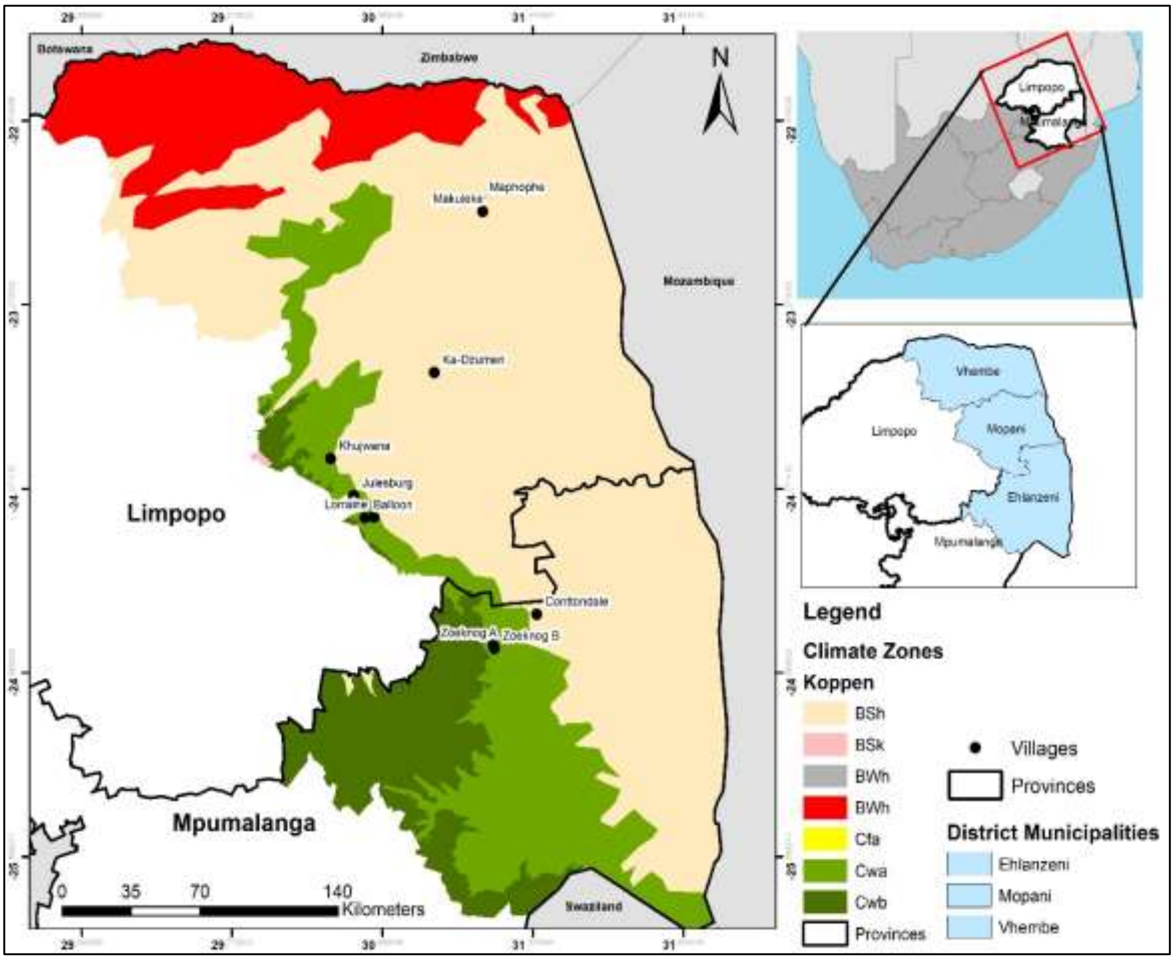


***Figure 3.1*: Map showing Limpopo and Mpumalanga Provinces within the district municipalities and villages and different climatic zones.**

3.2.2 Procedure for sampling and administration of questionnaires

Both the quantitative and qualitative data collection methods were used. Local authorities and extension officers from all sampled villages were contacted before data collection to help in identifying pigeon pea farmers. A structured questionnaire was used to interview farmers individually and participant observation was also used as described by Cohen *et al*., (2011) during field visits to allow participants to express themselves more openly. Information such as pests, diseases, and crop conditions was also collected through field observations because most farmers are unable to identify pests and diseases. Additional information was also collected through interviewing key informants (tribal authorities, extension personnel, and farmers' representatives) during group discussions to validate information provided by pigeon growers, and this information was used for results discussions.

A non-probability sampling method using a purposive and snowball sampling technique was used to collect information from the growers. A snowball sampling technique was used to identify pigeon farmers because pigeon peas are produced by a limited number of farmers in both Provinces. The snowball sampling technique was also used in increasing the sample size where respondents helped to identify pigeon peas growers who met the required criteria (Biernacki and Waldorf, 1981). The interest was to select and interview only farmers who are involved in pigeon peas production. A total of 114 pigeon peas growers were reached and interviewed individually using a structured questionnaire and the number was reached through the help of extension officers in both Provinces (Table 3.1).

Table 3.1 Geographical coordinates, altitude, daily mean temperatures, and mean annual rainfall of the six municipalities of the two Provinces of South Africa.

Province	District	Municipality (Number of respondents interviewed)	Village	Coordinates	Altitude (m.a.s.l.)	Daily temp mean(°C) (2019/20)	Annual rainfall (mm/yr) (2019/20)
Mpumalanga	Ehlanzeni	Bushbuckridge (n=31)	Segagule(Cottondale)	24˚35'49"S; 31˚08'32"E	725	Max.=25	
			Zoeknog A and B	24˚45'24"S; 30˚58'34"E		Min.=16	1189
Limpopo	Vhembe	Collins Chavane (n=31)	Maphophe	22˚48'57"S; 30°54'36"E	508	Max.=28	
						Min.= 18	950
		Malamulele (n=14)	Makuleke	22˚52'12"S;30˚54'59"E	560		
	Mopani	Giyani (n=6)	Mageva (KaDzumeli)	23˚28'02"S;30˚46'18"E	545	Max.=20	580
						Min.=19	
		Maruleng (n=10)	Balloon	24˚04'60"S;30˚22'0"E	606		657
			Lorraine	24˚11'23"S;30˚25'36"E		Max.=29	
						Min.=18	
		Tzaneen (n=22)	Julesburg	24˚05'11"S;30˚18'29"E	764	Max.=28	779
						Min.=16	
			Lephaphane (Khujwane)	23˚59'17"S; 30˚11'58"E			

m.a.s.l =meters above sea level, °C degree Celsius, mm/yr =millilitre per year, n=number of respondent, Max=maximum, Min=minimum

3.2.3 Data collection and statistical analysis

Data was collected using a structured questionnaire and participant-observation methods. The questionnaire was subdivided into the following segments:

1. Pigeon peas production and utilization (farmer category, water sources, allocation of land size, number of plants ha^{-1}, and grain yields (kg/ha).
2. Production practices (varietal use, use of cropping systems, management practices such as pest control, weed control, irrigation methods, and use of fertilizers)
3. The utilization of pigeon peas (products, preference, and preparation of pigeon peas meals)
4. Socio-economic information (gender, source of income, land ownership, farm size); pigeon peas processing (products, preference, preservation methods, access to information, and training). Survey questionnaire was used for data collection (Appendix 1)

The data were collected to address the following research questions

1. What are the production practices/recommendations for pigeon peas?
2. What are the production and utilisation of pigeon peas?
3. What are a farmer's demographic and its relationship?
4. Are farmers involved in pigeon pea processing?
5. What is the marketing opportunities of pigeon pea?

The data collected during the survey was recorded numerically in an excel spreadsheet and was subjected to statistical analysis using a statistical package from the SAS Institute version 9.4 (SAS, 2016). A descriptive statistic was computed (frequency, proportion, and mean) was used to achieve the study objectives and to generate frequencies of response. Likelihood ratio chi-square (x^2) was used to draw significant tests and to determine the relationship between municipalities and measured variables. The formula used to analyze the data:

G= 2£f.ln (f/fi) where G= represent the likelihood ratio statistic; 2= observed values; f= expected value, and In=the log to be taken.

The statistical interpretations at the probability levels of $p<0.05$, $p<0.01$, and $p<0.001$ were used to test the significant relationship. The data collected through participant observation was analyzed using content analysis by grouping and coding the gathered information and themes together.

3.3 RESULTS

3.3.1 Farmers' category in pigeon peas production

One hundred and fourteen pigeon peas farmers were interviewed in the survey (Table 3.1) in six municipalities in the two Provinces of South Africa. The study indicated that the majority of pigeon peas producers are in subsistence farming (Figure 3.2). Most farmers were from Malamulele and Collins Chabane, with 100% and 97%, respectively. The study also recorded a lower percentage of farmers who are smallholder farmers, and Maruleng and Collins Chabane had 30% and 13%, respectively. The study also noticed that all municipalities attained the lowest number of smallholder farmers producing pigeon peas. The study indicates that commercial farmers are not involved in pigeon peas production in all study areas. Only 11 were smallholder farmers and 103 were subsistence farmers in all municipalities.

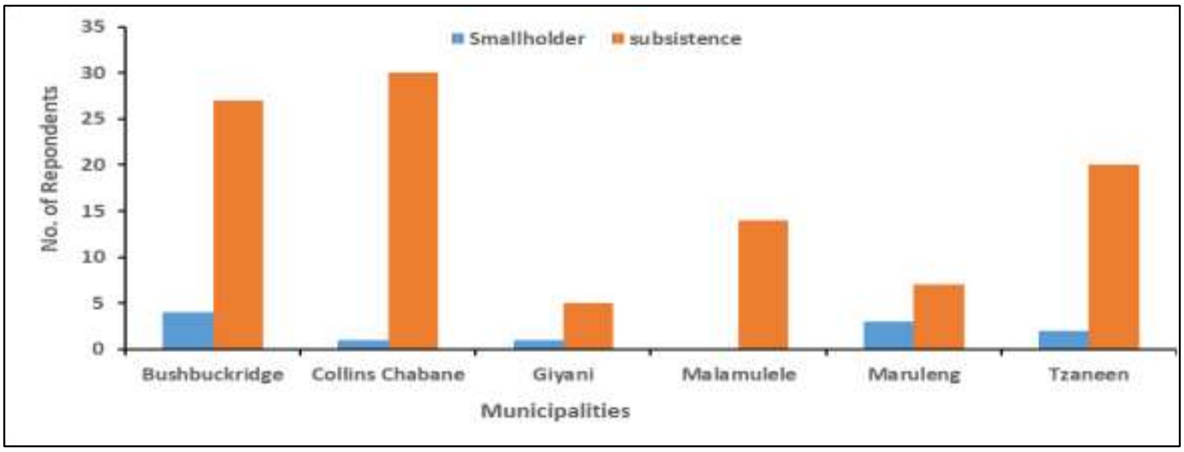


Figure 3.2: Farmer category and production area of pigeon peas production in six municipalities of the two Provinces of South Africa during the 2020/21 growing season.

3.3.2 Land size allocation for pigeon peas production

The study found significant variations (p<0.001) in land size distribution across all municipalities (Figure 3.3). Municipalities such as Malamulele and Bushbuckridge achieved the highest with 100% and 98%, respectively. The majority of farmers produced pigeon peas under 1 ha of land. Only 2% of the farmer's cultivated pigeon peas on less than 5 ha of land.

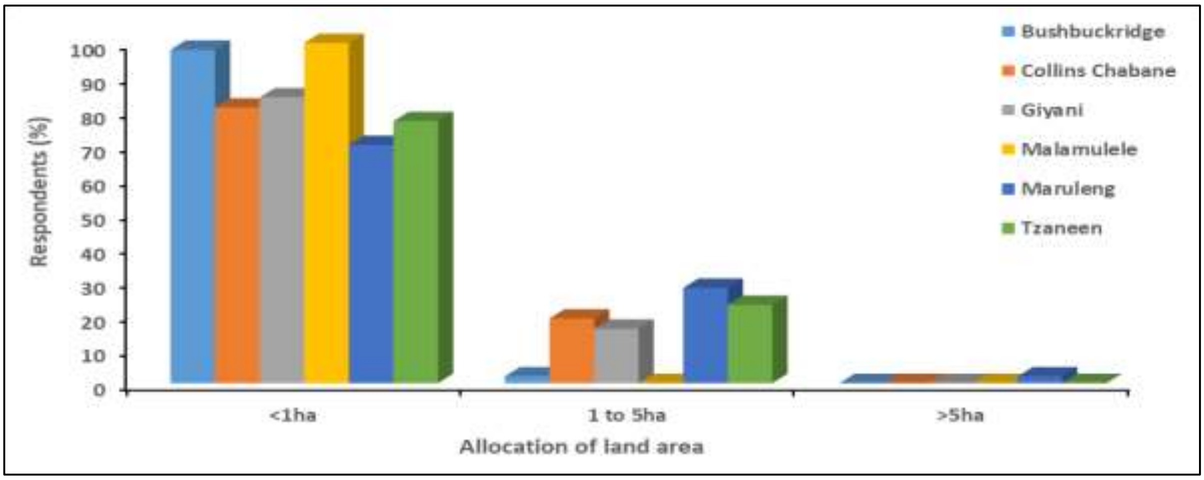


Figure 3.3: Farmers' allocation of land area for pigeon peas production in six municipalities during the 2020/21 growing seasons in the two Provinces of South Africa.

3.3.3 Pigeon peas production sites

A positive association between municipalities and production sites (Figure 3.4) was observed (p<0.001). Pigeon peas were mostly grown in backyard gardens in all six municipalities, with 92%, 89%, and 86% in Malamulele, Giyani, and Tzaneen, respectively. More farmers produced pigeon peas in irrigation schemes and were recorded in Collin Chabane. Only a few farmers grew pigeon peas on commercial land. When compared to other municipalities, Maruleng had the most farmers that cultivated pigeon peas on their farms (22%).

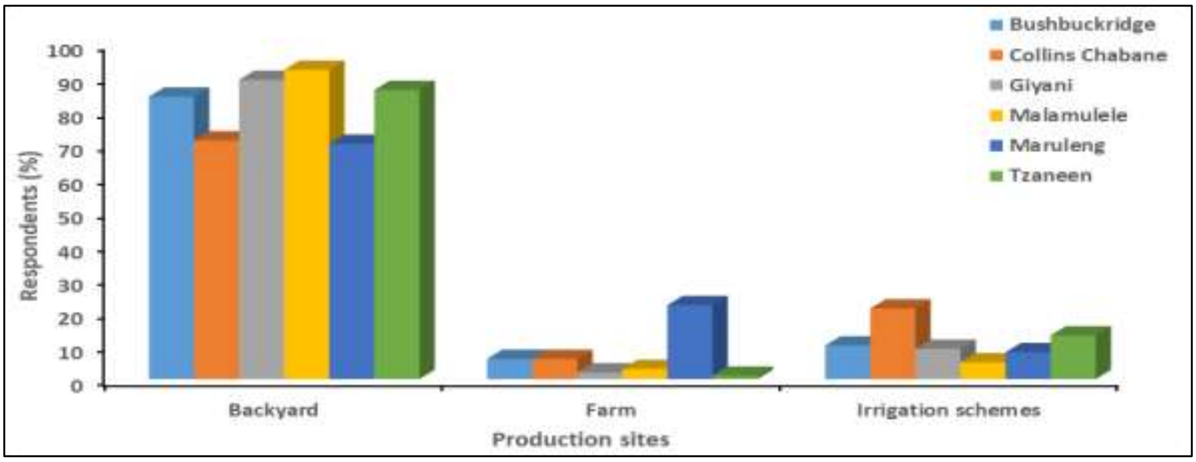


Figure 3.4: Pigeon peas production sites in various municipalities in the two Provinces of South Africa during the 2020/21 growing seasons.

3.3.4 Pigeon peas variety used by farmers

The study results revealed a positive association (p<0.001) between municipalities and the variety used by farmers (Figure 3.5). The study found that 66% of farmers planted unknown pigeon peas seeds. The majority of farmers who cultivated the unknown pigeon seeds were located in Giyani, Malamulele, and Maruleng, with 100%, 93%, and 90%, respectively. Farmers in Bushbuckridge used improved pigeon peas seeds. Improved pigeon peas seeds were used by 32%, 10%, 7%, and 2% of farmers in Collins Chabane, Maruleng, Malamulele, and Tzaneen, respectively.

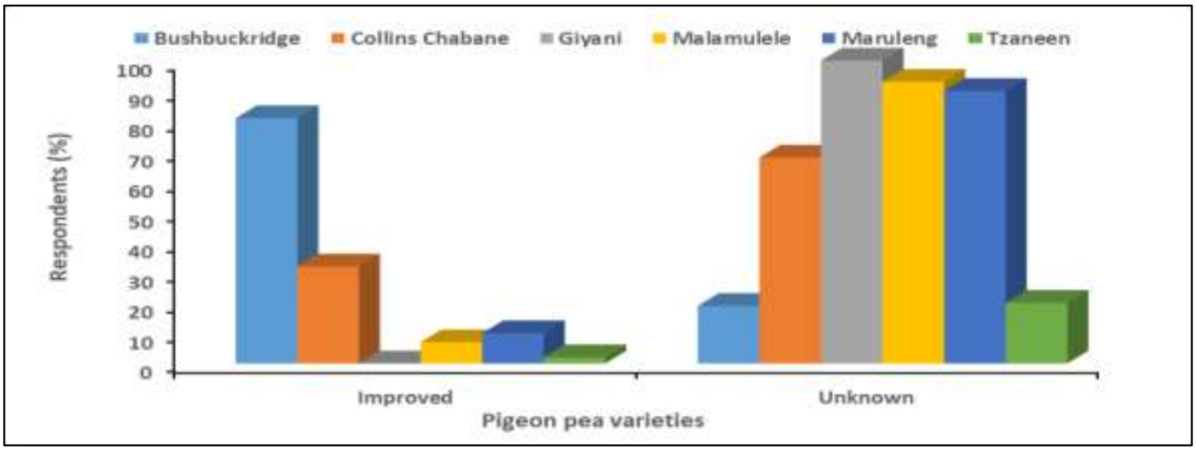


Figure 3.5: Pigeon peas variety used by farmers during the 2020/21 growing periods in six municipalities in the two Provinces of South Africa.

3.3.5 Pigeon peas seed source for farmers

Significant variations between pigeon peas' source of seeds and municipalities were observed (Figure 3.6). At Giyani, more farmers (100% and 95%, respectively) relied on neighbors for seeds. Bushbuckridge and Maruleng had the highest number of farmers; 55% and 50% received seeds from researchers, respectively.

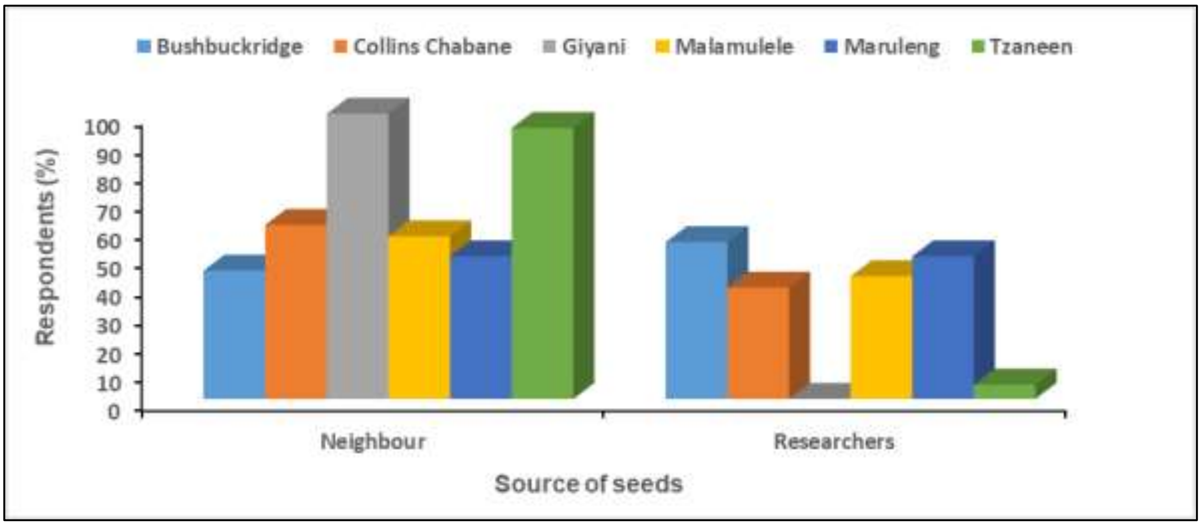


Figure 3.6: Farmers' source of pigeon peas seeds in all six municipalities in the two Provinces of South Africa.

3.3.6 Production of pigeon peas grain

Pigeon peas grain production was significantly different ($p<0.019$) between municipalities (Figure 3.7). The majority of farmers produced less than 10 kg ha^{-1}, with 37% and 33% recorded in Collins Chabane and Bushbuckridge, respectively. Across municipalities, a small number of farmers produced more than 200 kg ha^{-1} of pigeon peas grain yields. The study found that pigeon peas yields of above 200 kg ha^{-1} were not reported in Collins Chabane and Malamulele.

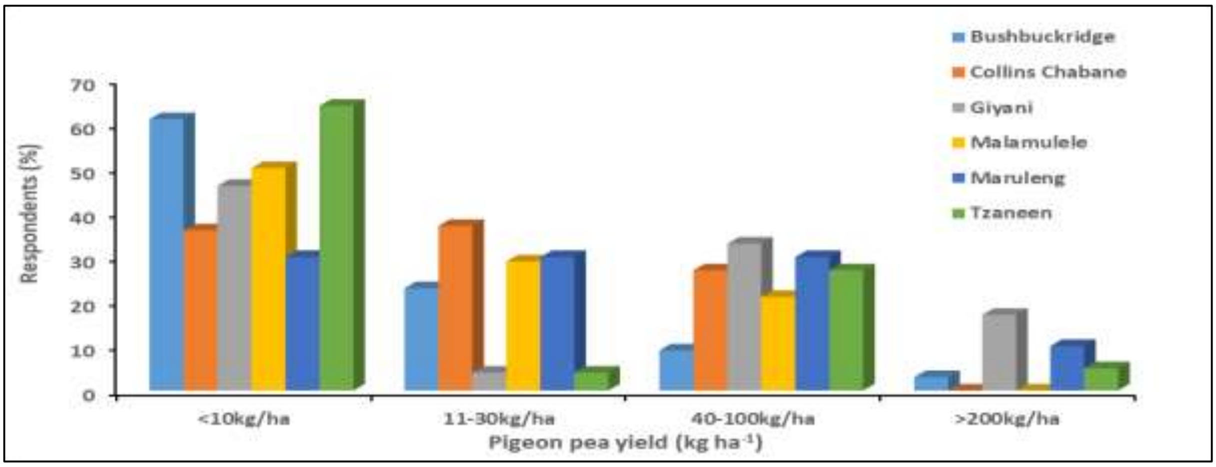


Figure 3.7: Pigeon peas grain yield produced by farmers in various municipalities of South Africa's two Provinces during the 2020/21 growing season.

3.3.7 Cropping systems used by pigeon peas farmers

Despite the none significant effect ($p < 0.583$) shown in cropping system utilization across all municipalities (Figure 3.8). The study results showed that 64% of farmers used intercropping system. Only 7% of the farmer's cultivated pigeon peas as a sole crop. In Collins Chabane, the majority of farmers used sole cropping, and, 3% of farmers in Bushbuckridge planted in intercropped and agroforestry systems. Few farmers (5%) across municipalities grew pigeon peas using rotational cropping. In Giyani, around 17% of farmers utilized a rotational crop system, but in Maruleng and Tzaneen, no farmers adopted a rotational crop system. About 18% of farmers intercropped pigeon peas with maize. Giyani had the highest number of farmers (83%) who intercropped pigeon peas with cereal crops. Only 64, 3, and 18% of the total farmers across all municipalities intercropped maize, fodder, and fruits, respectively.

farmers were reported intercropping pigeon pea with fodder crops in Giyani or Malamulele.

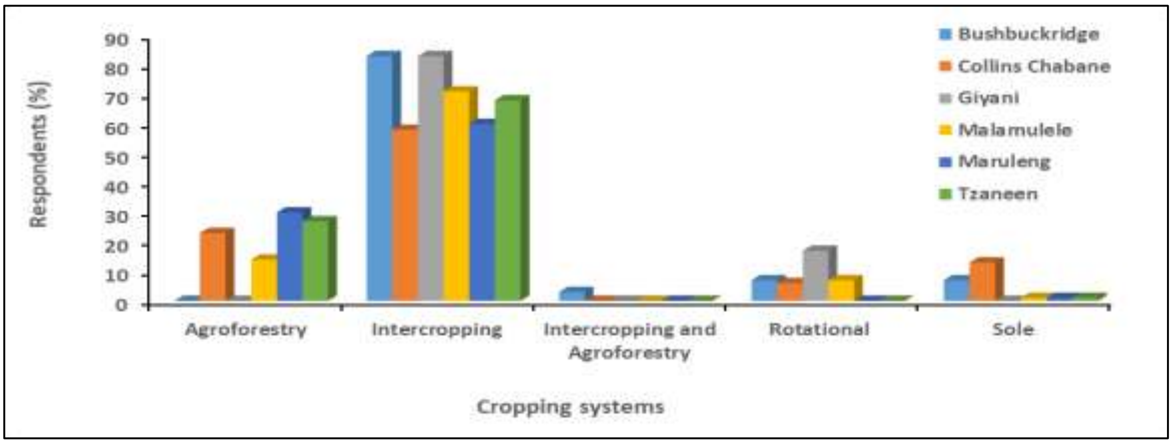


Figure 3.8: Cropping systems used by farmers in six municipalities in South Africa's two Provinces.

3.3.8 Weed control methods used by pigeon peas farmers

The study results showed that the relationship between weed control frequency and municipalities did not differ in all municipalities. Approximately, 70% of farmers throughout municipalities controlled weeds during pigeon production, with only a few farmers in Collins Chabane indicating that they did not control weeds (Figure 3.9). Farmers who controlled weeds twice during the pigeon production cycle contributed 50% in all municipalities. Only 14% of farmers from the study controlled weeds once during the pigeon peas production cycle. Wedding is commonly done manually by a majority of farmers across all municipalities. The study found no variations in pest management practiced by farmers across all municipalities.

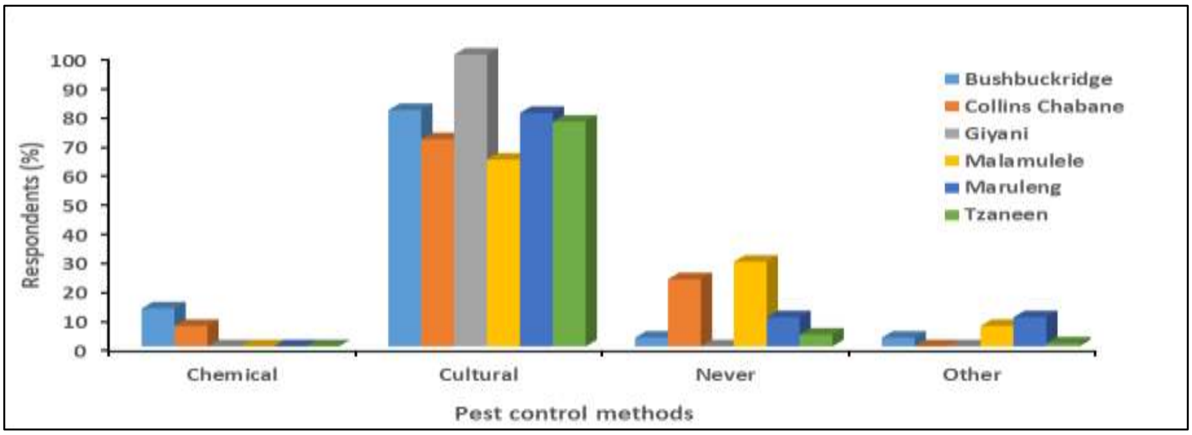


Figure 3.9: Pest control methods used by pigeon pea farmers during the 2020/21 and 2020/22 growing periods in six municipalities in the two Provinces of South Africa.

3.3.9 Pigeon pea farmers' use of soil fertility improvement

Approximately, 64% did not apply any commercial fertilizers to improve pigeon pea production (Figure 3.10). The majority of farmers in all municipalities used organic fertilizers to improve soil fertility. Kraal manure and compost were the only organic materials mostly used by farmers throughout municipalities to produce pigeon peas. Farmers in Bushbuckridge primarily used mixed fertilizer (NPK), nitrogen fertilizer (LAN and Urea), and phosphate fertilizer. It was also shown that a high percentage of pigeon pea farmers used organic fertilizers such as kraal manure since it is easily accessible and less expensive to farmers because some of the farmers had livestock, and it is less expensive than inorganic fertilizers.

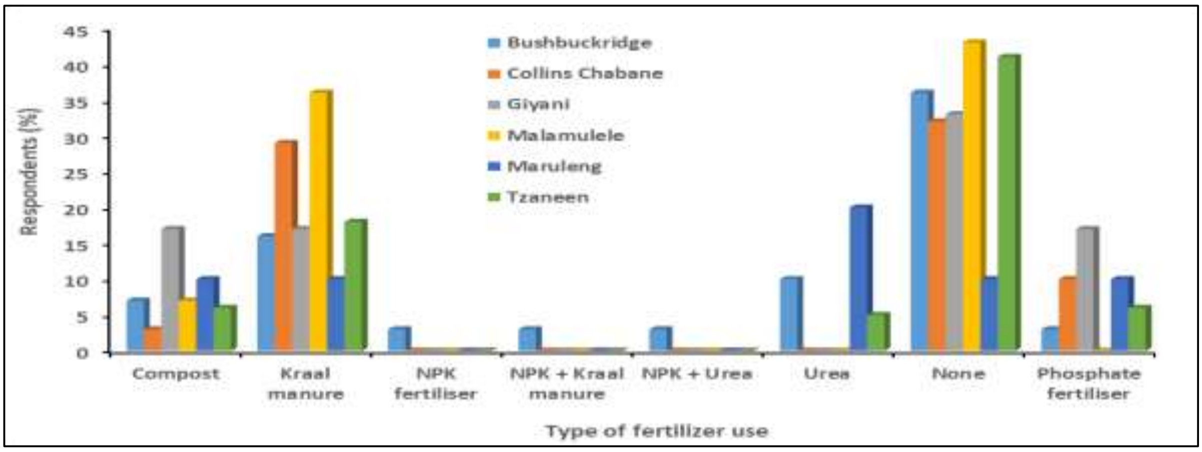


Figure 3.10: Illustration of farmers' fertilizer choices in producing pigeon peas in six municipalities across two South African Provinces.

3.3.10 Farmers' preferences for pigeon pea products

The majority of farmers in the survey preferred pigeon pea soup. More farmers preferred pigeon pea soup (52%) and vegetables (35%) primarily for human consumption (Figure 3.11). Only 22% of farmers in Giyani favored a combination of soup and medicine. Relatively low farmers regarded the crop as a medicine and were 9%, 7%, and 3% of Giyani, Collins Chabane, and Bushbuckridge farmers, respectively. The study recorded that 3% of total farmers in Bushbuckridge preferred pigeon peas as a snack.

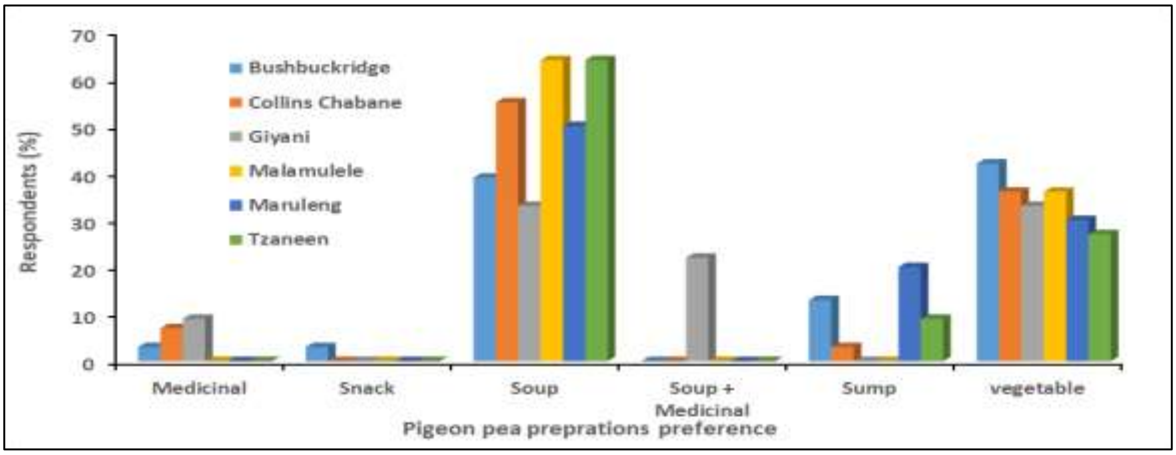


Figure 3.11: Pigeon pea preparations used by farmers in six municipalities across two South African Provinces.

3.3.11 Farmer's access to production information

Almost 81% of farmers do not have access to information from many municipalities. All farmers reported that they did not receive knowledge regarding pigeon pea production, marketing, or processing. Approximately 23% of farmers in Bushbuckridge had access to information.

3.3.12 Utilization of pigeon pea processed products

The study showed a significant relationship ($p < 0.016$) between municipalities and the utilization of pigeon pea products (Figure 3.12). The majority of the respondents across municipalities (86%) used pigeon peas mainly used as dried grains. Only 7% of farmers in Bushbuckridge processed pigeon peas into flour for human consumption. Other municipalities, recorded that 100 % of the farmers were not involved in pigeons' pea processing. All farmers across municipalities used pigeon peas as a fodder supplement for feeding livestock. A high percentage of farmers, 50% and 40%, responded in Giyani and Maruleng, using the crop for livestock feeding. Giyani, Collins Chabane, and Bushbuckridge were the only municipalities with 33%, 6%, and 3% of farmers using pigeon pea as a medicinal product to treat diseases. The study result showed significant variations (p <0.001) in pigeon pea preservation between municipalities. Almost 81% of the respondents stored and used pigeon peas as dry seeds. Only 32 out of 114 farmers do not preserve pigeon peas and consume them as fresh vegetables.

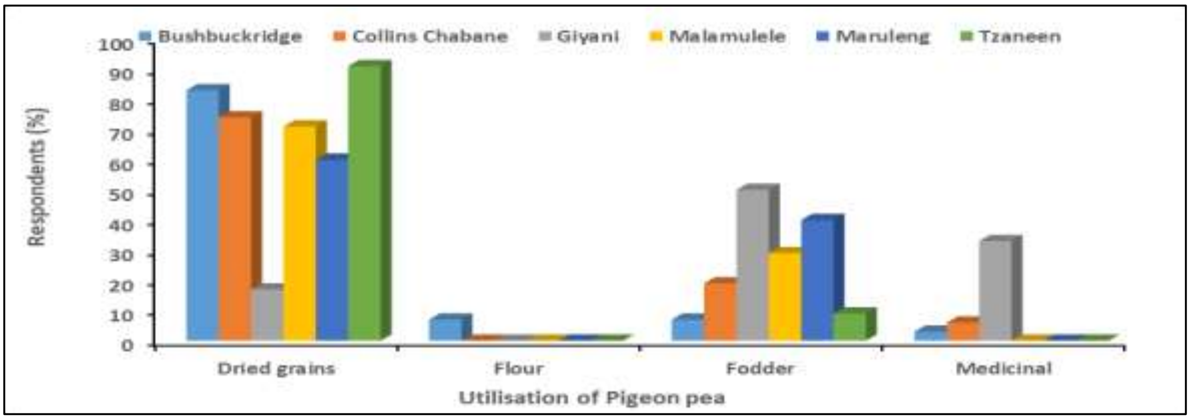


Figure 3.12: Farmers' processed products of pigeon pea in all municipalities of the two Provinces of South Africa.

3.3.13 The utilization of pigeon peas

Figure 3.13 demonstrates farmers' preferences for pigeon pea utilization. Pigeon pea was used by 73% of farmers to generate income (Figure 3.13). Only 58% of the farmers in the survey grew pigeon peas primarily for human consumption. Pigeon pea was also used as fodder by 3% for livestock feeding and were 20%, 15%, and 10% in Maruleng, Malamulele, and Collins Chabane, respectively. Only 3% of farmers in Collins Chabane municipality adopted pigeon peas as mulch or cover crops, mostly to improve soil fertility.

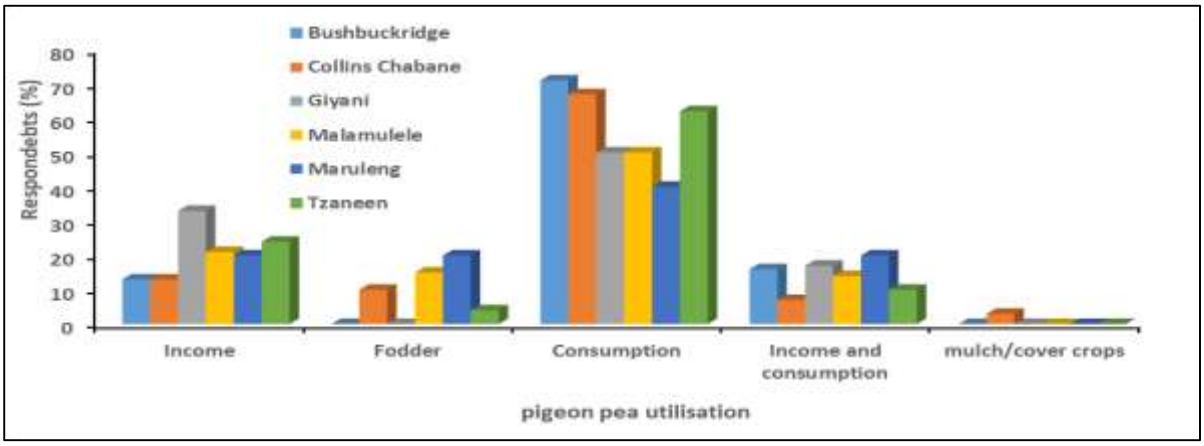


Figure 3.13: Farmers' choice of pigeon pea utilization in all six municipalities in the two Provinces of South Africa

3.3.14 Access to pigeon pea agro-processing information

The study observed a significant change ($p<0.030$) in access to pigeon pea processing information across all municipalities. In Bushbuckridge, Tzaneen, and Collins Chabane, respectively, only 23%, 9%, and 3 % of farmers who participated in the survey were trained in pigeon pea processing (Table 3.2). The study identified that in some municipalities, 100% did not receive any information on pigeon pea processing. Only 37% of farmers said they were unwilling to be trained in agro-processing and value-added practices. Farmers were aware of the market potential for processed pigeon pea products. The majority of farmers interviewed for the study lacked access to the equipment and storage facilities required for pigeon pea processing.

3.3.15 Farmers' source of information

The result of the analysis showed a significant association ($p<0.001$) between municipalities and the information source. Bushbuckridge, Malamulele, Maruleng, and Collins Chabane, farmers were 54%, 53%, 50%, and 42% received access to information (Table 3.2). The majority of Giyani and Tzaneen farmers relied on farmer-to-farmer information sharing. This type of information is based on the farmer's experience with the crop.

3.3.16 Socio-economic characteristics of pigeon pea farmers

The socioeconomic aspects of pigeon pea production in the two Provinces are shown in Table 3.2. The total number of farmers interviewed was 114, 82 were females and 32 were males. Female farmers made up 94% of subsistence farmers, and 18% of smallholder farmers. The study observed that female farmers (72) were more involved in food security initiatives than male farmers (75%), and was more on economic development. The results analysis found no significant difference between gender and the farm category (Table 3.2). A large number of farmers took part in the survey, with 56% receiving a social grant. Only 26% were involved in agricultural activity. Only farmers with 7 to 10 years of farming experience dominated subsistence farming over smallholder farming activities.

The majority of these farmers owned land for agricultural purposes. About 57% were females and 25% were males, with land ownership in all municipalities (Table 3.2). The land was possessed by only 5% of farmers between the ages of 36 and 40. The study observed that land was owned by farmers with were 51 to 60 years old. The study found that farmers who own land are typically elderly women. The allocation of 1–5 hectares of land was dominated by both female and male participants (Table 3.2). However, the findings revealed an insignificant difference in land size allocation across gender. Only 6% of male farmers were allocated more than 5ha of land, whereas no female pigeon pea farmer had more than 5ha of land.

The study observed that the production areas of pigeon peas and gender did not differ significantly (Table 3.2). Only 7 and 6% of female and male farmers produced pigeon peas in irrigation schemes, respectively. In backyard gardens, female farmers produced the crop at a higher rate (84%) than on farms and irrigation projects. Only 66% of men grew pigeon peas in household gardens, while 16% and 19% were allocated to farms and irrigation, respectively.

Access to irrigation water and gender were shown to have a significant relationship ($p<0.031$) (Table 3.2). The majority of farmers 85% did not have access to water for pigeon pea irrigation. Only 34% of male farmers have access to irrigation water. A significant variation ($p<0.011$) was detected between the irrigation water source and gender. Pigeon pea production was dependent on rainfall by both female and male farmers. The study observed that 86% of female farmers relied on rainfall, whereas 32% of farmers used rivers/canals for pigeon pea production. Approximately 18% of female farmers and 26% of male farmers, used boreholes. Because pigeons are mostly grown in backyard gardens, only 6% of the farmers interviewed used municipal water for irrigation purposes.

The use of a cropping system with pigeon peas showed a significant difference ($p<0.006$) with gender (Table 3.2). Pigeon pea and maize were intercropped by female and male farmers (67% and 56%, respectively), primarily for food production and income. The study recorded that 19% of men grew pigeon peas with fodder while women dominated maize, fruits, and single cropping with 67%, 18%, and 9%, respectively. Female farmers (51%) used an unknown pigeon type for cultivation. Only 32% and 20% of female and male farmers, who planted improved varieties of pigeon peas. More farmers used pigeon peas for income generation (Table 3.3). The study noticed that more farmers of all ages sold pigeon peas in both local and national marketplaces. The survey revealed that farmers were aware of market opportunities in pigeon pea cultivation. Pigeon pea was used primarily for income generation by approximately 85% of farmers with 4-6 years of agricultural experience. The study pointed out that farmers were aware of market opportunities existing in pigeon pea production. About 85% of farmers with 4-6 years of farming experience used pigeon peas mainly for income generation.

The study revealed a significant difference ($p<0.045$) between access to information and gender (Table 3.2). The outcome of the study observed no significant relationship between the use of pigeon peas and gender across all municipalities. Approximately 3% of male farmers utilized pigeon pea as fodder for livestock, whereas no female farmers used pigeon pea as fodder. Pigeon pea was utilized by the majority of female and male farmers to generate income. Only 4% of female pigeon pea farmers used the crop as mulch or cover crops.

Table 3.2 Frequency and percentage of socio-economic characteristics in pigeon pea production and their relationship with other variables

Socio-economic attributes		Frequency		No. of respondents		Likelihood	Chi-Square (X2)
		F (n=82)	M (n=32)	F (%)	M (%)	Value	P
Farmer category	Subsistence	77	27	94	84	3.5173	0.061ns
	Smallholder	5	5	6	16		
Land ownership	No	17	4	20	12	1.1628	0.281ns
	Yes	65	28	80	88		
Allocation of Land size	1ha	57	22	70	69	2.0738	0.355ns
	1-5ha	25	8	30	25		
	>5ha	0	2	0	5		
Production Area	Backyard	69	21	84	65	7.6205	0.055*
	Farm	5	5	6	16		
	Irrigation schemes	8	6	10	19		
Irrigation of pigeon pea	No	70	21	85	66	4.6778	0.031*
	Yes	12	11	15	34		
Source of irrigation water	Borehole	2	1	3	3	11.313	0.011**
	Municipal	3	4	4	12		
	Rainfed	71	18	86	56		
	River/dam	6	9	7	32		
Intercropping system	Fodder	0	6	0	19	19.655	0.006**
	Fruits	15	4	18	13		
	Maize	55	18	67	56		
	Grain & fruits	3	2	4	6		
	Vegetable	2	1	2	3		
	Sole	7	1	9	3		
Varietal choice	Improved	24	15	29	47	1.582	0.209ns
	Unknown	58	17	71	54		
Market Opportunity	No	34	9	41	28	0.035	0.925ns
	Yes	48	23	58	72		
Utilisation of pigeon pea	Consumption	59	7	72	22	2.256	0.689ns
	Fodder	0	1	0	3		
	Income	19	24	72	75		
	Mulch/cover crops	3	0	4	0		

N= numbers participants, % = percentage, F= Female, M= Male, p- value =probability, ns= not significant differences at p<0.05, * significant at p<0.05, ** significant differences P<0.01, *** highly significant difference at p<0.001

3.4 DISCUSSION

3.4.12 Pigeon pea status in the two Provinces at the moment

The study found that pigeon pea is primarily produced by women in household gardens with less than 1 ha of land in all six municipalities across two South African Provinces. The study also noticed that the allocation of land area and size varies by gender in different municipalities. Pigeon pea is a subsistence crop, and female farmers have been observed participating in food security activities. Each municipality's average pigeon pea producing land size is less than 1 hectare. because the crop is not yet recognized as a field crop in South Africa. Subsistence farmers in Limpopo, Mpumalanga, and KwaZulu-Natal grow it as a single plant or as hedges in or around their backyard gardens (DAFF, 2009). Despite the fact that pigeon pea is a multi-purpose crop (Odeny, 2007), it is one of the most neglected and underutilized legume crops in South Africa.

In Southern Africa, pigeon pea is an important grain legume crop. The survey recorded a high number of male farmers who cultivated the crop on large farms, irrigation schemes, and access to production resources such as water and land. Male farmers were shown to have greater access to production resources than their female counterparts. In order to solve food insecurity, the study proposed that production resources be spread evenly across gender and age groups. The study results indicated that water is a major rare resource in South Africa, with only 4% of total respondents having access to borehole water. For pigeon pea production, a large proportion of farmers relied on rainfall. Pigeon peas, on the other hand, are drought resilient because of their deep root structure, which allows the crop to access water sources in deeper soil layers (Odeny, 2007). During prolonged droughts, water availability for pigeon pea irrigation is crucial, and it also depends on the variety chosen and the plant growth stage (Basu and Bandyopadhyay, 2009). Despite the fact that many farmers are concerned with food supply and income generation. The study results revealed that farming interest varies across gender, age, and farming experience. Out of 114 participants, 57% were female farmers who owned land across all municipalities (Table 3. 2). The study reported only 5% of farmers between the ages of 36 and 40 owned land. Most farmers (83%) who owned land were between the ages of 51 and 60. The study also revealed that farmers who own land are typically elderly women. The findings of the current study contradict the conclusions of Amefiene *et al*. (2014), who indicated that farmers aged 40 to 45 years had access to land, followed by those aged 30 to 35 years.

3.4.13 Pigeon pea production practices:

Approximately 78% of the farmers who participated in the survey planted unknown pigeon pea seeds (Picture 1). The study indicates that farmers exchanged and conserved seeds from past harvests for planting, and the same observation was made by Ayenan *et al*. (2017). In this study, seeds were exchanged from farmer to farmer and from one location to the other. Farmers in Bushbuckridge, Maruleng, and Tzaneen used a low percentage of improved pigeon seeds obtained from researchers during on-farm research trials. The survey also indicated that 33% achieved 10–20 kg ha^{-1} grain yields, and the low yields were caused by farmers' planting unknown pigeon pea seeds, which germinate poorly lack genes, and lack genetic vitality. The low yield might cause by climatic conditions such as drought and poor soil fertility The same findings were also reported by the following scientists (Hogh-Jensen *et al*., 2007; Ayanan *et al*.,2017; Saxena *et al*., 2020). Farmers in Giyani, Maruleng, Tzaneen, and Bushbuckridge were the only ones who produced more than 200 kg ha^{-1} of pigeon grains. Similar results were also reported by Mergeai (2001) farmer pigeon yields ranged from 200 to 500 kg ha^{-1} and revealed that pigeon pea grain yields were low when compared to improved varieties used by researchers. The lack of improved pigeon pea seed varieties with high-yielding traits remains a significant barrier to increasing pigeon pea production levels in South Africa. There are currently no seed suppliers in South Africa that supply pigeon pea seeds.

Picture 1: Field source survey, 2020/21

Picture 2: *Field source survey, 2020/21*

The study revealed that 70% of farmers practiced an intercropping system to grow pigeon peas, primarily with maize crops and the same observation was also reported by Ayenan *et al*. (2017). Picture 2 shows pigeon pea intercropped with grains and fruits and grown as hedges in and around backyard gardens at Collins Chabane Municipality in Limpopo. Fewer farmers grew pigeon peas with fodder crops and were introduced by researchers from the two local universities (Venda and Limpopo), who transferred the adoption practices to local farmers and extension officers. The use of pigeon pea in rotational cropping and agroforestry practiced by fewer farmers was also observed in all municipalities The same finding was also reported by Mergeai (2001), who found few farmers adopted rotational and agroforestry in pigeon pea production compared to intercropping. Pigeon pea cultivation has been studied for its impact on soil fertility and farming system sustainability in Ghana (Ajei-Nsiah, 2012). The use of cropping systems is mainly for food diversification (Rusinamhodzi *et al*., 2011), not for soil fertility improvement. The majority of farmers were unaware that pigeon peas improved soil fertility.

The observation made was that farmers diversify food production (Rusinamhodzi *et al*., 2011) using limited resources such as land, water, and production inputs. The study revealed that 64% of farmers did not use commercial fertilizers. As a subsistence and poor resource farmer, pigeon pea is mainly cultivated with no fertilizer application. Subbarao *et al.* (2000) stressed that pigeon peas can fix atmospheric nitrogen up to 235 kg ha^{-1} in the soil. However, other nutrients such as phosphorus and potassium are also important for improved pigeon pea production. Nndwambi *et al*. (2016)

reported that the application of 45 kg P ha^{-1} of inorganic fertilizer resulted in a pigeon pea grain yield increase in an intercropping system. Many pigeon pea producers did not use commercial fertilizers in the study because they were too expensive due to rising prices. Although many farmers use organic fertilizers such as kraal manure, the amount and nutrient content of these organic fertilizers remain unknown to the farmers. The current study recommends that farmers should integrate organic and inorganic fertilizers with legume crops to maintain soil fertility sustainably.

Pest and weed control: Cultural practices to control pests, diseases, and weeds in pigeon production was dominated across municipalities. Only 5% of the total farmers used chemicals (pesticides, insecticides, and herbicides) to control pests in pigeon peas. The use of chemicals to control pests was observed in Bushbuckridge and Collins Chabane only. The current study observed that most farmers used cropping systems such as intercropping and crop rotation to control insect pests on pigeon peas. Similar findings were also reported by Adjei-Nsiah, (2012). The study proposed that improved pigeon pea varieties that are tolerant to pests should be introduced to farmers to reduce problematic pests such as pod borer and seed borer, which contribute to low pigeon pea yields and was also revealed by Ayenan *et al*., (2017). The use of chemicals both in weeds and pest control is limited by all farmers across municipalities, and this is due to a lack of financial resources and support to purchase chemicals. The same challenges were also reported by Ayenan *et al.* (2017), who indicated that a lack of pest control by farmers limits pigeon pea production. Although the Department of Agriculture supports farmers with fertilizers, pesticides, and herbicides, not all farmers qualify to receive the production inputs.

3.4.14 Farmers' knowledge of pigeon pea utilization

Pigeon pea as food consumption: Pigeon pea has been identified as a viable and healthy food security crop as a result, the crop in South Africa is currently underutilized. Farmers used pigeon peas for food consumption because the food supply is their primary goal. The study showed that 52% of farmers used pigeon peas as soup, followed by 35% as vegetables. The pigeon peas were prepared and consumed in the same way as cowpeas and dry beans were by these farmers. Pigeon peas were the least popular snack, accounting for only 3% of the population in Bushbuckridge.

Cooked and dried snack pigeon peas were combined with groundnuts and mealie meals.

A high percentage of farmers used the product as dry grain rather than flour at a later stage. The use of flour from pigeon peas was unknown to most of the farmers interviewed in the study. Legumes are a cost-effective source of high-quality protein in the diet, and they contain more protein than most other bean crops (Saxena *et al*. 2010). The study highlighted the need to promote pigeon peas as an important food legume that can be planted to help poor people overcome protein deficiency.

Pigeon pea as a medicinal crop: Only a few farmers stated that pigeons were exploited to heal human illnesses. Pigeon pea was used as medicine at Giyani, Collins Chabane, and Bushbuckridge municipalities. The study findings revealed that pigeon pea has health advantages, the crop relieves kidney disorders, snake bites, and dizziness in humans (Ayenan, *et al*., 2017). The current study understood that pigeon pea varieties varied in the concentration of the chemical compound that attribute to medicinal attributes. Future research should be carried out to determine the efficacy of pigeon peas as a therapeutic plant and which pigeon peas genotypes can be used for medicinal purposes. The study also found that pigeon pea soup is used as a medicine by farmers at Giyani. Farmers stated that a combination is recommended because it addresses both nutrition and health issues.

Pigeon pea as fodder: Pigeon pea was regarded as a fodder crop in Giyani and Maruleng with 50 and 40%, respectively of male farmers used the crop for livestock feeding during drought seasons as a feed supplement. Pigeon leaves and discarded pods are used as animal fodder, according to Mathew *et al.,* (2001a and 2001b). The current study observed that most male farmers owned livestock while female farmers were more focused on-farm activities such as weeding, processing, and cooking.

Pigeon pea is important in conservation agriculture because of its benefits. Only 4% of female pigeon pea growers used the product as a mulch or cover crop while male farmers were found to be less interested in soil conservation. More studies on pigeon peas for soil fertility improvement showed increased maize productivity while decreasing pigeon pea production (Adjei-Nsiah, 2012). According to studies conducted in Ghana, legumes provide a complementary or alternative role as a source of organic fertilizer in smallholder farming systems (Giller *et al*., 2001; Adjei Asiah, *et al*., 2014). All stakeholders must promote farmer awareness about the use of pigeon peas as a leguminous crop, to promote soil fertility and decrease soil erosion.

Pigeon pea was grown for food and income generation. The current study finding was that pigeon pea was used by a large number of farmers to supplement their income. The survey found that farmers of all ages marketed pigeon peas in both local and national markets. Farmers were aware of the market potential existing in pigeon pea production. Pigeon pea was primarily used for income generation by 85% of farmers with 4-6 years of farming experience. The findings revealed that new pigeon pea producers are market-oriented. Even though the study found pigeon pea market is available locally and gradually growing, farmers require reliable information (market and processing) both locally and internationally to compete with other income crops as also reported by Mponda *et al*., (2013). According to Matthews and Saxena (2000), the demand for pigeon peas both immature pods and dry seeds locally and internationally is high and this proves shows that markets are available for the crop.

The study revealed a significant relationship ($p < 0.027$) between income source and processed pigeon pea products. In Bushbuckridge, just 7% of farmers were active in pigeon pea flour processing. As a result, pigeon pea flour consumption is quite low. It might be that pigeon pea types for processing were introduced to farmers in Mpumalanga Province by Matthews *et al*. (2001a & 2001b). The current study found that male farmers are not participating in pigeon pea processing in all municipalities. These might cause by a lack of processing, infrastructural, and storage facilities. The same challenges were also reported by Amefiene *et al*. (2014). The study also revealed that the majority of farmers relied on farmer-to-farmer information sharing. The information was based on farmers' experience with the crop and lacked a scientific basis in most cases.

3.5 CONCLUSION

Currently, the production level of pigeon peas in the two Provinces is still low. The majority of farmers are still producing the crop in the backyard gardens, mostly in a subsistence manner. The study found that the allocation of land to pigeon pea production was very low, less than 1ha as compared to other leguminous crops.

Production levels of pigeon peas are also deteriorating due to the unavailability of improved varieties with high yielding, good quality, and drought tolerance traits. The study also found that most women produced the crop mainly for home consumption. Farmers were aware of the utilization of the crop as food, feed, and medicinal, but were unaware that pigeon pea improves soil fertility status and is also a good source of protein.

This low production of pigeon peas might also be caused by a lack of recent information on improved production practices that enhance the productivity of pigeon peas. The study observed that farmers are not aware of the improved production practices such as herbicides, pesticides, fertilizers, and cropping systems that improve production. Farmers rely mainly on their indigenous knowledge and also on the exchange of information among themselves. However, researchers from both Provinces tried to introduce the crop and provide knowledge to farmers. The study revealed that the adoption of pigeon pea production by farmers needs all role players to invest in skill development. Agricultural extension should be the main actor in facilitating the adoption of practices and promoting the crop through access to production, marketing information, and farmers led participatory on-farm trials. Lack of infrastructure, processing, and storage facilities was also identified to be one of the main limitations of adopting pigeon production. Though farmers produced and sell the crop locally, farmers are interested in crops that have a high return on investment.

The study suggests that the following measures be taken to increase pigeon pea production levels and improve food security, and that essential attention be focused on the following aspects:

1. To increase production yields, improved pigeon pea varieties that are high quality, drought, pest, and disease tolerant should be introduced.

2. Extension agencies and researchers should invest in providing current and researched information to pigeon farmers, as well as provide training in agronomic techniques, marketing, value addition, and processing.

3. Provide pigeon pea farmers with production inputs and infrastructure support to increase yields.

4. To promote its commercialization, the cost-effectiveness of pigeon pea production must be assessed to ensure that the crop gives farmers a return on investment.

5. More effort should be placed on skill development and infrastructure assistance to commercialize pigeon pea cultivation because farmer decisions are based on resource availability, information access (production and processing), and reliable market data.

CHAPTER 3.B: PIGEON PEA [*CAJANUS CAJAN* (L.) MILLSP.] RISKS MANAGEMENT STRATEGIES FOR SMALLHOLDER FARMERS IN SOUTH AFRICA

Abstract

Pigeon pea [*Cajanus cajan* (L.) Millsp.] is a legume crop that is widely grown throughout the world's tropical and subtropical climates, but its production has just been suboptimal in South Africa. The majority of smallholder grain producers in the country are dryland farmers who are continually threatened with several dangers associated with climate change and climate variability. The purpose of this study was to identify the critical risk variables affecting pigeon pea productivity and to establish management techniques for smallholder farmers on how to control the prevalent risk factors in pigeon pea production.

The study was undertaken in six South African local municipalities within two Provinces throughout the growing 2020/2021 seasons. A standardized structured questionnaire was utilized to identify, select, and collect data from farmers using the snowball sampling technique. Pigeon pea is a minor crop whose production is rapidly declining in South Africa. Through the cooperation of farmers, local extension employees, and researchers, a total of 114 pigeon pea farmers were identified. Within each municipality, farmers were interviewed individually. Statistical software (SAS, 2016) was used to analyze the data, and the likelihood ratio chi-square (X^2) test was used to identify significant differences across municipalities, variables, and sociodemographic characteristics.

The study results revealed that drought is a major climatic hazard in pigeon pea production and 60% of farmers are affected by drought. The majority of these farmers grew pigeon peas under rainfed conditions. Long-term pigeon pea grain yields (from 2012 to 2020 growing seasons), revealed that the majority of female farmers (53%) achieved low grain yields, and relatively low farmers across genders produced moderate to high grain yields. The study found that drought, extreme temperatures, poor agronomic practices, and insect and disease outbreaks all contributed to low production yields. More farmers, 54%, stated that the unavailability of improved pigeon pea seed varieties affected crop yields. Farmers primarily used cropping systems to diversify their crops, and the majority of these farmers were unaware that the diversification of cropping systems improved soil fertility and suppresses weeds, insect pests, and diseases. Moreover, the study noticed that a lack of infrastructure, processing facilities, and production information resulted in a decreased pigeon pea yield and income. Introduction of new technologies, resilient crop varieties, early-maturing varieties, investment in water supply for irrigation during severe drought periods, promoting utilization of conservation agriculture to conserve natural resources, relaxation of credit facilities, and promotion of the pigeon pea value chain for an increased profit. All these need to be implemented if the livelihoods of rural communities are to be improved to address food insecurity challenges.

Keywords*:* risk factors, pigeon pea, management strategies, smallholder farmer

3.1B INTRODUCTION

Climate change refers to a change in the state of the climate that can be identified by changes in the mean and or the variability of its properties and that continues for an extended period of time, typically decades or longer (Levin *et al.*, 2022). The recent changes in rainfall patterns and temperatures due to climate change are one of the major risk factors that negatively affect dryland pigeon pea production in South Africa. The instability and rise in temperatures, low and erratic rainfall, floods, and sea-level rise have a significant influence on field crops that are entirely dependent on rainfall, such as pigeon peas. These changes have the potential to exacerbate the difficulties already confronting smallholder farmers (Musokwa and Mafongoya, 2021), and contribute to food insecurity.

South Africa is a semi-arid region characterized by infrequent and irregular rainfall coupled with high temperatures. In this area, improved farming and innovative practices are needed to offset crop yield losses caused by climate change, which jeopardizes food security (Madegwa *et al*., 2016). Pigeon pea [C*ajanus cajan* (L) Millsp.] is an important legume crop that is widely grown throughout the world in tropical and subtropical regions. According to several scientists, pigeon pea is a drought-tolerant crop that thrives in climates where other grain crops fail (Odeny, 2007;

Hogh- Jensen *et* al., 2007; Emefiene *et al*., 2013). This depends on the extent to which drought can damage or affect the crop, which depends on the level of exposure. However, the pigeon pea's deep root structure enables it to absorb water and nutrients deep in the soil profile, which aids in its survival during drought periods (Odeny, 2007). Due to its drought tolerance trait, pigeon peas can thus be planted by smallholder farmers as a dryland grain crop to adapt to climate change.

Smallholder farmers are always faced with all kinds of risks since dryland farming has become increasingly risky. The unavailability of pigeon pea improved seed with a good quality grain of high yielding traits is still a major challenge in the smallholder farming system in South Africa. The maturity duration of pigeon peas is an important factor that determines the adaptation of varieties to various agro-climatic zones and cropping systems (Matthews *et al.*, 2001a). According to Mergeai *et al*. (2001), late-maturing pigeon pea genotypes, which are mostly landraces, produced relatively low grain production and are mostly intercropped with maize, sorghum, and millet. However, some of these genotypes are photoperiod sensitive (Gwata and Shimelis, 2013), susceptible to heat stress (Chaudhary *et al*. 2011), and prone to pests and disease (Matthews *et al.*, 2001b).

The selection of pigeon pea variety features following current climatic circumstances and farmer preferences are critical factors in increasing its production. In addition, the crop is mostly grown in poor and nutrient-depleted soils caused by continuous maize cropping with little or no fertilizer inputs (Kgonyane *et al*., 2013). Inorganic fertilizers are generally not affordable to the majority of smallholder farmers in South Africa, which generally results in poor quality grain yield variation in the smallholder farming system (Kgonyane *et al*., 2013). Despite these obstacles, various scientists have proved that pigeon pea is capable of fixing up to 235 kg of nitrogen (N) ha^{-1} (Subbarao *et al*., 2000; Odeny, 2007). Due to the resource constraints faced by the majority of these smallholder farmers in South Africa, incorporating N-fixing legumes such as pigeon peas into their farming systems can help to address poor soil fertility and escalating prices of inorganic fertilizers in farmers' fields.

Before 200 years ago, the climate had a significant impact on food production and security in both rural and urban areas (FAO, 2008). Addressing risks and difficulties faced by under-resourced farmers in economic decision-making is crucial for rural communities' food production and livelihood. Pigeon pea is a minor crop produced by few farmers in South Africa and received little attention from many stakeholders. As a result, this study was initiated to identify the critical risk variables affecting pigeon pea productivity and to establish management techniques for smallholder farmers on how to control the prevalent risk factors in pigeon pea production. These objectives are to assist smallholder farmers in dryland farming circumstances in enhancing crop yield and income generation, thereby increasing food security and providing information to influence agricultural policy formulation.

3.2B MATERIAL AND METHODS

3.2.1B Study sites

The study was conducted in two Provinces of South Africa, namely Limpopo and Mpumalanga Provinces during the 2020/21 growing season. The detailed study sites were explained in Chapter 3 under 3.2 and Figure 3.1.1. Information on the number of respondents interviewed in the study, the geographical coordinates, weather information, and the altitude of the six municipalities are presented in Table 3.1.1

3.2.2B Sampling procedures, data collection, analysis, and interpretation

The detailed sampling procedure and questionnaire administration used (Appendix 3.1 and 3.2), data collection, analysis, and interpretation are explained in chapter 3. under 3.2.2 and 3.2.3.

3.3B RESULTS

3.3.1. Risk and vulnerability factors affecting pigeon pea production

Figure 3.14 depicts the risk and vulnerability characteristics affecting pigeon pea growers across all study locations. The present study focused on natural, biological, and environmental factors that influence pigeon pea production in the six studied municipalities located across two South African Provinces. It also included risk and vulnerability in smallholder farming, addressing hazards, exposure, and vulnerability. Climate (temperature, rainfall, and drought), biological (weeds, insect pests, diseases, improved varieties, and access to information), and environmental (tillage, cropping system, production system, and fertilizer use) risk factors for pigeon pea productivity in the two Provinces. Climate change is impacting smallholder farmers as well as communities owing to food shortages caused by reduced crop production. The study also observed that risk vulnerability differs between area, gender, age, and farming experience.

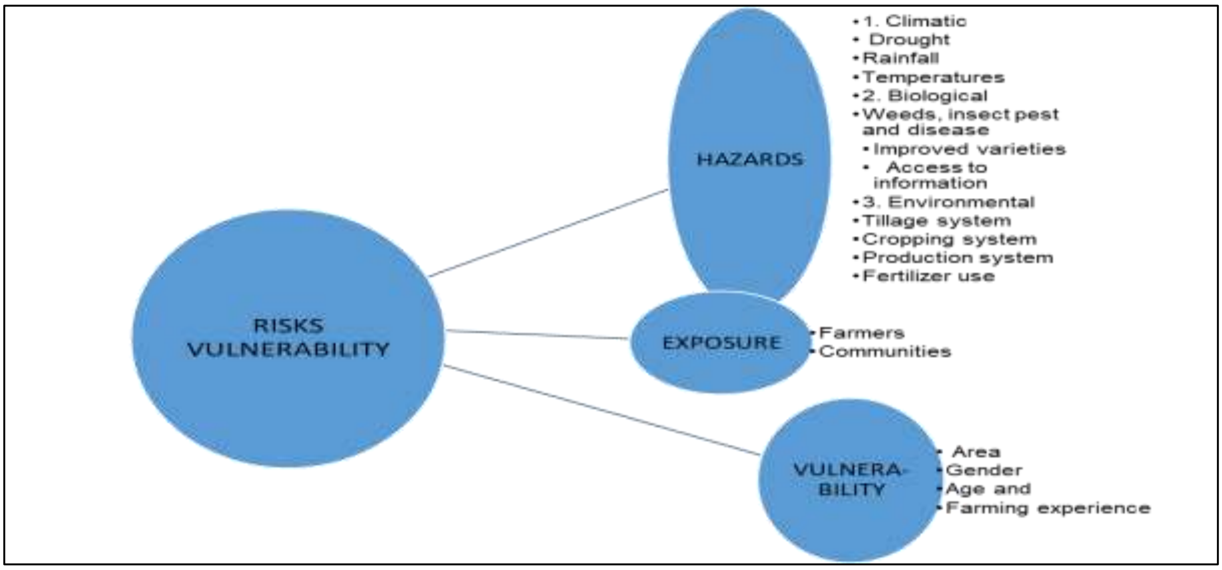


Figure 3.14: Risk and vulnerability factors affecting pigeon pea farmers in all municipalities.

3.3.2 Socio-economic characteristics in pigeon pea production

The socio-demographic characteristics of the study focused on gender, age, farmers' category, farming experience, and allocation of land area (Table 3.3). Female farmers made up 72%, while male farmers made up 28% across the municipalities. It was observed that farmers' ages differed significantly ($p<0.007$) between municipalities. Young farmers between 30-40 years old were 5% across all municipalities. The majority of farmers were between 51 and 60 years, with an average of 55% across all municipalities.

Subsistence farmers in Malamulele, Collins Chabane, and Tzaneen were 100%, 98%, and 91%, respectively. Smallholder farmers were 30%, 17%, and 13% in Maruleng, Giyani, and Bushbuckridge, respectively. The study revealed a significant difference ($p<0.008$) between the municipalities and farming experiences. Farmers with farming experience of 1 to 3 years were 16% and 30% in Collins Chavane and Tzaneen, respectively. Except in Maruleng, where 80% of farmers have less than 4 to 6 years,33 % of farmers had 7 to 10 years and 29% had more than 10 years of farming experience. A highly significant difference ($p<0.001$) was detected between the allocation of land within the municipalities. High proportion of farmers (53%) produced pigeon peas in less than 1 ha in all municipalities. Maruleng is the only municipality with 26% of pigeon pea farmers allocated more than 20 ha of land.

Table 3.3 Socio-demographic characteristics of six municipalities in six municipalities of South Africa

Municipalities		Bushbuckridge	Collins - Chabane	Malamulele	Giyani	Maruleng	Tzaneen				
Variables	Category				%			Mean	DF	(X^2)	P-value
Gender	Female	68	84	79	83	70	50	72	5	8.6403	0.1243[ns]
	Male	32	16	21	17	30	50	28			
Age	30-40	0	7	0	17	0	9	6	15	31.3511	0.0079*
	41-50	16	29	0	33	20	45	24			
	51-60	61	45	86	33	60	46	55			
	>60	23	16	14	17	20	0	15			
Farmer 'category	Subsistence	87	97	100	83	70	91	88	5	8.6403	0.1243[ns]
	Smallholder	13	3	0	17	30	9	12			
	Commercial	0	0	0	0	0	0	0			
Farming experience	1-3 yrs	0	16	0	0	0	32	8	15	38.5222	0.008*
	4-6 yrs	23	7	14	0	80	9	22			
	7-10 yrs	45	29	43	83	0	23	37			
	>10 yrs	32	48	43	17	20	36	33			
Allocation of land	<1ha	97	81	0	83	20	77	60	10	72.2020	0.001**
	1-5ha	3	19	100	17	50	23	35			
	>20	0	0	0	0	30	0	5			

%=percentage; DY= degree of freedom; X^2= Likelihood ratio Chi-Square; p- value= probability; yrs= years; > =more than; <less than; ha= hectare

3.3.3 Natural factors affecting pigeon production

The study recorded a high number of respondents indicating that drought had a negative impact on pigeon pea production (Figure 3.15). The analyzed result demonstrated that heat stress reduced pigeon pea yields. Pigeon pea were impacted by a mixture of drought and heat stress, but drought was the primary reason for reduced yields. Only 4% indicated that extreme weather conditions had no impact on pigeon pea yields.

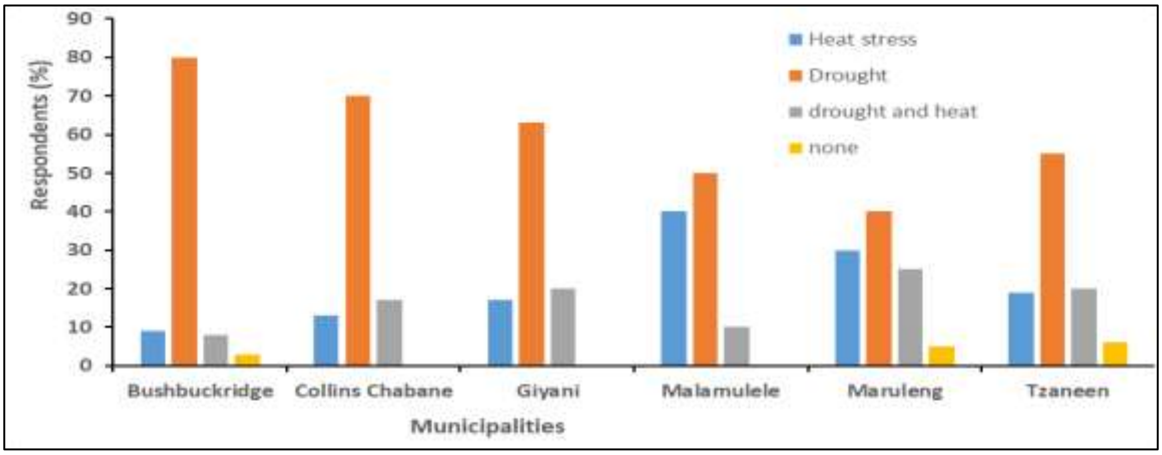


Figure 3.15: Effect of climate extremes on pigeon pea production in six municipalities in six municipalities of South Africa.

The study found significant variations ($p<0.029$) in water sources among municipalities (Figure 3.16). Only farmers in Collins Chabane and Giyani have access to boreholes for irrigation. In Collins Chabane and Tzaneen, just a few farms had access to municipal water. In all municipalities studied, more farmers relied on rainfall for pigeon pea production.

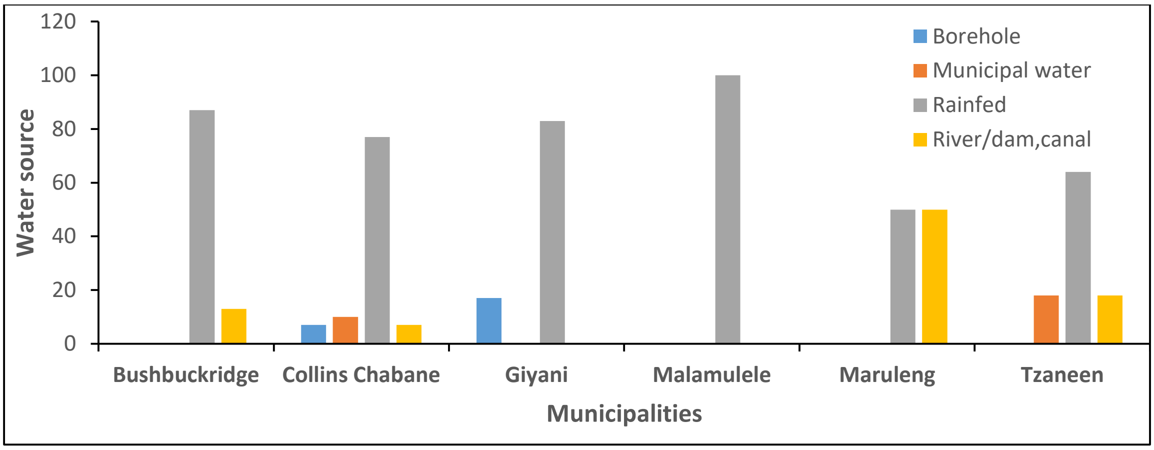


Figure 3.16: Sources of water used for irrigating pigeon pea products in six municipalities of the two Provinces of South Africa.

During the 2012 to 2020 growing season, more males than women achieved high grain yields. The study results indicated that the majority of farmers reported low or very low pigeon pea grain yields (Figure 3.17). In all municipalities, female farmers produced low and very poor pigeon pea grain yields, respectively. The study findings show that pigeon pea grain yields were poor across gender.

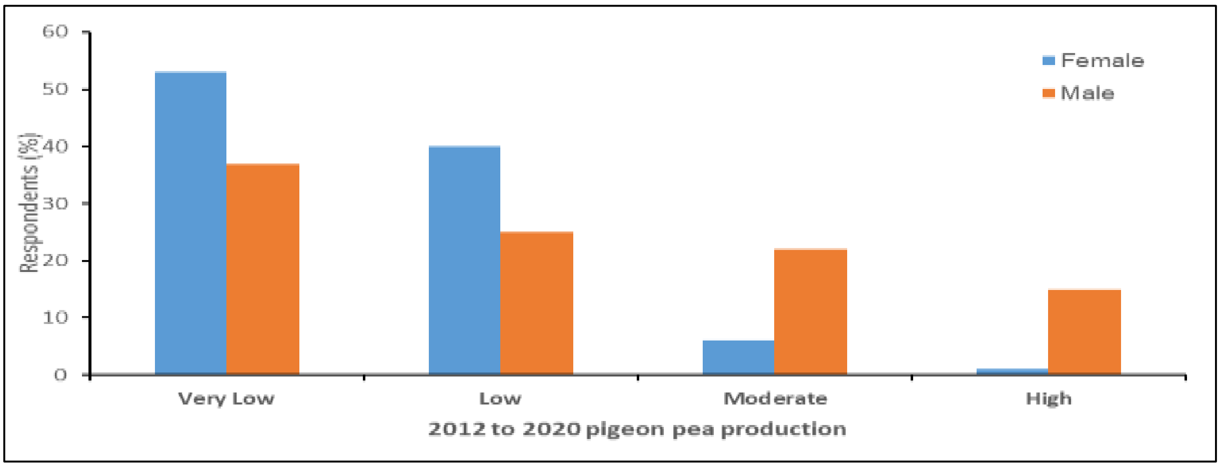


Figure 3.17: Pigeon pea grain yields between 2012 and 2020 by gender in six municipalities of the two Provinces of South Africa.

3.3.4 Biological factors affecting pigeon pea farmers

Across all study locations, the majority of female farmers (53%) mentioned the absence of better seeds as the main constraint affecting pigeon pea yield (Figure 3.18). The current study also found that lack of mechanization and high production costs affected 6% and 13% of male farmers, respectively. Drought, insect pests, and diseases were indicated by 24% and 17 % of female farmers interviewed as the second and third most severe limitations limiting pigeon pea yield, respectively. The study revealed that 17% of female farmers were affected by insect pests and diseases. The study also revealed that male farmers used agrochemicals such as pesticides, insecticides, and fungicides to control pests in pigeon peas (Figure 3.9, in chapter 3a). Most of the female farmers relied on the use of cropping systems to control pest infestation.

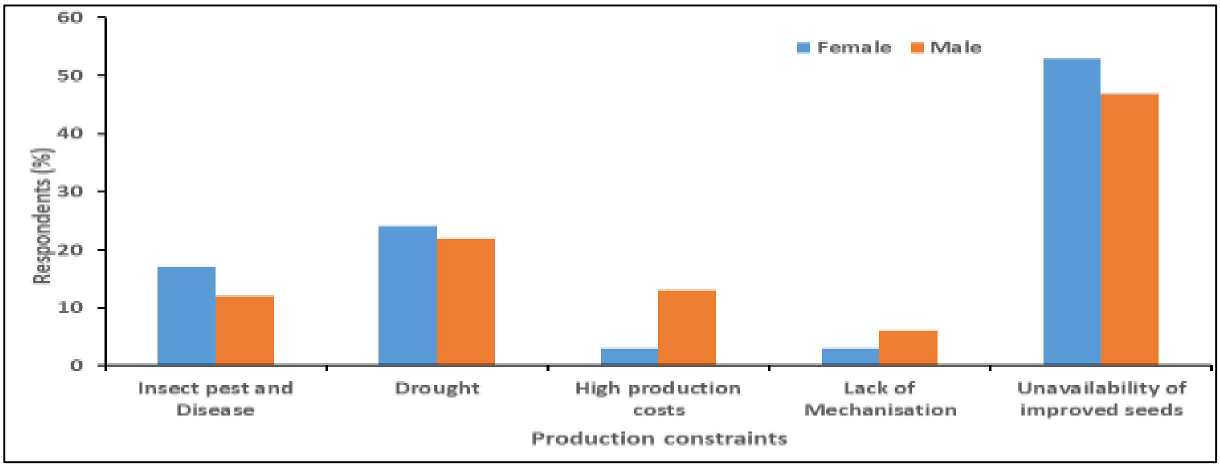


Figure 3.18: Pigeon pea production constraints by gender in six municipalities of the two Provinces of South Africa.

Access to production information:

A positive relationship between access to production information and municipalities was observed. (Figure 3.19). The majority of participants indicated that access to production information on pigeon pea production is limited.

Access to processing information:

The study observed a significant difference in access to processing information within the municipalities (Figure 3.19). In Bushbuckridge, Collins Chabane, and Tzaneen, respectively, only 23%, 3%, and 9% of farmers had access to processing information.

Access to processing equipment and facilities:

In all study areas, all respondents, regardless of gender, age, or farming experience, stated that they do not have access to processing equipment or facilities (Figure 3.19). This could be due to a lack of knowledge about pigeon pea processing and market access available in pigeon pea processed products.

Access to market opportunities:

There was a significant difference in access to market opportunities between the different municipalities (Figure 3.19). In Bushbuckridge, Collins Chabane, Malamulele, and Tzaneen, 19%, 27%, and 28% were unaware of market opportunities. However, most of the farmers who took part in the study in Maruleng and Giyani stated that they were aware of market opportunities for pigeon peas.

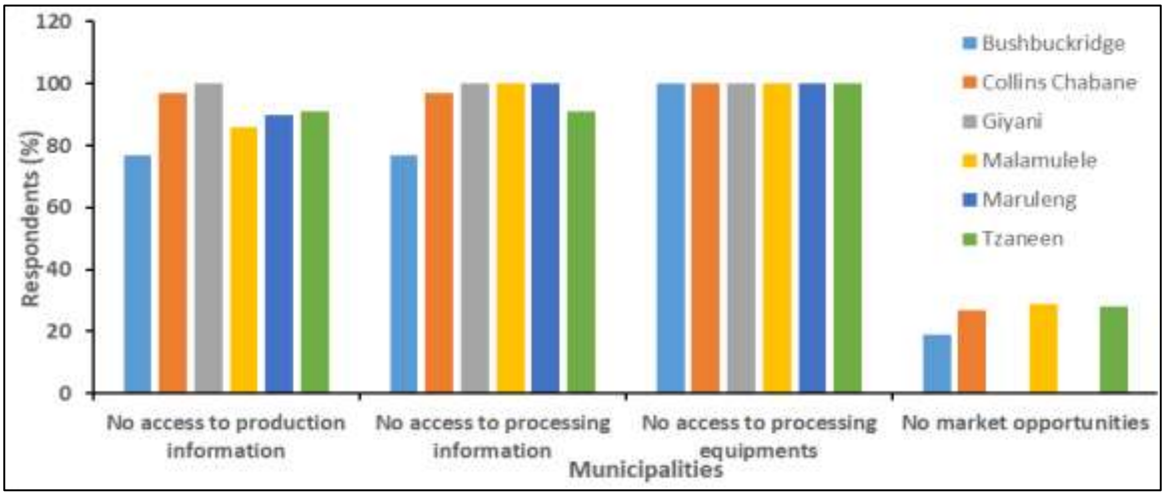


Figure 3.19: Farmers' constraints in pigeon pea production in six municipalities of the two Provinces of South Africa.

Respondents highlighted a variety of pigeon pea traits that they prefer for increasing production yields (Figure 3.20). Across all municipalities, grain production was the most desired pigeon pea trait by both male and female farmers. Across gender and municipalities, good taste was the second most desired pigeon pea trait. The majority of female farmers (12%) adopted varieties with early-maturing, insect pests, and disease tolerance characteristics in all municipalities. The study noticed that the majority of male farmers (56%, 22%, and 13%) chose high production, good taste, and grain quality qualities in pigeon peas.

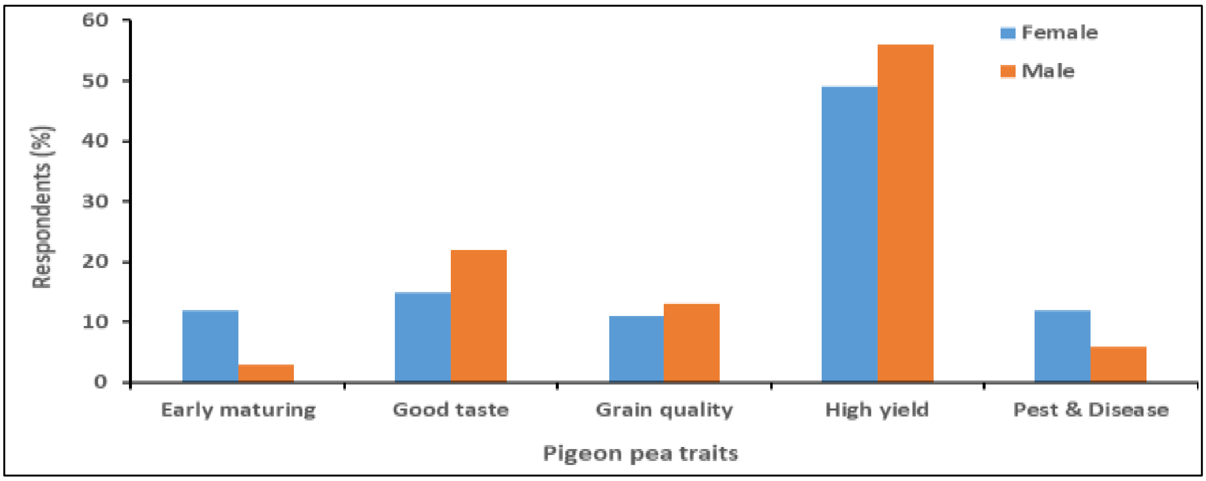


Figure 3.20: Pigeon pea traits by gender in six municipalities in the two Provinces of South Africa.

In all municipalities, the majority of female and male farmers (74% and 53%) used manual weed management methods (Figure 3.21), respectively. Manual methods including using a hand hoe were the most used by farmers. The study also indicated that the majority of males (25%) used herbicides to control weeds, while just 4% of females did. The study found that 20% of female farmers used cultural measures to control weed infestations, such as cropping systems and mulching, while only 3% of male farmers did. The findings also suggest that very low, about 1% of female farmers used a combination of manual, chemical, and mechanical weed management in pigeon pea production. Only 10% of male farmers interviewed used a combination of manual and chemical methods.

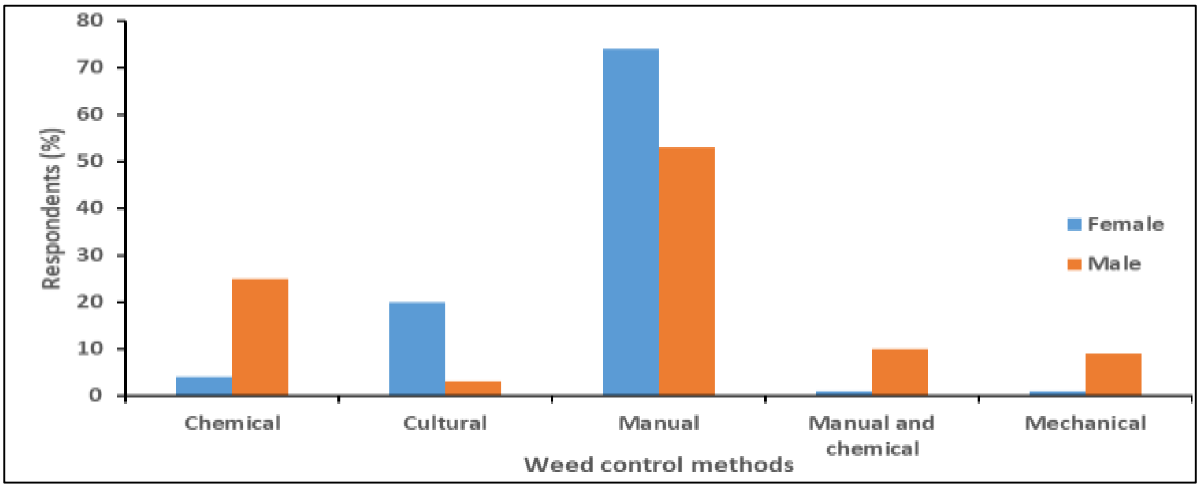


Figure 3.21: Weed control methods used by gender in six municipalities of the two Provinces of South Africa*.*

3.3.5 Environmental effects affecting pigeon pea farmers

More farmers adopted minimum tillage in pigeon pea production in all six municipalities (Figure 3.22). Eighty-one percent of female and 72% of male farmers used minimum tillage in pigeon pea production, respectively. Farmers used a hand hoe to prepare the soil because it was largely planted in homestead gardens. In all municipalities, conventional tillage was the second main tillage system. Only a few farmers adopted convectional tillage; only 29%, 36%, and 36% of farmers in Bushbuckridge, Tzaneen, and Malamulele used a conventional tillage approach, respectively. The no-till practice was only practiced in Maruleng and Collins Chabane.

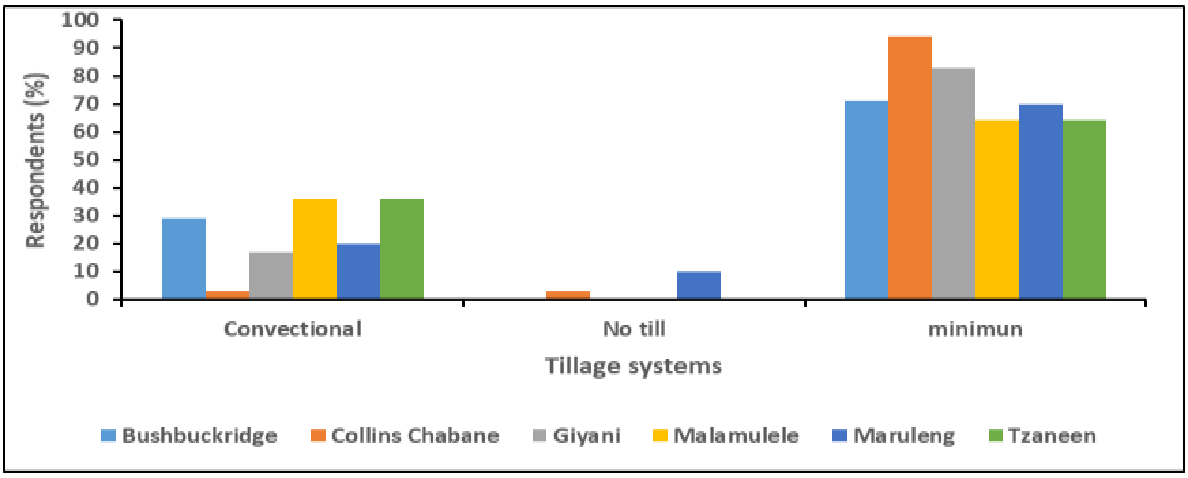


Figure 3.22: Farmers' use of tillage systems in pigeon production during the 2020/21 growing season in six municipalities in the two Provinces of South Africa.

In all municipalities, 80% of female farmers used an intercropping system in pigeon pea production (Figure 3.8) in chapter 3a. Furthermore, the majority of male farmers, about 56%, planted their pigeon peas under sole cropping in all study areas. About 12% of female farmers were found to use pigeon pea in agroforestry and rotational cropping and male farmers were very low at 6 and 3%, respectively. More farmers (46%) did not utilize organic and inorganic fertilizers in all municipalities (Figure 3.10, chapter 3a). The majority of these female farmers (33% and 12%) used kraal manure and compost, and male farmers were 16% and 6%, respectively. The study also revealed that a high percentage of male farmers 31.6% and 9% used commercial fertilizers such as NPK (22), Urea (46), and phosphorus (single or double superphosphate) fertilizers, respectively.

3.4B DISCUSSION

3.4.1 Climatic Hazards affecting pigeon pea production

Drought

Pigeonpea is a multipurpose leguminous crop that offers food, forage, and wood to smallholder farmers. The study revealed that pigeon pea productivity in South Africa is vulnerable to a variety of risks. Climate change accounts for the majority of these risk factors since low and erratic rainfall coupled with severe temperatures put food security, water, and the environment at risk (FAO, 2008 and 2015). In all six municipalities, drought, unpredictable rainfall, and high temperatures are all severe climatic threats. It was observed that female farmers, less experienced farmers, and older farmers were the most vulnerable to extended drought caused by severe temperatures and unpredictable rainfall. Emefiene *et al*. (2013) reported similar results, stressing that food security is jeopardized due to extreme climatic conditions. The majority of pigeon pea farmers grow the crop under rainfed conditions and are thus vulnerable to drought. Drought conditions affected 60% of the farmers in the study, and farmers also noticed significant changes in the climate.

Temperature

The study found that heat stress caused by high temperatures is the second most important climatic hazard, followed by floods. According to climate data obtained from Agricultural Research Council-Institute for Soil, Climate, and Water (ARC, ISCW).

Limpopo Province receives less than 600 mm of rain per year with high summer temperatures reaching up to 40°C during the summer season, and winters are warm with no or occasional rain. Mpumalanga Province, on the other hand, receives more than 1000 mm of rain per year, with frequent floods and average maximum temperatures of 26°C with frequent frost during winter. Farmers in both Provinces reported a shift in rainfall from October to December and had been extremely short with extreme temperatures. Farmers also indicated that heat stress due to continuous high temperatures caused a plant to wilt and affected plant growth resulting in very low yields. Similar results have been reported in Bioversity International & CIAT (2020). Farmers in Mpumalanga Province reported low yields which were caused by wide variations in temperature, which hampered crop growth. The reduction in yields reported by farmers was also might cause by heat stress affection flowers and pod to drops. Similar findings were reported by Mahapatra *et al*. (2020) in pea (*Pisum sativum*). This might be because some pigeon pea varieties are sensitive to photoperiod affection flower development and maturity period (Gwata and Shimelis, 2013).

Rainfall

The majority of these farmers in the study areas depended on rainfall for pigeon pea production. The frequent flooding during pigeon pea growth stages resulted in reduced plant growth and decreased yields due to poor germination rates. Ayanan *et al*. (2017) also observed that high rainfall during pigeon pea flowering reduced yield caused by flower drops. Some farmers reported a reasonable production of pigeon peas when compared to other legumes and cereals. The findings matched those of Emefiene *et al*. (2014), who reported that legumes yield was better compared to cereal crops due to severe drought conditions.

The findings from the current study also observed that farmers in all six municipalities have no infrastructure such as boreholes, or reservoirs for irrigating pigeon peas during severe drought periods. More male farmers had access to infrastructure than their female counterparts. These variations in resource allocation require immediate attention to address food insecurity issues. According to the current study, female farmers who participated in the survey are more vulnerable to a variety of risks. Though the majority of female farmers grow pigeon peas primarily for consumption and cash income (Mergeai *et al*., 2001). Low yields had impacted their livelihoods and food security (Singh *et al.,* 2020).

3.4.2 Biological hazards affecting pigeon pea production

Unavailability of improved varieties

Despite its ability to withstand drought conditions, the yield of pigeon peas has remained low in smallholder farmers' fields in the two Provinces. The majority of these farmers stated that the major constraint limiting pigeon pea production was the lack of improved seeds which was also reported by Matthews *et al*. (2001a). A study conducted by Emefiene *et al*. (2013) suggested that the inclusion of pigeon pea drought-tolerant varieties in smallholder farming systems can reduce the risks faced by these farmers. The crop capable of producing under adverse climatic conditions (Saxena *et al*., 2010) improved varieties are important to vulnerable farmers as it ensures food security and income generation (FAO, 2015).

Incidence of insect pests and diseases

Insect pests and diseases have a significant negative impact on both pigeon pea productivity and seed quality. The presence of insect pests and diseases was considered to be the second most significant constraint limiting pigeon pea production. Farmers interviewed for the study identified the pod borer (*Helicoveropa armigera*), pod sucking bug (*Clarigralla spp*.), aphids (*Aphis craccivora*), thrips (*Megalurothrips usitatus*), and termites (*Isoptera Termitidae*) as the most troublesome insect pests. These findings were supported by Dasbak *et al*. (2012). These insect pests primarily feed on flowers, pods, and seeds, causing significant economic losses. Because pod borers feed on pods and seeds, infestations of pod borers in pigeon peas significantly reduced production yields in smallholder farming systems. Farmers also observed an outbreak of termites as a result of prolonged drought conditions. The same observation was also reported by Dasbak *et al*. (2012). The findings of this study concurred with the conclusion reported by Vasnisth *et al*. (2016) that the infestation of pod-sucking bugs, thrips, and bollworms differs across genotypes, planting dates, locations, and climate conditions.

Production constraints

Only a few farmers in the study responded that they were not aware of pigeon pea market opportunities. The study revealed that the main market is locally followed by national. There was a general lack of market information for pigeon pea export markets and value-adding products. According to the study, farmers were found to be more vulnerable to price risks due to a lack of market information. The study also identified that the lack of production information was due to the crop's status as an underutilized and neglected legume crop. All farmers interviewed indicated that they lack support in processing equipment for pigeon peas and they are willing to be trained in this area. Infrastructure support and skill development, especially for female pigeon pea farmers, are important to address food security challenges. Male farmers were more interested in pigeon pea variety traits such as high yield, grain quality, and flavor, whereas female farmers were more interested in early-maturing, pest, and disease-tolerant varieties. This indicates that male farmers are using the crop mostly for economic purposes and female farmers for food security. Kimani (2001; Gwata and Shimelis, 2013) found that early-maturing varieties are less photoperiod sensitive and can flower and mature during short summer seasons. Drought-tolerant legume crops like pigeon peas are important, especially in areas where water is scarce due to drought. Farmers should be exposed to a variety of improved pigeon pea varieties.

3.4.3 Control measures used for insect pests, diseases, and weeds

Insect pests, diseases, and weeds are all controlled using various methods. The study found that the majority of these farmers were unaware that cropping systems such as intercropping, rotation, and agroforestry also reduced pest, disease, and weed incidence. Atachi *et al*. (2009); Ayenan *et al*. (2017), who reported a reduction in pests in an intercrop with pigeon pea. An additional study has also demonstrated that pigeon pea roots inoculated with mycorrhiza fungi tolerated nematodes and diseases, but this varied among varieties and the environment (Emefiene *et al*.,2014).

The study's findings also revealed that chemicals were mostly used by male farmers and grown pigeon peas primarily for income generation. The current study revealed that young, new, and inexperienced farmers preferred chemicals to control insect pests and diseases. The study concluded that a pigeon pea spray program should be recommended to reduce insect pest resistance to pesticides. Fewer farmers, irrespective of gender, used indigenous methods such as ash, a mixture of garlic, liquid soap, and water to control insect pests and diseases. This method was mostly used by elderly female farmers. Other methods were shown by Ganesh and Liu, (2014) the use of red soil to control insect pests in seed storage. The present study revealed that ash was used for storing the seeds of legume crops. Fungal diseases were the major diseases detected during farm visits and were dominant in Mpumalanga Province due to high rainfall and frequent humidity conditions. The majority of these female farmers used manual weed control. The study also recommended weed control using a cropping system and studies show that the crop suppresses weed growth in a cropping system, benefiting the succession crop during rotations (Emefiene *et al*., 2014).

3.4.4 Environmental hazards affecting pigeon peas production

Tillage system.

The majority of farmers ploughed their land using a hand hoe which is minimal tillage. This tillage system is used because pigeon pea is primarily grown in homestead gardens in both Provinces, either as a single plant or as hedges in or around the home gardens (DAFF 2009). The study also found that most farmers using conventional tillage were those who received mechanization support from the provincial Department of Agriculture in both Provinces. The current study also revealed that conventional tillage had a number of drawbacks, including soil erosion, nutrient loss, and a high soil evaporation rate. Busari *et al*. (2015) also reported similar results. Fewer farmers have adopted the no-till system to mitigate the effects of climate change. Mainly for its advantages as it reduces soil erosion, nutrient loss, and evaporation, improves soil fertility, and retain soil moisture.

Cropping systems

The use of cropping systems was to provide insurance against total crop failure due to moisture stress. In this study, farmers indicated that intercropping, rotation, and agroforestry are used mainly for food diversification and soil fertility improvement for the subsequent maize crop (Musokwa and Mafongoya, 2021). The study findings also agreed with the observation by Ayenan *et al.* (2017), who reported that farmers used cropping systems mainly for soil fertility improvement, insect pests, disease, and weed control for the subsequent crop. This indicates that female farmers used cropping systems such as intercropping, rotational, and agroforestry to reduce the impact of drought during pigeon pea production.

Fertilizer application

The majority of farmers did not use inorganic fertilizers when growing pigeon peas. The study revealed that pigeon pea is grown with little or no fertilizer application and similar findings was reported by Kgonyane *et al*. (2013) observed maize production in smallholder farmers' fields, in Limpopo Province. A large proportion of farmers use kraal manure to produce pigeon pea, mainly because it is accessible and less expensive. The farmers are unaware of the nutrient content in kraal manure and the quantity required per hectare. More research is needed to investigate the possibility of water contamination caused by the continuous application of kraal manure.

3.5B CONCLUSION

According to the current study findings and observations made during farmer interviews, the following management strategies can be used to mitigate the hazards of pigeon pea production in smallholder farming systems in both Provinces:

Drought

i. Introduce early and medium-maturing types that mature earlier and are heat tolerant to dry seasons and drought.
ii. Improve production yields by using drought-tolerant cultivars that can produce even under extreme drought circumstances. It can only be achieved if all pigeon pea stakeholders promote knowledge of diversity traits, selection, and adoption.
iii. Integrated nutrient management for improved soil fertility through the utilization of both organic and inorganic fertilizers.
iv. Involvement of all stakeholders, including research institutes and universities, to stimulate research, new innovation, and the adoption of new varieties.
v. Regulation enforcement is achieved through the development and promotion of policies that address climate change and its associated risks.

vi. Encourage effective agronomic practices such as crop rotation, fertilizer application, and irrigation system efficiency to improve crop productivity.

Temperature

i. Promote an integrated pest, disease, and weed management strategy to reduce crop resource competition.
ii. Expand the use and support of agrochemicals (pesticides, fungicides, insecticides, and herbicides) to combat insect pests and diseases.
iii. Make resilient varieties available and encourage variety selection.
iv. Strengthen and promote the use of CA principles to mitigate temperature effects and promote crop development (cropping methods, mulching, limited soil tillage, and cover crops).

Rainfall

i. Encourage integrated water management through water and soil conservation to minimize the impact of drought. roof water harvesting, ponds, dams, and all water harvesting structures for efficient water use during severe drought.
ii. The use of an appropriate cropping system and irrigation systems that conserve water and minimize total crop failure during moisture stress.
iii. Encourage water-saving agriculture strategies such as mulching, minimum or no-tillage for increased organic matter content, and water conservation.
iv. Revise water rights licensing rules to ensure that disadvantaged farmers have access to water for food production. involvement of water-controlling institutions in the country (water board, department of water and sanitation, Department of Agriculture, and water research commission). Dams, reservoirs, catchments, and irrigation systems should all be revitalized.

Access to information

i. Communication, training, farmer field schools, farmer-to-farmer sharing, advising, and networking are all ways to improve access to information.
ii. Involvement of all stakeholders for successful skill transfer, recent knowledge, information, and new technology transfer

Access to processing and marketing information

i. Public-private interventions to provide financial resources and invest in skills development.
ii. Manage revenue fluctuations and credit availability, access to insurance markets, and credit easing for farmers with limited resources such as climate change insurance schemes.
iii. Promote the pigeon pea value chain for increased profit through collaboration and cooperative work programs among all essential parties.
iv. Support infrastructure to increase export marketing, including marketing data and financial assistance. Improve marketing accessibility by forming organizations and cooperatives.

Access to infrastructure (boreholes, processing equipment), mechanization, and production inputs.

i. Make legislation that addresses the issues that smallholder farmers face. Support for water infrastructure (boreholes, dams) and irrigation projects should be improved.
ii. All stakeholders must be involved in the provision of processing equipment and storage facilities.
iii. increase the availability of mechanization and agricultural inputs (seeds, fertilizers, and chemicals) to help farmers reduce production costs.

Chapter 4: RESPONSE OF PIGEON PEA [*CAJANUS CAJAN* (L.) MILLSPAUGH] BIOMASS PRODUCTION, PHOSPHORUS YIELD, PHOSPHOROUS RECOVERY EFFICIENCY, AND GRAIN YIELD TO PHOSPHORUS FERTILIZATION UNDER RAINFED NO-TILL SMALLHOLDER FARMING SYSTEM

Abstract

Pigeon pea (*Cajanus cajan*) is one of South Africa's most underutilized and neglected legume crops. Dryland experiments were carried out on smallholder farmers' fields at Ofcolaco and Zoeknog from December 2019 to July 2021 without disruption under dryland) conditions. The field experiment was established as a randomized complete block design (RCBD) in a 4 x 2 factorial arrangement with four replications at each location. The two treatment factors were pigeon pea varieties, namely, Komboa, Tumia, Ilonga 14-M2, local landrace, and phosphorus (P) fertilizer application rates of 0 kg ha^{-1} and 60 kg ha^{-1}. Plant biomass, plant height, stem diameter, chlorophyll content, and grain yield were collected and measured. Harvest index (HI), P yield, and PRE were also determined.

The study results showed that shoot biomass ranged from 5375 to 9937 kg ha^{-1} and 5532 to 10149 kg ha^{-1} at Ofcolaco and Zoeknog, respectively. The results show that Komboa had a thinner stem diameter and was shorter than Ilonga 14-M2 at Ofcolaco and Zoeknog respectively. Significant variations in chlorophyll content among varieties were only observed at Zoeknog. P yield ranged from 11.10 to 23.89 kg ha^{-1} at 120 DAP and 15.11 to 41.4 kg ha^{-1} at 470 DAP, respectively. P yield in Komboa, was 60% and 63% lower than Ilonga 14-M2 at Ofcolaco and Zoeknog, respectively. The PRE ranged from 7.35 to 60.9% in all varieties across sampling dates. Grain yield ranged from 507 to 1136 kg ha^{-1} and 725 to 1306 kg ha^{-1} in the first and second harvests at Ofcolaco. The study concluded that shoot biomass, chlorophyll content, PRE, and HI were significantly influenced by variety and P fertilizer application. Plant height, stem diameter, P yield, and grain yield were not affected by P fertilizer application and the interaction of V x P.

Keywords: Growth variables, P yield shoot biomass, pigeon pea varieties, P- fertilizer application rates, grain yield, yield components.

4.1 INTRODUCTION

Pigeon pea [*Cajanus cajan* (L.) Millsp.] is grown on 7, 02 million hectares (M ha) in Asia, Latin America, and Eastern and Southern Africa, yielding 0.97 t ha^{-1} on average. (FAOSTAT, 2017). In South Africa, pigeon pea is not yet considered a field crop, and it is primarily grown by smallholder farmers in homestead gardens in Limpopo, Mpumalanga, and KwaZulu-Natal, either as a single plant or as hedges in or around the homestead gardens (DAFF, 2009). Although pigeon pea is classified as a multi-purpose crop (Matthews et al., 2001a; Odeny, 2007), it is one of the most underutilized and neglected legume crops in South Africa. Pigeon pea, commonly known as red gram, is the sixth most significant grain legume in India in terms of area under cultivation, after beans (*Phaseolus vulgaris* L.), peas (*Pisum sativum* L.), and chickpeas (*Cicer arietinum* L.) (FAOSTAT,2015). With 83% of the global market, India and Myanmar are considered the largest pigeon pea producers, with Malawi, Tanzania, Kenya, and Uganda considered the major African producers (FAOSTAT, 2015).

Pigeon pea is primarily grown in tropical and subtropical conditions between 30° North and 30° South latitude, according to Jones (2002). Because of their photosensitive and insensitive characteristics, pigeon pea cultivars have short and extended days (Gwata and Shimelis, 2013). Pigeon pea thrives in rainfall ranges of 400 to 750 mm $annum^{-1}$, as well as in places with less than 600 mm per $annum^{-1}$ (Jones, 2002). Since the crop is mainly produced under rainfed conditions, delayed, low, and erratic rainfall leads to terminal moisture stress, which affects pigeon pea productivity. The maturity period is an essential element that influences pigeon pea variety adaptation to various agro-climatic zones and cropping systems (Matthews and Saxena, 2000).

Pigeon peas are classified according to maturity duration periods. The short-duration types are relatively insensitive to photoperiod (Gwata and Shimelis, 2013) and temperature interactions. Medium to long-duration types take seven months to reach their maturity and are photosensitive as they require short days and low temperatures to initiate flowers. Matthews *et al.* (2001a and 2001b) found that short-duration pigeon peas are suitable for the subtropical regions because they have high yielding traits, a short height, and moderate biomass production. The medium to long-duration pigeon pea type is suitable for the tropical environment due to its reduced photoperiod sensitivity, perennial growth habit, high biomass production, and tolerance to drought. However, the unavailability of improved pigeon peas is still a major constraint in smallholder farming systems. Although pigeon pea improved varieties are reported to have high yield potential in the tropics (Hardev *et al*., 2016), their performances in smallholder farming systems under no-till in diverse agro-ecological zones in South Africa have not yet been tested.

The majority of farmers are reluctant to apply even major nutrients when producing the crop, and this contributes to low crop productivity. Phosphorus (P) is one of the major nutrients which stimulates photosynthesis and root development. Purwanto and Junaidah (2015) reported that P increased the pigeon pea's growth and its chlorophyll content. Nitrogen (N) is also a major nutrient required in large quantities, mainly for plant growth and promotion of plant organ development such as leaf chlorophyll content, which is critical for increasing grain yield (Nagaraj *et al*., 2019). The chlorophyll content is known to be an important component of photosynthesis, a key physiological function that is enhanced if nutrients such as nitrogen and phosphorus are applied adequately (Malik *et al*., 2011).

Pigeon pea is a multipurpose crop that provides food, fodder, and wood for smallholder farmers in Southern Africa (Matthews and Saxena, 2001a). However, in South Africa, it remains one of the neglected, underutilized, and little researched crops compared to other legume crops. The majority of smallholder farmers in South Africa still grow the traditional unimproved pigeon pea landraces which comprise a mixture of genotypes. In addition, the crop is mostly grown in poor and nutrient-depleted soils caused by continuous maize cropping with little or no fertilizer inputs (Kgonyane *et al*., 2013). This results in yield variation of low-quality grains across farmers' fields. Information on pigeon pea growth, nutrient use, grain yield, and yield components as influenced by variety and P fertilizer application under a no-till system in South Africa is not yet documented. The information generated on these parameters of pigeon peas is critical if the crop is to be sustainably produced and to improve its utilization under a changing climate in South Africa. The objective of the study was to determine the effect of pigeon pea variety and phosphorous fertilizer application on the crop's biomass and chlorophyll production, phosphorous uptake, phosphorus use efficiency (PUE), and grain yield.

4.2 MATERIAL AND METHODS

4.2.1 Study area

The experiment was carried out at two distinct agro-ecological zones in Limpopo and Mpumalanga Provinces during the 2019/2020 and 2020/2021 growing seasons without disruption under a no-till system. The first location was Itemeleng Ba-Makhutswe primary cooperative, Bembrough farm (24° 06' 38.3" S and 30° 23' 11.8" E) in Ofcolaco, Limpopo Province, located 43 km southeast of Tzaneen town at an elevation of 757 m (Figure 4.1). The long-term average annual precipitation is less than 500 mm annum^{-1}, with the majority falling between the months of November and March. Annual maximum and minimum average temperatures of 18°C and 30°C, respectively (www.weathersa.co.za). The winters are warm and dry, with no frost. According to the soil classification working group (1991), the soil is sandy loam and classified as the Hutton soil form with 750–1200 mm depth. Hutton soils are dominated by reddish-brown to reddish-brown and are weakly structured without water stagnation.

The second location was Mohlala farm (24° 45' 30.20" S and 30° 57' 30.05" E) located at Zoeknog, Mpumalanga Province, located 39 km northwest of Hazyview town, at an elevation of 757 m (Figure 4.1). The long-term annual average rainfall is above 750 mm, of which 80% falls in the October and March months. The winters are cool with low rainfall, with average maximum and minimum annual temperatures of 16°C and 22°C, respectively, with occasional frost. Soils are loamy sand soils with a depth of 600–1200 mm and are classified as the Fernwood soil form. The soil is distinguished by a greyish to brown soil color, a structureless clayey material with signs of wetness, and poor water drainage.

Weather data (annual rainfall, maximum and minimum temperatures) at the two experimental locations during the study period were collected from the automatic local weather stations situated at Metz and Hazyview, 13 and 49km from Ofcolaco and

Zoeknog, respectively. The weather data is managed by the Agricultural Research Council-Institute for Soil, Climate, and Water (ARC, ISCW). The annual averaged weather results for the experimental locations from the 2019/2020 and 2020/2021 growing seasons are presented in figure 4.2

4.2.2 Field management

The experimental field at Ofcolaco had been rested for the past five years, and at Zoeknog, 10 years since it was claimed and handed over to the local community. Before the establishment of the research, a Roundup-Turbo EC herbicide (450g/l glyphosate acid) was applied to control weeds. The trials were planted 14 days after herbicide application on the 12th of December 2019 and the 19th of December 2019 at Ofcolaco and Zoeknog, respectively. The soil was loosened only in rows for seed placement using a hand hoe. The experiment was established as a dryland trial at both locations. Based on initial soil analysis and pigeon peas being a legume, no other fertilizers were applied besides P as a treatment factor. The P was applied as single superphosphate. Seeds were planted manually at a 0.9 m distance between rows and 0.3 m between plants in a row, resulting in a plant density of 37037 plants ha^{-1}. Three seeds were placed in a hole and thinned out 30 days after planting to ensure good stand establishment due to low seed germination percentage.

During the study period, weeds were controlled only once using a hand hoe at 40 and 45 DAP at Ofcolaco and Zoeknog, respectively. Infestation by insect pests such as bollworms and thrips was also detected during the reproductive stage, but these were controlled using Cypermethrin 200 EC (220 g/l cypermethrin pyrethroid). Disease infestations during the growth periods in the experiments were not detected at both locations.

Figure 4.1: A map of the study area at Ofcolaco and Zoeknog during the 2019/2020 and 2020/2021 growing seasons

4.2.3 Experimental layout

The experiment was laid out as a randomized complete block design (RCBD) in 5 × 2 factorial arrangements with three replications at each of the two locations. The two treatment factors were four pigeon pea varieties, consisting of Komboa (V1); Tumia (V2); Ilonga 14-M2 (V3); local (V4), and two P fertilizer application rates at 0 (P1) and 60 kg ha^{-1} (P2). Treatment combinations are presented in Table 4.1

Table 4.1 The factorial arrangements of treatment combinations.

Pigeon pea variety	P fertilizer application rates (kg ha^{-1})	
	P1 (0 kg ha$^{-1)}$	P2 (60 kg ha^{-1})
V1	T1	T5
V2	T2	T6
V3	T3	T7
V4	T4	T8

V1=Komboa, V2= Tumia, V3= Ilonga 14-M2, V4= Local landrace, P = phosphorus, T1-T8= eight treatment combinations, P1 and P2 = phosphorus fertilizer levels

Single superphosphate (10.5% P) fertilizer was applied during planting through band placement in rows 5 cm away from the seeds in all P treatments. The plot size for the treatment was 5m x 2.7m, with 4 rows within each treatment. A row spacing of 0.9 and within rows spacing of 0.3 m was used. The total number of plants in plot^{-1} was 32 with 8 plants per row. A net plot area of 5.4 m^2 in each treatment was used for non-destructive data collection at both experimental locations.

4.2.4 Soil sampling procedures

Soil samples were collected randomly within the experimental plots using a hand soil auger before planting at 0–60 cm depth in both field experimental trials for physical and chemical analysis. Organic carbon was determined using the Walkley-Black method (Jackson, 1967), and total N was determined by the macro-Kjeldahl digestion method (Bremmer, 1955). Available P was extracted using Bray1 (Kuo, 1996). Potassium, Mg and Ca were determined using the ammonium acetate method (Chapman, 1965). Soil pH was measured in KCl (1:1) and water using a ratio of 1:2.5 (Eckert, 1988) and a pH meter. Sand, silt, and clay were determined using the hydrometer method, soil color using the Munsell color chart, and bulk density using the core sampler ring method. Soil samples for nutrient determinations were analyzed at the Agricultural Laboratory in Tzaneen, Premiepark for the soil pH, P, K, Ca, Mg, and Na. Organic carbon, Total N, and Clay% were measured at the Department of Agriculture and Rural Development (DARD), Kwazulu-Natal's Fertilizer Advisory Service, Research and Development, and Analytical Services. The initial soil analysis results are presented in Table 4.2.

Table 4.2 Initial soil physical and chemical properties at the two experimental sites

Soil depth	Ofcolaco	Zoeknog
	0 to 60 cm	
pH(KCl)	5.0	7.2
pH(H_2O)	5.7	7.9
Clay (%)	23	6
Organic Carbon %	0.9	0.4
Total Nitrogen (N) %	0.25	0.4
Phosphorus (P) (mg kg^{-1})	7	29
Potassium (K) (mg kg^{-1})	103	108
Magnesium (Mg (mg kg^{-1})	70	135
Zink (Zn) (mg kg^{-1})	9	5.3
Manganese (Mn) (mg kg^{-1})	80	37
Copper (Cu) (mg kg^{-1})	5.6	6.7
Sodium (Na) (mg kg^{-1})	7	32

4.2.5 Plant sampling procedures

Three aboveground plant samples were harvested randomly from the two border rows in all treatments at 30 days intervals starting from 60 days after planting (DAP) until 560 DAP. Plant samples were harvested using hand pruning shears at 5 cm above ground level in all experimental locations. Pigeon pea leaves that dropped to the ground were regained constantly to add to the total biomass in each plot. The total sample wet weight was determined before collecting sub-samples. Plant sub-samples were cut into small pieces, packed in brown sampling bags, and immediately weighed using a 22 Adam CBK 8h weighing scale to determine the fresh weight. Sub-samples were oven-dried at 65 °C to a constant weight to determine dry weight biomass production as the proportion of dry weight multiplied by the harvested fresh weight: [Sample dry weight/sample wet weight] *harvested fresh weight].

4.2.6 Determination of stem diameter

At each biomass sampling, stem diameter (mm) was measured from the middle rows in a 5.4 m^{-2} net plot area per experimental unit for the two experimental locations. Data was collected by measuring three plants at 1 to 2 cm from the stem base, which is where most stem growth is higher, using a 150 mm electronic digital Vernier caliper (mm), and the data were averaged.

4.2.7 Plant height

Average plant height (cm) in each treatment plot at both experimental locations was measured from 10 randomly selected plants from the middle rows in a 5.4 m^{-2} net plot area to determine plant growth. Measurements were taken from the stem base, where roots start to grow, to the tip of the plant using a measuring tape (cm).

4.2.8 Chlorophyll content of leaves

The chlorophyll content of green leaves was measured in three randomly selected plants from the two middle rows in a 5.4 m^{-2} net plot area in all treatments at the experimental locations was high. In this study, a chlorophyll concentration meter (Konika Minolta model, SPAD-502) was used to determine chlorophyll content, expressed in µmol m^{-2} of a leaf.

4.2.9 Determination of P yield in plant tissue

Three aboveground plants were harvested from the middle rows in a 5.4 m^{-2} net plot area randomly at 120 and 470 DAP reproductive stages. The samples were shade dried at room temperatures of 25°C for 114 and 228 hours for 120 and 470 DAP, respectively. All samples were rotated every 72 hours to suppress the growth of mold samples. Dry matter Samples were ground to pass through a 2 mm sieve and 40g of each treatment sample was collected and packaged in zip-locked plastic bags and sent to an accredited laboratory for nutrient analysis. Phosphorus content in plant tissue was determined using spectrophotometric detection of a colored phosphomolybdate complex using the molybdenum blue method. Phosphorus yield was calculated using an equation.

P yield in shoot (kg ha^{-1}) = shoot biomass weight (kg ha^{-1}) x % P in the shoot as described by Schiemenz & Eichler-Löbermann, (2010). Where total P content is taken from the result of the nutrient analysis.

Phosphorus recovery efficiency (PRE) was estimated using an equation by Cassman *et al*. (2002).

$$PRE\ (kg\ ha^{-1}) = [PF\ (kg\ ha^{-1}) - PU\ (kg\ ha^{-1})] \times 100 / PA\ (kg ha^{-1})$$

Where PRE is the PRE in kg ha^{-1}, PF is the total phosphorus yield of the fertilized plot in kg ha^{-1}, PU is the total P yield of the unfertilized plot in kg ha^{-1} and PA is the quantity of P- fertilizer applied (P_2O_5 kg ha^{-1}).

4.2.10 Phenological variables

The number of days to 50% flowering and physiological maturity was recorded at both experimental locations. The number of days to 50% flowering was determined when 50% of the plants' floral buds were opened in a plot. Physiological maturity (PM) was recorded when 75% of the pods in a plot turned brown in all experimental locations. The second flowering and maturity days of pigeon pea varieties were measured in days after the initial harvest.

4.2.11 Grain yield and yield components

Grain yield and yield components were recorded for the two growing season trials at Ofcolaco and Zoeknog. At Zoeknog, the second harvest was not collected due to damage to the experimental plots by a hail storm just before harvest. Grain yield after physiological maturity was determined from a 5.4 m^2 area in the middle of each experimental plot. The number of pod plant $^{-1}$ was counted from the harvested plants in a 5.4 m^{-2} area in each plot. Pod wet weight was obtained by weight pod collected per plot in a 5.4 m^{-2} area using a 22 Adam CBK 8h weighing scale. Harvested pods were oven-dried to a constant heat of 65°C for 48 hours. Pod dry weight was determined by weighing pod per plot using a 22 Adam CBK 8h weighing scale. The number of seeds per pod was obtained by selecting 10 pods per plot, shelled, and counted manually. The grain weight per plot was determined by harvesting the matured pods in a defined area within the plots, shelling the pods manually, and weighing the grain using a 22 Adam CBK 8h weighing scale. One hundred-seed weight (g) was determined from the grain yield sample of each experimental unit using the electric weighing scale.

Harvest Index (%)

The harvest index (HI) was determined as the ratio of grain to total shoot dry matter and is a measure of reproductive efficiency. The pigeon pea harvest index for the two experimental locations was calculated using the following equation:

$$HI\ (\%) = \frac{\text{Grain yield}}{\text{Total biomass + grain yield}} \times 100$$

4.2.12 Statistical analysis and interpretation of data

The SAS Institute's statistical package was used to perform an analysis of variance (ANOVA) on the data. to determine the effect of pigeon pea varieties, P fertilizer application rates, and their interaction effect (V x P) on the measured parameters in the two field experiments. The two locations were analyzed separately. The least significant difference (LSD) was also used to separate the means at probability levels of $p<0.05$, $p<0.01$, and $p<0.001$, only where a significant treatment effect was observed (Gomez and Gomez, 1984). Correlation and regression analyses were also performed to assess potential relationships between grain yield and yield components.

4.3 RESULTS

4.3.1 Rainfall, evapotranspiration, and temperatures during the growing seasons

Figure 4.2 depicts rainfall (mm) data collected during the growing seasons. The data revealed that rainfall at both locations rainfall was far higher in November 2020/2012 growing season than in November 2019/2020. The total rain received during the two seasons from 2019 November to 2021 July was 1760.76 mm and 1249.15 mm at Ofcolaco and Zoeknog, respectively. Data obtained also revealed that both locations experienced relatively minimal rain from May to July in the two seasons. The evapotranspiration at both locations was relatively higher than the rainfall. The data shows that evapotranspiration increased in summer periods and decreased in winter periods following the same pattern as rainfall at Ofcolaco and Zoeknog.

Table 4.3 displays the average maximum and minimum temperatures at the two experimental locations during the 2019/20 and 2020/21 growing seasons. The temperatures (°C) fluctuate between the two locations, with Ofcolaco having the highest average maximum and the lowest temperatures being recorded at Zoeknog. The minimum average winter temperatures at Zoeknog and Ofcolaco (May to July) were 9.0°C, 5.6°C, and 4.7°C, 14.2°C, 11.3°C, and 11.1°C, respectively. This suggests that winters in Zoeknog are quite chilly, while winters and summers at Ofcolaco are warmer. Maximum average temperatures reach up to 31°C during the summer season at Ofcolaco and 28°C at Zoeknog.

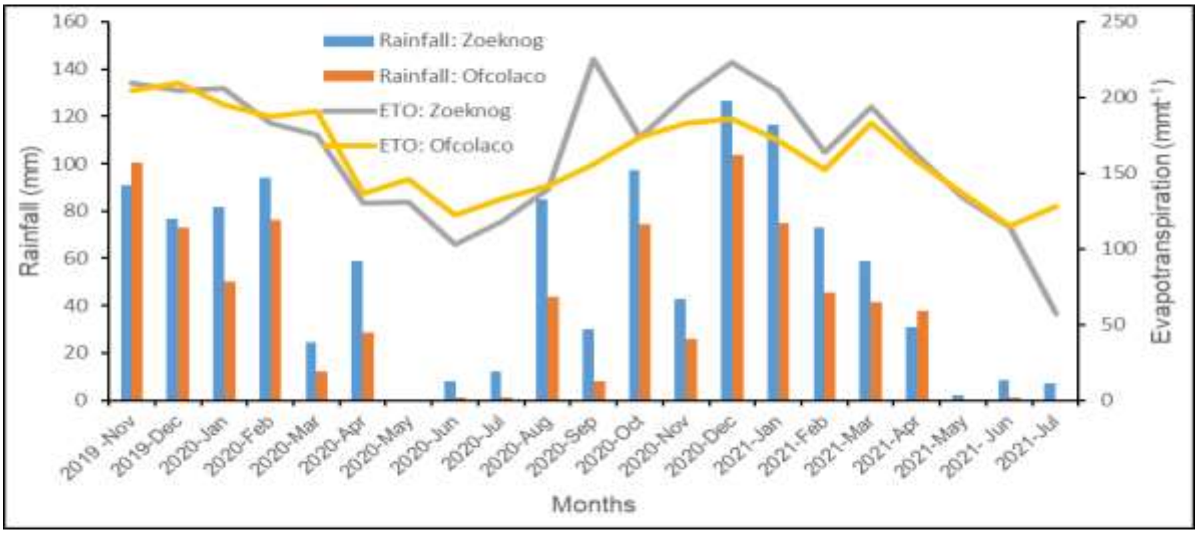


Figure 4.2: Weather data recorded during 2019/20 and 2020/21 growing seasons at Ofcolaco and Zoeknog experimental trials (ETO= evapotranspiration).

Table 4.3 Monthly maximum and minimum temperature (°C) collected during the two growing seasons (November 2019 to July 2021) at Ofcolaco and Zoeknog

Year/Month	Maximum Temperature Ofcolaco	Minimum Temperature Ofcolaco	Maximum Temperature Zoeknog	Minimum Temperature Zoeknog
		°C		
2019/Nov	33.5	20.4	31.4	17.6
2019/Dec	32.6	20.6	30.5	17.4
2020/Jan	32.8	21.5	30.5	19.4
2020/Feb	32.1	20.6	30.5	15.3
2020/Mar	31.9	19.5	30.1	16.5
2020/Apr	29.4	17.5	27.2	15.2
2020/May	29.3	14.2	26.2	9.00
2020/Jun	26.3	11.3	24.2	5.6
2020/July	26.5	11.1	24.5	4.7
2020/Aug	28.2	13.4	26.2	7.9
2020/Sep	29.2	15.9	21.3	10.8
2020/Oct	29.2	17.6	29.0	14.5
2020/Nov	32.5	19.8	31.3	17.2
2020/Dec	32.2	21.4	31.1	19.2
2021/Jan	32.5	21.3	30.8	19.9
2021/Feb	31.3	20.7	29.3	19.3
2021/Mar	32.3	19.8	30.2	17.3
2021/Apr	31.5	16.5	29.3	12.8
2021/May	29.6	13.8	27.3	8.89
2021/Jun	27.5	11.5	25.5	6.16
2021/Jul	26.1	10.5	26.0	6.97

4.3.2 Pigeon pea shoot biomass production

Significant ($p<0.001$) variations in shoot biomass were observed among varieties at both locations. Differences in shoot biomass production ($p<0.0207$) due to P-fertilizer application were observed only at Ofcolaco. No significant interaction effect of V x P on shoot biomass was observed at both locations.

4.3.2.1 Varietal variation in shoot biomass production

Ofcolaco:

The Ilonga 14-M2 variety produced the highest shoot biomass, followed by local, Tumia, and Komboa (Figure 4.3). Shoot biomass increases with an increase in growth stages and ranges from 3180 to 7328 kg ha^{-1} at 180 DAP. The mean shoot biomass for Komboa, Tumia, Ilonga, and the local landrace, was 5275 kg ha^{-1}, 8155kg ha^{-1}, 9937 g ha^{-1}, and 8419 kg ha^{-1} respectively. At 560 DAP, Komboa, Tumia, and the local landrace still produced less shoot biomass compared to Ilonga 14-M2 which were 39%, 10%, and 9% less respectively.

Zoeknog:

Shoot biomass production at Zoeknog followed a similar trend as that observed at Ofcolaco, with Ilonga 14-M2 producing the highest biomass among the four varieties over time (Figure 4.3). At 180 DAP, shoot biomass production was 3959 kg ha^{-1}, 6509 kg ha^{-1}, 8237 kg ha^{-1}, and 7294 kg ha^{-1} in Komboa, Tumia, Ilonga 14-M2, and local landrace, respectively, during the first harvest. During the second harvest at 560 DAP, shoot biomass production was 10000 kg ha^{-1}, 1496 kg ha^{-1}, 19257 kg ha^{-1}, and 17280 kg ha^{-1} for Komboa, Tumia, Ilonga 14-M2, and local landrace, respectively. At both harvest periods, Komboa attained 51% and 48% lower in shoot dry matter production relative to the vigorous Ilonga 14-M2 cultivar, and Komboa attained the lowest among the varieties over the growing season.

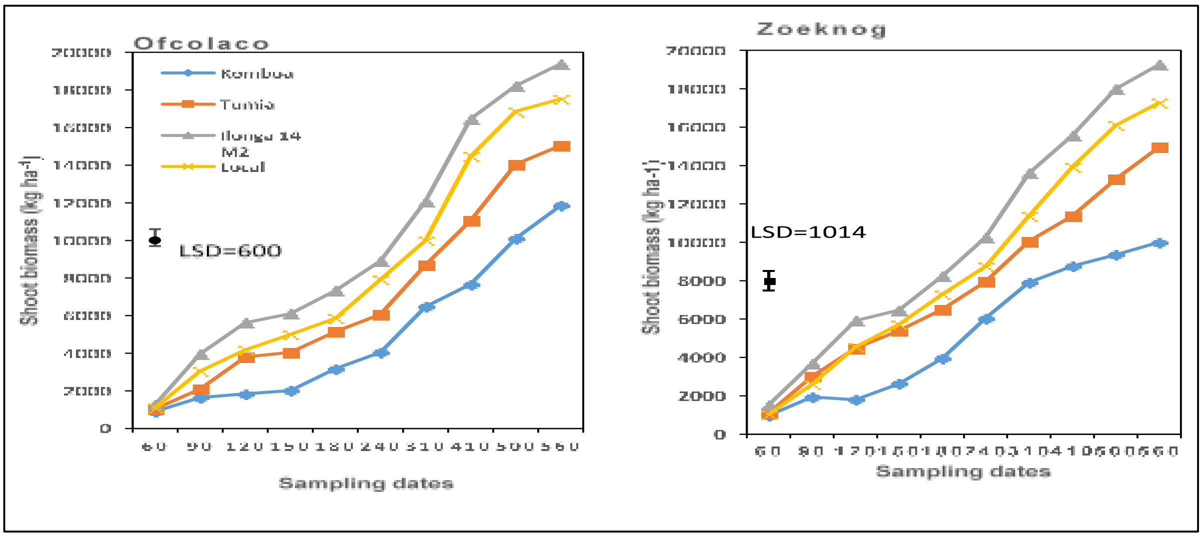


Figure 4.3: Shoot biomass (kg ha^{-1}) influenced by variety at different sampling dates (V x DAP) during 2019/20 and 2020/21 growing seasons at Ofcolaco and Zoeknog. (Vertical bar represents LSD value)

4.3.2.2 Effects of P fertilizer application on shoot biomass production at different sampling dates

Ofcolaco:

At Ofcolaco, a significant response of shoot biomass production to the phosphorous application was only observed at 180 DAP and not at the other sampling dates (Figure 4.4).

Zoeknog:

The results show no significant differences in biomass production as a result of P-fertilizer application over the growth stages (Figure 4.4). However, there was a marginal increase in shoot biomass with P fertilization from 410 DAP.

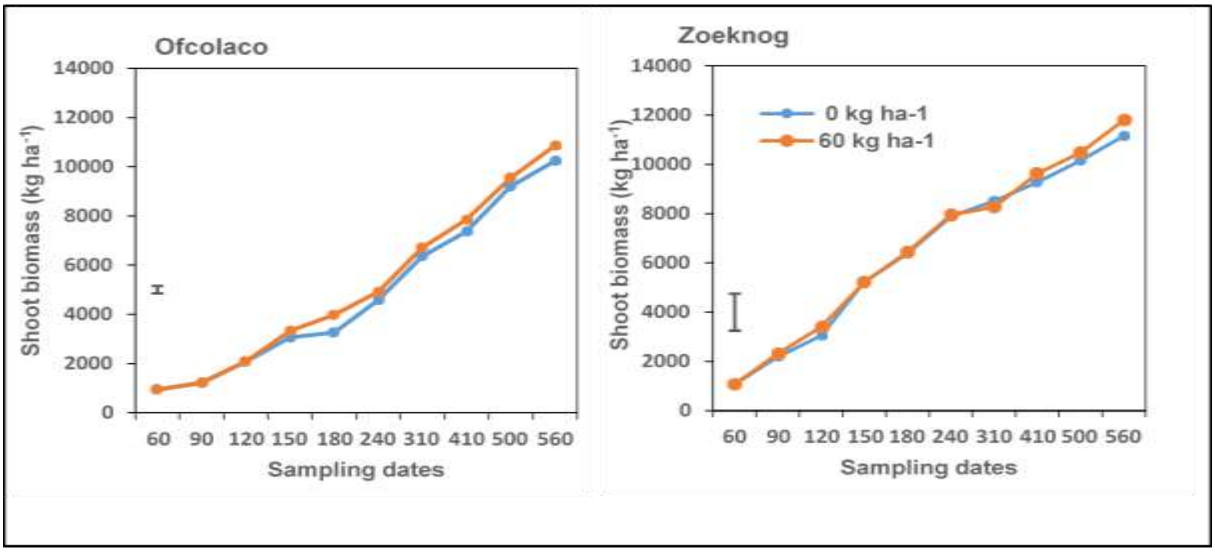


Figure 4.4: Shoot biomass production (kg ha^{-1}) as influenced by P fertilizer application and different days after planting at Ofcolaco and Zoeknog (Vertical bar represents LSD value)

4.3.3 Pigeon pea stem growth (mm)

Figure 4.5 shows the effect of pigeon pea varieties on stem diameter at the two locations. Significant differences in pigeon pea stem diameter among varieties at both Ofcolaco and Zoeknog. The effect of P fertilizer application and its interaction effect did not affect stem diameter at both locations.

4.3.3.1 Pigeon pea variety effect on stem diameter

Ofcolaco:

Significant variations were observed in pigeon pea stem diameter. The local landrace had the thickest stem, followed by Ilonga 14-M2 and Tumia (Figure 4.5) The stem diameter ranged from 19.42 mm to 22.11 mm. Komboa produced the thinnest stems among the varieties.

Zoeknog:

The local landrace and Ilonga 14-M2 were thickest at Zoeknog whereas Komboa again produced the thinnest stem diameter (Figure 4.5). Tumia had a medium stem diameter of 32.95 mm.

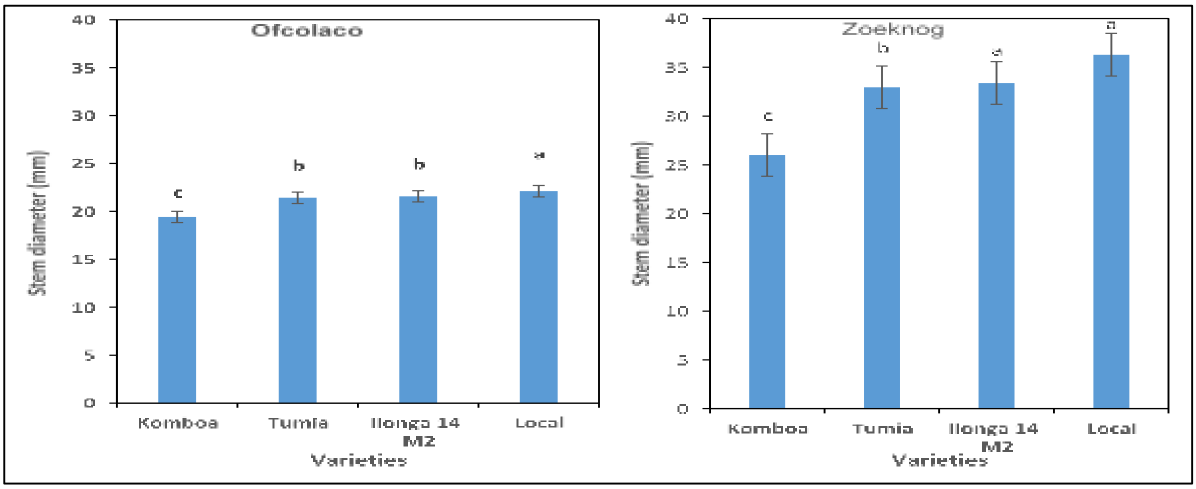


Figure 4.5: Influence of pigeon variety on stem diameter (mm) at Ofcolaco and Zoeknog. (Different letters mean significant differences whereas similar letters mean no significant differences).

4.3.3.2: Stem diameter (mm) at different growth stages.

Table 4.4 shows the pigeon pea stem diameter at different growth stages at Ofcolaco and Zoeknog. The study found significant differences in stem diameter as influenced by variety and not phosphorous at the different growth stages.

Ofcolaco:

No significant differences in stem diameter amongst the pigeon pea varieties were observed during the first 180 days after planting (Table 4.4). Beyond 180 DAP, the stem diameter of Tumia, Ilonga 41-M2, and the local landrace was the largest and similar whereas Komboa had the lowest stem diameter.

Zoeknog:

At Zoeknog, differences in stem diameter among the pigeon pea varieties were observed as early as 90 DAP and continued that way until the end of the experimental period (Table 4.4). Similar to Ofcolaco, Komboa had the thinnest stem, whereas, the stem diameter among the remaining varieties and the landrace were generally similar.

Table 4.4 Stem diameter (mm) of pigeon pea influenced by varieties and growth stages during 2019/20 and 2020/ growing seasons at Ofcolaco and Zoeknog

		Growth periods (DAP)					
		………. ……………….…cm…………………………………					
Location	Varieties	90	120	180	240	410	560
	Komboa	12.38a	13.5a	15.95a	17.53b	21.14b	39.43b
Ofcolaco	Tumia	12.45a	12.80a	16.53a	21.50a	26.21a	42.63ba
	Ilonga14-M2	11.95a	13.02a	17.40a	21.08a	25.63a	43.60a
	Local	12.90a	13.46a	15.58a	22.10a	26.02a	42.62ba
	LSD (0.05)	1.785	1.797	1.936	2.456	4.039	3.514
	Significance	ns	ns	ns	*	**	*
	Varieties	90	120	180	240	410	560
Zoeknog	Komboa	13.33b	14.90b	25.72b	30.00b	34.33c	36.50b
	Tumia	15.85a	18.35a	35.88a	39.43a	45.66b	47.53a
	Ilonga 14-M2	15.27a	18.10a	40.20a	45.10a	48.09ba	50.13a
	Local	16.67a	17.55a	38.87a	44.74a	50.92a	51.99a
	LSD (0.05)	1.287	1.813	7.673	6.864	5.067	4.723
	Significance	*	*	**	**	**	**

DAP= days after planting, LSD= least significant difference, * significant at $p<0.05$, ** significant at $p<0.01$ ns = not significant

4.3.4 Plant height in pigeon peas.

Significantly different variations in plant height among varieties were detected at both locations. However, P fertilizer and the interaction of V x P did not influence plant heights at both locations.

4.3.4.1 Varietal effect on plant height

Ofcolaco:

Differences in height among the varieties at Ofcolaco were detected throughout the experimentation period, with Ilonga 14-M2 being the tallest and Komboa the shortest variety at the end of the experiment (Table 4.5). Tumia and the local landrace were of similar height.

Zoeknog

At Zoeknog, pigeon pea plant height followed the same trend as indicated at Ofcolaco. The height of the varieties ranged from 132.17 cm to 240.76 cm. Ilonga 14-M2 was again the tallest and Komboa the shortest at the end of the experimentation period (Table 4.5). The study results also show that plant growth increases steadily with time until 410 DAP and tapered off at 560 DAP. At 180 and 560 DAP, Ilonga 14-M2 attained 239.89 cm and 317.51 cm, respectively. At 560 DAP, an increase of 32% in plant height of Ilonga 14-M2 was recorded compared to 180 DAP.

Table 4.5 Plant height (cm) of pigeon pea varieties at growth periods during 2019/20 and 2020/21 growing seasons at Ofcolaco and Zoeknog

		Growth period (DAP)					
		....................................cm..					
	Varieties	90	120	180	240	410	560
Ofcolaco	Komboa	84.42b	107.36b	135.01c	143.43c	161.53c	164.63c
	Tumia	113.87a	149.09a	200.6b	230.74b	270.5b	271.45b
	Ilonga 14-M2	119.23a	157.55a	239.89a	271.8a	314.57a	317.51a
	Local	119.07a	153.52a	189.1b	214.85b	260.42b	267.28b
	LSD(0.05)	11.67	13.58	32.31	29.25	18.82	18.36
	Significance	**	**	**	**	**	**
	varieties	90	120	180	240	410	560
Zoeknog	Komboa	67.1c	101.77b	149.50c	156.7b	168.64d	177.33c
	Tumia	89.52ab	157.15a	244.31b	275.65a	294.63c	307.17b
	Ilonga 14-M2	96.18a	160.06a	282.18a	284.85a	327.48a	340.62a
	Local	88.13b	169.21a	231.34b	257.02a	314.08b	315.483b
	LSD(0.05)	7.422	24.544	28.38	37.58	12.033	15.078
	Significance	*	**	**	**	**	**

DAP= days after planting, LSD= least significant difference, * significant at $p<0.05$, ** significant at $p<0.01$ ns = not significant.

4.3.5 Chlorophyll concentration in pigeon peas

The leaf chlorophyll concentration was significant ($p<0.001$) among pigeon pea varieties only at Zoeknog and not at Ofcolaco (Figure 4.6). The response of leaf chlorophyll concentration to the P fertilizer application ($p<0.0170$) and the interaction effects of V x P ($p<0.0053$) were significant at Zoeknog and not at Ofcolaco.

4.3.5.1 Effect of pigeon pea varieties on chlorophyll content (µmolm^{-2})

Ofcolaco:

Though the chlorophyll content of the leaf ranged from 47.84 to 49.01 µmolm^{-2} at Ofcolaco this did not differ amongst varieties.

Zoeknog:

At Zoeknog, the chlorophyll content ranged from 31.38 to 45.34 µmolm^{-2}, with Komboa producing the highest chlorophyll content (Figure 4.6). The chlorophyll content of Tumia, Ilonga 14-M2, and the local landrace was similar.

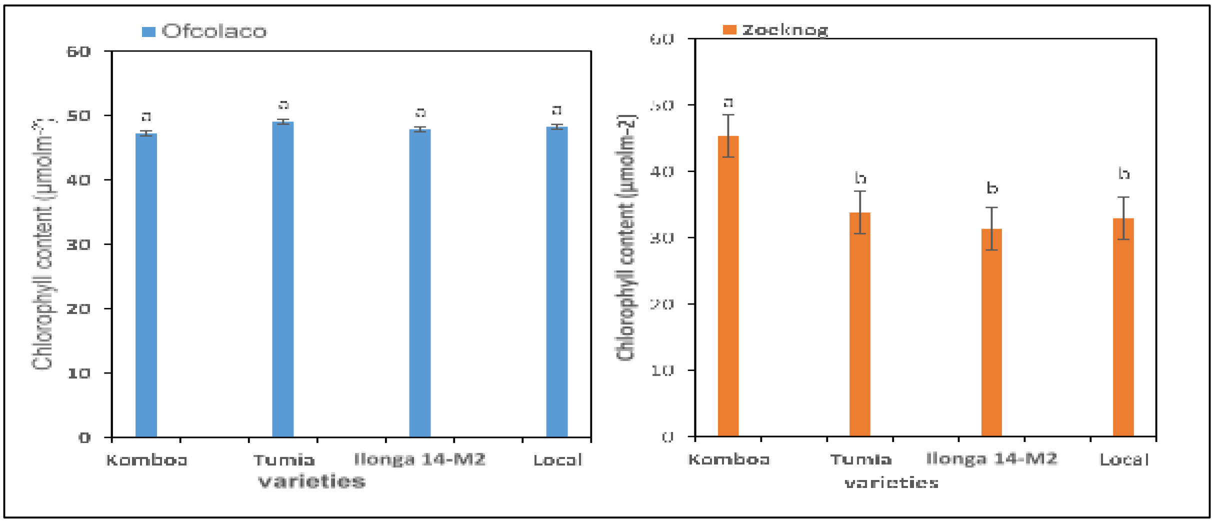


Figure 4.6: Chlorophyll content (µmolm^{-2}) of pigeon pea varieties during 2019/20 and 2020/21 growing seasons at Ofcolaco and Zoeknog (Different letters mean significant differences whereas similar letters mean no significant differences).

4.3.5.2 Effect of chlorophyll content at different growth stages

Significant differences in chlorophyll concentration over growth stages at both locations were observed (Table 4.6).

Ofcolaco:

The chlorophyll content was high at 240 and 440 DAP at Ofcolaco, then reduced until 390 DAP and started to increase during the reproductive stage at 410 with 49.19 µmolm^{-2} (Table 4.6). Most of the varieties were at their flowering stages at 410 and 440 DAP. The lowest pigeon pea chlorophyll content was recorded at 390 DAP.

Zoeknog:

The maximum chlorophyll content was recorded at 240 and 410 DAP with 57.25 and 49.19 µmolm^{-2}, during the vegetative stage, respectively (Table 4.6). The lowest chlorophyll content was also attained at 440 DAP (26.50 µmolm^{-2}) where the crop was at the reproductive stage. At 500 DAP, the chlorophyll content was reduced but did not differ from the chlorophyll content at 390 and 410 DAP, indicating that the crop had reached physiological maturity. The results show that chlorophyll content in leaves was higher during vegetative stages, decreased as the crop grow, and attained the lowest value at maturity.

Table 4.6 Chlorophyll content (µmolm^{-2}) influenced by growth stages during the regrowth stages at Ofcolaco and Zoeknog.

	Chlorophyll content .. ……………µmolm^{-2}……………………	
Sampling dates	Ofcolaco	Zoeknog
240	57.25±6.90a	50.66±9.20a
270	48.42±6.22c	44.20±9.68ba
310	52.17±4.29b	39.12±7.94bc
360	46.66±6.51c	35.08±8.40dc
390	41.90±4.42d	31.17±7.56de
410	49.19±9.66cb	28.92±9.96de
440	52.43±7.15b	26.51±6.74e
500	47.62±6.22c	31.13±32.64de
Mean	49.46	37.82
LSD (0.05)	3.575	6.788

±SD=standard deviation; LSD= least significant difference (Different letters mean significant differences whereas similar letters mean no significant differences)

4.3.5.3 Interaction effect of pigeon pea variety and P fertilizer application on chlorophyll content

Ofcolaco:

Though the interaction of V x P on chlorophyll was higher, the study results showed no significant variations among pigeon pea varieties and P fertilizer application rates, nor the interaction effects (Figure 4.7).

Zoeknog:

At Zoeknog, P fertilizer application at 60 kg ha^{-1} enhanced chlorophyll content by 12% across varieties when compared to the unfertilized plants (Figure 4.7). A strong interaction effect of P X V was also observed at this location. An application of 60k kg P ha^{-1} enhanced pigeon pea chlorophyll content in the local landrace but not in the other varieties. In the landrace, the P fertilizer application increased the leaf chlorophyll content by 54%.

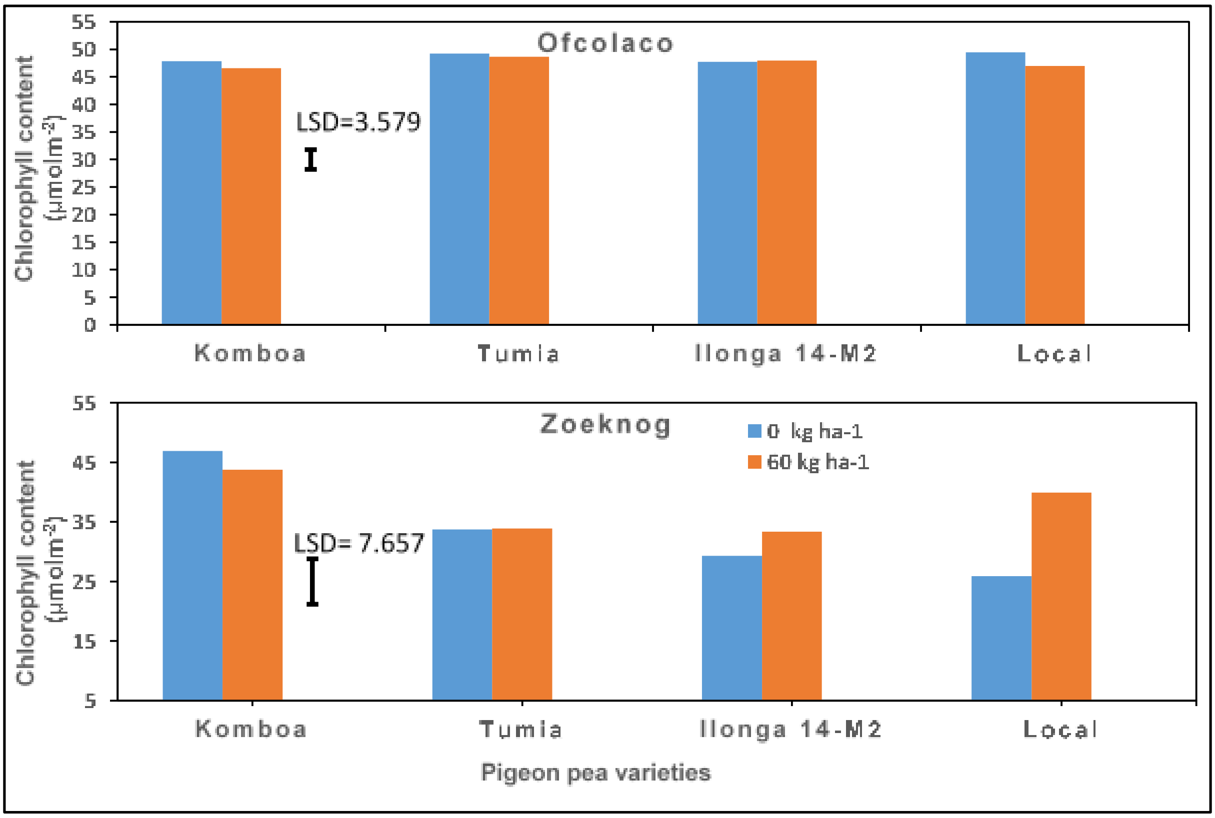


Figure 4.7: Phosphorous application effect on the chlorophyll content of pigeon pea varieties at Ofcolaco and Zoeknog. (Vertical bars represent LSD value).

4.3.6 Phosphorus yield in pigeon pea plant tissue

Phosphorus yield data was determined during reproductive phases at 120 and 470 DAP at both locations. Phosphorus yield (kg ha^{-1}) differed significantly ($p<0.001$) amongst pigeon pea varieties at both locations (Figure 4.8). However, the P fertilizer did not result in a measurable impact on the P yield at both locations. The results also did not show a significant effect on phosphorous yield at both locations.

4.3.6.1 Effect of variety on P yield in plant tissue

Ofcolaco:

The phosphorus yield of the varieties ranged from 11.11 kg ha^{-1} to 23.89 kg ha^{-1} at 120 DAP and 15.11 kg ha^{-1} to 41.47 kg ha^{-1} at 470 DAP at Ofcolaco (Figure 4.8). Ilonga 14-M2 accumulated a relatively higher P per unit area at 470 DAP compared to the other varieties producing a P yield of 41.47 kg ha^{-1} which constituted a 53% increase compared to the P yield at 120 DAP. Komboa produced the lowest P yield at

470 DAP followed by the Local landrace and then Tumia. The P yield of Komboa was 60 and 63% lower relative to Ilonga 14-M2 at 120 DAP and 470 DAP respectively.

Zoeknog:

The P accumulation by the pigeon pea varieties at Zoeknog followed a fairly similar pattern as that at Ofcolaco (Figure 4.8). The highest accumulation occurred at 470 DAP in all the varieties with Ilonga 14-M2 accumulating the highest P per unit area. The local landrace accumulated a relatively higher P per unit area at 470 DAP at this location compared to the Ofcolaco. Komboa again produced the lowest P yield at 470 DAP, 46% and 56% lower than Ilonga 14-M2, respectively.

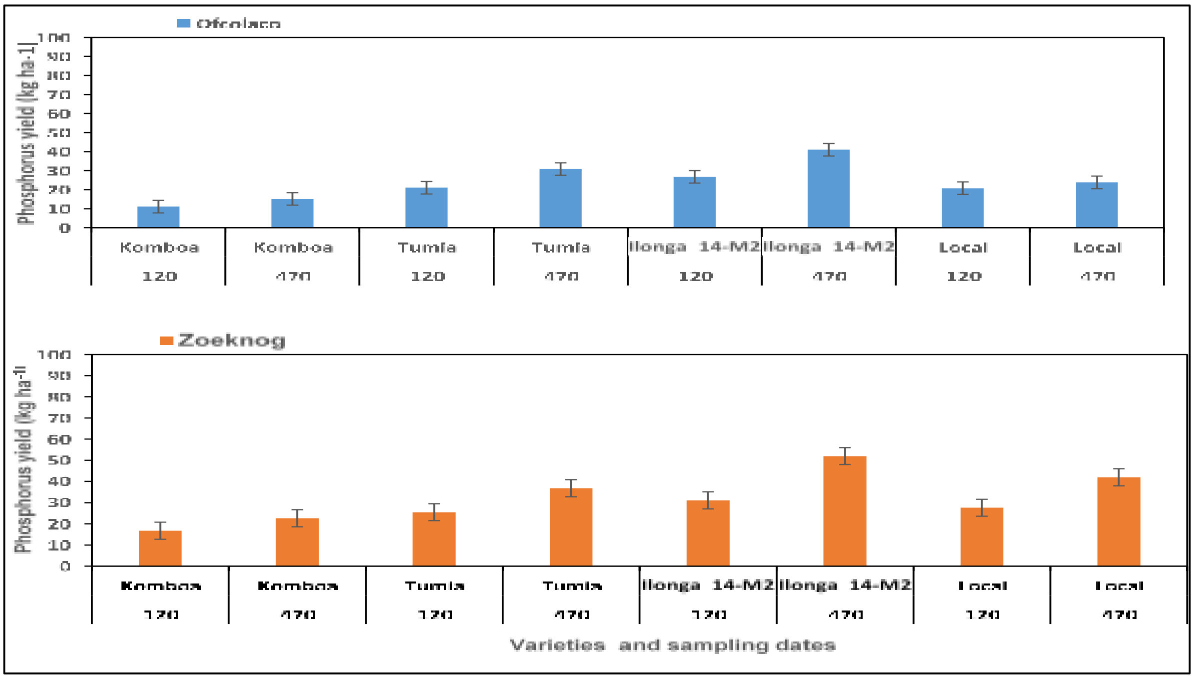


Figure 4.8: Pigeon pea varieties P yield (kg ha^{-1}) at Ofcolaco and Zoeknog as influenced by sampling dates.

4.3.7 PRE in Pigeon pea (%)

The results of the study revealed significant differences in PRE at 120 DAP and 470 DAP among the pigeon pea varieties at Ofcolaco (Figure 4.9). The study also showed significant differences in PRE at Zoeknog at 120 DAP ($p<0.011$) and 140DAP ($p<0.032$) due to the effect of variety. The application of P fertilizer was influenced by PRE only at Ofcolaco during the first sampling.

4.3.7.1 Varietal effect on PRE

Ofcolaco:

PRE ranged from 4.29 to 9.69% and 16.98 to 49.98% in all varieties at 120 and 470 DAP, respectively. PRE varies by pigeon pea variety (Figure 4.9). According to the study results, Ilonga 14-M2 showed higher PRE across all sampling dates. However, the PRE of Ilonga 14-M2 did not differ significantly from Tumia and local varieties at 470 DAP. Among the pigeon pea varieties evaluated at both locations, Komboa had the lowest PRE throughout the sampling dates.

Zoeknog:

The study revealed that the efficiency of phosphorus recovery followed the same trend as the yield of P in plant tissue and was higher during the second sampling (Figure 4.9). At both sampling dates, Ilonga 14-M2 attained the highest and Komboa was the lowest in PRE.

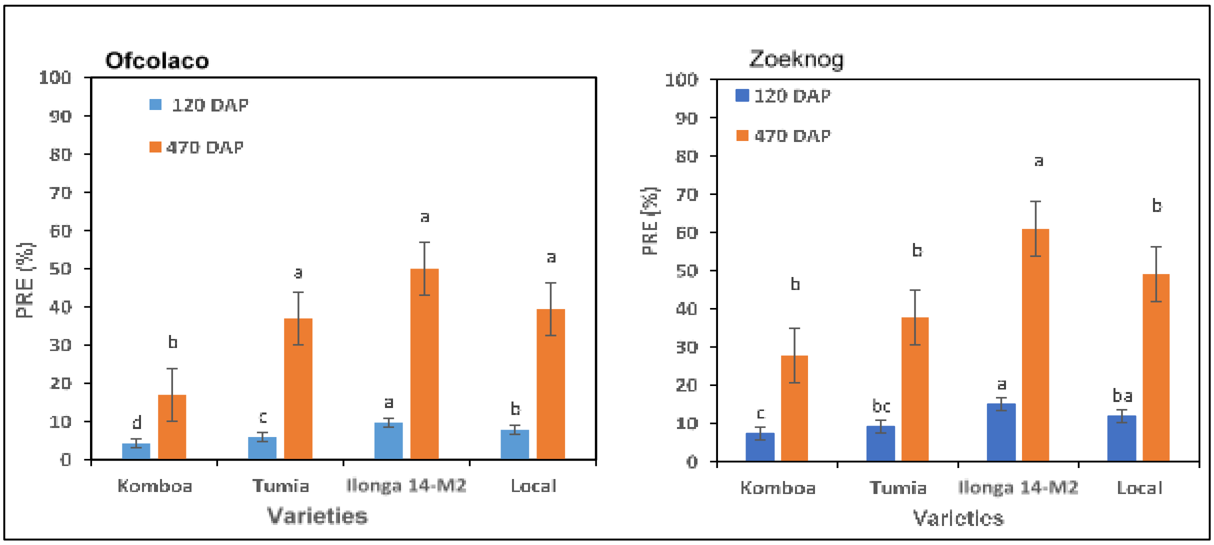


Figure 4.9: Phosphorus recovery efficiency (%) influenced by pigeon pea variety at two sampling dates during the 2019/20 and 2020/ growing seasons at Ofcolaco and Zoeknog (Different letters mean significant differences whereas similar letters mean no significant differences).

4.3.7.1 Application of P fertilizers influencing phosphorous recovery efficiency

A significant difference (p<0.009) in phosphorous recovery efficiency was only observed at Ofcolaco at 120 DAP (Figure 4.10). Though, the results show an increase in phosphorous recovery efficiency influenced by P fertilizer application, did not differ significantly at Zoeknog in both sampling periods.

Ofcolaco:

The study results show that the application of P fertilizers at 60 kg P ha^{-1} decreased phosphorous recovery efficiency was 34 and 61% at 120 and 470 DAP, respectively (Figure 4.10). The study also observed a decrease in phosphorous recovery efficiency with the application of P fertilizer at 60 kg ha^{-1} at both locations at 120 DAP

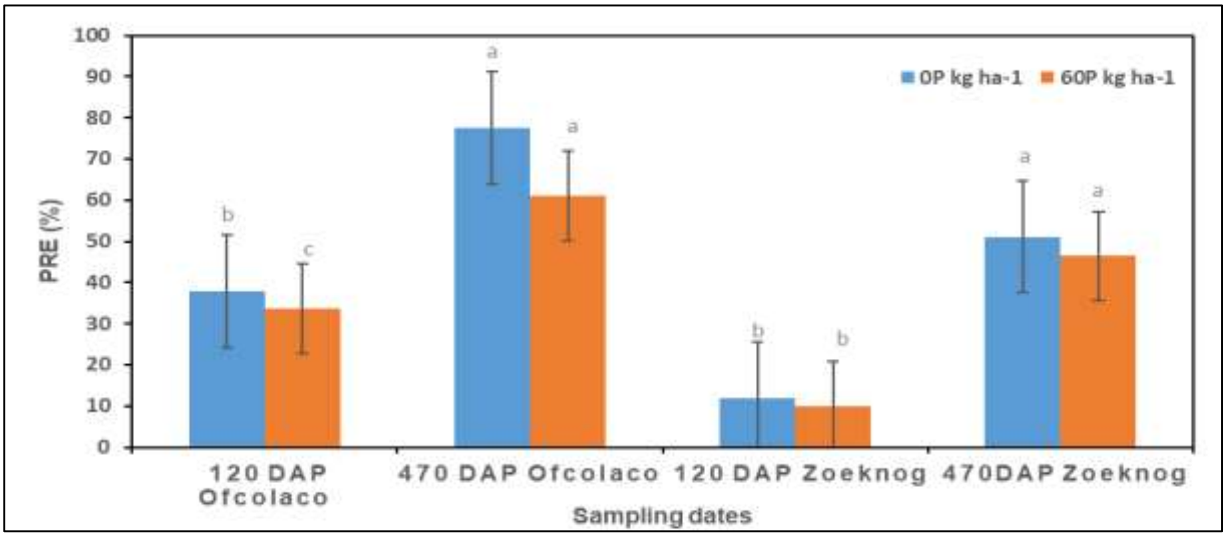


Figure 4.10: Phosphorus fertilizer application rates affecting pigeon pea PRE in different sampling periods during the 2019/20 and 2020/ growing seasons at Ofcolaco and Zoeknog. (Different letters mean significant differences whereas similar letters mean no significant differences).

4.3.8 Phenological variables response to treatments

The second flowering and maturity days of the pigeon pea varieties were measured in days after the initial harvest. There were significant differences in days to 50% flowering and physiological maturity among all pigeon pea varieties (Table 5.7). The study also observed that P fertilizer application did not affect days to flowering and maturity at both locations. The interaction of the V x P effect was also not significant at both locations.

Ofcolaco:

Komboa tends to flower and mature earlier than Ilonga 14-M2 and other local varieties. It takes longer for the Ilonga 14-M2 pigeon pea variety to reach 50% flowering and physiological maturity (144 to 190 DAP) (Table 4.7). Komboa took 98–109 days to reach 50% flowering, and 149 and 150 DAP to mature, respectively. Ilonga 14-M2 and local varieties flower and mature after Komboa has attained 50% physiological maturity.

Zoeknog:

Ilonga 14-M2 pigeon pea variety took 135 to 184 DAP to reach 50% flower and physiological maturity, respectively (Table 4.7). Pigeon pea Komboa flowers mature earlier than all other pigeon pea varieties and took 100 to 145 days to reach 50% flower to maturity. Tumia and local varieties are intermediate in days to flower and reach maturity among the varieties

Table 4.7 Pigeon pea variety response to phenological parameters during the 2019/20 and 2020/21 growing seasons at Ofcolaco and Zoeknog.

Location	Year	Phenology	Komboa	Tumia	Ilonga14-M2	Local	LSD(0.05)
			………………… DAP	…………………	…………………	…………………	
Ofcolaco	2019/20	1st 50% flowering	109.58d	124.20c	144.33a	133.25b	5.1807
		1stPhysiological maturity	148.89d	172.70c	190.83a	182.58b	5.8698
2020/22		2nd 50% flowering	98.33d	123.25c	142.33a	132.32b	7.4904
		2ndPhysiological maturity	150.33d	160.33c	189.25a	171.33b	7.1367
Zoeknog	2019/20	1st 50% flowering	100.25d	121.17c	135.11a	128.8b	5.433
		1stPhysiological maturity	145.33a	163.33a	184.67a	173.67a	63.448

DAP= days after planting, DAH= number of days after the first harvest, LSD= least significant difference, different letters= means significant difference, same letters= non- significant)

4.3.9 Grain yield production of the pigeon pea variety

Pigeon pea grain yield varied significantly ($p<0.001$) among pigeon pea varieties at both locations. Phosphorus fertilizer application and the interaction effect on grain yield were not significant at either location. At Zoeknog, grain was obtained only during the first harvest since the experiment was hit by a hail storm with severe winds shortly before the plant reached 50% physiological maturity.

4.3.9.1 Influence of variety on pigeon pea grain yield production

Ofcolaco:

Grain yield at Ofcolaco ranged from 507 to 1136 kg ha^{-1} and 725 to 1306 kg ha^{-1} during the first and second harvests, respectively. Total grain production was higher in the second harvest compared to the first harvest across all varieties (Figure 4.11). Komboa produced the highest grain yields of 1136 and 1306.11 kg ha^{-1} during the two harvest periods increasing by 15% compared to the first harvest. Ilonga 14-M2 and the local landrace yielded the lowest grain yield. The grain yield of Ilonga 14-M2 was 46 and 30% compared to Komboa and Tumia during the first harvest, respectively.

Zoeknog:

Grain yield production followed the same trend as in Ofcolaco, ranging from 691 to 1431 kg ha^{-1} across all varieties (Figure 4.11). Komboa produced the highest grain yield compared to the other varieties. The study also found that Ilonga 14-M2 and the local landrace produced the lowest grain yield, relative to Komboa and Tumia.

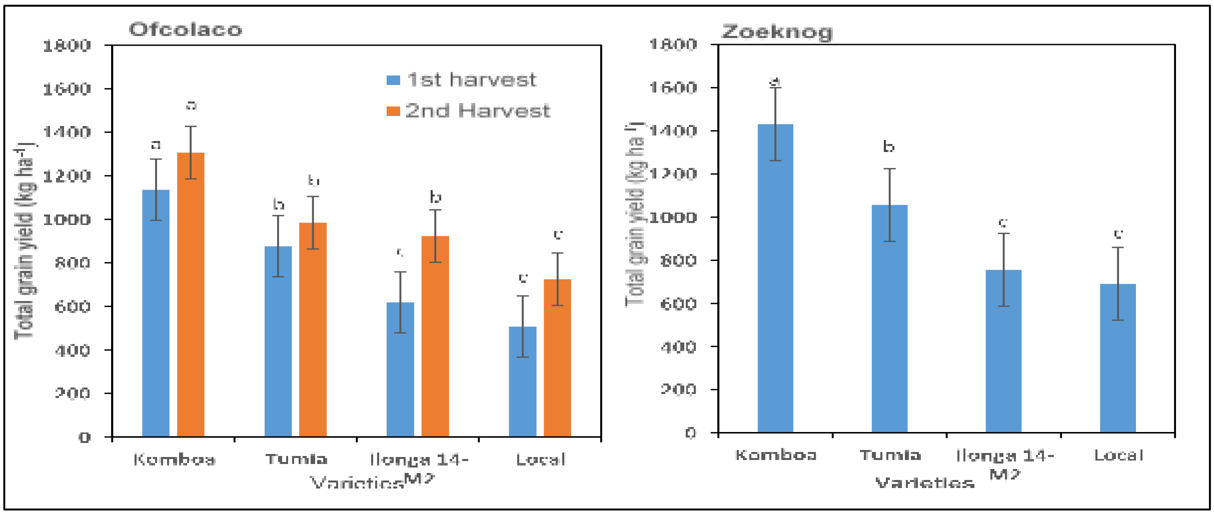


Figure 4.11: The effect of variety on grain yield production (kg ha^{-1}) during the 2019/20 and 2020/21 harvest periods at Ofcolaco and Zoeknog (Different letters mean significant differences whereas similar letters mean no significant differences).

4.3.10 Yield components

The effect of variety on yield components differed significantly at both locations (Table 4.8). The study found no significant effect of P fertilizer application and their interaction of V x P on yield components at both locations.

Pod yield (kg ha^{-1})

Ofcolaco:

The analysis of the results revealed a significant difference in pod yield kg ha^{-1} between varieties during the first ($p<0.002$) and second harvest ($p<0.001$) at Ofcolaco (Table 4.8). Pigeon pea Komboa achieved the highest pod yield, with 1618 kg ha^{-1}, followed by Tumia with 1304 kg ha^{-1} during the first harvest. Ilonga 14-M2 produced more than the local landrace. During the second harvest, Tumia and Ilonga were significantly the same, and the local landrace attained the lowest pod yield.

Zoeknog:

Pod yield followed the same trend as indicated at Ofcolaco during the first harvest (Table 4.8). Though grain yield was higher than at Ofcolaco among all varieties.

Number of pod plant^{-1}

Ofcolaco:

The number of pod plant^{-1} varied among varieties. The results show that Komboa produced the highest number of pod plant^{-1}, with 260 and 291 obtained during the first and second harvest periods, respectively (Table 4.8), and were high during the second harvest in all varieties. The local landrace recorded lower pods plant^{-1} at both harvest periods but did not differ from Ilonga 14-M4 during the first harvest.

Zoeknog

The number of Pods plant^{-1} in pigeon pea, Komboa, and Tumia did not differ significantly (Table 4.8). Pigeon pea Ilonga 14-M2 had the lowest number of pod plants^{-1} and, however, was similar to the local landrace.

Number of seeds pod^{-1}

Ofcolaco:

Pigeon pea varieties did not affect the number of seed pods^{-1} (Table 4.8). The number of seeds pod^{-1} varied between 4 and 3 seeds pod^{-1} across varieties.

Zoeknog:

Significant variations in the number of seeds pod^{-1} were observed. Komboa had the highest seed pod^{-1} and recorded 4 seeds pod^{-1} among the four varieties. Tumia, Ilonga 14-M2, and the local varieties have a similar number of seeds pod^{-1}.

100 seeds weight (g)

The study's findings demonstrate a significant difference in 100 seed weight (g) across pigeon pea varieties at the two locations (Table 4.8).

Ofcolaco:

Pigeon pea Komboa had the highest seed weight with 16.39 g and 18.80 g during the first and second harvests. The study also noticed that seed weight was higher during the second harvest relative to the first harvest. Ilonga 14-M2 and the local landrace did not differ significantly at both harvest periods.

Zoeknog:

The seed weight ranged from 14.51g to 17.80 g for the four varieties (Table 4.8). The study results found Komboa has the highest seed weight and the study also found that Tumia, Ilonga 14-M2, and local varieties did not differ significantly in seed weight.

Table 4.8 Grain yield components of pigeon pea varieties at Ofcolaco during the first and second harvest at Ofcolaco and Zoeknog.

Location	Harvest Periods	Varieties	Pods yield	# Pods plant^{-1}	# seeds pod^{-1}	100 seeds weight
			kg ha^{-1}			(g)
Ofcolaco	1st Harvest	Komboa	1618.89a	260.40a	3.9a	16.39a
		Tumia	1304.33b	187.70b	3.9a	15.64a
		Ilonga 14-M2	1088.89bc	145.10c	3.9a	14.27b
		Local	1070.49c	103.73d	3.87a	13.98b
		LSD (0.05)	227.94	21.821	0.2235	0.876
		Significance	***	***	ns	*
	2nd Harvest	Komboa	1668.95a	372.42a	4.27a	18.80a
		Tumia	1365.74b	257.07b	4.27a	18.80a
		Ilonga 14-M2	1321.91b	225.00b	3.97b	14.13b
		Local	1195.86c	186.85c	3.93b	15.46b
		LSD (0.05)	119.97	35.332	0.2827	1.33
		Significance	***	***	*	*
Zoeknog	1st Harvest	Komboa	1668.95a	291.63a	4a	17.80a
		Tumia	1365.74b	248.62a	3.9a	15.67b
		Ilonga 14-M4	1321.91c	175.70b	3.9a	15.12b
		Local	1195.86c	135.12b	3.9a	14.51b
		LSD (0.05)	338.63	59.946	0.199	0.678
		Significance	***	**	ns	*

LSD= least significant difference*; different letters mean significant differences whereas similar letters mean no significant differences*)

4.3.11 Harvest index

The study found a highly significant difference ($p<0.001$) in the harvest index of pigeon peas due to variety throughout the harvest periods at Ofcolaco and Zoeknog. P fertilizer application significantly ($p<0.0150$) influenced HI only during the first harvest at both harvests at Ofcolaco and Zoeknog. The interaction effect was not significant at Ofcolaco and Zoeknog.

4.3.11.1 Varietal effect on the pigeon pea harvest index

Ofcolaco:

Komboa has the highest harvest index, followed by Tumia, Ilonga 14-M2, and local varieties, respectively (Table 4.9). In addition, low HI was attained by Ilonga 14-M2 at both harvest periods. Harvest index values of 25.36%, 10.74%, 6.90%, and 6.02% were obtained in Komboa, Tumia, Ilonga 14-M2, and local varieties during the first harvest at Ofcolaco, respectively. The harvest index was higher during the second harvest period.

Zoeknog:

Harvest indices for Komboa, Tumia, Ilonga 14-M2, and the local varieties were 25.87%, 8.87%, 7.45%, and 8.38%, respectively (Table 4.9). Varieties followed the same tendency on the harvest index as observed at Ofcolaco. A harvest index was not recorded at Zoeknog during the second harvest period because grain yields were not harvested due to a hail storm that destroyed the crop just before harvest.

Table 4.9: Pigeon pea harvest index (%) during the first and second harvest periods at Ofcolaco and Zoeknog.

		1st Harvest (%)				
Location	Komboa	Tumia	Ilonga 14-M2	Local	LSD(0.05)	Significance
Ofcolaco	25.36a	10.74b	6.90c	6.02c	3.99	***
		2nd Harvest (%)				
Ofcolaco	29.19a	12.07b	10.42b	8.60b	3.55	**
		1st Harvest (%)				
Zoeknog	25.87a	8.87b	7.45b	8.38b	3.05	*

*** Significant at ($p<0.001$); ** significant at ($p<0.01$); * significant ($p<0.05$)

4.3.11.2 Effect of P fertilizer application on Harvest index

Ofcolaco:

The study findings revealed that unfertilized plants had higher harvest indices of pigeon pea varieties of 30.64% relative to the fertilized plants at 60 kg ha^{-1}, which was 27.23% during the first harvest (Figure 4.2). The study revealed a decrease in harvest index during the second harvest at Ofcolaco when compared to the first harvest due to P fertilizer application. The harvest index at the second harvest did not differ between the fertilized and the unfertilized plants.

Zoeknog:

The results also demonstrate that harvest indices were similar between the unfertilized and fertilized plants at Zoeknog (Figure 4.12).

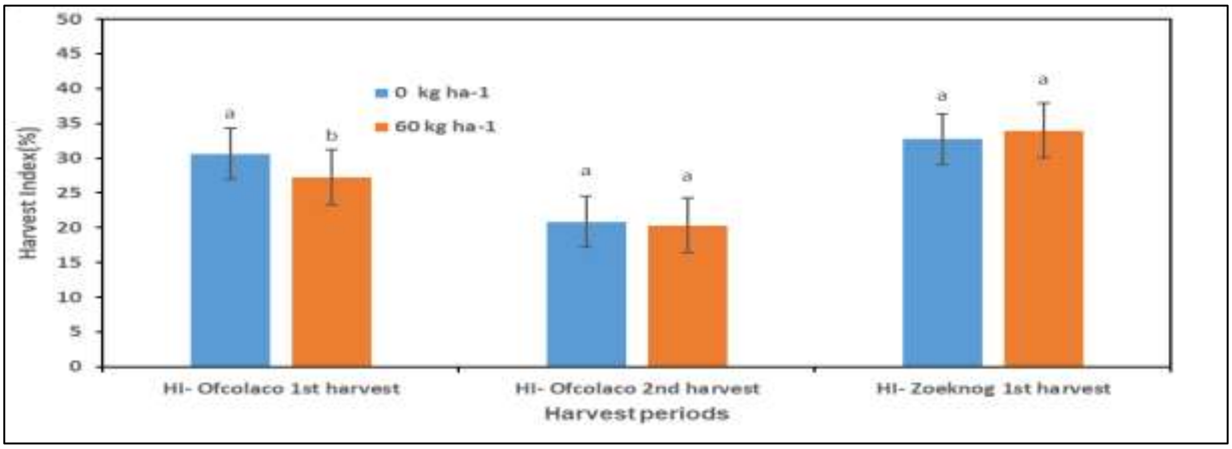


Figure 4.12: Harvest index (%) of pigeon pea as influenced by P fertilizer application rates during harvest periods at Ofcolaco and Zoeknog (Different letters mean significant differences whereas similar letters mean no significant differences).

4.3.12 Correlations between pigeon pea grain yield and yield components

Tables 4.10 to 4.12 show the correlation between pigeon pea yield variables and yield components during the first and second harvest periods at Ofcolaco, as well as during the first harvest at Zoeknog. During the first harvest at Ofcolaco, the study showed a substantial positive association between grain yield and the number of pods plant^{-1} (0.969**), pod yield (0.864**), and 100 seed weight (0.864**). During the first harvest at Ofcolaco, the correlation between grain production and the number of seed pod^{-1} was positive but very weak (0.110 ^{ns}). Correlations followed the same pattern during the second harvest, and it was also found that correlations between grain yield and the number of pod plants^{-1} (0.947**) were slightly reduced (0.853**). At Ofcolaco, the number of seeds pod^{-1} increased from 0.110 during the first harvest to 0.595 during the second harvest.

Negative strong correlations were also found between the number of days to flowering, physiological maturity, and yield components; a negative association was only found during the first harvest between the number of days to 50% flowering and the number of seed pod^{-1} (r = -0.159^{ns}). The study revealed a considerable negative association between flowering and the number of seeds per pod (r = -0.764*) at Ofcolaco during the second harvest.

Similar to Ofcolaco, the results at Zoeknog demonstrated that grain production positively correlated with pod plant^{-1} (r = 0.813**), pod yield (r = 0.897**), and 100 seed weight (r = 0.729*). A strong negative association between grain yield and the number of days to 50% flowering (r = -0.807**) (Table 5.11) was found. There was also a slight relation between grain yield and seed pod^{-1} (r = 0.243^{ns}). The findings revealed weak positive relationships between physiological maturity and yield components, which were only negative with regard to the number of seed pods^{-1} (r = -0.451*).

Table 4.10 Correlations between grain yield and yield variables of pigeon peas during the first harvest at Ofcolaco.

Yield variables	Grain yield kg ha-1	Physiological maturity (DAP)	50% flowering (DAP)	# pods plant-1	Pod yield kg ha-1	100 seed weight (g)	# Seeds pod-1
Physiological maturity	-0.718 *	1					
50% flowering	-0.731 *	0.974**	1				
# Pods plant-1	0.948**	-0.757 *	-0.773 *	1			
Pod yield	0.854**	-0.774 *	-0.787 *	0.863**	1		
100 Seed weight	0.864**	-0.718 *	-0.732 *	0.948**	0.854**	1	
# Seeds pod-1	0.596*	-0.789 *	-0.765 ns	0.717*	0.594*	0.596*	1

Significance levels: $p<0.05$, $p<0.01$, and $p<0.001$

Table 4.11 Correlations between grain yield and yield variables of pigeon peas during the second harvest period at Ofcolaco.

Yield variables	Grain yield (kg ha^{-1})	Physiological maturity (DAP)	50% flowering (DAP	#pods $plant^{-1}$	Pods yield (kg ha^{-1})	100 seeds weight(g)	# seeds pod^{-1}
Physiological maturity	-0.775 *	1					
50% flowering	-0.819 *	0.953**	1				
#pods $plant^{-1}$	0.970**	-0.740 *	-0.815*	1			
Pods yield	0.865**	-0.691*	-0.697 *	0.825**	1		
100 seeds weight (g)	0.865**	-0.679 *	-0.703 *	0.811**	0.764*	1	
# Seeds pod^{-1}	0.111 ^{ns}	-0.066 ^{ns}	-0.159 ^{ns}	0.214 ^{ns}	0.236 ^{ns}	0.118 ^{ns}	1

Significance level: p<0.05, p<0.01, and p<0.001, ns-not significant

Table 4.12 Correlations between grain yield and yield variables of pigeon peas during the first harvest period at Zoeknog.

Yield variables	Grain yield (kg ha^{-1})	Physiological maturity (DAP)	50% flowering (DAP	# Pods $plant^{-1}$	Pod Yield (kg ha^{-1})	100 seed weight (g)	# seeds pod^{-1}
Physiological maturity	0.050 ^{ns}	1					
50% flowering	-0.808 *	0.059 ^{ns}	1				
#pods $plant^{-1}$	0.813 **	0.131 ^{ns}	-0.584 ^{ns}	1			
Pod yield	0.898 **	0.108 ^{ns}	-0.666 *	0.672*	1		
100 Seed Weight	0.729**	0.105 ^{ns}	-0.734 *	0.529*	0.550*	1	
#Seeds pod^{-1}	0.243 ^{ns}	-0.452 ^{ns}	-0.272 ^{ns}	-0.002 ^{ns}	0.2119 ^{ns}	0.270 ^{ns}	1

Significance levels: $p<0.05$, $p<0.01$, and $p<0.001$,ns= not significant

4.4 DISCUSSION

4.4.1 Effect of variety on biomass production

Pigeon pea growth differs amongst varieties in shoot biomass production because of different production cycles. The average shoot biomass average ranged from 5375 to 10149 kg ha^{-1} across varieties and locations. The study results agree with the report by Mugi-Ngenga *et al. (2021),* who recorded pigeon pea biomass production ranging from 200 to 1190 kg ha^{-1}. The variation in biomass production among pigeon pea varieties was also reported by Elema *et al.,* (2022). The study results showed that the pigeon pea variety, Komboa produced the lowest shoot biomass at both locations. The low biomass production in Komboa might be because the variety is a short-duration, bushy, and of a spreading type and because of its genetic makeup. The current study supported the findings of Hogh-Jensen *et al*. (2007), who found that the short-duration type, ICEAP 00068 pigeon pea genotype produced less biomass than the long-duration types ICEAP 00053, ICEAP 00040, and ICEAP 00020. The study also revealed that this type of pigeon pea variety can grow and produce a yield in a short period, mainly to escape drought conditions.

Ilonga 14-M2 and local varieties produced the highest biomass production of 9937 and 10149 kg ha^{-1} at Ofcolaco and Zoeknog, respectively. The study findings agreed with the report of Edje (2014), which demonstrated that the long-duration pigeon pea type had twice the biomass production compared with the short-duration type. Tumia and local landrace biomass production were intermediate, higher than Komboa, and lower than Ilonga 14-M2. High values of shoot biomass production recorded in varieties during the second regrowth periods might be because biomass production in the study was recorded over two years without disruption. Shoot biomass increases with an increase in growth periods and the highest was obtained at 560 DAP, during the second harvest. High rainfall during the 2020/21 growing season might also have contributed to high biomass production (Figure 4.2). The differences in shoot biomass production in the two locations might cause by the differences in environmental conditions. The study concluded that Ilonga 14-M4 is suitable for fodder production due to its higher shoot biomass production.

4.4.2 Effects of P fertilizer application and their interaction with shoot biomass production

Significant differences in shoot biomass production ($p<0.0207$) were observed at 180 DAP during the first harvest only at Ofcolaco (Figure 4.3.3). At Zoeknog, no significant variations due to P fertilizer application were observed. A similar finding was observed by Gitari and Mureithi (2003), who reported that additional P fertilizer application did not affect biomass accumulation in *Mucuna pruriens*. The effect of P fertilizer application rates in biomass production differs among varieties and P fertilizer rates at Ofcolaco. Similar findings were reported by Ajei-Nsiah *et al*. (2004), who found that varieties of pigeon peas differ in growth rate under different P fertilization rates. The current study found that P fertilizer application at 60 kg ha^{-1} increased biomass production, but this depends on the growth stage, and climatic conditions. Similar results were also reported by Ade *et al.* (2018) who found that P fertilizer at 60 kg ha^{-1} increased pigeon pea biomass production than when applied at 40 and 50 kg ha^{-1}. In this study, biomass production with additional P fertilizer application was significant at 180 DAP in Ofcolaco. However, P application started to increase biomass production at 120 DAP during the first flowering period. This might indicate that P-nutrients are mostly utilized during the reproductive stages of plants and moisture was available to promote the P-uptake. The interaction effect of V x P did not show any significant changes in shoot biomass production across all locations.

4.4.3 Pigeon pea variety effect on stem diameter

The study results revealed that stem diameter differs significantly among pigeon pea varieties, growth stages, P fertilizer application rates, and the interaction of V x DAP in both locations. Stem diameter ranged from 19. 04 to 22.11 and 27.20 to 36.29 mm at Ofcolaco and Zoeknog, respectively. The stem diameter of pigeon pea varieties measured by Yuniastuti *et al*. (2020) ranged from 16.5 to 26.56 mm. The current findings on stem diameter at Ofcolaco were within the range indicated by the above author. The study recorded thicker stems at Zoeknog and was due to varietal traits and the environment. The study revealed that the varieties with thick stems are suitable for firewood. The quality of firewood production in pigeon peas was reported to be high in energy yield with a rate of 4350K-cal kg^{-1} (Yude *et al*., 1993). This will help the majority of rural people in Limpopo and Mpumalanga Provinces who are still using firewood for cooking (Makhado *et al*., 2014). The current results show that pigeon pea stem diameter was thicker in medium and long-duration types (local and Ilonga 14-M2) but thin in short-durations types (Komboa). The thickness of the stem helps the plant resist lodging during strong winds and hail storms. The results also revealed that stem diameter increased with an increase in plant growth. Similar findings were also reported by Cargnelutti Filho *et al*. (2017) who studied linear relations among pigeon pea traits. This might be because pigeon pea is a perennial shrub and it can be grown and produced for more than five years, and this also depends on the variety, climatic conditions, environment, and management practices. The effect of P fertilizer application and its interaction effects on stem diameter were not significant at both locations.

4.4.4 Effects of different pigeon pea varieties on plant height

The study revealed that plant height differs among pigeon pea varieties due to genotype, environment, and management practices. Pigeon pea differs in plant height because some are bushy and spreading types and other types have erect branching (Matthews *et al*., 2001a). The current study observed that the bushy and spreading pigeon pea types (short durations) are shorter while the erect branching types (medium and long-duration types) are taller. These variations in pigeon pea plant height are caused by differences in the plant growth of varieties. Plant height ranged from 126.80 cm to 226.96 (cm) and 132.17 cm to 240.76 (cm) at Ofcolaco and Zoeknog, respectively. However, Purwanto (2007) recorded a 50 cm to 500 cm of pigeon pea height, while Mula and Saxena (2010) recorded a pigeon pea height of up to 500 cm. Other scientists also stressed that pigeon peas grow to a height of 250 cm (Krisnawati, 2005). In this study, it was observed that the highest average plant height was

Ilonga 14-M2 with 226.96 cm and 240.76 (cm) at Ofcolaco and Zoeknog. The present study found pigeon pea plant height was within the range recorded by other scientists. Climatic conditions such as rainfall amount and distribution, light, and temperature might have contributed to increased plant height. The current study found pigeon pea plant height increased with an increase in growth duration across all varieties and locations. The study findings agreed with the study conducted by Gitiara *et al*. (2019), who reported an increase in plant height with an increase in sampling dates of pigeon pea varieties.

4.4.5 Effect of P fertilizer application on pigeon pea plant height

The study also detected non-significant differences influenced by P fertilizer application in plant height at Ofcolaco and Zoeknog. The same findings were also reported by Stephen *et al*. (2014) who reported that plant height at all six P fertilizer application rates was similar to that with 0 kg ha^{-1} P fertilizer. However, the response of pigeon peas to P fertilizer application was inconsistent because some scientists reported that P fertilizer influences plant height. Babu *et al*. (2014) reported an increase in pigeon pea plant height planted under a pigeon pea–sunflower cropping system with 30 kg ha^{-1} than at 15 and 0 kg ha^{-1}. The current study findings on P fertilizer in plant height might cause by high rainfall during the 2020/21 growing season which might have influenced the growth of pigeon pea

4.4.6 Chlorophyll content in pigeon pea varieties.

Significant variation in chlorophyll content of pigeon pea varieties was observed at Zoeknog ($p<0.001$), and not at Ofcolaco. The outcome of the results also indicated that pigeon pea varieties differ in photosynthesis processes and production yields. Komboa pigeon pea variety had the highest chlorophyll content among pigeon pea varieties, followed by Tumia, Local, and Ilonga 14-M2 at Zoeknog, respectively. The same trend was also observed in total grain yield production. The reduction of chlorophyll in Ilonga 14-M2 might cause by the destruction of an enzyme responsible for green pigment synthesis (Dutta *et al*., 2009). Chlorophyll leaf content ranged from 47 to 49 and 31 to 45 $\mu molm^{-2}$

at Ofcolaco and Zoeknog, respectively. Nagaraj *et al*. (2019) also recorded chlorophyll content of 40.50 to 44.96 µmolm^{-2} in pigeon peas.

Chlorophyll is an essential component for photosynthesis and mostly occurs in chloroplasts (a green pigment in photosynthetic plant tissues). The lower chlorophyll content at Zoeknog might due to low temperatures with high humidity during winter periods than at Ofcolaco. These temperatures are known to promote the development of fungal diseases, and this might hinder the interception of light on leaves at Zoeknog.

4.4.7 Effect of P on chlorophyll content

Non-significant differences in chlorophyll content influenced by P fertilizer application were found at Ofcolaco, but significant at Zoeknog. The significant differences recorded at Zoeknog might be due to the difference in environmental conditions and available soil nutrients compared to Ofcolaco. This might also cause by increased pigeon pea growth which might influence P uptake and chlorophyll content. Nndwambi *et al*. (2016) also found no significant variations in leaf chlorophyll content due to applied P fertilizer application rates in pigeon peas cropping systems in Limpopo Province. Accumulation of photosynthesis products is improved if nutrients such as P are applied adequately (Malik *et al*., 2011; Nagaraj *et al.*, 2019). Phosphorus is known to stimulate photosynthesis processes in crops, and this might contribute to higher grain yields. Other scientists also reported that chlorophyll content was higher in pigeon pea planted in low salinity (Tayyab *et al*., 2016) and salt-induced plant growth and reproduction processes.

4.4.8 Phosphorus yield in plant tissue is influenced by variety.

Phosphorus yield data was obtained during reproductive phases at 120 and 470 DAP in both locations. Phosphorus is essential for global food security and is a limited non-renewable resource, making its efficient use vitally important. In this study, pigeon variety differences in P uptake, yield, and utilization have been observed. Phosphorus yield in plant tissue was found to differ among varieties and locations. The same observations were reported by Hogh-Jenson, *et al*. (2007) who reported variation in P yield in leaves and shoots of pigeon pea and varied within varieties and locations. Phosphorus yield in plant tissue ranged from 11.11 to 3.0 kg ha^{-1} at 120 DAP and 15.11 to 52.0 kg ha^{-1} at 470 DAP across locations. P uptake by pigeon pea varieties also varies due to the growth duration and biomass production of pigeon peas. Babu *et al*. (2014) found the P content of pigeon pea stover was reduced at harvest than at 60 to 120 days after sowing (DAS). In the current study, P yield was determined at flowering stages. The study found that Ilonga 14-M2 had higher P accumulations in plant tissues, plant height, and biomass production. In this study, P yield in plant tissue significantly increases plant growth and varies among varieties, climatic conditions, and durations of the variety.

The study found that the long-durations type, Ilonga 14-M2 attained a higher P yield than the short-durations type (Komboa) with lower biomass production. These variations were because long-durations have a strong, deep root system that enables the plant to utilize deep water and nutrients (Odeny, 2007) than the short-durations type with poor root development. In this study, Ilonga 14-M4 had high biomass and also the ability to utilize fixed and inactive P through translocation of P in the root system. The current study found that P yield in Ilonga 14-M2 did not influence grain production as it had produced the lowest grain yield but increased biomass production. It was also observed that the P uptake rate was higher at 470 DAP than at 120 DAP. The low P accumulation in plant tissue at 120 DAP might be due to low initial soil P, which was 7 and 29 mg kg^{-1} at Ofcolaco and Zoeknog, respectively (Table 4.2). This also explained that P uptake by plants was influenced by root systems and pigeon pea at 470 had fully developed root systems.

4.4.9 Phosphorus fertilizer application rates effects on plant tissue P yield

Though, the current study results showed no significant differences influenced by the application of P fertilizer rates and their interaction of V x P at both locations. The positive response of P fertilizer application in P yield in plant tissue reported by Barbieri *et al*. (2014) found an increase in plant tissue P accumulation at 150 kg P ha^{-1} than at 25 and 50 kg P ha^{-1} in wheat. Singh *et al*. (2013); an additional 40 to 80 kg P_2O_5 ha^{-1} increased P uptake and Ade *et al*.

(2018) increased application at 60 kg P_2O_5 ha^{-1} increased P uptake in pigeon peas plant tissue. The study concludes that P application of more than 60 kg ha^{-1} increased P yield in plant tissue and this also depends on the genetic traits of the variety, soil conditions and moisture availability, and availability of other soil nutrients. The study concludes that additional P application rates of up to 120 kg P_2O_5 should be investigated.

4.4.10 Varietal effect on PRE

Most parts of South Africa are characterized by a low concentration of soil P and are caused by poor crop management practices. The study found significant differences in phosphorous recovery efficiency among pigeon pea varieties. In this study, phosphorous recovery efficiency ranged from 4.29 to 9.69 %, and 16.98 to 49.9% at 120 and 470 DAP at Ofcolaco. Higher P recovery efficiency was recorded at Zoeknog, ranging from 7.35 to 60.9% at both sampling dates. However, Singh *et al*. (2014) recorded phosphorous recovery efficiency ranging from 3.72 to 12.84% in pigeon pea varieties. The current study recorded very low and high phosphorous recovery efficiency in pigeon pea varieties. The high values might be due to the effect of varietal genetic makeup and growth period that might have contributed to high phosphorous recovery efficiency.

Agronomic management practices by smallholder farmers might also contribute to lower phosphorous recovery efficiency. The study findings reported by Roberts and Johnson (2015) recommended the implementation of 4R's (applying the right source, at the right time, right application rate, and at the right location) for improved phosphorous recovery efficiency.

4.4.11 Phosphorus fertilizer application affects phosphorous recovery efficiency

The application of P fertilizers reduced phosphorous recovery efficiency across all sampling dates and locations. Several scientists have reported the same observations. Kumar and Kushwaha (2006); Barbieri *et al*. (2014); and Singh *et al*. (2014) found higher phosphorous recovery efficiency at lower P fertilizer rates in pigeon peas. Singh *et al*. (2014) recorded an increase in the phosphorous recovery efficiency at 40 kg P ha^{-1} and it was lower at 90 kg P ha^{-1}. The variation might be due to different root growths that enable the plant to absorb P in the soil. The short-duration type in the study produced low phosphorous recovery efficiency which might be due to shorter root growth that enables the plant to absorb deep soil P. Ade *et al*. (2018) also reported poor uptake of P by short-duration due to poor root system. Other factors contributing to reduced recovery efficiency might be moisture stress coupled with higher temperatures in summer seasons during the reproductive stages of long-durations types. In comparison with cereal crops, pigeon pea is proven to have efficient exploitation of applied P for uptake. The right application rate to increase the phosphorous recovery efficiency needs to be investigated.

4.4.12 Effect of variety on pigeon pea phenological variables

The differences in attaining flowering and physiological maturity differ with pigeon pea variety and location. Maturity duration in pigeon peas is an important factor that determines the adaptation of varieties to different agro-climatic conditions (Matthews *et al*., 2001a)). Several scientists have also reported that temperature and photoperiod sensitivity control pigeon pea durations in the field (Kimani, 2001; Gwata and Shimelis, 2013; Orr *et al*., 2013).

The variations in days to flowering and maturity were due to the pigeon pea's genetic makeup. The current study observed that the early-maturing type tended to flower and mature earlier in both locations. This variety takes a maximum of 109 DAP and 150 DAP to flower and reach physiological maturity. The same number of days was also recorded by Matthews *et al*., (2001a) who found that the short-duration type takes up to 150 DAP. In this study, the pigeon pea variety Komboa was found to be an early-maturing variety due to its maturity duration period and insensitive character to photoperiod. The variety grows and matures in a short period during the summer season (Kimani, 2001).

It was also observed that pigeon pea Tumia is a medium maturing type compared with Komboa, Ilonga 14-M2, and local varieties. This type of variety takes a maximum of 124 to 172 DAP to reach 50% and reach maturity. The study observations agreed with the report by Matthews *et al*. (2001a), which indicated that medium durations take 151 to 180 DAP. The same observations were reported by Gitiara *et al*. (2019) reported that different locations and climatic conditions were found to affect the phenological characteristics of plants. Long-duration types, in this study, were Ilonga 14-M2 and local varieties, which took a maximum of 190 and l82 DAP, respectively. Being photosensitive (Kimani 2001; Jones 2002), Pigeon pea varieties tend to flower and mature earlier at Zoeknog than at Ofcolaco. The variations might be due to different temperatures in the two locations (Silim, 2001), rainfall (Figure 4.1), and soil type and soil conditions (Table 4.2) at the two locations.

4.4.13 Varietal response to grain yield production

Grain yield production differs among pigeon pea varieties. These differences in grain yield production of pigeon pea varieties were also reported by Ade *et al*. (2018). Grain yield production averaged 507–1306 kg ha^{-1} at Ofcolaco and 690–1431 kg ha^{-1} at Zoeknog. The study recorded higher grain yields relative to the global mean grain yield of 800 kg ha^{-1} in India (FAOSTAT, 2015). Numerous researchers attained different pigeon grain yields. Lower grain production was also reported by Makelo (2011) who recorded 400 kg ha^{-1} by local landraces in India and Nndwambi *et al*. (2016) obtained 922 and 1141.7 kg ha^{-1} under maize/pigeon pea intercropping and sole in Limpopo Province, South Africa. Higher grain yields were also reported by Matthews *et al.* (2001b who reported 1834 to 1905 kg ha^{-1} for short durations and 1296 to 1695 kg ha^{-1} for medium and long durations in Mpumalanga Province, South Africa. Singh *et al.* (2013) obtained 1450 and 1750 kg ha^{-1} grain yields in pigeon pea/mung bean intercropping. Differences in grain yields recorded might be caused by genetic traits of the variety used in the study and also moisture stress during winter seasons. The current study obtained similar grain yield production as reported by Mugi-Ngenga *et al*. (2021), who recorded average pigeon pea grain yields ranging from 500 to 1400 kg ha^{-1}.

The present study revealed that Komboa produced the highest grain yield among varieties, with 1300 and 1400 kg ha^{-1} at Ofcolaco and Zoeknog. The study agrees with the findings of Matthews *et al.* (2001) who found extra short and short-durations produced 1360 to 1369 kg ha^{-1}. Though being the highest yielding variety, Komboa produced the lowest shoot biomass among varieties. This indicates that the production of biomass in this variety did not contribute to grain production. Komboa is a short-duration type and the high grain yield in this variety might be because of its bushy and spreading growth type (Matthews *et al* 2001a). Pigeon pea local landrace attained the lowest grain yield but had higher biomass production than Komboa and Tumia. This indicates that these varieties are adaptable to local conditions but lack genetic traits for high grain production. Tumia is an intermediate variety that produces low grain yields relative to Komboa but higher grain production than Ilonga 14-M2 and local varieties. Local varieties recorded an average of 507 to 725 kg ha^{-1} which was above the 400 kg ha^{-1} recorded by Makelo (2011).

The study recorded the lowest grain yield production in the Ilonga 14-M2 variety, ranging from 618 kg ha^{-1} to 922 kg ha^{-1} across locations. The results contradict the findings of Matthews *et al*. (2001a), who reported high grain yields (1300 to 1379 kg ha^{-1}) for medium to long-duration types. This low grain yield might be caused by moisture stress as the variety grows, flowers, and matures during dry conditions. The study also reported that pigeon pea Komboa compared with Ilonga 14-M2 produced 48% and 50% more grain yield at Zoeknog and Ofcolaco, respectively.

4.4.14 The impact of P fertilizer application on grain yield

The application of P fertilizers did not significantly influence pigeon pea grain yield across all varieties at both locations. However, the results show a slight increase of 2.7% and 2.1% in grain yield when P fertilizer at 60 kg ha^{-1} was applied during the 1st harvest at Ofcolaco and Zoeknog. The results also revealed that the interaction effects of V x P on grain production were also non-significant. Several scientists reported an increase in pigeon pea grain yield due to lower P fertilizer application rates. Low application of P of 17–26 kg ha^{-1} increased grain yield by 300 to 600 kg ha^{-1}. (Kantwa *et al*., 2011). Other researchers also reported that 40 to 45 kg P ha^{-1} increased grain yields (Kantwa *et al.,*2004. Nndwambi *et al*., 2016) also reported additional P fertilizer up to 60 and 80 kg ha^{-1} did not significantly increase pigeon pea grain yield. Other scientists reported increased grain yield due to the high application of P fertilizer. Singh *et al*., (2014) and Ojwang *et al*., (2016) concluded that P fertilizer applied at a rate of above 50 kg ha^{-1} improved the growth and grain yield of pigeon pea. Seed weight was increased to 80 kg P ha^{-1} (Mahelele and Kushwaha, 2011). The current study found that increased application of P fertilizer at 60 kg ha^{-1} did not show a favorable response to grain yield. This negative response of P in grain yield might be due to different environmental conditions between the two locations and the genetic traits of the varieties.

However, the current study found that P fertilizer application rates and the interaction effect of V x P did not increase grain yield production of pigeon pea varieties in both locations. The study concluded that the impact of P fertilizer application on grain yield production depends on the variety, climatic conditions, and agronomic crop management. Smallholder farmers should be encouraged to apply P fertilizers based on the soil analysis results and to apply other important nutrients such as nitrogen.

4.4.15 Grain yield components as influenced by a variety

Grain yield components differ significantly ($p<0.001$) among varieties. Pigeon pea Komboa had the highest pod production (kg ha^{-1}), number of pods per $plant^{-1}$, number of seeds per pod^{-1}, and 100 seed weight (g) and was followed by Tumia. Less production in yield components was documented in pigeon pea Ilonga 14-M2 and the local landrace, and these pigeon pea varieties resulted in low grain yield production. A strong positive correlation was revealed between grain yield and yield components. However, a negative strong relationship between grain yields and days to 50% flowering and maturity was observed. The study found no significant differences in P fertilizer application and the interaction of V x P on yield components in each location. The effect of variety was, however, significant across all locations. However, Mahetele and Kushwaha (2011) and Ahmad *et al*. (2015), reported increased yield components due to the additional application of P fertilizer in mung beans.

4.4.16 The effect of the harvest index on pigeon pea varieties

Improvement of grain crops is associated with the harvest index. The current study found harvest indices were between 6.02 and 29.19 across all varieties at both harvest periods at Ofcolaco. The harvest index at Zoeknog ranged from 7.45 to 25.87 across all varieties. Other scientists reported a harvest index of 14.9 to 16.1 in pigeon peas (Sekhona *et al*., 2018). The study also noticed that the long-durations varieties with higher biomass production resulted in a low harvest index across all locations. The higher HI in Komboa (short-duration type) might have partially contributed to higher grain yield production The results contradict the finding of Hogh-Jensen *et al*. (2007), who found a low harvest index in short-duration types. The variations in harvest index among pigeon pea varieties might be due to genotypic makeup amongst varieties. The increase in temperatures and moisture stress decreased grain yields of pigeon peas. This was evident at Ofcolaco and resulted in a lower harvest index as compared to Zoeknog. The effect of moisture stress and temperatures on the harvest index was also observed by Asefa (2019). The higher harvest index at Ofcolaco compared to Zoeknog was because of differences in climatic and soil conditions. Similar observations were also reported by Abdalla *et al*. (2015), who found a reduced harvest index in faba beans due to climatic conditions.

4.4.17 Effect of P fertilizer on harvest index

Additional application of P fertilizer did not increase the pigeon pea harvest index, though at Zoeknog a slight increase was observed but was found not significant. However, the following scientists found the application of P fertilizer did not affect harvest index: Hogh-Jensen *et al.* (2007) in pigeon peas; Hussain *et al*. (2020) in rice. Other scientists also reported an increase in harvest index due to P fertilizer application at 30 kg ha^{-1} in pigeon peas under intercropping (Babu *et al.* 2014.), ranging from 24.33% to 25.57 %. Kaur *et al*. (2017) reported an increase in harvest index of pigeon pea that ranged from 23.3% to 26.02% with an added 400 kg of lime. The current study recorded a 27.23% to 33.97% harvest index with 60 kg ha^{-1} of P fertilizer application at Ofcolaco and Zoeknog. Harvest index was higher with 30.64% in unfertilized control treatments at Ofcolaco. The current study found the application of P fertilizer at 60 kg ha^{-1} reduced the harvest index of pigeon pea varieties during the first harvest at Ofcolaco.

4.4.18 Correlations between pigeon pea grain production, phenotypic and yield component variables

Correlation analysis determines the mutual relationship between several agricultural variables. The current study showed a substantial positive association between grain yield and the number of days to 50% flowering, with r = -0.777*, r = -0.717*, and r = 0.049*, with days to maturity r = -0.0819ns, r = -0.731*, and r = -0.807* at Ofcolaco (1st and 2nd harvest periods) and Zoeknog, respectively. Kandarka *et al*. (2020) identified a weak negative relationship between pigeon grain yield and days to 50% flowering (r =-0.024) and days to maturity (r =-0.135). The current study findings were that number of days to 50% flowering of pigeon pea correlated with days to maturity at Ofcolaco in both harvest periods (r = 0.953** and 0.974**) and reported r = 0.802**. Similar findings were also reported by Kandarka *et al*., (2020) Weak strong relationships were reported at Zoeknog, which could be due to the two locations' different climatic circumstances. Several scientists (Padi, 2003; Bal *et al*., 2018; Chandra *et al*., 2020) agreed with the current findings that grain production had a strong positive relationship with the number of pod plant^{-1}, pod yield (kg ha^{-1}), and 100 seed weight (g). The study also showed a weak positive association between the number of seeds per plant and pod yield (kg ha^{-1}) and 100 seed weight (g).

4.5 CONCLUSION

Pigeon pea biomass production, phosphorous uptake, and grain yield production differed among the pigeon pea varieties, P fertilizer application rates, and locations. The study found that Komboa produced the lowest shoot biomass with a thin stem diameter and short plant height at both locations. The study found that shoot biomass production in Komboa did not attribute to higher grain yield production. Being, the highest grain yield and was consistent in both harvest periods and locations. The high chlorophyll content might have resulted in higher pod production, 100 seed weight, and total grain yield production in Komboa. The higher grain yield in Komboa could partially be attributed to higher HI. The lower P yield in plant tissue and PRE might have contributed to lower shoot biomass and did not attribute to grain yield production. The study results also showed that the duration of a pigeon pea variety's flowering and maturing depends on the genetic trait of the variety and agro-ecological conditions. The study found Komboa a short-duration type as it flowered and reached maturity within 150 DAP and was the earliest among varieties. The variety is less sensitive to photoperiod, and flowers mature during the summer season (Kimani, 2001). It can be grown in areas where water is not a challenge because it matures earlier to escape drought in winter periods. The high grain yield, yield components, and harvest index recorded in the study show that the variety has high grain yield genetic traits. This variety is suitable for farmers who want to invest and produce grain yield production for income generation.

Ilonga 14-M2 and local, are long-duration types with erect plant branches. The study found that the variety outperformed all other varieties with respect to biomass production, stem diameter, and plant height. The vegetative and reproductive stages are in the summer and winter periods, meaning the reproductive coincides with low rainfall during the winter seasons. This might be the reason that these varieties produced lower grain yields. The low chlorophyll content and lower pod plant^{-1}, seed pod$^{-1,}$ and 100 seed weight might have contributed to lower grain yield production. The higher shoot biomass recorded might cause by its long duration period to flower and mature as it takes 190 DAP. Being photosensitive (Matthews and Saxena, 2001a), the varieties need short days to initiate flowers. The higher P yield in plant tissue and high PRE prove that the variety had genetic traits that enabled the plant to utilize deep water and inorganic P in the soils, and the higher P yield and PRE have not contributed to grain yield production. Moreover, the high shoot biomass might be partially, and lower grain yield production might have partially contributed to lower HI. The long-duration types are characterized by high fodder production genotype traits. The study concluded that this variety is best suited in dry areas of Limpopo Province as it is characterized by drought conditions. With high biomass production, the variety is good for fodder production and can be used by livestock farmers as a supplement during dry conditions.

The Tumia variety is a medium maturing type, most being the second or the third in biomass, stem diameter growth, and plant height. The variety is photosensitive and flowers mature during dry periods. However, it had higher grain yield, yield components, and harvest index compared to Ilonga 14-M2 and local varieties but lower compared with Komboa. The present study found Tumia as an intermediate and dual-purpose variety as it has higher shoot biomass and grain yield. Farmers who are interested in both fodder and grain could use this variety.

The study also revealed that pigeon pea varieties differ in their ability to utilize P fertilizers for improved crop productivity. Additional application of P fertilizer at 60 kg ha^{-1} increased shoot biomass, chlorophyll content, harvest index, and PRE. The following measured parameters such as stem growth, plant height, P yield, total grain yields, and their components were found not to respond to increased application of P fertilizer and its interaction with V x P. These increases depend on the growth period, variety of traits, locality, climatic conditions, soil type, and agronomic management practices. PRE is important because it provides a source of fertilizer and this might help smallholder farmers to reduce the cost of P fertilizers and also increase crop yields which contribute to food security. Positive correlations between grain yield and yield components show that increased grain yield is attributed to increased total grain yield.

Chapter 5: DROUGHT TOLERANCE ATTRIBUTES FOR PIGEON PEA [*CAJANUS CAJAN* (L.) MILLSPAUGH] VARIETIES AND P-FERTILIZERS THROUGH ROOTS BIOMASS PRODUCTION, STOMATAL CONDUCTANCE, AND WATER USE EFFICIENCY IN DIVERSE AGRO-ECOLOGICAL ZONES

ABSTRACT

The changes in rainfall and temperatures due to climate change threaten food security and the livelihoods of smallholder farmers in South Africa. Experimental trials were conducted at Ofcolaco and Zoeknog to evaluate pigeon pea varieties and P-fertilizer applications as a management technique for drought tolerance through water use efficiency (WUE), stomatal conductance, and root biomass production of pigeon peas. The trials were laid out as a randomized complete block design (RCBD) in a 4 × 2 factorial arrangements with three replications. The two treatment factors were four pigeon pea varieties, namely Komboa; Tumia; Ilonga 14-M2; local landrace, and two levels of P-fertilizers at 0 kg and 60 kg P ha^{-1}. The experiment was conducted for two continuous years which the plants experience drought and high evapotranspiration during the autumn and winter months.

Pigeon pea Ilonga 14-M2 produced the highest root biomass with 3185 and 3867 kg ha^{-1} at Ofcolaco and Zoeknog, respectively. Gravimetric moisture content in pigeon pea varieties varied significantly and ranged from 18 to 20% and 16 to 19%, at Ofcolaco and Zoeknog, respectively. Komboa attained the highest photosynthetic, transpiration rates, whereas Ilonga 14-M2 had the lowest. However, P-fertilizer application rates and the interaction were found to influence stomatal conductance only at Ofcolaco. Komboa variety had the highest intercellular CO_2 concentration with 287.06 µmol mol^{-1}. However, at Zoeknog Komboa recorded 194.42 µmol mol^{-1}. Application of P-fertilizer at 60 kg ha^{-1} significantly influenced intercellular CO_2 concentration only at Zoeknog. Komboa had higher intrinsic WUE at both locations whereas instantaneous WUE was higher in Ilonga 14-M2 at both locations. P-fertilizer application had a positive impact on instantaneous WUE but did not show in intrinsic WUE.

The study concluded that root biomass, photosynthetic rates, transpiration rate, stomatal conductance, intercellular CO_2 concentrations, instantaneous and intrinsic WUE differ across a variety and locations. Increased P-fertilizer application at 60 kg ha^{-1} improved plants to tolerate drought conditions and long-duration types responded positively.

Keywords: Leaf gaseous exchange, pigeon pea varieties, phosphorus fertilizer, root length, root biomass, water use efficiency

5.1 INTRODUCTION

Southern Africa is an arid and semi-arid environment and it is characterized by low and erratic rainfall with high temperatures. The change in climatic conditions has a major impact on rainfed crops, including pigeon peas (Basu and Bandyopadhyay, 2009). The pigeon pea (*Cajanus cajan* [L.] Millsp.) is a member of the family Fabaceae and one of the major legume crops of the tropics and subtropics. The crop has several attributes that make it valuable as either a production or rotation crop. Some of the benefits of incorporating pigeon peas into a cropping system include their ability to act as a soil fertility enhancer, fix nitrogen (Tairo and Ndakidemi 2013), and high drought tolerance (Odeny, 2007). Pigeon pea is a multipurpose leguminous crop and is known to be drought-tolerant (Odeny 2007). Pigeon peas are grown under dryland conditions by smallholder farmers.

Water availability to crops is important because it influences growth in all crop stages (vegetative and reproductive). According to a study reported by DAFF (2019), several crops grow well in an environment with rainfall ranging from 400 to 750 mm $annum^{-1}$ in South Africa. The same author also stressed that crops prefer moist soil conditions for the first two months and drier conditions during flowering and harvesting. Water deficits have a negative effect on pigeon production, and it also depends on the stage of crop development during which the stress occurs (Choudhary *et al*., 2011). Improvements in varieties of pigeon peas have been evaluated for drought-tolerant traits (Uddin *et al*., 2013; Suresh *et al*., 2015). Root length, root biomass, and root-shoot ratio were used to select the most promising genotype under dry conditions. The impact of physiological processes affecting pigeon pea productivity has not been widely studied in South Africa.

Leaf photosynthesis is an essential biological process that influences plant growth and production (Wilson *et al*., 2012). In the context of climate change, simulation of the consequences of drought on crop plants is needed to select more efficient and water-serving crops because drought stress has a negative impact on the photosynthetic rate in plants (Onyia and Herzog, 2004). Several researchers reported that when CO_2 exchange is reduced, the photosynthetic rate decreases, resulting in less assimilate production for plant growth and grain yield (Liu *et al*., 2014; Ayalew *et al*., 2022). Phosphorus (P) is one of the limiting minerals in smallholder farming systems. Limited P in soil depressed the amount and activity of RuBisco and decrease CO_2 assimilation capacity (Xin *et al*., 2006). The variations in leaf gaseous exchange differ from one species to the other. According to Kleimert *et al*. (2014), transpiration and photosynthetic rates are sensitive to low P supply and the uptake of P depends on the root systems (Pang *et al*., 2018) and the variety (Fujita *et al*., 2004).

Water use efficiency (WUE) is the physiological mechanism that enables plants to withstand low soil moisture content and perform well under water stress. Stomata play an important role in plant adaptation to changing environmental conditions as they control both water losses and CO_2 uptake in plants. Aliniaeifard *et al*. (2014). Stomatal conductance increases when light intensity increases and decreases as light intensity decreases (Zhang *et al*., 2019). The variation in water use efficiency among species might be due to the variation in genetic traits of the species and their interaction with the environment. According to Munjonji *et al*. (2018), cowpea genotypes vary in stomatal conductance under drought conditions and the variation is more severe at the vegetative growth stage. However, such information on the response of stomatal conductance, transpiration, and photosynthesis influenced by pigeon pea varieties and P fertilizer application under rainfed conditions is still limited in South Africa.

Several researchers have reported that rain-fed pigeon peas produce reasonable yields even in severe drought conditions in Southern and Eastern Africa (Matthews and Saxena, 2000; Saxena *et al*., 2010). South Africa's climate is dominated by diverse and unrealistic climatic conditions. Therefore, it is important to document the performance of pigeon pea varieties and P fertilizer application under such prevailing climatic conditions. Four pigeon pea varieties and two rates of P fertilizer application were evaluated for drought tolerance on root biomass production, root length, root-shoot ratio, leaf gaseous exchange, and water use efficiency under rainfed conditions in a smallholder farming system.

5.2 MATERIALS AND METHODS

5.2.1 Study Area

Information on the study areas, field management, experimental designs, and soil sampling procedures, are the same as described in Chapter 4 under material and methods (4.1.1 to 4.1.4).

5.2.2 Roots biomass production

Plant root samples from each experimental treatment were harvested using a destructive method. Three plants from the border rows in each plot were manually dug carefully to the end of the roots using a pick axe. Root samples were collected at intervals at both experimental sites. Soils were dug and roots were collected from 0 to 100 cm during the first growing season at 60, 90, 120, 150, and 180 days after planting (DAP). During the second growing period, samples were taken at 240, 310, 410, 500, and 560 DAP from 0 to 80 cm depth, depending on the root growth. Harvested samples were separated into above and below-ground samples by cutting at the base of the stem where roots start to grow. Below-ground samples in the study include surface and deep roots. Soils from root samples were carefully removed by shaking the samples. Wet weight was taken immediately after packing using a chargeable Micro CW weighing scale (g). Sub-samples from the three root samples in each treatment were collected and weighed. Samples were oven-dried to a constant weight at 65°C for three days to determine their dry weight. The dry weight was used to determine the root biomass (kg ha^{-1})

5.2.3 Determination of pigeon pea root length

At each below-ground sampling, roots were measured from the base of the stem where they started to grow to the root tip. Measurements were taken from the three root samples in the field using a hand measuring tape (cm) in each treatment at the two experimental sites. The sampling depth was from 0 cm up to 150 cm at both locations depending on the root depth and soil conditions.

5.2.4 Determination of the root-shoot ratio

Total below (root) biomass divided by the aboveground (shoot) biomass in each treatment. The root-shoot ratio of each treatment was calculated for the two experimental sites.

5.2.5 Measurements of leaf gaseous exchange

Leaf gas exchange measurements for stomatal conductance (gs) (mmol $m^{-2}s^{-1}$), photosynthetic rate (A) (µmol $m^{-2}s^{-1}$) transpiration (E) (mmol m^{-2} s^{-1}), and intercellular CO_2 concentration (Ci) (µmol mol^{-1}) were measured using a portable LCi–SD ultra-compact photosynthesis system (ADC Bio Scientific, Hoddesdon, UK). Measurements were taken on the three fully expanded leaves from the middle rows in a 5.4 m^2 net plot area per experimental unit. Measurements were taken during a clear sunny day between 10H00 and 14H00 at 240, 270, 310, 360, 390, 410, 440, and 500 DAP in all experimental sites. Adjustments and values of the instrument were recorded and maintained during its operations. Leaf gaseous exchange measurements were recorded during the plant regrowth stages in a monthly interval from 240 to 500 days after planting (DAP) due to COVID-19 regulations (restriction of movements).

5.2.6. Determination of Water-use efficiency (WUE)

At the leaf level, $_{intrinsic}$ and $_{instantaneous}$ WUE was calculated using an equation described by Munjonji *et al.* (2018) equation:

$_{Intrinsic}$ WUE = A/gs, where A is the photosynthetic rate and gs is the stomatal conductance measured.

$_{Instantaneous}$ WUE = A/E, where A is the photosynthetic rate and E is the transpiration rate. The data for the A, gs, and E in the equation above was recorded from the measurements of leaf gaseous exchange using a portable LCi–SD ultra-compact photosynthesis system (ADC Bio Scientific, Hoddesdon, UK).

5.2.7 Gravimetric moisture content (%)

Soil moisture content in each experimental unit for the two experimental sites was measured using the gravimetric method. Soil samples were collected from 0 to 60 cm depth in each treatment using a soil augur. Samples were collected from the middle rows in a 5.4 m^2 net plot area per experimental unit at 240, 270, 310, 360, 390, 410, 440, and 500 DAP. Soils were carefully dug and mixed thoroughly before being packed in a plastic zip bag to maintain moisture content. Wet weight was measured using a chargeable Micro CW weighing scale (g) and immediately packed in brown bags, labeled, and placed in an oven at 105˚C for 24 hours until a constant dry weight was obtained. The gravimetric soil moisture percentage per treatment at both experimental sites was determined and calculated using the equation below (Scott, 2000):

soil water (%) = (wet soil weight – dry soil weight) x 100 ÷ dry soil weight

5.2.8 Statistical analysis and interpretation

Data were subjected to the analyses of variance (ANOVA) using a statistical package of SAS Institute, SAS@ 9.4 Language (SAS,2016) to calculate the effect of variety (V) and P fertilizer application rates and their interaction effect (V x P) on the measured drought-tolerant parameters. The least significant difference (LSD) was also used to separate the means at probability levels of $p<0.05$, $p<0.01$, and $p<0.001$, only where a significant treatment effect was observed (Gomez and Gomez, 1984). Correlation and regression analyses were performed in Microsoft Excel to assess potential relationships between root biomass and growth stage, leaf gaseous exchange parameters and growth stage, leaf transpiration rate with photosynthesis, stomatal conductance, and intercellular CO_2 concentration.

5.3 RESULTS

5.3.1 Rainfall, evapotranspiration, averaged maximum and minimum temperatures (°C)

For the two experimental sites, rainfall (mm) data, evapotranspiration (mm), and average monthly maximum and minimum temperatures (°C) during the 2019 November to July 2021 growing seasons are presented in Figure 5.1 and Table 5.1 below.

The total rainfall (mm) received during the two growing seasons was 1249.15 and 1760.76 (mm) annum^{-1} at Ofcolaco and Zoeknog, respectively. The climatic information revealed that rainfall at both locations was higher from November 2020 until March 2021, but diminished from April to October. The data obtained also showed that at both locations, low and very low rainfall was recorded between May and July in both years when the medium and long-duration pigeon peas are at reproductive stages. The short-duration types reach maturity in May. The evapotranspiration at both locations was relatively higher than the rainfall received during the 2019/20 to 2020/21 growing period. The climatic data also revealed that evapotranspiration increases in summer periods and decreases during winter periods, following the same trend as rainfall at Ofcolaco and Zoeknog.

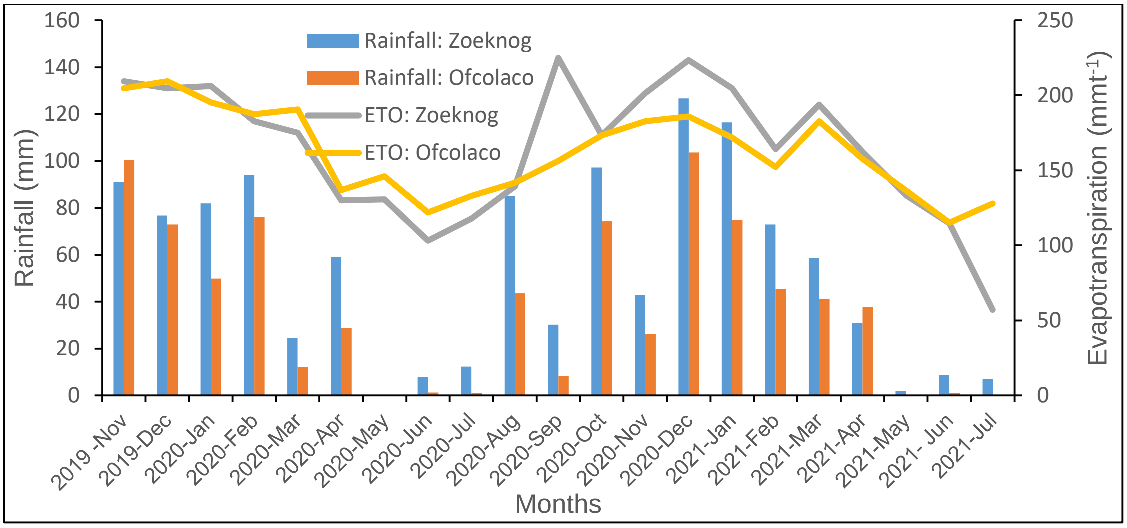


Figure 5.1: Weather data recorded during 2019/20 and 2020/21 growing seasons at Ofcolaco and Zoeknog experimental trials (ETO= evapotranspiration).

Table 5.1 displays the average monthly maximum and minimum temperatures from November 2019 to July 2021 at the two experimental locations. The temperatures (°C) fluctuated between the two locations; at Ofcolaco the monthly maximum temperatures were higher and Zoeknog had the lowest temperatures. These variations in temperatures affect pigeon pea growth, especially at the flowering stage. During the winter season (May to July), the minimum monthly temperatures at Ofcolaco and Zoeknog were 14.2, 11.3, 11.1°C, and 9, 5.6, and 4.7°C, respectively. The climatic information shows that winters at Zoeknog are very cold and summers at Ofcolaco are warmer. Maximum average temperatures reach up to 32.8°C during the summer season at Ofcolaco.

Table 5.1: Monthly maximum and minimum temperatures collected during growing seasons at Ofcolaco and Zoeknog

Months	Maximum Temperature Ofcolaco	Minimum Temperature Ofcolaco	Maximum Temperature Zoeknog	Minimum Temperature Zoeknog
19-Nov	33.5	20.4	31.4	17.6
19-Dec	32.6	20.6	30.5	17.4
20-Jan	32.8	21.5	30.5	19.4
20-Feb	32.1	20.6	30.5	15.3
20-Mar	31.9	19.5	30.1	16.5
20-Apr	29.4	17.5	27.2	15.2
20-May	29.3	14.2	26.2	9.00
20-Jun	26.3	11.3	24.2	5.6
20-Jul	26.5	11.1	24.5	4.7
20-Aug	28.2	13.4	26.2	7.9
20-Sep	29.2	15.9	21.3	10.8
20-Oct	29.2	17.6	29	14.5
20-Nov	32.5	19.8	31.3	17.2
20-Dec	32.2	21.4	31.1	19.2
21-Jan	32.5	21.3	30.8	19.9
21-Feb	31.3	20.7	29.3	19.3
21-Mar	32.3	19.8	30.2	17.3
21-Apr	31.5	16.5	29.3	12.8
21-May	29.6	13.8	27.3	8.89
21-Jun	27.5	11.5	25.5	6.16
21-Jul	26.1	10.5	26	6.97

5.1.2 Pigeon pea root biomass production (kg ha^{-1})

Root biomass significantly varied among varieties at both locations. However, P fertilizer application on root biomass was significant at Ofcolaco from 150 to 500 DAP, whereas at Zoeknog the significant variations were only detected at 500 DAP. The interaction effect of V x P had no influence on root biomass production at both locations.

Ofcolaco:

Ilonga 14-M2 produced the highest root biomass followed by local varieties at all growth stages (Figure 5.2). The lowest root biomass in all the sampling dates was recorded in Komboa. Root biomass production at 180 DAP was 1240, 1103, 1199, and 1559 kg ha^{-1} for pigeon pea Komboa, Tumia, Ilonga 14-M2, and local varieties, respectively. At 560 DAP, root biomass was 2250; 4367, 7315, and 5320 kg ha^{-1} for Komboa, Tumia, Ilonga 14-M2, and the local landrace, respectively.

Zoeknog:

Pigeon pea varieties followed the same trend as at Ofcolaco. (Figure 5.2). At 180 and 560 DAP, the Komboa variety produced 28 and 75% less root biomass compared with Ilonga 14-M2 at the same sampling dates, respectively.

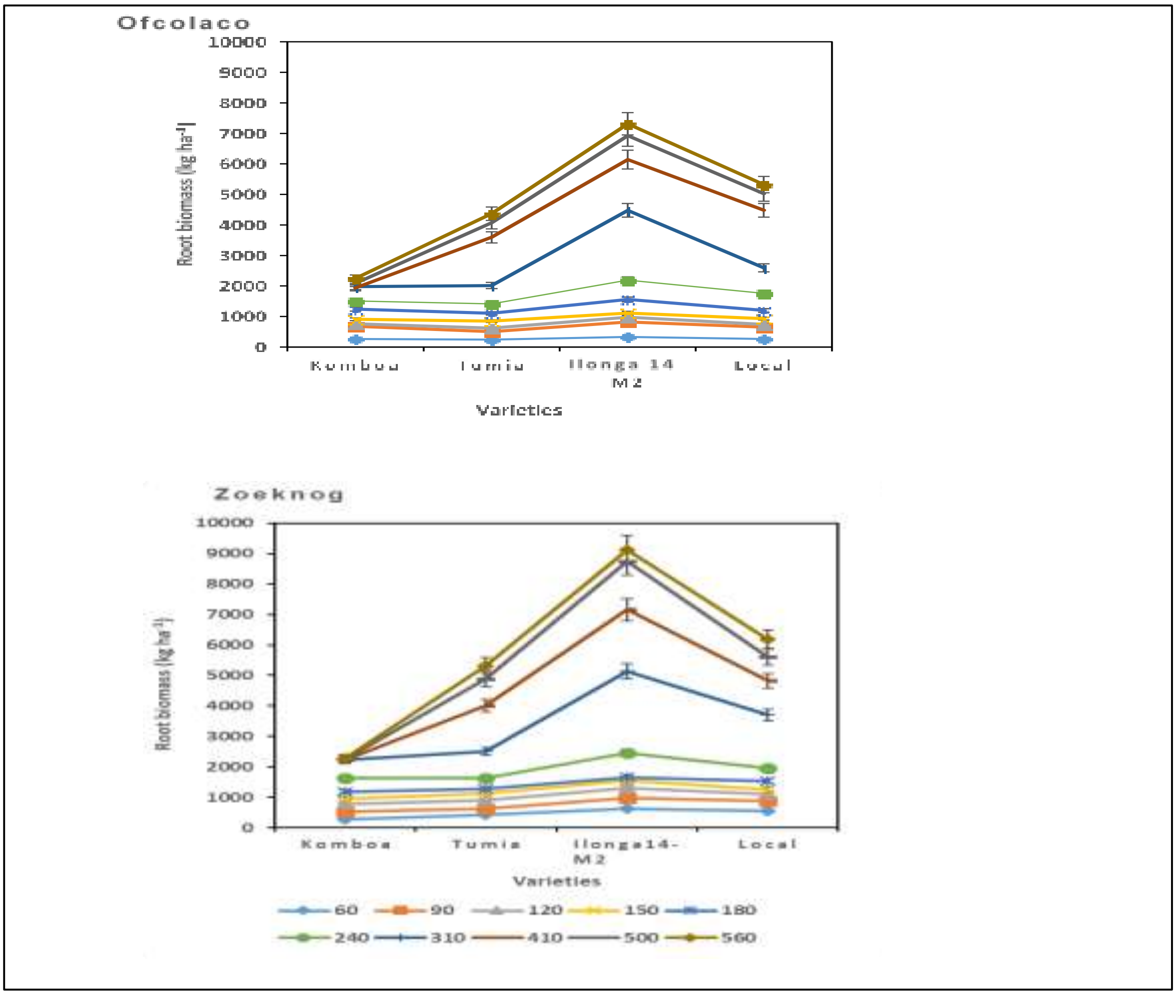


Figure 5.2: Root biomass (kg ha^{-1}) of pigeon pea at different growth stages during 2019/ 2020 and 2020/2021 growing seasons at Ofcolaco and Zoeknog.

The effect of P fertilizer application and growth stages (P x DAP) in root biomass production (kg ha^{-1})

Ofcolaco:

The current study found that root biomass production was influenced by P fertilizer application at a specific growth stage. The variations effect was at 150 DAP until 500 DAP only, (Figure 5.3). Other days did not show any significant variations in root biomass production. Application of P fertilizer at 60 kg ha^{-1} increased root biomass by 8% relative to 0 kg ha^{-1} in 410 DAP.

Zoeknog:

The effect of P fertilizer rates on root biomass production was significant only at 500 DAP ($p<0.0358$). Application of P fertilizer at 60 kg ha^{-1} increased root biomass and it was increased with an increase in plant growth (Figure 5.3).

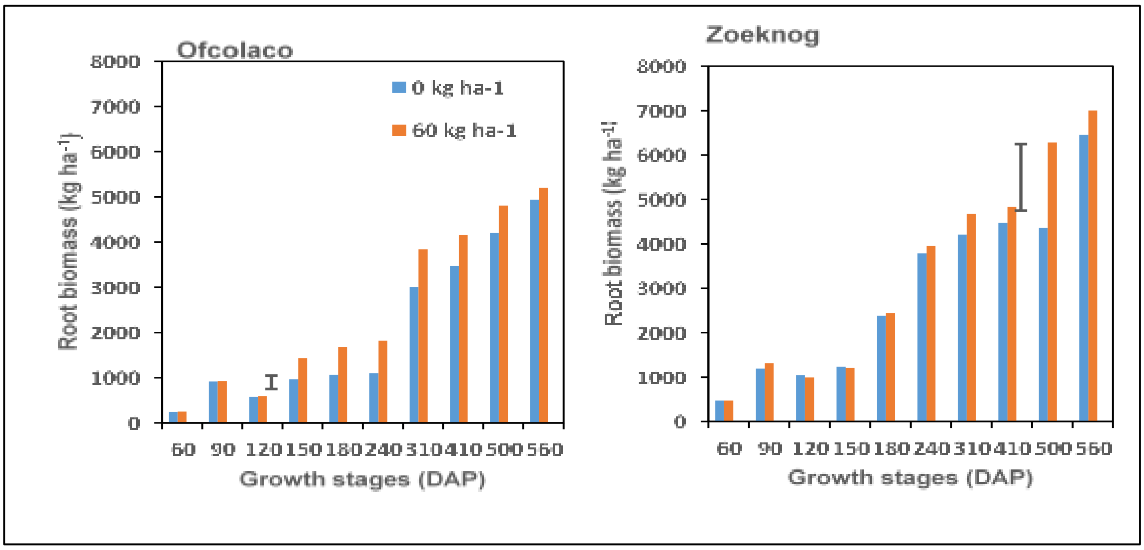


Figure 5.3: Root biomass (kg ha^{-1}) influenced by P fertilizer application at different growth stages during the 2019/2020 and 2020/2021 growing seasons at Ofcolaco and Zoeknog (Vertical bars represent LSD value)

5.1.3 Pigeon pea root growth

Root length varied significantly among pigeon pea varieties at the two locations. Phosphorus fertilizer application and their interaction effects of V x P did not influence pigeon pea root growth at both locations. Significant variations were only observed in the interaction effects between P and growth stages (P x DAP) but at a specific growth period at Ofcolaco and Zoeknog.

Varietal effect on root length

Ofcolaco:

The root length of all pigeon pea varieties increased with an increase in plant growth (Figure 5.4). The longest root length among pigeon pea varieties was attained by Ilonga 14-M2, whereas Komboa had the shortest roots, and this was consistent throughout the growth periods. At 560 DAP, root length was 62.80 cm, 73.17 cm, 82.14 cm, and 90 cm for Komboa, Tumia, Ilonga 14-M2, and the local landrace. Komboa produced the shortest root length among pigeon pea varieties throughout the sampling dates.

Zoeknog:

The root length of pigeon pea varieties followed the same trend as at Ofcolaco. (Figure 5.4). At 560 DAP, pigeon pea Ilonga 14-M2 had a root length of 142.30 cm which was double, compared to Komboa which attained a root length of 65.47 cm during the second harvest.

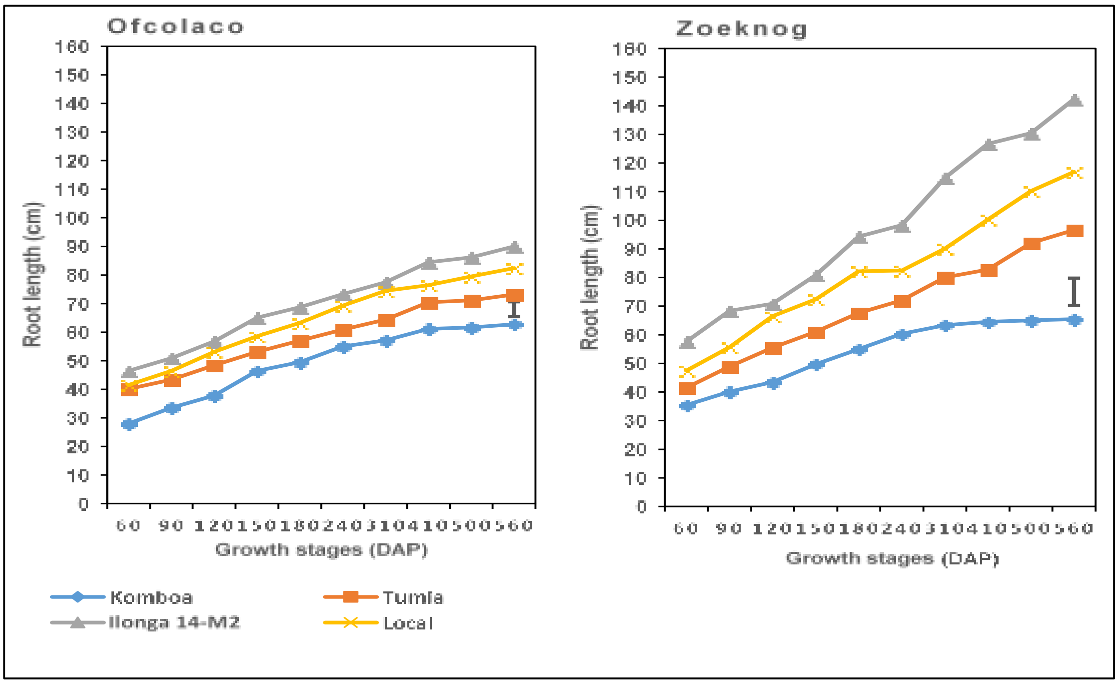


Figure 5.4: Root length (cm) at different growth stages during 2019/20 and 2020/21 growing seasons growing periods at Ofcolaco and Zoeknog (Vertical bars represent LSD value).

Interaction effects of P- fertilizer application and growth periods (P x DAP) on pigeon pea root length

The application of P fertilizer significantly increased the root growth of pigeon pea varieties at a specific growth period. At Ofcolaco, a significant variation in root length due to the application of P fertilizer was observed at 560 DAP ($p<0.069$). Whereas at Zoeknog, significant variations were only detected at 180 and 560 DAP

Ofcolaco:

The root length of pigeon peas was longer in the control treatments, where P fertilizer was not applied (Figure 5.5). The reduction of root growth due to increased P fertilizer application of 60 kg ha^{-1} started at 180, 240 310, 410, and 500 DAP. Unfertilized P fertilizer treatments (0 kg ha^{-1}) produced longer root and was only significant during the physiological maturity stage at 560 DAP.

Zoeknog:

The application of P fertilizer at 60 kg ha^{-1} reduced pigeon pea root growth during the regrowth stages from 240 to 510 DAP (Figure 5.5). Across all growth stages, significant differences were only observed at both harvest periods (180 and 560 DAP). Application of P fertilizer at 60 kg ha^{-1} influenced root growth from 120, 150, and 180 DAP, but it was significant only at 180 DAP.

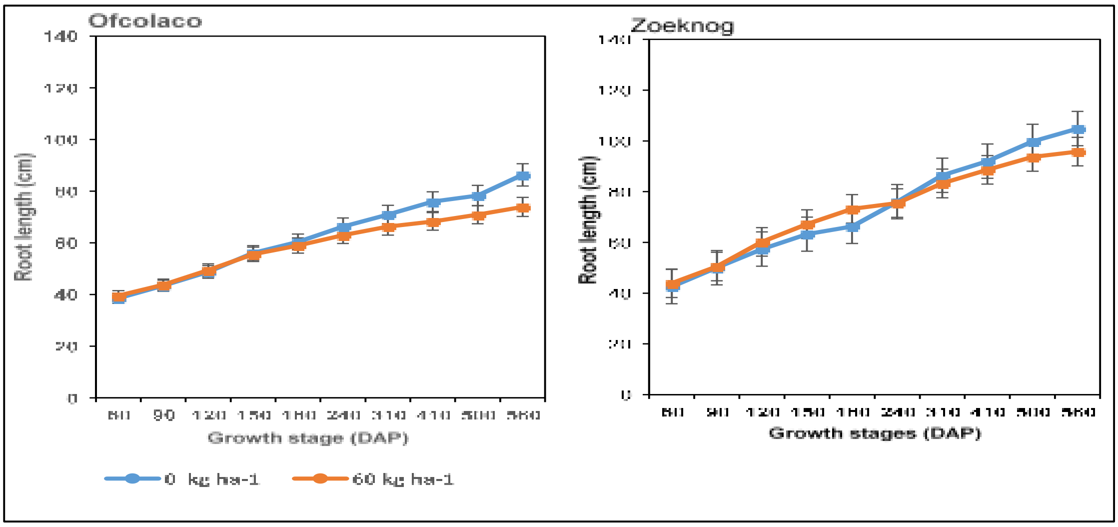


Figure 5.5: Effect of P fertilizer application and growth periods on pigeon pea root length (cm) during 2019/20 and 2020/21 growing seasons at Ofcolaco and Zoeknog

5.1.4 Root-shoot ratios

Pigeon pea varieties at different growth periods varied in root-shoot ratio. Root-shoot biomass was not significantly influenced by P fertilizer application at both locations. However, the analysis results showed significant variations in the root-shoot ratio affected by the interaction of P and growth stages (DAP) at both locations. The interaction effect of V x P in the root-shoot ratio did not differ significantly.

Ofcolaco:

The root-shoot ratio differed across all growth stages among varieties. Tumia had the lowest root-shoot ratio of 0.20 across all growth stages (Table 5.2). The root-shoot ratio in Ilonga 14-M2 variety was 0.26 and 0.08 at 60 and 560 DAP, respectively. The highest root-shoot ratio amongst pigeon pea varieties was observed in Komboa, with an average of 0.26 across all sampling dates. Ilonga 14-M2 had a root-shoot ratio of 0.22 across all sampling dates and the lowest was recorded at 560 DAP.

Zoeknog:

The root-shoot ratio did not follow the same trend as at Ofcolaco. Ilonga 14-M2 had the highest root-shoot ratio with 0.33, followed by the local landrace, 0.28 (Table 5.2) on all sampling dates. Tumia and Komboa had the lowest root-shoot ratio among the four varieties.

Table 5.2: Root-shoot ratio at different growth stages during 2019/20 and 2020/21 growing seasons at Ofcolaco and Zoeknog

	Growth stages	Komboa	Tumia	Ilonga 14-M2	Local	C.V (%)	P-value	Significance
Ofcolaco								
	60	0.29b	0.23a	0.26b	0.23b	10.61	0.003	**
	120	0.23c	0.16c	0.17c	0.18b	11.75	0.001	***
	180	0.39a	0.20ab	0.21b	0.24b	12.46	0.030	*
	240	0.37a	0.21b	0.25b	0.26a	13.61	0.045	*
	410	0.20c	0.26a	0.39 a	0.31a	15.65	0.007	**
	560	0.05d	0.05d	0.08d	0.06c	17.33	0.082	ns
Significance		**	**	**	**			
Zoeknog								
	60	0.27a	0.20b	0.35b	0.44a	25.96	0.022	*
	120	0.10c	0.10c	0.22c	0.24c	14.27	0.032	*
	180	0.24b	0.22ab	0.23c	0.23c	11.83	0.009	**
	240	0.27a	0.25ab	0.24c	0.24c	14.36	0.026	*
	410	0.25a	0.28a	0.46a	0.32b	15.47	0.003	**
	560	0.23b	0.30a	0.47a	0.18d	11.07	0.001	***
Significance		**	*	*	**			

DAP= days after planting, RSR= root-shoot ratio, CV%= coefficient variation percentage, p-value=probability, * significant at p<0.05, **significant at p<0.01, *** highly significant at p<0.001 and ns = not significant at p<0.05

Phosphorus fertilizer application effect on root-shoot ratio

Figure 5.6 show the effects of P fertilizer application On the root-shoot ratio at different growth stages of pigeon pea at Ofcolaco and Zoeknog. Application P fertilizer and different growth stages of pigeon peas influenced the root-shoot ratio at a specific growth stage at Ofcolaco and Zoeknog.

Ofcolaco:

The root-shoot ratio was influenced by the application of P fertilizer at flowering ($p<0.023$) and physiological maturity ($p<0.034$) at 410 and 560 DAP (Figure 5.6). Unapplied P fertilizer control treatment at 0 kg ha^{-1} increased root-shoot ratio at flowering stages (310 and 410 DAP) and physiological maturity was increased by the application of P at 60 kg ha^{-1}.

Zoeknog:

Significant influence of P fertilizer on the root-shoot ratio was only detected from 150 DAP until 240 DAP (Figure 5.6). During the early growth stages (60, 90 DAP), unfertilized P fertilizer treatments had a higher root-shoot ratio than P fertilized treatments. At flowering and physiological maturity stages (310, 410, 500, and 560 DAP), increased application of P fertilizers did not increase the root-shoot ratio.

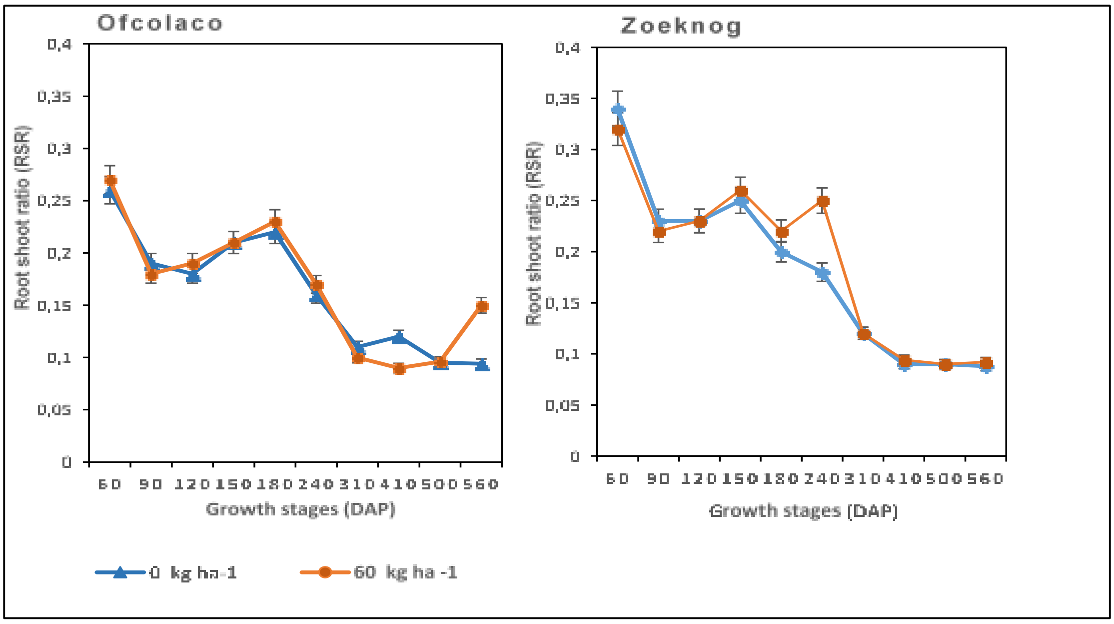


Figure 5.6: Effect of root-shoot ratio of pigeon pea influenced by P fertilizer over a growth period during 2019/20 and 2020/21 growing seasons at Ofcolaco and Zoeknog.

5.3.5 Effect of gravimetric soil moisture content

The influence of varieties on gravimetric soil moisture is presented in Figure 5.6. Gravimetric soil moisture differed significantly ($p<0.056$) among varieties and was only significant at Zoeknog. The study found gravimetric soil moisture was not affected by P fertilizer application rates. The interaction effects of V x P in gravimetric soil moisture did not show any significant differences at both locations. A significant difference was observed in the interaction of P x DAP ($P<0.036$) only at Ofcolaco.

Effect of gravimetric soil moisture in pigeon pea varieties

Ofcolaco:

There were no significant variations among pigeon pea varieties in gravimetric soil moisture content. Gravimetric soil moisture content remains similar in all pigeon pea varieties. However, the study recorded a higher percentage of gravimetric soil moisture ranging from 18 to 20% across all varieties (Figure 5.7). The similarities and a high percentage of gravimetric soil moisture revealed by the results might due to high pigeon pea growth during the early stages and high clay content (23%).

Zoeknog:

The study observed significant differences in gravimetric soil moisture among the four varieties. The local landrace had the highest gravimetric soil moisture, followed by Tumia, Ilonga 14–M2, and Komboa (Figure 5.7). Komboa recorded the minimum gravimetric soil moisture content. The measured gravimetric soil moisture ranged from 16.1 to 19.4% in all four pigeon pea varieties. The local landrace had increased gravimetric soil moisture by 2.2% relative to Komboa. Tumia and Ilonga had similar gravimetric soil moisture.

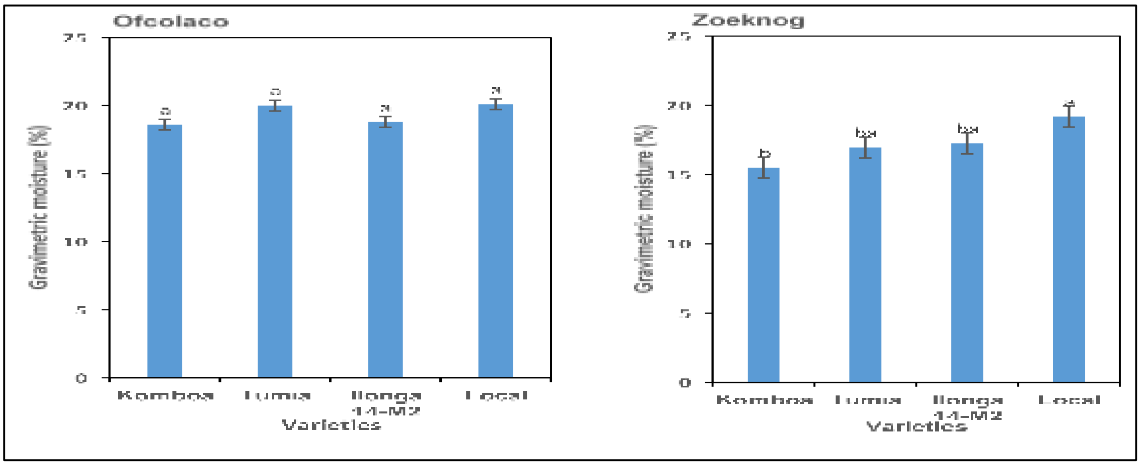


Figure 5.7: Gravimetric moisture(%) influence by pigeon pea variety at Ofcolaco and Zoeknog during the two growing seasons (Different letters mean significant differences whereas similar letters mean no significant differences).

The study observed significant differences (p<0.001) in gravimetric moisture influenced by sampling dates. Gravimetric soil moisture content was higher during rainy seasons in December, January, February, and March and low during winter dry periods and this differed in the locality (Figure 5.8). Unexpected, gravimetric soil moisture was lower in January at Ofcolaco whereas Zoeknog attained the highest soil moisture.

Ofcolaco: The highest gravimetric soil moisture attained in February 2021 was 31%. The study results show that gravimetric soil moisture content was lower during December, increased in January, and start to decrease in March (Figure

5.8). A significant decrease was recorded in June and July 2021. A strong relationship between gravimetric soil moisture and sampling dates (r=0.745) was also observed.

At Zoeknog, the highest gravimetric soil moisture 29.79% was recorded in January 2021, and the lowest, 8.44% and was in July when it is very dry with limited rains (Figure 5.8). The high gravimetric soil moisture coincided with high rainfall during December and January. A negative linear relationship was also found between gravimetric moisture content and growth periods (r= 0.694).

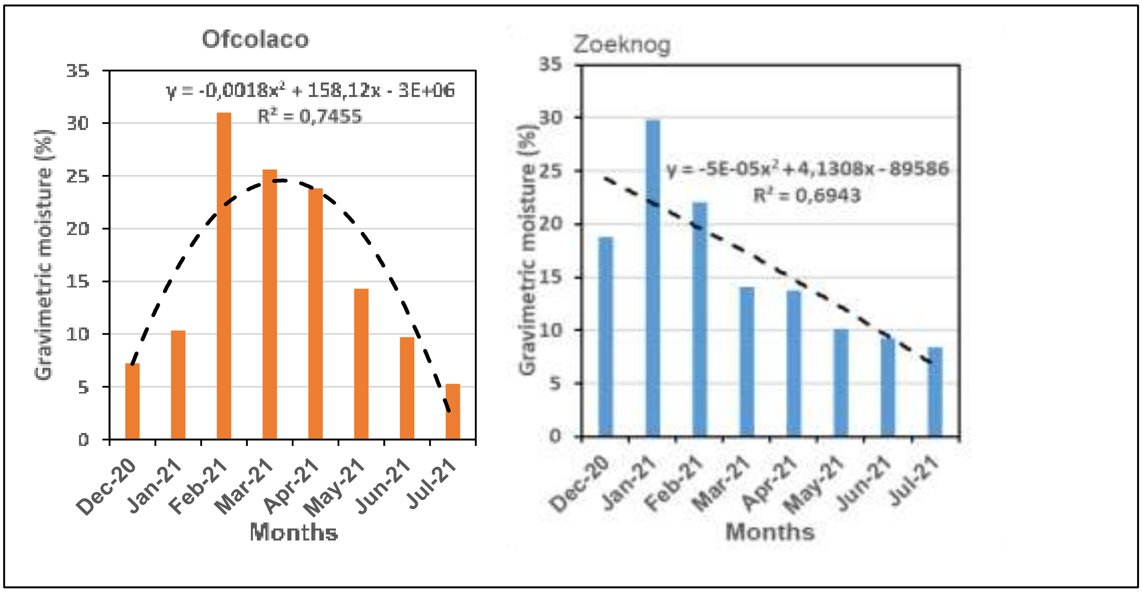


Figure 5.8: Gravimetric soil moisture (%) influenced by sampling stages during the regrowth periods at Ofcolaco and Zoeknog

The interaction effects of V x P and P x DAP dates on gravimetric soil moisture.

The interaction of V x P did not influence gravimetric soil moisture content at both locations. However, the study revealed that the interaction effect of P x DAP significantly increased gravimetric soil moisture and the differences were detectible only at Ofcolaco. Application of P fertilizer at 60 kg ha^{-1} increased gravimetric soil moisture content at 240, 310, 360, and 390 DAP (Table 5.3). The effect of P fertilizer application influenced by sampling dates in gravimetric soil moisture was also inconsistent throughout the growing season at both locations.

Table 5.3: Interaction effects of P-fertilizer x sampling dates on gravimetric soil moisture (%) during the regrowth periods at Ofcolaco and Zoeknog

		Gravimetric moisture									
		…………………………….. (%)……………….............................									
		Growth stages									
	P- fertilizer (kg ha^{-1})	240	270	310	360	390	410	440	500	P- value	Significance
Ofcolaco	0	6.6b	10.5a	25.7a	31.1a	23.4b	14.3a	9.7a	5.4a	P<0.036	*
	60	7.9a	10.2b	25.5b	31.2a	24.3a	14.2a	9.7a	5.1b		
Zoeknog	0	13.8a	31.9a	21.5a	20.4a	12.8a	13.4a	10.5a	8.8a	P<0.713	ns
	60	13.8a	27.2a	22.7a	15.7a	13.8a	12.7a	9.5a	9.1a		

(p-value= probability, ns = non-significant differences* =significant (p<0.05)

5.3.6 Effect on leaf gaseous exchange parameters

Due to COVID-19 restrictions, measures, and protocols, leaf gaseous exchange parameters were only measured during the regrowth period (second growing period). Most of the varieties were at a regrowth stage at 240 DAP. Measurements were carried out until the second harvest and collected once a month at both locations.

Varietal effect on leaf gaseous exchange

Photosynthetic rate (A)

The study observed no significant variations in varieties, P fertilizer application and interaction effects on photosynthetic rates at Ofcolaco. However, at Zoeknog, pigeon pea varieties, P fertilizer application, and the interaction of V x P were significant.

Ofcolaco:

Photosynthetic rates were equivalent among pigeon pea varieties (Figure 5.9) and with relatively low values.

Zoeknog:

The photosynthetic rate is demonstrated in Figure 5.9. Komboa had the highest photosynthetic rates, followed by Ilonga 14- M2 and Tumia, respectively. The photosynthetic rate in all varieties ranged from 39.06 to 26.39 (µmol $m^{-2}s^{-1}$) across all varieties. The photosynthetic rate of Ilonga 14-M2 was reduced by 23% relative to Komboa.

Transpiration rate (E)

Significant variations in pigeon pea varieties and P fertilizer application were only observed only at Zoeknog. At both locations, the interaction effect was not significant.

Ofcolaco:

Transpiration rate ranged from 2.93 to 3.31 (µmmol $m^{-2}s^{-1}$) across all varieties but overall, the study results indicated that pigeon pea varieties had similar transpiration rates.

Zoeknog:

Komboa had the highest transpiration rate with 8.7 (mmol $m^{-2}s^{-1}$) among varieties (Figure 5.9). The lowest transpiration rates were observed in Ilonga 14-M2 and the local pigeon pea varieties with 5.22 and 5.03 (mmol $m^{-2}s^{-1}$), respectively.

Stomatal conductance (gs)

The response of pigeon peas to stomatal conductance was similar in all varieties at both locations

Intercellular CO_2 concentration (ci)

Zoeknog:

Figure 5.9 shows the intercellular CO_2 concentration of pigeon pea varieties is presented. The maximum concentration of intercellular CO_2 was observed in Ilonga 14-M2, followed by Local, Tumia, and Komboa, respectively.

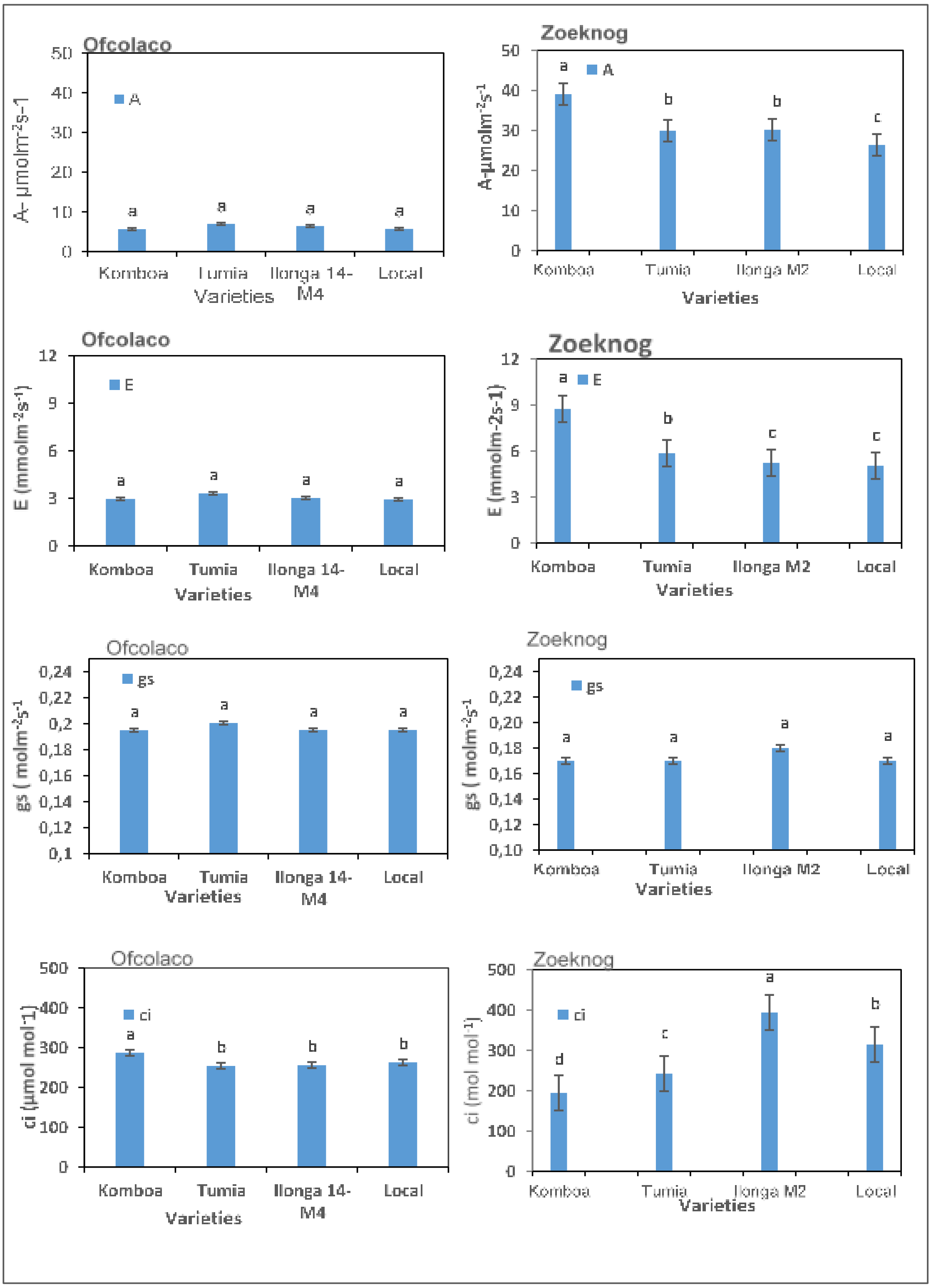


Figure 5.9: Mean of photosynthetic rate (A), transpiration (E), intercellular carbon concentration (ci), and stomatal conductance (gs) during the regrowth periods at Ofcolaco and Zoeknog (Different letters mean significant differences whereas similar letters mean no significant differences).

Response of leaf gaseous exchange parameters at different growth stages

Response of photosynthetic, transpiration rates, stomatal gaseous exchange, and intercellular CO_2 concentrations for the two locations at different growth stages

Photosynthetic rates

Ofcolaco:

Photosynthetic rates were 33.98, 30.96, and 32.70 (µmol $m^{-2}s^{-1}$) at 240 during the vegetative growth stage (240 DAP), at flowering (440 DAP), and pods setting the stage (500 DAP), respectively (Figure 5.10). A strong positive relationship (r = 0.696) was observed in photosynthetic rates influenced by different growth periods.

Zoeknog:

Photosynthetic rate followed the same pattern as in Ofcolaco, where it was higher during vegetative stages and decreased during reproductive stages (Figure 5.10). An increase in photosynthetic was observed during mid-summer at 310 DAP and winter periods at 410 and 440 DAP. The study observed that photosynthetic rates were higher during vegetative growth and lower during the reproductive stage. The study result showed a weak positive relationship between photosynthetic rate and growth stages ($r = 0.447^{ns}$).

Rates of transpiration

Ofcolaco:

Transpiration rates influenced by different growth periods are illustrated in Figure 5.10. The analyzed results revealed that transpiration rates and sampling dates have a weak correlation and r = 0.344.

Zoeknog:

Responses to transpiration rate were inconsistent but followed the same trend as at Ofcolaco. Significant variations were observed in the response of transpiration rates at different growth stages of pigeon peas (Figure 5.10).

Transpiration rates reached their highest at 240DAP and ranged from 8.33 to 3.31 (µmol m-^{2}s^{-1}). Low transpiration rates were observed during the reproductive stages of early-maturing pigeon peas at 390 DAP and remained low during winter periods at 440 and 500 DAP. The study found a positive relationship between transpiration rates and different growth periods (r= 0.537).

Intercellular CO^2 concentration

Ofcolaco:

Intercellular CO_2 concentration increased with an increase in growth of pigeon peas. The highest intercellular CO_2 concentration was 309. 04 (µmol mol^{-1}) and was attained at 500 DAP (Figure 5.10). The lowest was 170.63 (µmol mol^{-1}) recorded during the vegetative stage at 240 DAP. The study results showed a correlation between intercellular CO_2 concentration and growth stages was also positive (r= 0.872).

Zoeknog:

Intercellular CO_2 concentration ranged from 226.75 to 310.38 (µmol mol^{-1}). The highest intercellular CO_2 was observed during the plant regrowth period at 310 DAP and recorded at 334.71 (µmol mol^{-1}). At 390 DAP, attained the lowest with 226.75 (µmol mol^{-1}) when the short-duration type was in the reproductive stage. The study also revealed that the relationship between intercellular CO_2 and different growth stages had weak relationship (Figure 5.10). This was because intercellular CO_2 concentrations followed an inconsistent trend throughout the growing seasons.

Stomatal conductance (mol $m^{-2}s^{-1}$)

Ofcolaco:

The opening and closing of the stomata at all growth stages did not respond positively (Figure 5.10). The study also observed that the correlation between stomata rates and growth periods was very weak (r = 0.266). However, stomatal conductance recorded very low values and ranged from 0.1 to 0.04 (mol m^{-2}s^{-1}). The study also noticed that stomatal conductance was controlled at 390, 410, and 440 DAP, and most of the pigeon pea varieties were at flowering stages.

Zoeknog:

The study observed a strong relationship between stomatal conductance and growth stages and showed a strong positive relationship between stomatal conductance and growth periods (Figure 5.10). Stomatal conductance was higher during vegetative stages at 240 and 270 DAP, then decreased from 390 DAP. The lowest stomata opening and closing were attained at 390 DAP and was 0.04 (mol $m^{-2}s^{-1}$).

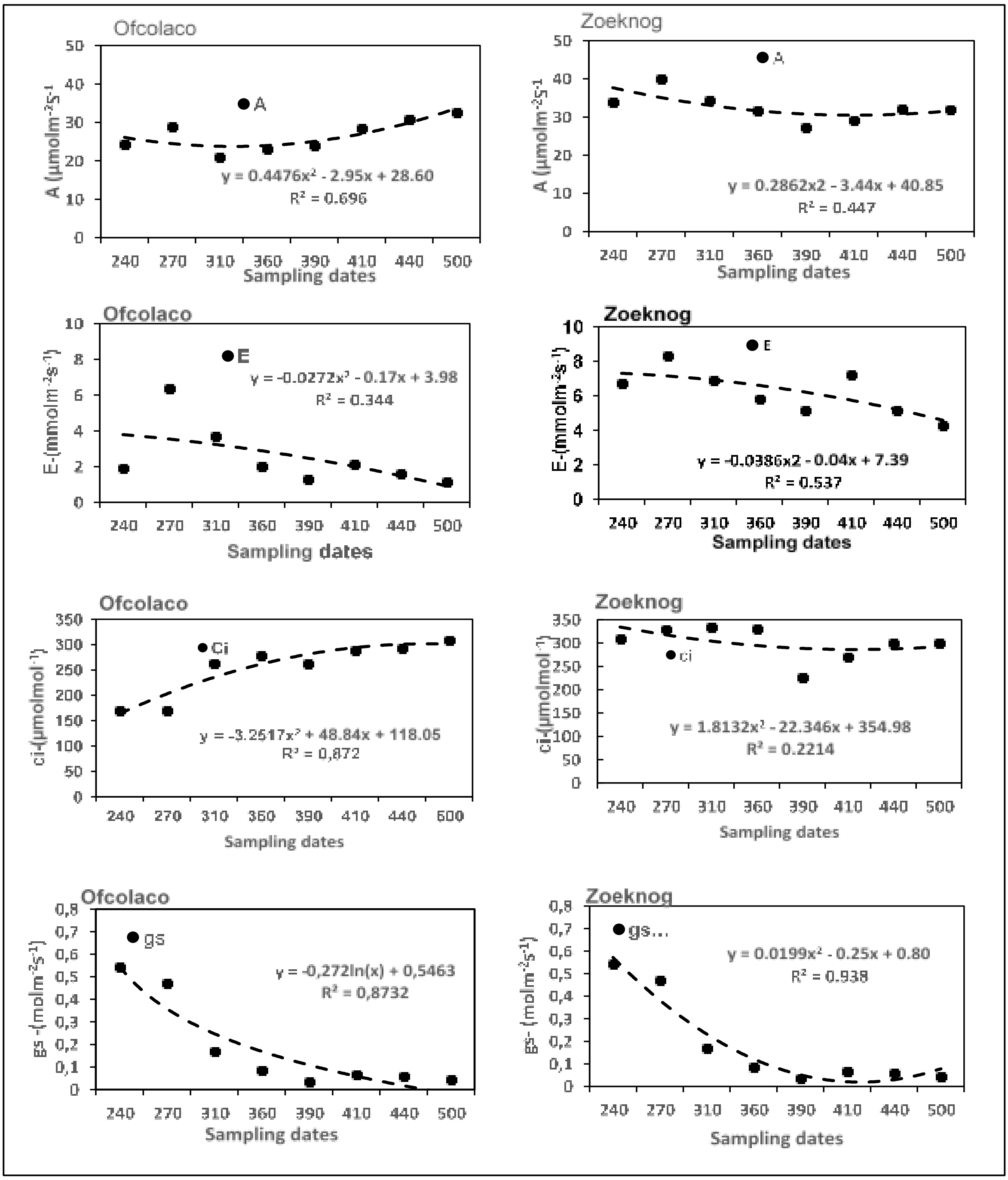


Figure 5.10: The relationship between (A) photosynthetic, (E) transpiration rates, and intercellular carbon concentration (ci) and stomatal conductance (gs) with growth periods during the regrowth periods at Ofcolaco and Zoeknog.

Interaction effect of V x P affecting leaf gaseous exchange parameters

Ofcolaco:

Interaction of V x P did not significantly the photosynthetic rates, transpiration, and intercellular CO_2 concentrations. Significant variation was observed in stomatal conductance. Komboa and Tumia at P fertilizer of 60 kg ha^{-1} influenced the behavior of the stomata (Table 5.4). However, the application of P fertilizer at 0 kg ha^{-1} influenced the stomatal to close

Zoeknog:

Transpiration and stomatal conductance were not influenced by the interaction effect of V x P. However, the study results showed significant changes in photosynthetic rates and internal CO_2 concentrations due to interaction effects (Table 5.4).

Komboa and application of P at 60 kg ha^{-1} had the highest photosynthetic rates (Table 5.4). Photosynthetic rates influenced by the interaction effects of V x P ranged from 26.24 to 41.25 µmol $m^{-2}s^{-1}$. Komboa with the application of P at 60 kg ha^{-1} increased photosynthetic rates by 6.3% compared to unapplied treatments (0 kg ha^{-1}). The lowest photosynthetic rates were recorded between local varieties in unapplied P fertilizers (0 kg ha^{-1}). Ilonga 14-M2 and Tumia varieties with 60 kg ha^{-1} had higher photosynthetic rates.

Intercellular CO_2 concentrations

Intercellular CO_2 concentrations responded positively in the interaction of V x P at Zoeknog only (Tables 5.4 and 5.5). The highest was observed between Ilonga 14- M4 and P fertilizer at 60 kg ha^{-1}, followed by the local with the same rate of P fertilizer application. The lowest was obtained between the interaction of Komboa and 60 kg ha^{-1}. The study also noticed that the long-duration types have more intercellular when 60 kg P ha^{-1} fertilizer was applied than the short-duration types.

Table 5.4: Interaction effect of V x P on photosynthetic rate (A), transpiration rate (E), Stomatal conductance (gs), and intercellular CO2 concentration during the regrowth periods at Ofcolaco

Varieties	P Fertilizer rates	Photosynthetic rate (A)	Transpiration rate (E)	Stomatal conductance (gs)	Intercellular CO_2 concentration (ci)
	kg ha^{-1}	µmol $m^{-2}s^{-1}$	mmol $m^{-2}s^{-1}$	mol $m^{-2}s^{-1}$	µmolmol^{-1}
Komboa	0	5.91a	3.03a	0.19b	277.22a
	60	5.32a	2.88a	0.20a	296.89a
Tumia	0	6.30a	3.03a	0.16b	255.97a
	60	8.07a	3.83a	0.27a	250.58a
Ilonga 14-M2	0	6.62a	3.16a	0.20a	260.63a
	60	6.14a	2.88a	0.19b	251.2a
Local	0	5.50a	2.90a	0.20a	259.41a
	60	5.90a	2.96na	0.20a	266.19a
C.V(%)		63.24	41.307	17.41	29.05
		ns	ns	***	ns

* =significant (p<0.05), **= C.V% coefficient variation percentage; * =significant (p<0.05), **= significant (p<0.01) ***(p<0.001) and ns (p<0.05) = not significance

Table 5.5: Interaction effect of V x P on photosynthetic rate (A), transpiration rate (E), Stomatal conductance (gs), and intercellular CO2 concentration during the regrowth periods at Zoeknog.

Varieties	P fertilizer rates	Photosynthetic rate (A)	Transpiration rate (E)	Stomatal conductance (gs)	Intercellular CO_2 concentration (ci)
Varieties	kg ha^{-1}	µmol $m^{-2}s^{-1}$	mmol $m^{-2}s^{-1}$	$molm^{-2}s^{-1}$	µmol mol^{-1}
Komboa	0	36.87b	8.55a	0.16a	172.25b
	60	41.25a	8.94a	0.19a	220.58a
Tumia	0	32.24a	5.70a	0.17a	202.72b
	60	28.78b	6.17a	0.18a	262.06a
Ilong 14-M2	0	28.41b	4.97a	0.17a	389.13a
	60	31.98a	5.48a	0.18a	398.82b
Local	0	26.24a	4.73a	0.17a	313.00b
	60	26.55a	5.34a	0.18ba	316.42a
C.V%		16.62	14.07	53.68	14.15
Significance		***	ns	ns	**

C.V%= coefficient variation, * =significant ($p<0.05$), **= significant ($p<0.01$) ***($p<0.001$) and ns ($p<0.05$) = not significance

5.3.7 Intrinsic and instantaneous WUE of pigeon peas

Varietal effect on intrinsic and instantaneous WUE

Water use efficiency intrinsic WUE

Though, the varietal effect on Intrinsic WUE was similar among pigeon pea varieties at both locations (Table 5.6).

Instantaneous WUE

Significant variations were revealed in instantaneous WUE among varieties at both locations (Table 5.6). The instantaneous WUE ranged from 1.41 to 2.44 and 4.41 to 5.95 (µmol mmol^{-1}) at Ofcolaco and Zoeknog, respectively. Ilonga 14-M2 recorded 5.95 µmol mmol^{-1} highest instantaneous WUE and the lowest instantaneous WUE was attained by Komboa. Komboa had reduced instantaneous WUE by 23%, 14%, and 15% relative to Ilonga 14-M2, Tumia, and local varieties at Zoeknog.

Table 5.6: Intrinsic (µmol mol^{-1}) and instantaneous (µmol mmol^{-}1) water use efficiency (WUE) of pigeon pea varieties during the regrowth period at Ofcolaco and Zoeknog

	Water use efficiency (WUE)			
Pigeon pea Variety	Intrinsic		Instantaneous	
	………. µmol mol^{-1}………		………..µmol mmol^{-1}……….	
	Ofcolaco	Zoeknog	Ofcolaco	Zoeknog
Komboa	459.31a	520.71a	1.41b	4.61
Tumia	375.04a	489.68a	2.39a	5.34b
Ilonga 14-M2	377.51a	493.12a	2.44a	5.95a
Local	370.65a	460.72a	2.13ab	5.43b
LSD (0.05)	108.373	120.33a	0.8242	0.4291
Variety	ns	ns	**	***
Phosphorus	ns	ns	ns	ns

* =significant (p<0.05), **= significant (p<0.01) ***(p<0.001) and ns (p<0.05) = not significance

Water use efficiency (WUE) increased intrinsically and instantaneously with the increase in plant growth but decreased at 410 DAP (Figure 5.11). The results detected that intrinsic WUE reached its peak at 390 DAP and was 670.56 (µmol mol^{-1}) and 965.91 (µmol mol^{-1}) at Ofcolaco and Zoeknog, respectively. At reproductive stages and physiological maturity stages (410, 500, and 560 DAP), $_{\text{intrinsic}}$ WUE showed a decreasing pattern at both locations. The study results also show that $_{\text{intrinsic}}$ WUE was lower at vegetative stages (240 and 270) DAP) and attained 68.98 µmol $mmol^{-1}$ and 94.24 µmol mol^{-1}, respectively. Pigeon pea growth stages at 310, 360, 410, 440, and 500 were comparable in $_{\text{intrinsic}}$ WUE at Zoeknog

I$_{\text{nstantaneous}}$ WUE was higher at 240 DAP during vegetative stages with 4.53 µmol $mmol^{-1}$ at Ofcolaco. In all other growth stages, $_{\text{Instantaneous}}$ WUE showed a reduction pattern at Ofcolaco. The lowest $_{\text{instantaneous}}$ WUE was attained at 310 DAP Ofcolaco with 1.03 µmol $mmol^{-1}$. Whereas at Zoeknog, the highest was attained at 440 DAP during reproductive stages with 6.76 µmol $mmol^{-1}$. The study results found a strong positive relationship (0.787 and 0.734) at Ofcolaco and Zoeknog, respectively

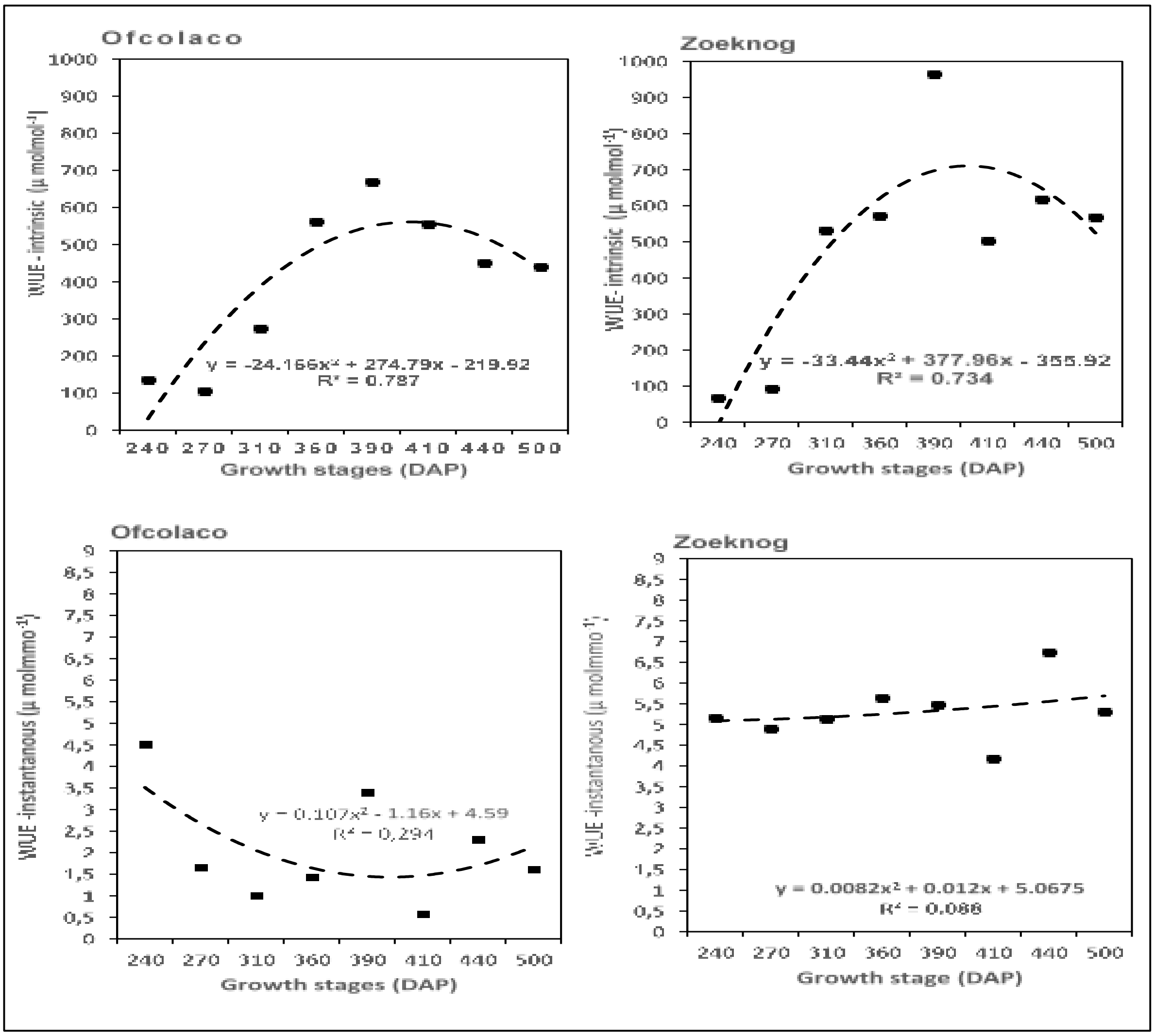


Figure 5.11: The relationship between intrinsic and instantaneous water use efficiency (WUE) growth stages during the regrowth stages at Ofcolaco and Zoeknog.

5.3.8 The interaction effect of pigeon pea variety and P fertilizer application on intrinsic and instantaneous WUE

Table 5.7 illustrates the interaction effect of pigeon pea variety and P fertilizer application for both locations. The study results indicate that the interaction effect of V x P in intrinsic and instantaneous WUE did not show any significant variations at Ofcolaco

Zoeknog:

The water use efficiency was reduced by the interaction effect of Komboa and Tumia with 60 kg ha^{-1} (Table 5.7). The results also identified that the Komboa pigeon pea variety and no application of P fertilizer (0 kg ha^{-1}) had the highest $_{intrinsic}$ WUE at Zoeknog.

$_{Instantaneous}$ WUE

At both locations, the response of Komboa, Tumia, Ilonga 14-M2, and the local landrace with 60 kg ha^{-1} significantly improved $_{instantaneous}$ WUE (Table 5.7). The highest WUE was observed between the interaction of Ilonga 14-M2 x 60 kg ha^{-1} at Zoeknog with 5.98 $\mu molmmol^{-1}$. The treatment where P fertilizer was not applied (0 kg P ha^{-1}) showed lower $_{instantaneous}$ WUE.

Table 5.7: Interaction effect of pigeon pea variety and P fertilizer application (V x P) on intrinsic (µmol mmol^{-1}) and instantaneous WUE (µmol mmol^{-1}) during the regrowth periods at Ofcolaco and Zoeknog.

		Water Use Efficiency (WUE)			
Pigeonpea variety	P- fertilizer rates	Intrinsic	Instantaneous	intrinsic	instantaneous
	kg ha^{-1}	µmolmol^{-1}	µmol mmol^{-1}	µmolmol^{-1}	µmol mmol^{-1}
		Ofcolaco		Zoeknog	
Komboa	0	62.86a	1.07a	199.42a	4.28b
	60	55.76a	1.76a	170.19b	4.94a
Tumia	0	76.18a	2.34a	136.79a	5.19b
	60	72.94a	2.50a	104.64b	5.64a
Ilonga 14-M2	0	68.98a	2.11a	135.62b	5.92b
	60	86.04a	2.77a	150.61a	5.98a
Local	0	67.93a	2.09a	177.71a	5.08b
	60	73.36a	2.16a	183.72a	5.78a
V x P		ns	ns	*	**
P-value		0.561	0.719	0.045	0.018

*= significant at p<0.05, **=significant at p<0.01, ns= non-significant differences.

5.3.9 Relationship between leaf transpiration and stomatal conductance, photosynthesis rate, and intercellular CO_2 concentration.

A strong relationship was observed in all leaf gaseous exchange parameters associated with transpiration (Figure 5.12). The relationship between transpiration and stomatal conductance shows that stomatal functioning influences transpiration rates. Transpiration rates were regulated by the opening and closing of the stomata. At both locations, the relationship between leaf transpiration and photosynthetic rates and also intercellular CO_2 was observed and was a strong positive relationship.

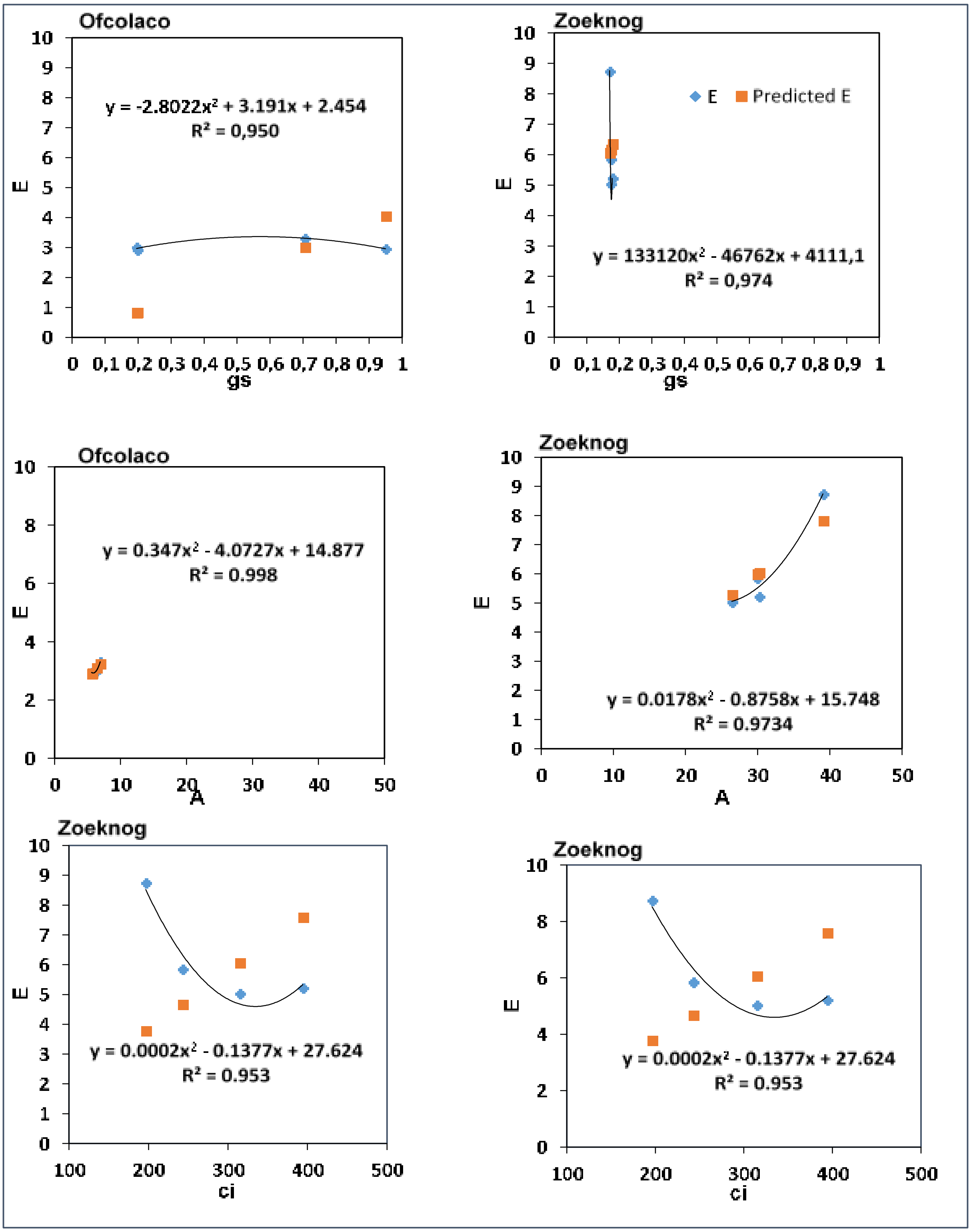


Figure 5.12: Relationship between transpiration and stomatal conductance, photosynthetic rates, and internal CO_2 concentrations during regrowth stages at Ofcolaco and Zoeknog.

5.4 DISCUSSION

5.4.1 Influence of pigeon pea variety on root biomass, and root length

Root biomass production is one of the attributes important for drought-tolerance in pigeon pea varieties (Hossaine *et al*. 2014). The study found that the Ilonga 14-M2 variety produced the largest root biomass and the longest roots among pigeon pea varieties at both locations (Figures 5.2 and 5.4). The Komboa variety produced the lowest root biomass with the shortest roots. Total root biomass production in pigeon pea Komboa was 50 and 51% less compared to Ilonga 14-M2 at Ofcolaco and Zoeknog, respectively. The study finding contradicts the observation of Pavani *et al*. (2022) who found lower root dry weight in long-duration types of pigeon peas. The current findings agreed with Subbarao *et al*., 2000 who indicated that the short-duration (Komboa variety) types produced low root biomass than the long-duration (Ilonga 14-M2 and local varieties) types because are unable to extract deep soil water and nutrients effectively. This also explained why short-duration types are sensitive to drought conditions. Several studies revealed that genotypes with deeper rooting systems have greater tolerance to water deficit in species such as chickpeas (Mafakheri *et al*., 2010) and pigeon peas (Odeny, 2007; Yaser *et al.* 2018). The current study agreed with the observation of the above authors that pigeon peas elongate roots growth under dry conditions to access moisture.

Pigeon peas are mostly adapted to semi-arid conditions and are known to have deep root systems (Makumba *et al*., 2009). This explained why pigeon peas remained green during the dry seasons when the majority of annual crops have dried. The study found that most of the roots were concentrated at 0 to 50 and 0 to 100 cm soil depth depending on the plant growth period, variety, and soil conditions. Makumba *et al.* (2009) recorded that 93% of pigeon pea roots occurred between 0 to 60 cm at 63 DAP. Ilonga 14-M2 root biomass and root length were almost double compared with the Komboa variety.

Soil texture influences root biomass production and root growth. At Ofcolaco, initial soil analysis results showed that soils are heavy with 23% clay content (Table 4.2). This type of soil limits root growth and result in lower biomass production and root length. Light-textured soils found at Zoeknog with 6% clay content, more root biomass, and longer roots were recorded. Natake (2012), found no significant variations between soil texture and root biomass, and also a negative relationship was also noted. The elongated root system is an important component for drought tolerance traits and nutrient assimilations due to the plant's ability to utilize deep inaccessible water (Hossain *et a*l., 2014; Odeny, 2007) during drought periods. According to Yaser *et al*. (2018), moisture stress promotes growth attributes such as roots for the long-duration type than the short-duration type.

5.4.2 Effect of P fertilizer application rates and growth stages (P x DAP) on root biomass and length of pigeon peas

Phosphorus plays a major role in many processes such as storage and transfer of energy, stimulation of root growth, flowering, fruiting and seed formation, nodule development, and N_2 fixation (Stevens *et al*., 2019). Significant differences due to P fertilizer application were growth specific. This indicates that pigeon peas absorb and utilize the applied P when the roots are fully developed and utilize the applied P fertilizer at a later stage for biomass production. Phosphorus fertilizer application at 60 kg ha^{-1} increased root biomass compared with 0 kg P ha^{-1} across locations. Contrary to root biomass, the results show that unapplied P fertilizer treatment (0 kg ha^{-1}) had a positive influence on root growth at both locations. This is more dominant at the later stage than during the early growth stages. The same finding was revealed by Sudharani *et al*. (2020) found that P application improved early root formation and improved crop drought tolerance in cowpeas. Asiwe *et al*. (2021) reported that the application of 30 kg P ha^{-1} and 45 kg P ha^{-1} increased root biomass production in cowpea and did not influence root biomass during the regrowth period. However, the present study showed that 60 kg ha^{-1} of P fertilizers increased root biomass during regrowth stages but reduced root length at both locations. The current study revealed that the response of pigeon pea varieties to P fertilizer application rates and their interaction effects (V x P) root biomass and length did not differ significantly

5.4.3 Influence of pigeon pea variety on the root-shoot ratio (RSR)

"Root-shoot ratio" is the total relative biomass allocation between roots and shoots (below and above ground). In this study, the root-shoot ratio was derived by dividing the total root biomass by the shoot biomass (Mokany *et al*., 2006). A decrease in shoot ratio was observed as the shoot biomass increased, and the reduction was at maturity (560 DAP). The same trend was also reported by Surech *et al*. (2016) who studied drought-induced changes in root and shoot in pigeon peas. Root-shoot ratios ranged from 0.22 to 0.47 and 0.24 to 0.31 at Ofcolaco and Zoeknog, respectively (Table 5.2). However, Ravindranath and Ostwald (2007) reported a narrow range of pigeon pea root-shoot ratio. Komboa and Ilonga 14-M2 had the highest root-shoots at Ofcolaco and Zoeknog, respectively. The current study findings are consistent with the findings of Uddin *et al*. (2013); Suresh *et al*., 2015, who reported that a high root-shoot ratio increased water uptake and grain yields under water stress conditions. The current study also found that long-durations pigeon pea types with deep root systems, high root biomass production, and resulted in a high root-shoot ratio at Zoeknog. These attributes enabled the variety to adapt to drought conditions.

5.4.4 Phosphorus fertilizer effects and growth periods on the root-shoot ratio

Though, the application of P fertilizer did not influence the root-shoot ratio of pigeon pea varieties. The study observed significant variations at a specific growth stage and the influence was not consistent throughout the growth stages. The study noticed an increase in root-shoot ratio due to no application of P fertilizer at the flowering stage (410 DAP) at Ofcolaco. Whereas, application of P fertilizer at 60 kg ha^{-1} increased root ratio at 560 DAP and 180 DAP at Ofcolaco and Zoeknog

5.4.5 Varietal effect on gravimetric soil moisture content

The local landrace maintained higher soil moisture content followed by Ilonga 14-M2 and Komboa attained the lowest at Zoeknog. These variations in soil moisture content among varieties at Zoeknog might be because the long-duration pigeon pea types produced more shoot biomass, which resulted in higher surface crop residues relative to the short-duration types. The surface crop residues are known to increase the infiltration rate and reduce soil water evaporation rate (Fu *et al*., 2021). The result also agreed with the findings of Viera *et al*. (2021), who reported that high crop residues increased gravimetric moisture content under no-till. At Ofcolaco, a high percentage of gravimetric moisture content was observed. The soil analysis showed that clay content was 23% and 6% at Ofcolaco and Zoeknog, respectively (Table 4.2). Higher soil clay content is known to have a higher water-retention capacity. Gravimetric soil moisture was also influenced by the growth stages of pigeon pea varieties. This might cause a senescence effect by dropping old and matured leaves on the soil surface to allow the regrowth of new leaves. Previous work reported that low soil gravimetric moisture is caused by the high plant density of Moringa (*Moringa Oleifera*) at the later growth stages (Mabapa *et al*., 2017). High amounts of soil water were recorded during the regrowth stages at 310, 360, and 390 DAP which falls in the summer seasons, and lower values during winter periods at both locations (Figure 5.8). The study concluded that climatic conditions (rainfall and temperatures), soil texture, and growth period influence the gravimetric soil moisture content

5.4.6 The interaction effect of P fertilizer and growth stages in gravimetric soil moisture

The interaction of P fertilizer and growth periods (P x DAP) influenced gravimetric soil moisture content and the effects were only detected at only Ofcolaco. The P fertilizer application at 60 kg ha^{-1} increased gravimetric soil moisture during vegetative and reproductive stages at 240 and 500 DAP. This shows that P fertilizer application at 60 kg ha^{-1} increased gravimetric moisture for increased growth and production yields.

5.4.7 Varietal effects on leaf gas exchange

Photosynthetic (A) (µmol $m^{-2}s^{-1}$) rates as influenced by variety were only significant at Zoeknog. Komboa had the highest photosynthetic rates among pigeon pea varieties. In comparison, Ilonga 14-M2 and Tumia, a local landrace, had low photosynthetic rates relative to Komboa. The difference in photosynthetic rate among pigeon pea varieties might be due to different leaf patterns found in pigeon pea varieties in intercepting light for photosynthesis. Similar observations were reported by Liu *et al.* (2014) indicating that photosynthetic rates are directly relative to the leaf light intercepting capacity. The larger the leaf size intercept more light and produced more photosynthetic rates accumulated relative to the small leaf size. The high photosynthetic assimilation in Komboa might have contributed to an increase in grain yield production. The findings from the current study differ from those reported by Mwanlima *et al.* (2020), who found high photosynthetic rates in indeterminate and low in determinate soybean cultivars. In this study, the determinate (short-duration types) had higher photosynthetic rates than the indeterminate (long-duration types), which attained low photosynthetic rates. The study noted that the response of pigeon pea varieties to photosynthetic rates was found to be variety specific.

Different climatic conditions and growth periods also influence photosynthetic rates (Baslam *et al*.,2020). The study results also detected that photosynthesis assimilations were higher at 270 and 310 DAP during the vegetative stages. This explains why the leaves of pigeon peas during their early growth stage are still green and able to intercept more light for photosynthesis processes than the aged, discolored leaves. Mathobo and Marais (2017) found growth stages did not influence the photosynthetic rates of dry beans. Higher values during the vegetative stage might also be influenced by favorable temperatures and the availability of soil moisture during January and February months (at 270 and 310 DAP).

The results also show that photosynthesis rates decreased as the crop reached reproductive stages (390 and 440 DAP) and were very low at harvest stages (560 DAP). This decline in photosynthetic rates during late growth stages might be caused by the aging of the leaves, which intercepts low light. The study also revealed that low photosynthetic rates at 410 to 500 DAP coincided with low rainfall during the winter season. At Ofcolaco the photosynthetic rates at 500 slightly increased as compared to 440 DAP. Several scientists observed that moisture stress has a negative impact on the photosynthetic rates of legume crops and reported this by Onyia and Herzog, (2004) cowpea; Wilson *et al*. (2012) pigeon pea; Vanaja, (2015) cowpea; Mathobo and Marais, (2017) dry beans; Munjonji *et al., (2018)* cowpea genotypes. This reduction of photosynthetic rates due to moisture stress was also observed in the long-duration types because they flower and mature during dry conditions.

Transpiration rate (E) (µmol $m^{-2}s^{-1}$): Significant variations in transpiration rate among pigeon peas were only detected at Zoeknog. Komboa had 8.7 µmol $m^{-2}s^{-}1$ was the highest transpiration rate in all varieties. Ilonga 14-M2 and the local landrace resulted in low transpiration rates, followed by Tumia at Zoeknog. The low transpiration rate measured in the long-duration type in the current study indicates that these varieties have deep root systems that enable them to absorb deep soil water and sustain the crop during dry conditions. The low leaf transpiration rate in Ilonga 14-M2 was because the variety's growth and reproductive stages coincided with low or no rainfall in April, May, June, and July, and low temperatures during the winter season at both locations were lower, especially at Zoeknog (Figure 5.1 and Table 5.1). Furthermore, the long-durations had higher gravimetric soil moisture content unlike the short-duration, which helps the variety to sustain itself during prolonged dry periods. Low transpiration rates in long-duration types might cause by higher gravimetric soil moisture and elongated root system that can absorb moisture deep into the soil.

Komboa had the highest transpiration rate among pigeon pea varieties. This indicates that short-duration types established their root systems very fast for water uptake and resulted in higher leaf transpiration. This type of variety is drought-sensitive; they grow and mature earlier to avoid water stress during dry periods. The same observation was reported by Munjonji *et al*. (2018) that cowpea varieties that established root systems faster had higher leaf transpiration rates. The opening of the stomata for a longer period increased transpiration rates, allowing CO_2 to enter the photosynthesis process. The leaf growth pattern (broad leaves) of the variety might also have allowed more water loss at the expense of CO_2 diffusion for photosynthesis. This increase in leaf transpiration rates due to the leaf growth structure has also been reported by Ayalew *et al*. (2022). Other scientists found the leaf area of species contributed to variations in transpiration rates (Wang *et al*., 2019). Hence, Komboa had a higher photosynthetic rate, and this might have contributed to an increase in grain yield production. The higher transpiration rates might also have been attributed to the availability of moisture, which coincided with high temperatures during the summer and autumn seasons. The results also revealed that leaf transpiration increased at 410 DAP during the flowering stage. The increase in leaf transpiration might be due to plants assimilating more CO_2 for photosynthesis, which is required for pod development in pigeon peas. Increased transpiration during reproductive stages might also be caused by higher CO_2 activity during the photosynthesis process because soil moisture and temperatures were also favorable. A positive relationship between transpiration rates and growth periods confirmed that transpiration rates decreased with an increase in plant growth. The study results agreed with the observations of Onyia and Herzog, (2004).

Intercellular CO_2 concentration (ci) ($\mu mol\ mol^{-1}$)

At Zoeknog, intercellular CO_2 concentrations were higher during February (Summer) at 310DAP. The study results also show that intercellular CO_2 concentrations increase during winter periods (April to July 2021). The lowest was at 390 DAP and was in the autumn season. The study observed variations in intercellular CO_2 between locations. During summer, the mean intercellular CO_2 concentration was 201.69 and 325.05 (µmol mol^{-1}), and in winter seasons was 297, 43, and 290, 83 (µmol mol^{-1}) at Ofcolaco and Zoeknog, respectively. At Zoeknog. the study observed intercellular CO_2 concentration was higher in summer with 12% more than in winter, whereas at Ofcolaco it was 48% more in winter periods compared to summer. The study observed that an increase in intercellular CO_2 also increases the photosynthetic rates but reduces the activity of stomata due to a reduction in leaf transpiration. A strong linear correlation between internal cellular CO_2 concentrations and plant growth stages was observed. The study noted that internal CO_2 concentration increases over a time period. High intercellular CO_2 concentration was observed at 500DAP which coincided with the drought period in June 2021 at Ofcolaco. This might cause by some of the varieties still in reproductive stages

Stomatal conductance (gs) (µmol $m^{-2}s^{-1}$).

The study results observed no significant difference between pigeon pea varieties in stomatal conductance at both locations. However, the results indicated that the stomata's functioning varied with species. Thuynsma *et al.* (2016) also found a non-significant difference in stomatal conductance. At Zoeknog, Ilonga 14-M2 controlled stomatal conductance and might be associated with a decrease in transpiration rates. Other scientists found that planting long-duration pigeon peas at a later stage resulted in higher stomatal rates than early planting, which is associated with low stomatal conductance (Wilson *et al*., 2012). The present study found that the long-duration varieties with high root biomass and deeper root systems maintained stomatal conductance more than the short-duration type with low root biomass and shallow root systems. The study agreed with the findings of Singh *et al.,* (2020) who reported that deep-rooted pigeon pea maintained its stomatal conductance longer than the shallow-rooted finger millet. Controlled stomatal functioning helps the crop to sustain itself during the dry period, which coincides with the reproductive stages. Low and controlled stomatal conductance with low transpiration rates shows that the variety has drought-tolerant traits, but this variety is found to have low photosynthetic rates. The low total grain production might have been attributed to low photosynthetic assimilation.

Stomatal conductance decreased as the number of days after planting increased. The was a decline in stomatal conductance over time because of the moisture stress and the lowest was attained at 500 DAP, which coincided with the winter period, low rainfall, and low average temperatures. The same results were reported by Munjonji *et al*. (2021), who found 75% of stomatal conductance is lower in winter as compared to autumn in citrus orchards. The increase in moisture stress causes a reduction in stomatal conductance. The low stomatal conductance at 500 DAP at physiological maturity might be due to old leaves not responding to stomatal conductance as they have reached maturity and also reduced CO_2 intake for photosynthesis. Similar results were reported by Matiru and Dakora (2004) found a reduction in stomatal conductance was associated with reduced CO_2 intake and the functioning of the Rubisco

5.4.8 Phosphorus fertilizer application and interaction of V x P effects on leaf gaseous exchange

Pigeon pea varieties and the application of P fertilizers had significant effects on the behavior of stomata in pigeon peas. The positive interaction effects of V x P observed were varied and location-specific. However, the current study found out that, Komboa and Tumia with P fertilizer at 60 kg ha^{-1} influenced the stomatal functioning of pigeon peas. Furthermore, Ilonga 14-M2 and the P fertilizer treatment (0 kg ha^{-1}) were found to influence stomatal behavior. The current findings contradict the findings of other scientists who found that low P in soils does not affect the changes in stomata but rather, the photosynthetic reaction of the mesophyll layer (Fujita *et al*. 2004; Kleinert *et al*., (2017). Increased application of P fertilizer at 60 kg ha^{-1} influenced the stomatal conductance of short and medium-duration types with low root biomass and short roots. The long-duration types in the study (Ilonga 14-M2 and Local) tended to utilize the available P in the soil more than the applied P in their deep root systems. Previously, the initial soil analysis results were 7 and 29 soil P (mg kg^{-1}) at Ofcolaco and Zoeknog (Table 5.2), respectively. Since the short-duration types are drought-sensitive, they grow and mature earlier during the short summer season to avoid drought conditions. Sufficient moisture and higher temperatures in the summer season may have influenced P uptake where 60 kg ha^{-1} was applied. The higher P uptake affected the opening of the stomata in the short-duration types. The current result also disagrees with the findings by Pang *et al*., 2018 who indicated that shallow root system grows better under P stress. However, the observation from this study that deep-rooted grow and survive better under severe drought conditions agrees with the same authors.

5.4.9 *intrinsic* WUE

Though there were no significant differences detected among pigeon varieties at both locations, the study revealed that the variety Komboa had the highest $_{\text{intrinsic}}$WUE. This indicates that this short-duration type had higher photosynthesis assimilations over stomatal conductance. The results revealed that the Komboa has mechanisms for drought tolerance and utilizes its photosynthetic rates for grain yield production in a short period.

5.4.10 I$_{\text{nstantaneous}}$ WUE

The variation in WUE among pigeon pea varieties might be due to the variation in genetic traits of the variety and also to the interaction with the environment. The current study found Ilonga 14-M2 had the highest $_{\text{instantaneous}}$ WUE with low photosynthetic and transpiration rates with maintained stomatal conductance. Ilonga 14-M2 produced high root biomass and growth. The elongated roots enable Ilonga 14-M2 variety to absorb inaccessible water during the dry period and utilize it for its growth and reproduction process during dry conditions. The low leaf transpiration rates and controlled stomatal conductance reported in the study show that variety sustains itself during dry conditions by reducing transpiration rates and preserving moisture for reproduction processes. Other scientists reported that WUE deteriorated as leaf transpiration increased, which induces stomatal closure (Musokwa and Mafongoya, 2021). In contrast, Komboa attained the highest photosynthetic rates, higher leaf transpiration, and low stomatal conductance. The high leaf transpiration rate recorded in Komboa did not activate the stomata to close. This might be caused by the available soil moisture content during the growing period. This variety is photo insensitive and sensitive to moisture stress (Shimelis and Gwata, 2013). The result from the study agreed with the findings of other scientists (Condon *et al*., 2002; Ayalew *et al*., 2022), explaining that high WUEcan be achieved either through lower stomatal conductance or higher photosynthetic rates or a combination of both. Positive, strong correlations between transpiration and stomatal conductance, photosynthetic rates, and intercellular CO_2 concentration were observed (Figure 5.3.11). Water deficits and fluctuations in temperature are the main drivers of stomatal activity in plants.

5.4.11 The interaction effects of V x P on $_{intrinsic}$ and $_{instantaneous}$ WUE

The interaction effect of V x P on $_{intrinsic}$ WUE did not differ significantly but was significant in $_{instantaneous}$ WUE. This indicates that the application of P fertilizer has a positive effect on $_{instantaneous}$ WUE. The results also indicate that moisture stress has an effect on the P uptake by pigeon pea varieties at Ofcolaco and Zoeknog. The application of 60 kg ha^{-1} increased $_{instantaneous}$ WUE and revealed that the long-duration types absorb more P during drought conditions (Pang *et al*., 2018). Ilonga 14-M2 variety has an extensive root system that is able to absorb and conserve moisture for future use by the plant. Komboa did not respond positively to increased P fertilizer application, which might be due to the low root biomass produced by this variety and its drought sensitivity. The study revealed that increased P application at 60 kg ha^{-1} improved plants' ability to tolerate drought conditions and long-duration types responded positively.

5.5 CONCLUSION

The study concludes that pigeon peas may thrive in extreme climatic conditions such as high temperatures coupled with moisture stress, which are frequent in Limpopo and Mpumalanga Provinces. Ilonga 14-M2 variety is a long-duration type and produces higher root biomass, longer root growth, and a high root-shoot ratio. The high biomass production, both below and above ground, demonstrates that Ilonga 14-M2 possessed drought tolerance attributes among the pigeon pea varieties. This variety also showed greater $_{instantaneous}$ WUE, low leaf transpiration rate, and ability to control its stomatal conductance, and all these proved that Ilonga 14-M2 has drought-tolerant traits. Ilonga 14-M2 is best suited for smallholder farmers in dryland farming conditions in Limpopo Province.

Komboa had the lowest root biomass, root length, intercellular CO_2 concentrations, and the lowest $_{instantaneous}$ WUE. The variety recorded the highest photosynthetic rates, transpiration rates, and the highest $_{intrinsic}$ WUE. This variety has some drought tolerance abilities by maturing earlier before drought spells and resulting in higher grain yields. Komboa variety is best suited for smallholder farmers in areas with sufficient rainfall during summer seasons, like in Mpumalanga Province. Tumia and the local landrace is a medium-duration type; the measured parameters were below and/or above Ilonga 14-M2 and Komboa at both locations. The Tumia variety had intermediate drought tolerance qualities and did not respond to increase P fertilizer application.

The long and short-duration pigeon pea types responded positively to the increased application of P fertilizer of 60 kg ha^{-1}. The study found that 60 kg ha^{-1} fertilizer induced the crop to resist drought conditions and improved production yields of long and short-duration types, respectively. The study concluded that P fertilizer application rates influenced root biomass, root growth, root-shoot ratio, gravimetric soil moisture, Leaf gaseous exchange, $_{\text{Intrinsic}}$ and $_{\text{instantaneous}}$ WUE at a specific growth stage due to varietal traits, season, crop duration, and the environment.

Chapter 6: NITROGEN AND PHOSPHORUS YIELD, NUTRITIVE VALUE, AND RESIDUAL SOIL NUTRIENTS OF PIGEON PEA [C*AJANUS CAJAN* (L.) MILLSPAUGH] AS INFLUENCED BY VARIETY AND PHOSPHORUS APPLICATION UNDER NO-TILL SYSTEM AND DRYLAND CONDITIONS

ABSTRACT

Keywords: nutritive value, N yield, pigeon peas grains, P fertilizer, P yield residual soil nutrient, and varieties.

6.1 INTRODUCTION

Pigeon pea [*Cajanus cajan* (L) Millsp.] is one of the important grain legumes for its production and utilization in Southern Africa. An estimated 3.8 million people in South Africa are malnourished from 2000 to 2022 and the number is increasing as compared to previous years (Statista, 2022). To ease the impact of malnourished, pigeon pea is one of the leguminous with an excellent source of crude fiber prepared into a variety of food. Dahl which is a thick soup is made from dry seeds in India (Matthews *et al*., 2001a and 2001b; Matthews and Saxena, 2001). The seed has a protein content of at least 26% (Dabhi *et al*. 2019), which is valuable in complementing the predominantly cereal-based diets in Sub-Saharan Africa (SSA).

Pigeon pea is multipurpose, and provides food, fodder, and wood for smallholders. The crop plays an important role in its nutritional (Saxena *et al*., 2010), medicinal (Matthews *et al.,* 2001a and Matthews, 2010), and therapeutic value (Ayenan *et al*., 2017). Regrettably, the unavailability of pigeon pea improved seeds of good quality and high yielding traits is still a major challenge in the smallholder farming system. Several authors also reported that the poor nutritive value of pigeon pea grain might be the result of climate change, low soil nutrients, and other environmental factors (Saxena *et al*., 2010) and nutritive value varies within pigeon pea genotypes (Fujita *et al*., 2004). However, information on the nutritive value and mineral elements of pigeon studies was not yet conducted in Limpopo and Mpumalanga Provinces, South Africa.

Pigeon pea is an important food legume that can be grown to eliminate protein malnutrition in Southern Africa. The supply of protein and minerals is inadequate to meet the protein and mineral requirements of the human population. Studies conducted by (Anjorin *et al*., 2010) stressed that minerals are only found in food crops and water content, minerals cannot be synthesized by animals but obtained from feeds and water. The demand for nutritional foods is increasing due to the increasing population and expensive meat proteins which are not affordable to the majority of the poor rural population in South Africa. Information on the nutritional quality of pigeon peas as influenced by variety, and P fertilizer application under no-till in smallholder farming systems are still scanty. However, improved pigeon pea varieties are known to have the high yielding potential of good quality grains and need to be documented under prevailing climatic conditions in South Africa.

Inadequate nutrients are one of the principal causes of low agricultural productivity and food insecurity in Southern Africa. The majority of smallholder farmers have been experiencing declining agricultural productivity, mostly due to soil fertility depletion (Kgonyane, 2013), leading to poor yield and food insecurity. According to Bekunda *et al*. (2010), the impact of induced nutrient depletion on production yields depends on the soil type and plant species. Pigeon pea Egbe and Anyam, (2011) studied N fixation in pigeon peas and recorded that the crop can fix up to 235 kg N ha^{-1} and produces more N $unit^{-1}$ area from the biomass than other legumes. According to the study conducted by Makelo (2011), pigeon peas are capable of bringing minerals from deep soil horizons to the soil surface. Other Scientists also indicated that the crop can substitute the use of 40 kg N ha^{-1} of fertilizers when it is used as green manure. Therefore, pigeon peas have the ability to improve soil fertility and quality when it is used in various cropping systems.

The crop is known to be rich in proteins, crude fiber, starch, fat, trace elements, and minerals compared to other leguminous crops (Saxena *et al*., 2010). No-till system is a technique in which the soil is disturbed only in the hole into which the seeds are planted. Mainly for its advantages as it reduces soil erosion, nutrient loss, and evaporation, improves soil fertility, and retain soil moisture. Previous studies reported that pigeon peas under a no-till system produced high crop residues (Viera *et al.*, 2021 Kumar, 2015, Herridge *et al*., 2013) as compared with conventional tillage. The incorporation of pigeon peas in smallholder farming systems, using improved seed varieties with adequate P-fertilizer application under dryland no-till systems has the potential to produce highly nutritious grains. This will contribute to the reduction of food and nutrition insecurity in the smallholder farming system. In addition, improved pigeon pea seed varieties have a high yielding potential of good quality grain that needs to be documented. The objective of the study was to assess the effect of pigeon pea variety and P fertilizer application rates on N and P yield, nutritive value, and residual soil nutrients.

6.2 MATERIAL AND METHODS

6.2.1 Study area

Information on the study areas, field management, experimental designs, and soil sampling procedures, are the same as described in Chapter 4 under material and methods (4.1.1, 4.1.2, 4.1.3, and 4.1.4).

6.2.2 Determination of N yield in plant tissue

Three plant samples were harvested randomly from the border rows in each experimental treatment. Samples were collected at 120 and 470 days after planting (DAP) during pigeon pea reproductive stages in both experimental sites. During both sampling dates, the majority of pigeon pea varieties were still in flowering stages. Plant samples were shade dried at room temperatures of 25°C for 114 and 228 hours at 120 and 470 DAP, respectively. All samples were rotated every 72 hours to suppress the growth of mold samples. Dry matter samples were ground to pass a 2 mm sieve and 200 g of each treatment sample was collected and packaged in zip-locked plastic bags. Samples were sent to the Department of Agriculture and Rural Development (DARD), plant laboratory in Kwa-Zulu Natal for nutrient analyses. Total N concentration was determined using the Association of Official Analytical Chemists (AOAC) following the Kjeldahl distillation method (Bremner and Mulvanery, 1982).

Nitrogen yield in shoot plant tissue was calculated using an equation:

N yield of the shoot (kg ha^{-1}) = biomass weight (kg ha^{-1}) x N % grains as described in Munjonji *et al*., (2018)

Where total N content used was from the above-ground plant samples nutrient analysis results as per treatment expressed in %, shoot biomass weight at 120 and 470 DAP as per nutrient sample treatments in kg ha^{-1}.

6.2.3 Determination of P and nutritive value in grains

Mature pods were harvested from the middle rows in a 5.4 m^2 net plot area and allowed to dry for 2 to 3 weeks under shade. Pods were manually threshed and seeds were weighed for the determination of total grain yield. Dry seed samples were collected randomly from the total grain yield in each treatment and location after the grain yield was determined. Seeds were packaged in small boxes, labeled, and sent to the DARD Plant laboratory in Kwa-Zulu Natal for nutrient analysis. Phosphorus was also determined using spectrophotometric detection of a colored phosphomolybdate complex using the molybdenum blue method. Phosphorus yield in grains was calculated using a formula:

Phosphorus yield in grains was calculated using an equation as described by Schiemenz & Eichler-Löbermann, (2010).

P yield of grains (kg ha^{-1}) = grain weight (kg ha^{-1}) x % P in grains

Water content using an electronic tester was determined after the samples were dried according to AOAC procedures. Ash, fat, and fiber content were analyzed by the AOAC, (2002) methods. Protein content was determined using the Kjeldahl method by multiplying total N% and multiplying with 6.25 (convection factor) using the below equation:

% of protein = total N% x 6.25

6.2.4 Mineral and trace elements determination in pigeon pea grains

Ash is the inorganic residue remaining after the water and organic matter have been removed by heating in the presence of oxidizing agents, which provide measures of the total amount of minerals within the grain. Mineral estimation was carried out by dry ashing the sample at 550°C according to the AOAC, (2002). Minerals such as potassium (K), and sodium (Na) were determined using a flame photometer- FES.

The concentration of phosphorus (P) calcium (Ca), copper (Cu) magnesium (Mg), zinc (Zn), Iron (Fe), and manganese (Mn), in the seed sample, were determined using a Varian Techtron 100 atomic absorption spectrophotometry – AAS (Gaines and Mitchell, 1979) after digestion with concentrated nitric acid. Phosphorus was also determined using spectrophotometric detection of a colored phosphomolybdate complex using the molybdenum blue method (Murphy and Riley 1962).

6.2.5 Soil sampling for chemical analyses at harvest

During harvest, soil samples were collected using a hand soil auger at a single depth of 0-60 cm depth. Soils were collected from the middle rows in a 5.4 m^2 net plot area in each treatment at both locations for nutrient analyses. Soil samples were packed in small soil sampling boxes and each box was labeled, then send to the Laboratory for nutrient analyses. Organic carbon was determined using the Walkley-Black method (Jackson, 1967), and total N was determined by the macro-Kjeldahl digestion method (Bremmer, 1955). Available P was extracted using Bray1 (Murphy and Riley,1962). Potassium, Mg and Ca were determined using the ammonium acetate method (Chapman, 1965). Soil pH was measured in KCl (1:1) and water using a ratio of 1:2.5 (Eckert, 1988) and a pH meter. Sand, silt, and clay were determined using the hydrometer method, soil color using the Munsell color chart, and bulk density using the core sampler ring method. All samples were sent to DARD, Fertilizer Advisory Service, Research and Development, and Analytical services in Kwa-Zulu Natal.

6.2.6 Data analysis and interpretation

The SAS Institute's statistical package was used to perform an analysis of variance (ANOVA) on the data to determine the effect of pigeon pea varieties, P fertilizer application rates, and their interaction effect (V x P) on the measured parameters in the two field experiments. The two locations were analyzed separately. The least significant difference (LSD) was also used to separate the means at probability levels of $p<0.05$, $p<0.01$, and $p<0.001$, only where a significant treatment effect was observed (Gomez and Gomez, 1984).

6.3 RESULTS

6.3.1 Accumulation of N in pigeon pea plant tissue

The total amount of nitrogen in plant tissue was significantly affected by varieties at both locations. However, the response of plant N to P fertilizer application rates and the V x P interaction effects were not significant at both locations. There were no significant differences in the interaction of V x P in the N yield of pigeon peas. However, pigeon pea varieties were significantly affected by the sampling dates at the two locations.

6.3.1.1 Varietal effect on N yield in plant tissue

Ofcolaco:

The accumulation of N in plant tissue differed among varieties (Figure 6.1) and sampling dates (120 and 470 DAP). Nitrogen in plant tissue was lower during the first harvest at 120 DAP ranging from 18 to 33 kg ha^{-1} and increased at 470 DAP (35 to 182 kg ha^{-1}). At 120 DAP which coincided with the first flowering, the plant N uptake was 66% lower compared to the second flowering at 470 DAP. Across varieties, the N yields ranking from highest to lowest were Ilonga (1), local (2), Tumia (3), and Komboa (4) (Table 6.1). The performances of varieties were consistent across all sampling dates.

Zoeknog:

Across varieties, N yield in plant tissue followed a similar trend as in Ofcolaco (Figure 6.1). The Ilonga 14-M2 variety attained the highest N yield across the two sampling dates. At 470 DAP, Ilonga 14-M2 recorded the highest N accumulation of 187.13 kg ha^{-1} relative to all varieties. The study found that the Komboa variety had the lowest N yields of 35 kg ha^{-1} and 51 kg ha^{-1} at 120 and 140 DAP, respectively. The local and Tumia were intermediate in N accumulation.

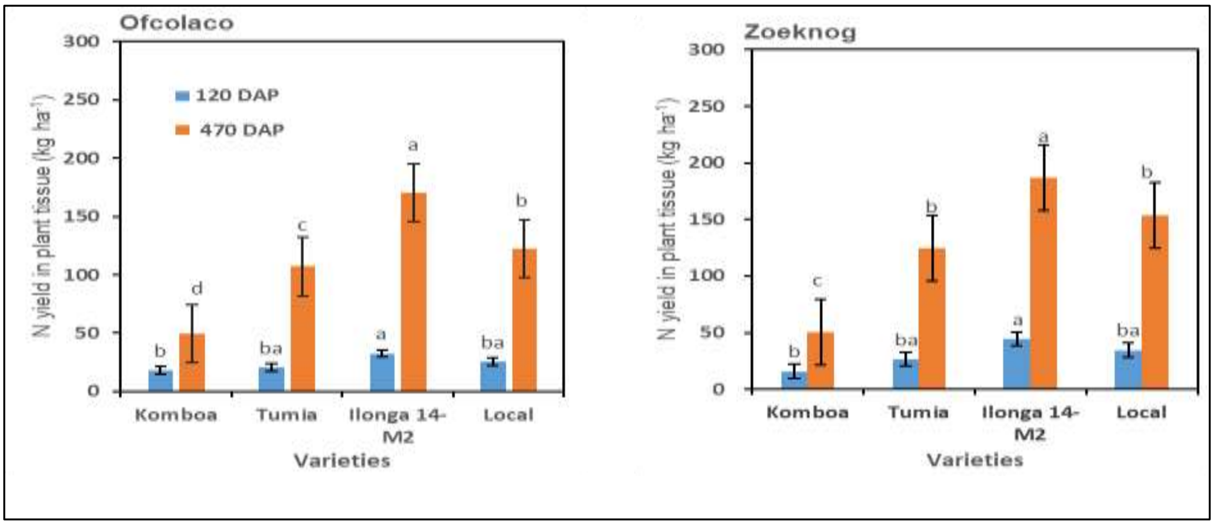


Figure 6.1: Nitrogen yield (kg ha^{-1}) in pigeon pea plant tissues influenced by sampling dates at Ofcolaco and Zoeknog (Different letters mean significant differences whereas similar letters mean no significant differences).

6.3.1.2 Nitrogen yield in plant tissue is influenced by P fertilizer application rates and the interaction of V x P.

Ofcolaco:

Significant variation was observed in the nitrogen yield of the pigeon pea at different sampling dates and P fertilizer application rates at Ofcolaco (Figure 6.2). The N yields were higher in P-fertilized plants at 470 DAP compared to 120 DAP where no difference was observed (Figure 6.2). Under the unfertilized plant, no difference in N yield resulting from the sampling date was observed. This indicates that plant tissue N accumulation increases with an increase in plant growth when P was applied.

Zoeknog:

Nitrogen plant tissue accumulation followed a similar trend as in Ofcolaco, where differences in N yield as a result of sampling date were observed in the P-fertilized plants and not the unfertilized plants (Figure 6.2).

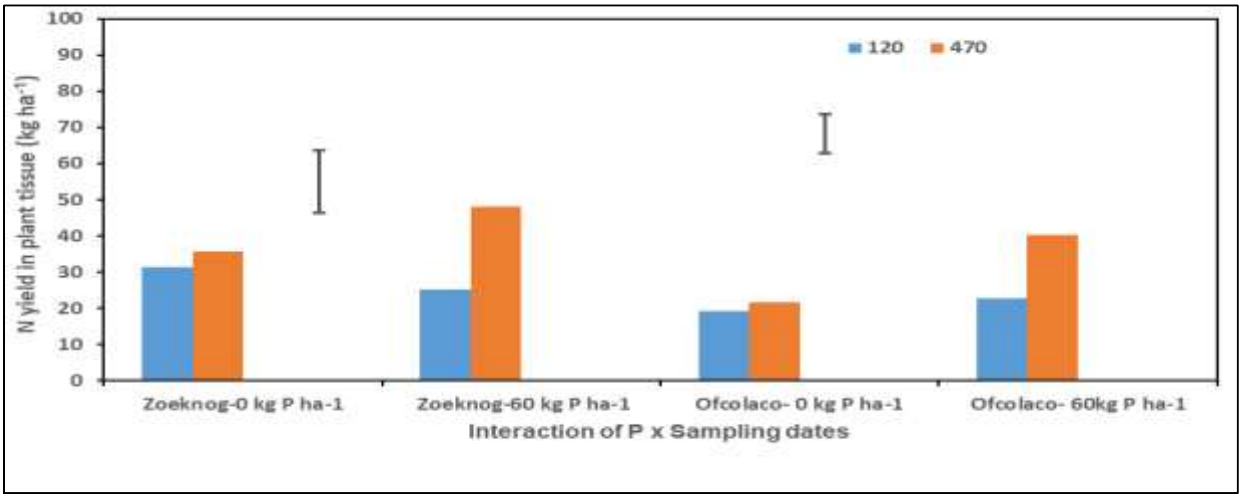


Figure 6.2: Plant nitrogen yield (kg ha^{-1})as influenced by the P fertilizer application and sampling date at Ofcolaco and Zoeknog (Vertical bars represent LSD value).

6.3.2 Phosphorus yield in pigeon pea grains

The effect of variety on P yield in pigeon pea grains was observed only at Ofcolaco at both harvest periods ($p<0.001$). No varietal effect was observed for P yield in pigeon pea grains at Zoeknog. At both locations, pigeon pea varieties did not vary significantly in P grain accumulation over P fertilizer applications and their interaction effects of V x P.

Ofcolaco:

The accumulation of P in the grains (Figure 6.3) differed among the varieties ($p<0.001$). Differences in grain P yield differed between the first and the second harvest periods in all varieties. Ilonga 14-M2 produced the highest P yield and was higher during the second harvest with 5.51 kg ha^{-1} than in the first harvest which was 3.91 kg ha^{-1}. The lowest P yield at both harvest periods was recorded in the local landrace.

Zoeknog:

There was no varietal effect observed in P yield across all varieties (Figure 6.3). Phosphorus yield in grains was 3.70 kg ha^{-1} (Komboa), 3.73 kg ha^{-1} (Tumia), 3.82 kg ha^{-1} (Ilonga 14-M2), and 3.77 kg ha^{-1} (local).

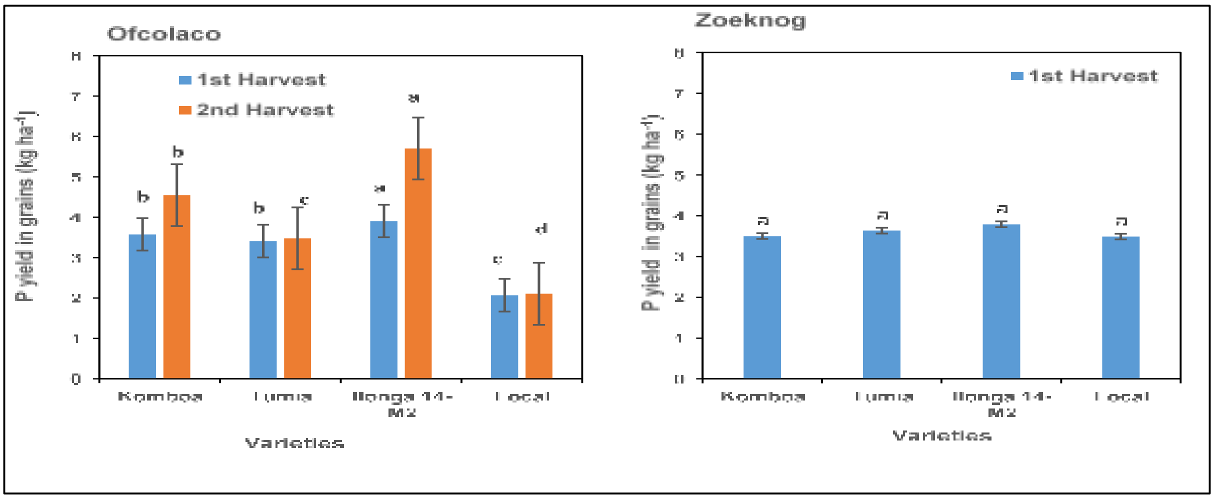


Figure 6.3 Phosphorus yield (kg ha^{-1}) in grains of pigeon pea varieties influenced by harvest periods at Ofcolaco and Zoeknog (Different letters mean significant differences whereas similar letters mean no significant differences).

6.3.3 Nutritive value of pigeon pea grains

6.3.3.1 Varietal effects on the nutritional composition of pigeon pea grains

The water content varied significantly among pigeon peas and harvest periods ranged from 9.46 to 10.12% in both harvests. Inconsistency was observed in water content among pigeon pea varieties in both harvests (Tables 6.1. and 6.2). Considerable variations in the moisture, protein content, and acid detergent fiber were observed among pigeon pea varieties at both harvest periods and the two locations. The neutral detergent fiber and ash content differed significantly among varieties only at Ofcolaco. The percentage value of fats did not show significant variations among varieties at both locations; ash content was only significant at Ofcolaco.

Water content

Ofcolaco:

The water content varied significantly among pigeon peas and harvest periods ranged from 9.46 to 10.12% in both harvest periods. Inconsistency was observed in water content among pigeon pea varieties in both harvest periods.

Zoeknog:

The water content in dry seeds varied (p<0.045) among varieties. Tumia has a higher water content of 10.40%, followed by Komboa (10.15%), local (9.85%), and the lowest was attained by Ilonga 14-M2 with 9.71%;

Protein content

Ofcolaco:

Significant variations (p<0.001) in protein content among the pigeon pea varieties were observed at both harvest periods. The protein content in dry seeds varied from 20.2 to 33.3% and 18.43 to 34.33% during the first and second harvest periods, respectively (Table 6.1). The mean protein content across all varieties and seasons was consistent. Ilonga 14-M2 attained the highest protein content among varieties in both harvest periods and was 33.44% and 34.33%. Local varieties recorded the lowest protein content in both harvests (20.2% and 18.43%), and the protein content was reduced during the second harvest period. The Tumia and Komboa varieties were ranked second and had similar protein content. The protein content in Ilonga 14-M2, Tumia, and Komboa was increased during the second harvest.

Zoeknog:

The protein percentage in grains varied significantly (p <0.001) among pigeon pea varieties. The mean protein content was 27.56% across all varieties (Table 6.2). Across varieties, the protein content ranking was 33.30%; 32.81%, 23.25%, and 20.84% for Ilonga 14-M2, Tumia, Komboa, and the local varieties, respectively. The mean protein content was 27% for the four varieties and was consistent at both locations. Ilonga 14-M2 and Tumia had the highest protein content but did not differ significantly. The same as Komboa and local varieties, they ranked second in protein content.

Fat content

Fat content in grains was relatively low and did not vary significantly at Ofcolaco ($p<0.756$) and Zoeknog ($p<0.589$). The fat content ranged from 1.74% to 1.85% and 1.82% to 1.88% across all varieties during the first and second harvests at Ofcolaco, respectively (Table 6.1 and 6.2). At Zoeknog, the fat content was also relatively low, ranging from 1.73 to 1.91 in all varieties.

Acid detergent fiber (ADF) concentration

Considerable variations in the acid detergent fiber in grains were observed among pigeon pea varieties at Ofcolaco ($p<0.0531$) and also between variety and harvest periods ($p<0.0588$). At Zoeknog, ADF showed significant variations ($p<0.001$) among varieties (6.1 and 6.2).

Ofcolaco:

The ADF value in grains (Table 6.1) ranged from a minimum value of 10.42% to a maximum value of 12.68% in local varieties in both seasons. Maximum values of 13.56% and 13.58% in Komboa and Ilonga 14-M2 during the first and second harvest periods, respectively. Ilonga 14-M2 and the local variety ADF in grains did not show any significant differences during the second season.

Zoeknog:

Acid detergent fiber content differed significantly among pigeon pea varieties (Table 6.2). The results of the analysis show that Ilonga produced the highest ADF with 14.96%, followed by Komboa (12.86%), Tumia (12.61%), and the lowest was recorded by the local variety (11.87%). Similarities were also found between Komboa, Tumia, and the local variety.

Neutral detergent fiber (NDF) content

Ofcolaco:

Substantial variations in NDF were observed among pigeon pea varieties at both harvest periods. The mean NDF dropped from 35.01% to 25.95% from the first to second harvest periods. Tumia obtained the highest NDF during the first season, but it was similar to Ilonga 14-M2 with 48.14% and 43.49%, respectively. The lowest NDF was attained by the local variety (35.01%) and Komboa was in-between Ilonga 14-M2 and the local variety.

Zoeknog:

Similarities in NDF content were observed in all pigeon pea varieties. However, the local variety had a higher NDF concentration of 47.93% and the lowest was Komboa with 36.36%.

Ash content

Ofcolaco:

The ash content in grains varied significantly ($p<0.026$) from 4.3% to 4.9% across varieties and seasons at Ofcolaco (Table 6.1). Tumia had the highest ash content in grains among the four pigeon pea varieties, followed by Komboa, and was consistent in both harvest periods. The lowest ash content was recorded in Ilonga 14-M2 with 4.5% in both seasons.

Zoeknog:

The ash content did not show any significant variations among pigeon pea varieties and attained 5.1% to 5.2%

Table 6.1 Nutritional composition of pigeon pea grains during the first and second harvest periods at Ofcolaco.

Harvest period	Variety	Moisture	Protein	Fats	ADF	NDF	Ash
1st harvest (DAP)				%			
180	Komboa	9.593b	26.178b	1.74a	13.615a	31.885c	4.727ab
180	Tumia	9.707b	27.9503b	1.85a	13.165a	45.135a	4.943a
180	Ilonga 14-M2	9.610b	33.435a	1.795a	11.298ba	43.486a	4.662b
180	Local	10.173a	26.942b	1.797a	10.420b	20.550d	4.361c
Mean		9.797	27.44	1.795	12.07	35.014	4.673
2nd harvest (DAP)							
560	Komboa	10.097a	28.215b	1.867a	11.423b	21.600c	4.602b
560	Tumia	9.850b	29.067b	1.883a	11.603b	26.243b	4.832a
560	Ilonga 14-M2	9.462b	34.333a	1.800a	13.583a	51.553a	4.533b
560	Local	9.882a	18.425c	1.820a	12.675ba	24.437b	4.533b
Mean		9.824	27.510	1.847	12.350	30.958	4.575
LSD(0.05)		0.269	5.055	0.099	1.368	4.759	0.154
Significance		**	**	ns	*	**	**

ADF= Acid detergent fiber; NDF= neutral detergent fiber; %=percentage; LSD= least significant difference

Table 6.2 Nutritional composition of pigeon pea grains during the first harvest period at Zoeknog.

			%			
Komboa	10.148a	23.273b	1.783a	12.86b	36.363a	5.131a
Tumia	10.396a	32.807a	1.733a	12.615b	43.407a	5.198a
Ilonga 14M2	9.713b	33.298a	1.905a	14.962a	45.778a	5.187a
Local	9.805b	20.842b	1.852a	11.867b	47.938a	5.182a
Mean	10.12	27.56	1.82	13.11	43.37	5.17
LSD(0.05)	0.512	8.438	0.283	2.219	15.176	0.147
Significance	*	**	ns	*	ns	ns

ADF= Acid detergent fiber; NDF= neutral detergent fiber; %=percentage; LSD= least significant difference

6.3.3.2 Interaction effect of V x P in nutritive value of pigeon pea grain

The interaction effect of V x P on moisture, protein content, fat, ADF, NDF, and ash content was not significant at both locations (Table 6.3 and 6.4). A significant interaction effect was however found in ash and water content at Zoeknog. Water content ranged from 9.28 to 10.19% across all varieties at Ofcolaco. The application of P fertilizer increased protein content only in the Komboa variety. In the remaining varieties, the protein content was generally higher in the unfertilized treatments. Ash contents varied from 5.11 to 5.27% and increased application of P fertilizers increased ash content in all varieties. The results showed that ash content was similar in all pigeon pea varieties at Ofcolaco.

Table 6.1 Interaction effects of V x P on the nutritional composition of pigeon pea at Ofcolaco

Variety	P fertilizer rates	Moisture	Protein	Fat	ADF	NDF	Ash
	kg ha^{-1}				%		
Komboa	0	9.95a	25.25a	1.82a	11.79a	25.10a	4.68a
	60	9.74a	30.14a	1.80a	12.95a	26.49a	4.65a
Tumia	0	9.88a	34.65a	1.85a	12.82a	32.21a	4.84a
	60	9.69a	24.27a	1.89a	11.95a	33.17a	4.73a
Ilonga 14- M2	0	9.28a	41.56a	1.70a	13.76a	37.18a	4.74a
	60	9.79a	38.41a	1.90a	13.83a	42.86a	4.46a
Local	0	10.9a	20.10a	1.86a	11.74a	22.74a	4.38a
	60	9.87a	18.53a	1.76a	11.35a	22.25a	4.52a
P-value		0.692	0.209	0.158	0.772	0.721	0.277
Significance		ns	ns	ns	ns	ns	ns

ADF= Acid detergent fiber; NDF= neutral detergent fiber; %=percentage; LSD= least significant difference

Table 6.2 Interaction effects of V x P on the nutritional composition of pigeon pea at Zoeknog

Variety	P fertilizer rates	Moisture	Protein	Fat	ADF	NDF	Ash
	kg ha^{-1}		%				
Komboa	0	10.66a	25.88a	1.78a	11.82a	39.16a	5.10b
	60	9.64b	22.67a	1.79a	13.90a	42.57a	5.16a
Tumia	0	10.98a	34.03a	1.89a	12.52a	42.69a	5.27a
	60	9.81b	31.61a	1.57a	12.71a	33.11a	5.22b
Ilonga 14- M2	0	9.61a	40.01a	1.85a	15.79a	49.98a	5.07b
	60	9.82a	36.59a	1.96a	12.13a	46.58a	5.32a
Local	0	9.52b	13.60a	1.87a	14.20a	48.03a	5.11b
	60	10.09a	16.09a	1.83a	11.43a	36.84a	5.25a
P-value		0.004	0.864	0.557	0.790	0.977	0.077
Significance		*	ns	ns	ns	ns	*

ADF= Acid detergent fiber; NDF= neutral detergent fiber; %=percentage; LSD= least significant difference

6.3.4 Mineral elements in pigeon pea grain as a result of a variety

Data on the mineral element contents in pigeon pea grains is shown in Tables 6.5 and 6.6. All mineral elements in the grain did not show a wide range of variation among varieties except manganese and phosphorus at Ofcolaco. However, magnesium and sodium were significantly varied among pigeon pea varieties.

Ofcolaco:

Minerals and trace elements in pigeon pea grains are illustrated in Table 6.5. Concentrations of calcium, iron, magnesium, copper, and zinc did not show any significant variations in the four pigeon pea varieties. However, P and manganese in grains varied significantly. Tumia had the highest concentration of manganese with 14%, and all other varieties did not show variations in manganese concentration (13%).

Zoeknog:

Sodium levels in grains were higher in Tumia, followed by Ilonga 14-M2 and Komboa. The local landrace had the lowest sodium levels among the varieties (Table 6.6). Magnesium levels in grains were higher in Komboa followed by the local variety, Tumia and Ilonga 14-M2, respectively. In all varieties, the magnesium concentration in grains was above 0.14%. However, sodium and Magnesium levels in grains were relatively low.

Phosphorus fertilizer application and interaction of V x P in minerals and trace elements in grains. The effects of P fertilizer application and interaction effects of V x P on minerals and trace elements in grains did not show any significant variations at both locations. Increased application of P fertilizer at 60 kg ha^{-1} did not affect mineral and trace elements in pigeon pea grain at both locations.

Table 6.3 Minerals and trace elements influenced by variety in pigeon pea grains on a dry weight basis during first and second harvest at Ofcolaco

Varieties	Potassium (K)	Calcium (Ca)	Phosphorus (P)	Magnesium (Mg)	Iron (Fe)	Sodium (Na)	Manganese (Mn)	Zinc (Zn)	Copper (Cu)
	%								
Komboa	1.51±0.202	0.13±0.031	0.36±0.074	0.16±0.022	44.33±11.316	0.05±0.034	13.66±3.201	28.75±3.414	10.42±3.28
Tumia	1.61±0.256	0.14±0.026	0.37±0.101	0.15±0.017	44.00±9.770	0.05±0.034	14.75±2.927	30.08±3.449	11.5±3.289
Ilonga 14-M2	1.60±0.244	0.13±0.025	0.34±0.083	0.15±0.017	49.42±13.800	0.05±0.040	13.58±2.679	30.42±3.704	11.5±3.503
Local	1.50±0.249	0.13±0.024	0.32±0.087	0.15±0.018	64.00±37.185	0.04±0.041	13.4±2.968	29.00±3.104	10.75±2.95
Mean	1.559	0.131	0.349	0.148	50.438	0.050	13.854	29.562	11.042
P value	0.901	1.001	0.049	0.631	0.700	0.302	0.001	0.294	0.337

± = standard deviation, p-value= probability

Table 6.4 Minerals and trace elements influenced by variety in pigeon pea grains during the first harvest at Zoeknog.

Variety	Potassium (Mg)	Calcium (Ca)	Phosphorus (P)	Magnesium (Mg)	Iron (Fe)	Sodium (Na)	Manganese (Mn)	Zinc (Zn)	Copper (Cu)
				%					
Komboa	1.582±0.034	0.146±0.011	0.350±0.048	0.168±0.004	47.000±5.138	0.013±0.005	13.500±1.871	32.667±2.658	9.333±1.033
Tumia	1.618±0.040	0.138±0.008	0.360±0.046	0.163±0.009	47.167±6.242	0.015±0.006	12.333±2.066	31.833±2.229	12.833±9.908
Ilonga 14-M2	1.617±0.051	0.137±0.010	0.407±0.205	0.162±0.004	49.833±6.210	0.013±0.005	12.833±1.472	33.000±2.450	10.000±1.549
Local	1.560±0.030	0.142±0.016	0.350±0.036	0.167±0.073	45.167±4.070	0.012±0.004	13.000±3.347	30.667±2.503	8.667±0.816
Mean	1.6	1.4	0.3	0.164	47.3	0.03	13.4	30.6	10.1
P-value	0.889	0.499	0.817	0.308	0.490	0.725	0.873	0.358	0.520

± = standard deviation; p-value= probability

6.3.5 Effects of variety, P fertilizer application rates, and V x P interaction on residual soil nutrients content after crop harvest

Soils were analyzed for physical and chemical properties in each treatment to determine the residual effects after crop harvest at both locations. The analysis of variance did not show any significant differences in residual organic C, clay%, or soil pH at both locations. Residual soil pH and total N, P, K, Ca, Mg, Mn, Cu, and Zn concentration levels in soil response to varietal effect, P fertilizer application rates, and the interaction of V x P at both locations (Table 6.7 and 6.8) did not show any significant variations.

Soil organic C

Though significant variations were not detected in residual soil C at both locations, the study analysis results showed that soil organic C was higher in Ilonga (1.4%) and Komboa had the lowest soil organic of 1.2%, and the differences were relatively low between varieties at both locations. In contrast with the initial soil analysis (Table 4.2), organic C increased from 0.9 and 0.4 to 1.24 and 1.91 at Ofcolaco and Zoeknog, respectively.

Clay content

At both locations, clay content after crop harvest was 19% and 14.9% in all for pigeon pea varieties and showed a 7% decrease in clay content at Ofcolaco relative to initial soil analysis results. However, an improvement in clay content was noticed at Zoeknog from 6% to 15% (Tables 6.7 and 6.8).

Soil pH (H2O)

The mean soil pH was 5.84 and 6.89 among pigeon pea varieties at Ofcolaco and Zoeknog (Tables 6.7 and 6.8). A comparatively low soil pH was observed at Ofcolaco from 5.7 to 5.8. At Zoeknog, soil pH was reduced from the initial soil pH (Table 4.2) of 7.9 to 6.89.

Total soil nitrogen content

Across varieties, residual total N content was 0.06% and 0.21% at Ofcolaco and Zoeknog, respectively. When compared with the initial soil analysis, the initial total N content was relatively higher (0.25% and 0.4%) at both locations.

6.3.6 Minerals and trace elements after crop harvest

There were no significant variations in residual soil P, K, Mg, Zn, Ca, and Na content among pigeon varieties at both locations. However, a decrease in soil P content was noticed compared to initial soil analysis results (Table 4.2) at both locations. Potassium concentrations at Ofcolaco and Zoeknog increased from 103 mg kg^{-1} and 108 mg kg^{-1} to 207 mg kg^{-1} and 662 mg kg^{-1}, respectively, compared to the initial soil analysis. Mineral elements such as manganese and copper were reduced relative to the initial soil analysis results by pigeon pea varieties. After crop harvest, the zinc content of the soil remains unchanged. Residual soil magnesium relative to initial soil analysis was increased from 70 mg kg^{-1} and 135 mg kg^{-1} to 145 mg kg^{-1} and 262 mg kg^{-1} at Ofcolaco and Zoeknog, respectively.

Table 6.5 Residual soil nutrients during the second harvest at Ofcolaco

Variety	Clay	Organic C.	Total N	Soil pH	P	K	Ca	Mg	Mn	Zn
	%	%	%	KCl	%		mg kg^{-1}			
Komboa	19.667±1.97	1.167±0.167	0.050±0.017	5.083±0.162	3.683±0.564	221.833±33.548	662.333±75.78	151.167±16.763	46.000±4.25	6.450±1.319
Tumia	19.195±1.95	1.200±0.200	0.060±0.105	5.227±0.187	4.083±0.520	205.000±33.680	610.500±37.73	142.167±13.848	57.333±9.221	5.600±1.350
Ilonga 14-M2	19.833±1.17	1.227±0.289	0.083±0.012	5.493±0.256	3.933±0.308	199.833±44.283	645.000±82.53	147.500±13.248	47.333±10.231	6.050±2.139
Local	19.000±0.63	1.217±0.189	0.055±0.014	5.160±0.146	3.983±0.453	205.167±48.670	676.167±28.78	144.500±13.041	44.00±6.603	3.983±0.453
P value	0.573	0.9251	0.625	0.446	0.7075	0.805	0.367	0.7818	0.0412	0.481

± = standard deviation; p-value= probability

Table 6.6 Residual soil nutrients during the second harvest at Zoeknog

Variety	Clay	Organic C.	Total N	Soil pH	P	K	Ca	Mg	Mn	Zn
	%	%	%	(KCl)	%		mg kg^{-1}			
Komboa	13.667±1.97	1.154±0.167	0.107±0.08	7.14±0.48	09.67±29.94	702.0±310.274	1936.33±548.11	287.167±88.76	23.502±10.95	6.251±2.85
Tumia	15.195±1.95	1.200±0.200	0.115±0.06	6.04±0.82	07.00±33.11	791.17±741.421	1537.00±640.04	238.500±56.56	0.063±0.02	24.171±8.95
Ilonga 14-M2	14.833±1.17	1.267±0.289	0.152±0.12	6.60±0.83	08.33±13.4	429.67±249.933	1935.67±762.28	282.66±94.757	21.172±8.42	5.233±1.52
Local	16.000±0.63	1.217±0.189	0.105±0.06	7.00±0.65	08.67±42.96	727.67±535.145	1571.50±249.39	242.167±85.06	21.000±6.03	4.552±2.42
P value	0.817	0.853	0.535	0.480	0.5468	0.6396	0.496	0.649	0.882	0.541

± = standard deviation; p-value =probability

6.4 DISCUSSION

6.4.1 Nitrogen yield in plant tissue

The accumulation of N in plant tissue differed among varieties (Figure 6.2) and sampling dates at 120 and 470 DAP. The present study recorded high N yield values in pigeon pea which was 170 kg ha^{-1} and 187 kg ha^{-1} at Ofcolaco and Zoeknog respectively. Across varieties, N yields in the variety Ilonga14-M2 were the highest followed by local landrace, Tumia, and the lowest was found in Komboa. The performances of varieties were consistent across all sampling dates. (Gan *et al*., 2010) reported that N yield in canola, dry pea, brassica, oilseeds, pulse, mustard, lentils, and wheat was affected by crop species but rarely by years. The present study found N yield was positively influenced by crop growth durations. Nitrogen in plant tissue was lower during the first harvest at 120 DAP and increased at 470 DAP. The authors also recorded lower N yield values in plant tissue relative to N yield in seeds and concluded that moisture stress affects N accumulation in plant tissue. The high N yield in plant tissue at Zoeknog might cause by high rainfall received during the growing season than at Ofcolaco (Figure 4.2)

The study found relatively low soil P affected the accumulation of N in plant tissues at both locations. Unfertilized treatments at 120 DAP reduced N yield in plant tissue relative to the P fertilizer at 470 DAP. This increase might be caused by the pigeon pea having poorly developed roots in the first season and being unable to absorb water and soil nutrients.

6.4.2 Phosphorus yield in grains

Grain phosphorus yield was affected by variety at Ofcolaco, but not at Zoeknog. Non-significant variations in the P yield of pigeon pea grains have also been reported by Hogh-Jensen *et al*. (2007). The present study observed an increase in grain P yield during the second harvest period from 3.1 to 4.0 kg ha^{-1} at Ofcolaco. Other scientists reported a decline in pigeon pea P yields in grains due to plant growth. (Høgh-Jensen *et al*., 2007) recorded pigeon pea P yields in grains reduced due to seasons. Fujita *et al*. (2004) found lower P yield in non-hybrid pigeon pea cultivars than in hybrid cultivars. The same observations were found in the current study and recorded increased values of P yield in the improved varieties than the local variety during the second harvest period. The Ilonga 14-M4 produced the highest P yield in grain and was 3,9 kg ha^{-1} and 5.7 kg ha^{-1} at both harvest periods. The variations in pigeon pea grains might be caused by differences in varietal trait genetic makeup and the environment. There were no significant differences observed in the P yield of pigeon pea grains influenced by P fertilizer application rates and the interaction effects of V x P at both locations.

6.4.3 Nutritive value on pigeon pea grains

The study found that pigeon pea grain water content ranged from 9.46% to 10.12% across all varieties and locations. Kachare *et al*. (2019) reported high values of water content and recorded 7.04 to 12.09% in pigeon pea grains. The mean protein content across all varieties and seasons was consistent and recorded at 27% at both locations. Ilonga 14-M2 attained the highest protein content among varieties in both harvest periods and locations. Several studies reported low values of protein content in pigeon peas ranging from 17 to 26%. Saxena *et al*., (2010) 18.8%; Makelo, (2011) 18-26%; Dabhi *et al*., (2012) 26%, Aruna and Devindra (2016) 23% and, (Kachare *et al*., 2019) 17-25%. Higher values of protein content in other leguminous crops were also reported by Megat Rusydi *et al*. (2011), namely 37.78% in kidney beans, 46.06% in mung beans, 30.88% soybeans, and 22.78% in peanuts. The variation in protein content might be caused by the differences in the variety, climatic conditions, and availability of soil nutrients.

The current study found that Ilonga 14-M2, which is a long-duration type, produced the highest protein content among varieties. The lowest protein content was observed in the local variety, and the same observations were also reported by Aruna and Devindra (2016). Some researchers indicated that grains contained low protein content relative to green pods or seeds (21%), and dhal with 24.6%, whereas the dry seeds contained 18.8% (Saxena *et al.*, 2010; (Aruna & Devindra, 2016). The fat content in pigeon pea seeds was 1.45%, recorded by Aruna and Devindra (2016). The current study reported a higher mean fat content of 1.8% and 1.9% at Ofcolaco and Zoeknog, respectively. The same values of fat content were also reported by Saxena *et al*. (2010), who found 2.3% in green seeds, 1.9% in dry grains, and 1.6% in dhal. Ash content in pigeon peas varies among varieties only at Ofcolaco at both harvest periods. The highest was obtained by Tumia and was consistent in both harvests with 4.8%.

6.4.4 Minerals and microelements in pigeon pea grains

Pigeon pea variety did not affect the mineral and trace elements (K, Ca, Mg, Fe, Na, Mn, Cu, and Zn. However, the content of Ca and Mg in grains was 0.13% and 0.16% lower than those reported by Saxena *et al.* (2010) who recorded 19.2% and 12.3 in pigeon pea matured seeds. Copper, zinc, potassium, and sodium were relatively lower than those reported previously by Saxena *et al*., (2010). In contrast, Saxena *et al*., (2010) reported less Fe and Mn at 14.7% and 10.8% in matured seeds of pigeon peas, and the current study reported high values of 50.4% and 13%, respectively.

6.4.4.1 Nutritive value and mineral elements influenced by phosphorus fertilizer application rates

The application of P fertilizer did not significantly affect the nutritive value, mineral, and trace elements of pigeon pea grains among the cultivars. There was also no interaction of V x P at both locations. The finding is contrary to other studies where the application of P influenced the nutritive value of the grain (Abbasi *et al*., 2012; Babu *et al*., 2014; Aher *et al*., 2015; Tairo and Ndakidemi, 2013). The study concluded that the nutritional value of pigeon peas contained more minerals than ordinary peas and other food legumes such as cowpeas and chickpeas, also observed by Makelo (2011).

6.4.5 Residual soil nutrients after experimentation

Though, the analysis of variance revealed that residual soil nutrients did not differ significantly as a result of varieties, P fertilizer application, and the interaction effect at both locations. A slight change in soil organic C, soil pH, and total N

were observed after crop harvest compared with the initial soil analysis before experimentation. Residual minerals such as Mg and K were increased from the study site after experimentation and Zn remains unchanged (Zn). The reduction of P, Mn, and Cu might cause by the crop utilizing a high amount of soil nutrients for improved growth and seed formation. However, a slight increase in soil organic C from 1.24 and 1.22 was noticed when compared with the initial soil organic C (Table 4.2) of 0.9 and

0.4 at Ofcolaco and Zoeknog, respectively. Recent findings reported a high value of soil organic C (1.35% to 2.46%) after harvesting pigeon peas (Elema et al., 2022). The present study agrees with the observation of Egbe and Anyan (2010) who stress that pigeon peas can add a substantial amount of organic matter to the soil. The soil pH from Ofcolaco was moderately acidic, 5.3 and 6.70 across all varieties. Reduction and increase of soil pH due to pigeon pea were also observed by Adu-Gyamfi *et al*. (2007); Kamanga *et al*. (2014); Garland *et al*., 2017); and Elema *et al*., (2022). The results also indicate that pigeon pea varieties reduced the soil pH of the study site before experimentation from 5.7 and 7.9 to 5.3 to 6.70 at Ofcolaco and Zoeknog, respectively. (Tables 6.7 and 6.8). The optimum soil pH of pigeon peas is important as it indicates the level of plant nutrient availability in the soil. Soil Texture: clay% was higher at Ofcolaco at 19% relative to Zoeknog at 14%. Regarding the clay content of the study sites before experimentation, the clay content at Ofcolaco was reduced, whereas at Zoeknog it was increased from 6% to 14%. The enhancement in soil texture might cause by the breakage of plow pans by the extensive root system of *Cajanus cajan* to improve the water holding capacity of the soil.

6.5 CONCLUSION

The Ilonga 14-M4 produced the highest N and P yield in grains and was consistent at both harvest periods and locations. The study indicates that P fertilizer application increased N yield in plant tissue but did not influence P yield in grains. Application of P fertilizer at 60 kg ha^{-1} increased the accumulation of N yield in plant tissue at 470 DAP. The study found that variety and P fertilizer application increased the N yield of pigeon pea in plant tissue which can be used as a valuable source of supplementary fodder for livestock feeding. There was a varietal effect on the nutritive value of pigeon pea varieties at both locations. The variety, Ilonga14-M2, consistently had the highest protein content at both harvests and locations. The local variety attained the lowest protein content. The P fertilizer application and interaction effect did not influence moisture, protein, fats, ADF, ash, or NDF at both locations.

Though the residual soil organic C, soil pH, and total N% were increased after harvest, non-significant differences were observed due to the varietal effect, P fertilizer application, and their interaction of V x P at both locations. The application of P fertilizer did not influence the nutritional value of pigeon pea grains but improved soil fertility status by increasing soil organic C and total N relative to initial soil analysis results at both locations. Ilonga 14-M2 is recommended for smallholder farmers for its ability to contain high P yield in grain, N yield in plant tissue, and high protein content. Pigeon pea can supplement expensive meat proteins which are not affordable to the majority of smallholder farmers in South Africa. The pigeon pea crop can be used for soil fertility enhancement through the decomposition of leaves to complement inorganic fertilizers which are not affordable to many smallholder farmers due to escalating prices of inorganic fertilizers. The study concluded that the pigeon pea is one of the leguminous species with a high source of proteins and is nutritionally well-balanced to ease the impact of food insecurity and malnutrition in South Africa.

Chapter 7: GENERAL CONCLUSIONS AND RECOMMENDATIONS

This chapter addresses the study findings as per study objectives, hypotheses, and the outcome of the study as well as outlining the recommendations for smallholder farmers. Possible future research areas are also identified.

Objective 1: to assess the status of pigeon pea production in Limpopo and Mpumalanga Provinces of South Africa through production practices, utilization, as well as potential markets of pigeon peas.
Hypothesis: Farmers' production practices, utilization, and potential markets are similar among smallholder farmers in Limpopo and Mpumalanga Provinces.
Reject: Pigeon pea production practices, utilization, and availability of markets varied among smallholder farmers and locations.
Conclusion: Currently, production levels of pigeon peas are still relatively low. The majority of farmers are still producing the crop in backyard gardens, mostly by subsistence farmers. The study found that the allocation of land to pigeon peas is very low, less than 1.0 ha as compared to other leguminous crops. The production levels of pigeon peas are also deteriorating due to the unavailability of improved varieties of good-quality seeds with high-yielding, and drought-tolerant attributes. Pigeon pea is mostly produced by women mainly for home consumption. Many farmers were aware of the utilization of the crop as food, feed, and medicine, but unaware that pigeon pea improves soil fertility status and it is a good source of protein. The study also revealed that more farmers are not aware of the production practices such as herbicides, pesticides, fertilizers, and cropping systems that improve productivity and yields of the crop. Farmers rely on their indigenous knowledge and also the exchange of information among themselves to produce the crop. However, researchers from both Provinces tried to introduce the crop and provide recent information to farmers. The study concluded that the adoption of pigeon pea production by farmers needs all role players to invest in skill development. Though farmers produce and sell the crop locally, farmers are interested in crops that have a high return on investment. The

demand for pigeon peas both as immature pods and dry seeds locally and internationally is high and shows that markets for this product are available.

Recommendations: Introduction of improved varieties that are high quality, drought, pest, and disease tolerant to farmers, involvement of extension agencies and researchers to provide expert information to farmers, as well as provision of training in agronomic techniques, marketing, value addition, and processing, are required to commercialize pigeon pea. capacity building through short training course programs and the provision of infrastructure support by the government will go a long way in developing pigeon pea production into a viable commercial enterprise.

Future research studies: research work should be carried out to determine the efficacy of pigeon peas as a therapeutic plant and which genotypes of pigeon peas can be used for medicinal purposes.

Objective 2: to determine the effect of pigeon pea variety and P-fertilizer application on the crop's biomass production, P-uptake, P use efficiency (PUE), and grain yield.

Hypothesis: Pigeon pea variety and P-fertilizer application do not influence pigeon pea biomass production, P-uptake, PUE, and grain yield.

Rejected: Significant variations were detected among varieties in shoot biomass, P yield, P recovery efficiency, and grain yield.

Conclusion: The study concluded that pigeon pea biomass, stem diameter, plant height, chlorophyll content, P yield in biomass, phenology variables, grain yield, and its components differ among varieties and P fertilizer application rates and locations. The pigeon pea variety Komboa produced low shoot biomass, and shorter plant height with thinner stem but was highest in grain yield and chlorophyll content, meaning that the photosynthesis assimilates increased grain production in this variety. However, Komboa had the lowest P yield and PRE in plant tissue among the varieties. The variety is less sensitive to photoperiod and flowers and matures during the summer season (Kimani, 2001). The high grain yield, yield components, and harvest index recorded in the study prove that the variety has high genetic traits for grain yield.

Ilonga 14-M2 and local, are long-duration types because they took almost 190 DAP to flower and mature. The study found that the variety outperforms all other varieties with respect to biomass production, stem diameter, plant height, suitability for fodder production, and soil improvement due to high leaf litter. It can be used in agroforestry systems for fodder production in the dry areas of South Africa. Ilonga 14-M2 also has a higher P yield and PRE in plant tissue, which proves that the variety had genetic traits that enabled the plant to utilize deep water and inorganic P in the soils. Being photosensitive, the varieties take time to flower and mature and need short days to initiate flowers. The vegetative and reproductive stages are in the summer and winter periods, respectively. This means that the reproductive stage of the variety coincides with low rainfall during the winter seasons. The long-duration types are characterized by high fodder production genotype traits and are tolerant to drought conditions. High P recovery is very important in smallholder farming systems as it reduces the cost of fertilizer and also increases production which contributes to food security. Tumia variety, a medium maturing type, is an intermediate and dual-purpose variety.

The study also revealed that pigeon pea varieties differ in their ability to utilize phosphorus fertilizers for increased crop productivity. Phosphorus fertilizer application at 60 kg ha^{-1} increased shoot biomass, chlorophyll content, harvest index, and PRE. The following measured parameters, stem growth, plant height, P yield, total grain yields, and their components, did not respond to P fertilizer application and the interaction of V x P. These increases due to the application of P fertilizers depend on the growth period, variety of traits, locality, climatic conditions, soil type, and agronomic management practices.

Recommendations: The Komboa variety is a short-duration type, has high grain production, and was consistent in both harvest periods and locations. This variety is suitable for smallholder farmers who want to invest and produce grain yield for income generation. The Ilonga 14-M2 variety is a long-duration type with high shoot biomass and P yield in plant tissue and it is suitable for high-quality fodder production. The same variety is tall with thick stems among varieties which make it suitable for utilization as firewood. Tumia is a medium or intermediate variety with the same perennial growth pattern as Ilonga 14-M2. The variety is recommended for dual-purpose, fodder, and grain production. Farmers who are interested in both fodder and grain could use this variety.

Future research studies: To explore the relationships between PRE and N fixation of pigeon pea varieties in smallholder farming systems in South Africa's agro-ecological zones.

Objective 3: Evaluate pigeon varieties and P-fertilizer application for drought tolerance through WUE, stomatal conductance, and root biomass production of pigeon peas.

Hypothesis: Pigeon pea variety and P-fertilizer application have no effects on the drought tolerance mechanism through WUE, stomatal conductance, and root biomass production of pigeon pea.

Rejected: root biomass, root-shoot ratio, transpiration, photosynthetic rate, gravimetric moisture, and WUE responded positively to the varietal effect. Root biomass, stomatal conductance, and $_{\text{instantaneous}}$ WUE responded to P fertilizer application rates.

Conclusion: Pigeon pea may thrive in extreme climatic conditions such as high temperatures coupled with moisture stress, which are frequent in Limpopo and Mpumalanga Provinces. The study found that the variety, Ilonga 14-M2 is a long-duration type, producing higher root biomass with longer root growth, and a higher root-shoot ratio. The high biomass production, both below and above ground, demonstrates that Ilonga 14-M2 possessed drought tolerance mechanisms among the pigeon pea varieties. The same variety also showed greater $_{\text{instantaneous}}$ WUE, low leaf transpiration rate, and ability to control its stomatal activity. All of these demonstrated that Ilonga 14-M2 has more drought-tolerant traits, able to conserve moisture and utilize it during dry conditions. Komboa had the lowest root biomass with short roots and recorded the highest photosynthetic rates and transpiration rates. This variety is sensitive to drought, so it avoids drought conditions by maturing earlier before the fall and winter drought spells. The study also recorded that the Komboa variety has the highest gravimetric soil moisture, $_{\text{intrinsic}}$ WUE, and the lowest $_{\text{instantaneou}}$s WUE, indicating that it also has drought-tolerant attributes with higher grain yield. Tumia and the local variety is a medium-duration type; the measured parameters were below and/or above Ilonga 14-M2 and Komboa at both locations. The variety did not respond to increased P fertilizer application rates. Long and short-duration types responded positively to increased application of P fertilizer of 60 kg ha^{-1}. The study found that 60 kg ha^{-1} of P fertilizer induced the crop to resist drought conditions and improved production yields of long and short-durations types, respectively.

Recommendations: The variety, Komboa, displayed some drought tolerance mechanism. However, it is more suitable in areas with relatively adequate water or rainfall during the summer season such as the Mpumalanga Province.

Ilonga 14-M2 had more drought-tolerant attributes, it is best suited in dryland farming systems where water deficits are prevalent and smallholder farmers rely primarily on rainfall for food production. Increased application of P fertilizer at 60 kg ha^{-1} is recommended for enhancing drought tolerance in pigeon peas.

Objectives 4 & 5: Investigate the effects of pigeon pea variety and P-fertilizer application on N-uptake, accumulation of P in grains, nutritional composition, and residual soil nutrients in a no-till system under dryland conditions.
Hypothesis: Pigeon pea variety and P-fertilizer application have no influence on N-uptake, residual soil nutrient content, and nutritional composition of pigeon pea grain.
Rejected: Varieties and P fertilizer have a positive effect on N yield, P yield, and nutritive value of pigeon pea grains.
Conclusion: The pigeon varieties studied vary in N yield, P yield, and nutritive value in grains. However, mineral and trace elements in grains and soils were similar in all varieties. The study further indicated that P fertilizer application influenced N yield in plant tissue but did not influence P yield in grains. Application of P fertilizer at 60 kg ha^{-1} and 470 DAP increased the N yield. Ilonga 14-M2 is recommended for smallholder farmers for its ability to contain high P yield in grain, N yield in plant tissue, and high protein content. Variety and P fertilizer application did not influence minerals and trace elements in grains. Pigeon pea is a perennial legume crop that improved soil fertility status by increasing soil organic C and total N relative to initial soil analysis results. The study concluded that pigeon pea is one of the leguminous crops with high protein content, ranging from 18.43 to 33.44, and is nutritionally well-balanced to ease the impact of food insecurity and malnutrition in Southern Africa.
Recommendation: Although, Komboa is recommended for its high grain yield production. The variety grains had lower P yield and protein content at both locations. Ilonga 14-M2 produced lower grain yield with substantial biomass production, the variety is recommended for smallholder farmers for its ability to accumulate high P yield in grain, produce more N per unit area, and have high protein content. The study found that variety and P fertilizer application increased N yield which can be used as a valuable source of supplementary fodder for livestock feeding. Pigeon pea grains can supplement expensive meat proteins which are not affordable to the majority of smallholder farmers in South Africa. The crop can be used for soil fertility enhancement through litter fall and decomposition to complement inorganic fertilizers

which are not affordable to many smallholder farmers due to escalating prices of inorganic fertilizers.

Possible future studies: Pigeon pea at three P fertilizer levels (low, medium, and high) and different climatic and soil types to test grain yield, the nutritive value, mineral elements, and residual soil nutrients of pigeon pea. Comparison of pigeon pea immature pods and dry seed protein of different genotypes to assess their nutritional value.

REFERENCES

ABBASI, M.K., TAHIR, M.M., ABBAS, W.A. & RAHIM, N. 2012. Soybean yield and chemical composition: in Response to phosphorus potassium nutrition in Kashmir. *Agronomy Journal*, 104,1476-1486.

ABDALLA, A.A., NAIM, E.I., AMED, A.F. & TAHA, M.B. 2015. Biological yield and harvest index of faba bean (Vicia fabaI L.) as affected by different agro-ecological environments. *World Journal of Agricultural Research*, 3, 78-82.

ABAIDOO, R., DARE, M.O., KILLANI, S. & OPOKU, A. 2016. Evaluation of early maturing cowpea (*Vigna unguiculata*) germplasm for a variation on phosphorus use efficiency and biological nitrogen fixation potential with indigenous rhizobial populations. The *Journal of Agricultural Science,* 115(1), 102-116

ADE, U.K., BHUSARI, S.A. MANE, S.G. & KALEGORE, N.K. 2018. Studies on growth, yield, and quality of pigeon pea (*Cajanus cajan* [L.] Millsp.) as influenced by different levels of phosphorus and liquid biofertilizer. I*nternational Journal of current microbiology and applied sciences,* 7,2303-2307

ADU- GYAMFI J.J., FUJITA, K. & OGATA, S. 1989. Phosphorus absorption and utilization efficiency of pigeon pea (*Cajanus cajan* (L) Millsp.) in relation to dry matter production and dinitrogen fixation. *Plant and Soil,*119, 315-324.

AHER, S.H., GOKHALE, D.N., KADAM, S.R. & KARANJIKAR, P.N. 2015. Effect of source and level of P on yield, quality, and P-uptake in pigeon pea. *International Journal of Agricultural Science,* 11(1), 59-62.

AJEI –ASIAH, S., LEEUWIS, C. & GILLER, K.E. 2004. Land tenure and differential soil fertility management practices among native and migrant farmers in Wenchi, Ghana: Implication for interdisciplinary action research, ‘’NJAS-Wageningen. *Journal. of Life Sciences*, 52 (3-4), 331- 348.

AJEI-NSIAH, S. 2012. Role of pigeon pea cultivation on soil fertility and farming system sustainability in Ghana. *International Journal of Agronomy*,1-8.

ALABI, R.A. & ESOBHAWAN, A.O. 2006. Relative economic value of maize okra intercrops in rainforest zone in Nigeria. *Journal of Central European Agriculture*, 7 (3), 33 – 438.

ALINIAEIFARD, S., MALCOLM MATAMOROS, P. & VAN MEETEREN, U. 2014. Stomatal malfunctioning under low VPD conditions: Induced by alterations in stomatal morphology and leaf anatomy or in the ABA signalling? *Physiologia Plantarum,* 152(4), 688–699. https://doi.org/10.1111/ppl.12216.

AMEFIENE, M.E., JOSHUA, V.L., NWADIKE C., YOROSON, A.Y. & ZWANON N.D.E. 2014. Profitability analysis of pigeon pea production in Royom Lga of Plateau state. *Academic Journal of interdisciplinary studies*, 3 (7), p44.

ANJORIN, T. S., IKOKOH, P. & OKOLO, S. 2010. Mineral composition of *Moringa oleifera* leaves, pods, and seeds from two regions in Abuja, Nigeria. *International Journal of Agriculture and Biology,* 12(3).

ANSARI, M.H., VERMA, B.K., ANSARI, M.A., MISHRA, D., SRIVASTAVA, A.K., KHAN, N. & SAQUIB, M. 2015. Impact of cropping pattern on growth, yield attributes and system productivity of citronella (*Citronella winterianus*) - pulses intercropping system in Central India. *Indian Journal of Agricultural Sciences*, 85 (3),392-396

AOAC, 2002. Official Methods of Analysis. 16th Edition., Association of Official Analytical Chemists, Washington, DC., USA.

ARUNA, T., & DEVINDRA, S. 2016. Nutritional and Anti-Nutritional Characteristics of Two Varieties of Red gram (*Cajanus cajan*, L) Seeds. *International Journal of Scientific and Research*, 6(9), 567. www.ijsrp.org

ASEFA, G. 2019. The role of harvest index in improving crop productivity: A review *Journal of Natural Science Research*, 9 (6), 24- 28.

ASIWE, J. N. A., NKUNA, M. K. & MOTAVALLI, P. P. 2021. Productivity of Phosphorus Fertilization in Cowpea-Maize Strip Intercropping under Rainfed Conditions. International Journal of Agriculture and Biology, 26(2), 270–276. https://doi.org/10.17957/IJAB/15.1834

ATACHI, P., ELIE, D. & RUREMA, D.G. 2009. Trap cropping and intercropping of pigeon pea (*Cajanus cajan* L. Millsp.) in pest management of cowpea (*Vigna unquiculata* L. Walp.) in Southern Benin: competing risk and pest status in pod attack. *Annual Science in Agronomy*, 9(1).

AYALEW, T., YOSEPH, T., HÖGY, P. & CADISCH, G. 2022. Leaf growth, gas exchange, and assimilation performance of cowpea varieties in response to Bradyrhizobium inoculation. Heliyon, 8(1). https://doi.org/10.1016/j.heliyon.2022.e08746.

AYENAN, M.A.T., OFORI, K., AHOTON, L.E. & DANQUAH, A. 2017. Pigeonpea [(*Cajanus cajan* (L) Millsp.)] production system, farmers' preferred traits and implication for variety development and introduction in Benin. *Agricultural & Food Security*, 6:48.

BABU, S., RANA, D. S., YADAV, G. S. & SINGH, R. 2014. Growth, yield, quality, and nutrient content of pigeon pea (*Cajanus cajan*) as influenced by sunflower stover and nutrients management under pigeonpea-sunflower (*Helianthus annuus*) cropping system. *African Journal of Agricultural Research,* 9(49), 3559–3570. https://doi.org/10.5897/AJAR2014.8648.

BAL, C.P., BHAVE, S.G., THAWARE B.L. & DESAI, S.S. 2018. Correlation and path analysis studies in pigeon pea (*Cajanus cajan*). *Global Journal of Biological Sciences and Biotechnology,* 7 (1), 70-73.

BARBIERI, P.A., ROZAS, H.R.S., COVAREVICH, F. & ECHEVERRIA, H.E. 2014. Phosphorus placement effects Phosphorus, Recovery efficiency in grain yields of wheat under no-tillage in humid pampas of Argentina. *International Journal of Agronomy,* 1-12.

BASLAM, M., MITSUI, T., HODGES, M., PRIESACK, E., HERRITT, M.T., IKER, A. & SANZ-SAEZ, A. 2020. Photosynthesis in changing global climate: Scaling up and Scaling down in crops. *Frontiers in plant science,* https://doi.org/103389/fpls.2020.

BASU, T.K. & BANDYOPADHYAY, S.R. 2009. Productivity of rabi pigeon pea (*Cajanus cajan* L. Millsp.) as influenced by scheduling of irrigation. *Journal of crop and weed,* 2, 90-91.

BEKUNDA, M., SANGINGA, N. & WOOMER, P. L. 2010. Restoring soil fertility in sub-sahara Africa. *Advances in Agronomy*, 108, Issue C). https://doi.org/10.1016/S0065-2113(10)08004-1

BENITES, J.R., DERPSCH, R. & MCGARRY, D. 2013. Current status and future growth potential of conservation agriculture in the world context. International Soil Tillage Research Organization 16th Triennial Conference

BIERNACKI, P. & WOLDORF, D.J. 1981. Snowball sampling: Problems and Techniques of Chain Referral Sampling. *Sociological Methods and Research,* 10 (2), 141-163.

BIOVERSITY INTERNATIONAL, CIAT, CGIAR, CCAFS, & GIZ. 2020. Adapting Green Innovation centres to climate change: Analysis of value change adaption potential, Baobab and pigeon pea value chains in Manice and Sefala Provinces, Mozambique.2020; https://cgspace.cgiar.org p1-49.

BOATENG, A. & OWUSU-BENNOAH, P. E. 2021. Effects of phosphorus availability on nodulation and nitrogen uptake by three legume crops in two Ghanaian soils. www.iprjb.org

BOTA, J., MEDRANO, H. & FLEXAS, J. 2004. Is photosynthesis limited by decreased Rubisco activity and RuBP content under progressive water stress? *New phytologist*, 162(3), pp:.671-681.

BREMMER, J.M.1955. Nitrogen distribution and amino-acid composition of fractions of a humic acid from a chernozem soil (‘’Hidesheimer Schwarzerde’’). Z. Pflanzenernaehr. Dueng. Bodenk, 71, 63-66.

BREMNER, J.M. & MULVANERY, C.S. 1982. Nitrogen-Total. Methods of soil Analysis, Page A.L. (Ed). *American Society of Agronomy*, 9(2), 595-624.

BUSARI M.A., KUKAL, S.S., KAUR, A., BHART, R. & DULAZI, A.A. 2015. Conservation tillage impacts on soil, crop and the environment. *International Soil and Water Conservation Research*, 3,119-129.

CARGNELUTTI FILHO, A., FASCO, G., OLIVEIRA DOS SANTOS, G., MENDONCA ALVES, B., BURIN, C. & KLEINPAUL, J.A. 2017. Linear relations among pigeon pea traits. *Communication Scientiae*, 8(3), 493 -500.

CARRYBERY, P.S., RANGANATHAN, R., REDDY, L.J., CHAUHAN, Y.S. & ROBERTSON M.J. 2001. Predicting growth and development of pigeon pea flowering response to photoperiod. *Field crops Research,* 69,151-162.

CASSMAN, K.G., DOBERMAN, A. & WALTERS, D. 2002. Agroecosystems, Nitrogen use efficiency and Nitrogen management. *Ambio*, 31(2), 132-140.

CARRIHER, V.A., HILL, G.M., BERNARD, J.K., JENKINS, T.C., WEST, J.W. & MULLINIX Jr. B.G. 2010. Pigeon pea as supplementary for lactating dairy cow-fed corn silage-based diets. *Journal of Dairy Science,* 93(11), 5309-5317.

CHAMAGO, A.M.Z. 2001. Improving grain yield of smallholder cropping system: A Farmer Participatory Research (FPR) approach with legumes for soil fertility improvement in central Malawi (p413-417), proceeding of the seventh Eastern and Southern Africa Regional maize conference held on 11-15 October 2001, Nairobi, Kenya, CYMMYT.

CHAPMAN, H.D. 1965. Cation exchange capacity. In: Black, C.A. (Ed.). Methods of soil analysis. American Society of Agronomy, Madison WI, 9: 891-901.

CHOUDHARY, A.K., SULTANA, R., NPRATAP, A., NADARAJAN, N. & U.C. JHA. 2011. Breeding for abiotic stresses in pigeonpea. *Journal of food legumes*, 24(3), 165-174.

CONDON, A.G., RICHARDS, R.A., REBETZKE, G.J. & FURIGUHA, G.D. 2002. Improving intrinsic water use efficiency and crop yield, *Crop Science,* 42, 122-131.

CORNIC, G.M BUKHOV, N.G., WIESE, C., BILGRY, R. & HEBER, U. 2000. Flexible coupling between light dependent electron and vectorial proton transport in illuminated leaves of C3 plants. Role of photosystem I – dependent proton pumping. *Planta* 210, 468-477.

DABHI, M., SANGANI, V. & RATHOD, P. 2019. Effect of enzyme pre-treatment on dehulling, cooking time and protein content of pigeon pea (variety BDN2). *Journal of food science and Technology,* 56,4552-4564.

DAHIYA, S.S., CHAUHAN, Y.S., JOHANSEN, C.J., WALDIA, R.S., SELHON, H.S. & NANDAL, J.K. 2002. Extra short-duration pigeon pea for diversifying wheat base cropping systems in the Tropics. *Experimental Agriculture,* 38, 1-4.

DAMOUR, G., SIMONNEAU, COCHARD, T. & URBAN, H.L. 2010. An- overview of models of stomatal conductance at the leaf level. *Plant, Cell and Environment,* 38, (9).

DANIA, S.O., FAGBOLA, O. & ALABI, R.A. 2014. The yield and farmers' economic advantage of maize-pigeon pea intercrop as affected by the application of organic base fertilizer. *European Scientific Journal*,10 (25), 358 – 374.

DAR, W. 2007. Carbon sequestration for better dryland productivity. The Hindu, India,

DASBAK, A.M., BONAVENTURE, C.E. & ASIEGBU, J.A. 2012. Field insect pests and crops manage the assessment of pigeon pea (*Cajanus cajan* [L.] Millsp.) grown under ratoon and in mixture with maize. *Chilean JAR Journal of Agricultural Research,* 72 (1), 45-52.

DEPARTMENT OF AGRICULTURE, FORESTRY & FISHERIES (DAFF). 2009. Pigeon pea production. Pretoria: Department of Agriculture, Forestry and Fisheries. Available online at http://www.nda.agric.za/.

DEPARTMENT OF AGRICULTURE, FORESTRY & FISHERIES (DAFF). 2012. Food security policy/zero hunger program of the Republic of South Africa. Pretoria: Department of Agriculture, Forestry and Fisheries. Available online at http://www.nda.agric.za/.

DINH, H.T., KAEWPRADIT, W., JOGLOG, S., VORASPPT, N. & PATANOTHAI, A. 2013. Biology Sabrao. *Journal of Breeding and Genetics*, 45, 491- 503.

DIOUF, J. 2002. The state of food insecurity in the world, published by the United Nations Viale Delle Terme di Caracalla, 00100 Rome, Italy, pp 51-53.

DUHAN, A., KHETARPAUL, N. & BISHNOI, S. 2002. Content of phytic acid and HCl-extractability of calcium, phosphorus and iron as affected by various domestic processing and cooking methods. *Food Chemistry*, 78(1), 9–14.

DUTTA, S., MAHAN, V.S & TRIPATHY, B.C. 2009. Role of temperature stress on chloroplast biogenesis and protein important in pea. *Plant Physiology,* 150,1050-1061.

ECKERT, D.J.1988. Soil pH. Recommended chemical soil test procedure for the North Central Region. Fargo: North Dakora. *Agricultural Experiment Station Bulletin*, 221,6- 8.

EDJE, O.T. 2014. Effect of intercropping maize [*Zea mays* L.] with pigeon pea [*Cajanus cajan L.*] on seed yield, litter, and fuelwood in middleveld, Swaziland. *African Journal of Applied Agricultural Sciences and Technologies*, 1(2), 1-8.

EGBE, O.M. & ANYAM, M.N. 2011. Effect of sowing density of intercropped pigeon pea with sorghum on biomass yield and nitrogen fixation in Southern Guinea Savannah of Nigeria Production. *Agriculture and Technology Journal*, 7, 1-14.

EGBE, O.M. & KALU, B.A. 2009. Evaluation of pigeon pea genotypes for intercropping with tall sorghum in Southern Guinea savannah of Nigeria. 4, 1-12.

ELEMA, R., NEGASH, S., TOLOSA, A. & ABDELLA, M. 2022. Evaluation of pigeon pea varieties and cultivars for soil nutrient addition and fertility levels in the case of Fodis district Eastern Haragne Zone. *Journal of Energy and Natural Resource,*11 (1), 26-31.

EMEFIENE, M.E., SALUDEEN, A.M. & YUSUF, Y.F. 2013. The use of pigeon pea (*Cajanus Cajan*) for drought mitigation in Nigeria. *Academic Journal of Interdisciplinary Studies,* 2 (12), 28-37.

EMEFIENE, M.E., JOSHUA, V.L., NWADIKE, C., YOROSON, A.Y. & ZWANON, N.D.E. 2014. Profitability analysis of pigeon pea production in Riyom LGA of Plateau state. *Academic Journal of interdisciplinary studies*, 3 (7), 44.

FAOSTAT (FAO statistical database).2017. Rome: Food and Agriculture Organisation of the United Nations, 2017 www.fao/faostat.

FAOSTAT.2015. FAO Statistic Division. Retrieved from http://faostat.fao.org/faostat/collection?version=ext&hasbulk08subset=agriculture. 2017 www.fao/faostat.

FASOYIRO, S. B. B., BABALOLA, S. O. O. & OWOSIBO, T. 2005. Chemical Composition and Sensory Quality of Fruit-Flavoured Roselle (*Hibiscus sabdariffa*) Drinks. *World Journal of Agricultural Sciences,* 1(2).

FATOKIMI, E.O. & TANIMONURE, V.A. 2021. Analysis of the current situation and future outlooks of pigeon pea (*Cajanus cajan*) production in Oyo State, Nigeria: A Markov chain model approach. *Journal of Agriculture and Food Research*, 6

FLEXAS, J., BOTA, J., CIFRE, J., ESCALONA, M., GALMÉS, J., GULÍAS, J., LEFI, E.-K., FLORINDA MARTÍNEZ-CAÑELLAS, S., MORENO, T., RIBAS-CARBÓ, M., RIERA, D., SAMPOL, B, & MEDRANO, H. 2004. Understanding down-regulation of photosynthesis under water stress: future prospects and searching for physiological tools for irrigation management. *In Annual Applied Biology,* 144.

FOOD & AGRICULTURE ORGANISATION OF THE NATIONS, (FAO). 2008. Climate change and food security: A framework document, Rome, 2008. www.fao.org.climatechange-2008.

FOOD & AGRICULTURE ORGANISATION OF THE UNITED NATIONS (FAO). 2015. The state of food and Agriculture (Social protection and agriculture: breaking the cycle of rural poverty), Rome, 2015. www.fao.org.family-farming/details-2015.

FOOD & AGRICULTURE ORGANISATION OF THE UNITED NATIONS (FAO). 2016. Nutritional benefits of pulses. 2016 International year of pulses. www.fao.org/pulses-2016.

FOOD & AGRICULTURE ORGANISATION OF THE UNITED NATIONS (FAO). 2017. www.fao.org/pulses-2017.

FU, B., CHEN, L., HUANG, H., QU, P. & WEI, Z. 2021. Impacts of crop residues on soil health: a review. *Environmental Pollutants and Bioavailability,* 33 (1), 164-173

FUJITA, K., KAI, Y., TAKAYANAGI, M., EL-SHEMY, H., ADU-GYAMFI, J. J. & MOHAPATRA, P. K. 2004. Genotypic variability of pigeon pea in distribution of photosynthetic carbon at low phosphorus level. *Plant Science*, 166(3), 641–649.

GAINES, T. P., ALLEN, G. & MITCHELL, G.A. 1979. “Boron determination in plant tissue by the azomethine H method.” *Communications in Soil Science and Plant Analysis,* 10, 1099-1108.

GAN, Y., CAMPBELL, C. A., JANZEN, H. H., LEMKE, R. L., BASNYAT, P. & MCDONALD, C. L. 2010. Nitrogen accumulation in plant tissues and roots and N mineralization under oilseeds, pulses, and spring wheat. *Plant and Soil,* 332(1), 451–461.

GANESH K. J. & LIU, B. 2014. Traditional methods of storing pigeonpea (*Cajanus cajan* L.) seeds using red soil. *Journal of Environmental Biology*,3 (10) 48- 52

GARG, B.K. 2003. Nutrient uptake and management under drought: nutrient – moisture interaction. *Curr Agriculture*, 27, 1-8.

GARLAND, G., BÜNEMANN, E. K., OBERSON, A., FROSSARD, E. & SIX, J. 2017. Plant-mediated rhizospheric interactions in maize-pigeon pea intercropping enhance soil aggregation and organic phosphorus storage. *Plant and Soil,* 415(1–2), 37–55.

GICHANGI, E.M. 2007. Enhancing Phosphorus availability in some phosphate fixing soils of the Transkei region, South Africa, using goat manure. PhD Thesis, University of Fort Hare, Alice, South Africa.

GILLER, K.E., HIJBECK, R., ANDERSON, J. & SUMBERG, J. 2001. Regenerative Agriculture: An agronomic perspective, *Outlook on Agriculture*, 50 (1), 13-25.

GITARI, J.N. & MUREITHI, J.G. 2003. Effect of P fertilization on legume nodule formation and biomass production in Mount Kenya Region. *East African Agriculture Journal,* 69, 183- 187.

GOMEZ, K.A., & GOMEZ, A.A. 1984. Statistical Procedure for Agricultural Research. John Wiley and Sons: Toronto, Canada.

GRANT, C., FLATEN, D., TOMASIEWICZ, D., SHEPPARD, S. & JOHNSTON, A. 2001. The Importance of Early Season Phosphorus Nutrition. *Canadian Journal of Plant Science.* 81. 10.4141/P00-093.

GUNDERSON, L. H., HOLLING, C. S., PRITCHARD LOWELL, J.R. & PETERSON, G. D. 2002. Resilience of large-scale resource systems. *Resilience and the Behaviour of Large-Scale Systems*, 60.

GWATA, E. T. & SHIMELIS, A. 2013. Evaluation of pigeon pea germplasm for important Agronomic Traits in Southern Africa. *Journal of Crop Production,* 10, 1 - 16.

HARDEV, C., SATYA, S., NOUSHAD, P., RAJOJWANGR, R. & SINGH, R.P. 2016. Performance of farmers' pigeon pea [*Cajanus cajan* L. MILLSP.] varieties:

Opportunities for sustained productivity and dissemination of varieties. *International Journal of Agriculture Sciences*, 8(61), 3471 – 3474.

HERRIDGE, D. F. & DAVID, F. 2013. New South Wales. Department of Primary Industries., Grains Research and Development Corporation (Australia), & University of New England. Managing legume and fertilizer N for Northern grains cropping.

HERRIDGE, D.F., PEOPLE, M.B. & BODDEY, R.M. 2008. Global inputs of biological Nitrogen fixation in agricultural systems. *Plant and Soil,* 311, 1-8.

HOGH-JENSEN, H., MNYAKA, K.A, SEKALA, W.D., KAMOLONGA, D., NGWIRA, A., VERSTERAZER, J.M., ODGAARD R. & ADU- GYAMFI, J.J. 2007. Yield and qualities of pigeon pea varieties grown under smallholder farmers' conditions in Eastern and Southern Africa. *African Journal of Agricultural Research,* 2 (6), 269 – 279.

HUSSAIN, A.I., ANWAR, F., SHEAZI, H.T.S. & PRZYBYISKI, R. 2008. Chemical composition, antioxidant and essential oil depend on seasonal variations *Food Chemistry*, 108, 986-999.

HUSSAIN, F., KHAN, R.U., HAYAT, A., AMED, H. & KHAN, A. 2020. Comparative scheduling of phosphorus application for enhancing rice yield and efficiency indices. *Pakistan Journal of Agricultural Research,* 33 (1), 72-77.

IGWE, C. U., OSUAGWU, C. & OJIAKO, O. 2010. Evaluation of the Chemical Compositions of the Leaf of *Spondias Mombin* Linn from Nigeria Article in. In *Australian Journal of Basic and Applied Sciences.*

Indian Journal of Agricultural Sciences,85 (3), 392-296.

JACKSON, M.L. 1967. Soil chemical analysis. Prentice Hall of India Ltd. New Delhi, Pg 498.

JONES. R.B., FREEMAN, H.A. & LO MONACO G. 2002. Improving the access of smallholder farmers in Eastern and Southern Africa to global pigeon pea markets. *Agricultural Research and Extension Network*, 120, 1-11.

JOSHI, P.K., PARTHASARATHY RAO, P., GOWDA, C.L.L., JONES, R.B., SILIM, S.N., SAXENA, K.B. & KIMAR, J. 2001. The world chickpea and pigeon pea economies' facts, trends and outlook. Patancheru 502 324, Andhra Pretesh, India: *International Crop Research Institute for the Semi-Arid Tropics*, 68pp.

KACHARE, D. P., SATBHAI, R. D., RATHOD, D. B. & NAIK, R. M. 2019. Evaluation of pigeon pea (*Cajanus cajan* l.) genotypes for nutritional quality. *Legume Research*, 42(4), 485–489.

KAHINDI, J.H.P., KARANA, N.P., ODEE, D, & MWAURA, F.B. 2004. The diversity of biological nitrogen fixing systems in Kenya. *Journal of tropical microbiology and biotechnology,* 3 (1), 35-47.

KAMANGA, B., WADDINGTON, S., WHITBREAD, A. & ALMEKINDERS, C., & GILLER, K. 2014. Improving the efficiency of use of small amounts of nitrogen and phosphorus fertilizer on smallholder maize in Central Malawi. *Experimental Agriculture*, 50, 229-249.

KANDARKA, K.G., KUTE, W.S., TAJANE, S.A. & INGLE, A.U. 2020. Correlation path and analysis for yield and its contributing traits in pigeon pea [*Cajanus cajan* (L.) Millsp.]. *Journal of Pharmacognosy and Phytochemistry*,9 (4), 1229-1632.

KANTWA, S.R., AHLAWAT, I.P.S. & GANGAIAH, B. 2011. Performance od sole and intercropped pigeon pea (*Cajanus cajan*) as influenced by land configuration, post-monsoon irrigation and phosphorus fertilization. *Indian Council of Agricultural Research*. www.agris.fao.org.

KANTWA, S.R., GANGAIAH, B. & AHLAWAT, I.P.S. 2004. Effect of land configuration, post monsoon irrigation and phosphorus on sole and intercropped pigeon pea (*Cajanus cajan*): In proceedings of national symposium on Resource Conservation and Agricultural productivity, 20-25, November 2004, PAU, Ludhiana, Punjab, pp 400-401.

KAUR, A., SINGH, H. & KANG, J 2017. Yield attributes and yield of pigeon pea [*Cajanus cajan* (L.) Mills.]as influenced by growth retardants and sowing dates. *International Journal of current microbiology and applied science*, 1201-1205.

KGONYANE, M.C., MARIGA, I.K. & DIMES, J.P. 2013. Low rates of nitrogen and phosphorus as fertilizer potions for maize production by smallholding farmers in drier regions of South Africa. *Journal of Research on Crops,* 14(2),444-454.

KIMANI, P. 2001. Pigeon pea breeding, objective and strategies in the eastern Africa. In: Silim, S.N, G. Mergeai, and P. Kimani, editors, Status and potential for pigeon pea in Eastern and Southern Africa. Proceedings of a regional Workshop, Nairobi, Kenya, 12-15 Sep. 2000. International Crops Research Institute for the Semi-Arid Tropics, Patancheru. 21-27.

KLEINERT, A.N., THYGNSMA, R., MAGADLELA, A., BENEDITO, V.A. & VALETINE, A.J. 2017. Metabolism and transport of carbon in legumes nodules under phosphorus deficiency, In Legume nitrogen fixation in soils with low phosphorus availability, ads. S., Sulleman and L.P Tran (Cham Springer International Publishing), 77-95.

KRISNAWATI, A. 2005. Prospek, Serta Pencandraai, Sifat, Kaulitatif Dan. Kaantitatif Kacang gude (*Cajanus cajan* Millsp.) Bulletin Polawija, 6 (9),1-10.

KUMAR, R., PASLARWAR, A.N., SINGH., U. & NAGAR, R.K. 2015. Effect of conservational tillage and growth and production and energetics of pigeon pea based intercropping system under rainfed area, International Science, Quarterly. *Journal of Environmental*, (1 & 2), 153-157.

KUO, S. 1996. Phosphorus, in: ''Methods of soil analysis. Part 3 Chemical methods''. In: Sparks D.L., (Ed.) SSSA and ASA. Madison, W.I. Pp 869-920.

LAKSHMI, M., SELTHINKUMAR, P., PARANI, M., JITHESH, M.N. & PARIDA, A.J. 2000. PCR- RFLP analysis of chloroplast gene regions in Cajanus and allied genera. *Euphytica Journal*, 116,243-250.

LEVIN, K. BOEHM, S. & CARTER, R. 2022. Six big findings from the IPCC 2022 report on climate impacts, adaptation, and vulnerability, 27 February 2022. https://www.wri.org/.

LI, I.I., WANG, X., LIANG, X., LYU, X., LI, S., GONG, Z., DONG, S., YAN, C. & MAI, C. 2021. Regulation of phosphorus supply on nodulation and nitrogen fixation in soybean plant with dual root system. *Agronomy,* 11, 2353-2354.

MABAPA, M.P., AYISI, K.K. & MARIGA, I.K. 2017. Effect of planting density and harvest interval on leaf yield and quality of moringa (*Moringa oleifera*) under diverse agro-ecological conditions of Northern South Africa. *International Journal of Agronomy,* 2017.

MADEGWA, Y., ONWANGA, R., SOLOMON, S. A. & KARKU, G.N. 2016. Farmer perception and adoption strategies on climate change in lower eastern Kenya: A case study of finger millet [Eleusine coracana (L) Gaerth] production. *Journal of Agriculture Science,* 8(12), 33.

MAFAKHERI, A., SIOEMARDEH, A., BAHRAMNEJAD, B., STRUIK, P.C. & SOHRABI, Y. 2010. Effect of drought stress on yield, proline and chlorophyll contents in three chickpea cultivars. *Australian Journal of Crop Science,* 4, 580-585.

MAFONGOYA, P.L., BATIONO, A., KIHARA, J. & WASWA, B.S. 2006. Appropriate technologies to replenish soil fertility in Southern Africa. *Nutrition cycled of Agroecosystems*, 76, 137-151.

MAHAPATRA, C, CHAND, R., TIWARI. J.K. & SINGH, A.K. 2020. Effects of heat stress during flowering and pod formation in pea (*Pisum sativum* L.). *Physiology Biology. Plants,* 26 (6), 1119-1125.

MAHETELE, D., & KUSHWAHA, H.S. 2011. Productivity and profitability of pigeon pea influenced by FYM, PSP and phosphorus fertilization under rainfed conditions. *Journal of food legumes*, 24 (1), 72-74.

MAJILI, Z. S., NYARUHUCHA, C., KULWA, K., MUTABAZI, K., RYBAK, C. & SIEBER, S. 2020. Preferences and consumption of pigeon peas among rural households as determinants for developing diversified products for sustainable health. *Sustainability* (Switzerland), 12, (15).

MAKELO, M.N. 2011. Development of pigeon pea hybrids for semi-arid Kenya. Ph.D. Dissertation, University of Kwazulu-Natal. Pietermaritzburg.

MAKUMBA, W., AKIMIFESI, F.K. & JENSSEN, B.H. 2009. Spatial rooting patterns of gliricidia, pigeon pea, and maize intercrop and effect on profile soil N and P distribution in Southern Malawi. *African Journal of Agricultural Research,* 4 (4), 278- 288.

MALIK, A.A., SURYAPANI, S. & AHMAD, J.2011 Chemical vs organic cultivation of medicinal and aromatic plants: the choice is clear. *International Journal of Medicinal Aroma Plants*, 1(1), 5-13.

MAPFUMO, E., GILLER, K.E., MPEPEREKI, S. & MAFONGOYA, P.L. 1999. Dinitrogen fixation by pigeon pea of different maturity types on granitic sandy soil in Zimbabwe. *Symbiosis*, 27, 303-318.

MATHOBO, R. & MARAIS, D. 2017. The effect of drought stress on yield, leaf gaseous exchange and chlorophyll fluorescence of dry beans (*Phaseolus vulgaris* L.). *Agricultural Water Management*, 180(A), 118-125.

MATIRU, V.N. & DAKORA, F.D. 2004. Potential Use of Rhizobial Bacteria as Promoters of Plant Growth for Increased Yield in Landraces of African Cereal Crops. *African Journal of Biotechnology*, 3, 1-7.

MATTHEWS, C. & SAXENA, K.B. 2000. Prospects for pigeon pea evaluation in drought-prone areas of South Africa, South Africa. *Pigeon pea Newsletter*, 8, 52-53.

MATTHEWS, C. SAXENA. K.B, & SILIM, S.N. 2001a. Evaluation of short, medium and long-duration pigeon pea cultivars in Mpumalanga, South Africa*.* *International Chickpea and Pigeon pea, Newsletter* (ICPN), 8, 37-38.

MATTHEWS, C., JONES, R.B. & SAXENA, K.B. 2001b. Maize and pigeonpea intercropping systems in Mpumalanga, South Africa. *International Chickpea and pigeonpea Newsletter,* 8, 52-53.

MEGAT RUSYDI, M. R., NORALIZA, C. W., AZRINA, A. & ZULKHAIRI, A. 2011. Nutritional changes in germinated legumes and rice varieties. *International Food Research Journal*, 18(2).

MENEZES, E.W., DE MELO, A.T., LIMA, G.H. & LAJOLO, F.M. 2004. Measurement of carbohydrate components and their impact on energy value of foods. *Journal of Food Composition and Analysis*,17, 331-338.

MERGEAI, G., KIMANI, P., MWANG'OMBE, A., OLUBAYO, F., SMITH, C., AUDI, P., BAUDOIN, J.P. & LE ROI, A. 2001. Survey of pigeon pea production systems, utilisation and Marketing in semi-1rid land of Kenya. *Biotechnology Agronomy Society and Environment*, 5(3), 145 – 153.

MISHRA, V., MUKKHERJE, S., KUMAR, R. & STONE, D.A. 2017. Heatwave exposure in India in current, 1.5°C and 2.0°C worlds. *Environmental Research Letter,* 12, 124012.

MOKANY, K., RAISON, R. J. & PROKUSHKIN, A. S. 2006. Critical analysis of root: shoot ratios in terrestrial biomes. *Global Change Biology*, 12(1). https://doi.org/10.1111/j.1365-2486.2005.001043.

MOHAR, S., NARINDER, K.G., MUKESH, K.R., OM P.D. & DUTTA, M.2014. Pigeon pea genetic resources and its utilization in India, current status and future prospects. *Journal of plant science research*,1 (2), 107

MORAKE, T.K., MUNTHALI, D.C., KARIKARI, S.K. & AMARTEIFIO, J.O. 2002. The composition of pigeon pea grown in Botswana. *Plant Foods for Human Nutrition,* 57, 173-177.

MPONDA, O., KIDUNDA, B. BENNETT, B. & ORR, A. 2013. A value chain analysis for pigeon pea in Southern regions of Tanzania, ICRISAT, Socioeconomics discussion paper. *Series*, 3, 1-42.

MULA, M.G. & SAXENA, K.B. 2010. Lifting the level of awareness on pigeonpea: Some global perspectives, ICRISAT, PATANCHERU, ANDHRA, Pradesh, India.

MULLER, U., GRIMME, K., MEYER, C. & EHLERS, W. 1986. Leaf water potential and stomatal conductance of field grown faba beans (Vicia faba L.) and oats (Avena sativa L.) *Plant and Soil,* 93, 17-33.

MUNJONJI, L., AYISI, K. K., BOECKX, P. & HAESAERT, G. 2018. Stomatal behavior of cowpea genotypes grown under varying moisture levels. *Sustainability* (Switzerland), 10(12), 1-16.

MUNJONJI, L., AYISI, K. K., BOECKX, P. & HAESAERT, G. 2018. Screening cowpea genotyped for high Biological Nitrogen Fixation and grain yield drought conditions. *Agronomy Journal*, 110 (5), 1-11

MUNJONJI, L., AYISI, K. K., MAFEO, T. P., MAPHANGA, T. & MABITSELA, K. E. 2021. Seasonal variation in soil CO2 emission and leaf gas exchange of well-managed commercial Citrus sinensis (L.) orchards. *Plant and Soil*, 465 (1–2), 65–81.

MURPHY, J. & RILEY, J.P. 1962. A Modified single solution for the determination of phosphate in natural waters. *Analytical Chimica Acta,* 27, 31-36

MUSOKWA, M. & MAFONGOYA, P. 2021. Pigeonpea yield and water use efficiency: A saviour under climate change induced water stress. *Agronomy,* 11(5), 1-14.

MWALWANDA, A.B., MUGHOGHO, S.K., SEKALA, D.W. & SAKA, A.R. 2003. The effect of phosphorus and sulphur on green manure legume biomass and the yield of subsequent maize in Northern Malawi: In Waddington SR(ed.), Grain Legume and Green manures for soil fertility in Southern Africa. Proceedings of a conference held 8-11 October 2002 at the Leopard Rock Hotel, Vumba Zimbabwe, Harare: Soil fertility Net and CIMMYT Zimbabwe, pp 197-204.

MWANLIMA, L.H., OUMA., P, & CHERUIYOT, E.K. 2020. Leaf gas exchange and root nodulation respond to planting density in soybean [Glycine max (L) Merrill.]. *Advance in Agriculture, 2020, 1-7.*

NATAKE, T. 2012. Patterns of soil texture and root biomass along humid tropical forest Hillslope Catena. Spring 2012, Nature Berkeley, edu/classes/es196/projects/2012final/natake_2012.

MUGI-NGENGA, E., ZINGORE, S. & BASTIAANS, L. 2021. Farm-scale assessment of maize–pigeonpea productivity in Northern Tanzania. *Nutritional Cycling Agroecosystems,* 120, 177–191

NNDWAMBI, F. H., MARIGA, I. K. & KUTU, F.R. 2016. Growth and yield responses of pigeon pea to variable phosphorus application rates when intercropped with maize under dryland conditions. *Journal of Agriculture and Crops*, 2(12),121 - 130.

ODENY, D. A. 2007 The potential of pigeon pea in Africa. *Natural Resources Forum,* 31, 297-305.

OJWANG, J.D. NYANKANGA, O.R., IMUNGI, J. & OLANYA, O.M. 2016 Plant characteristics and growth variables of vegetable pigeon pea cultivars. *Hortechnology,* 26(1),97-105.

OKALEBO, J.R., GATHUA, K.W, & WOOMER, P.L. 2002. Laboratory methods of soil and plant analysis: A working Manual Second Edition, SACRED Africa, Nairobi, Kenya.

ONYIA, A.O. & HERZOG. H., 2004. Water use efficiency, leaf area and leaf gas exchange of cowpea under mid-season drought. *European Journal of Agronomy*, 20, 327-335.

ORR, A., KABOMBO, B., ROTH, C., HARRIS, D. & DOYLE, V. 2013. Testing integrated food energy system: Improved stover and pigeon pea in Southern Malawi. *Series paper* 8.

ORWA, C., MUTUA, A., KIND, R., JAMNADASSI, R. & ANTHONY, S. 2009. Agroforestry database: a tree reference and selection guide version 4.0 world Agroforestry centre, Kenya.

PADI, K.K. 2003. Correlations and path coefficient analyses of yield and yield components in pigeon pea. *Pakistan Journal of Biological Science,* 6 (19), 1689- 1694.

PANG, J., RYAN, M. H., LAMBERS, H. & SIDDIQUE, K. H. 2018. Phosphorus acquisition and utilisation in crop legumes under global change. In Current Opinion in *Plant Biology*, 45, 248–254

PAVANI, R., JAYALALITHA, R., UMAMAMASH, V., SEEREKHA, M. & CUJAN RAO, C. 2022. Variation in root traits of pigeon pea [*Cajanus cajan* (L.,) Millsp.] Genotypes under rainfed conditions. *Biological Forum* 14(2) 464-465.

PIMENTEL, C. & DA SILVA, J.V. 1999. Effects of drought on O2 evolution and stomatal conductance of beans of beans at the pollination stage. *Environmental and Experimental Botany,* 42(2), 155-162.

PRAMANIC, M.Y.A., SARKAR, M.A.R., UDDIN, M.S. & FARUK, G.M. 2009. Effects of phosphorus on growth, nodulation and biomass yield of green manure crop. *Journal of Bangladesh Agriculture University,* 7(1), 23-28.

PRASAD, P.V.V., Staggenborg, S.A & Ristic, Z. 2008. Impacts of drought and/or heat stress on physiological development, growth, and yield processes of crop plants. In: Ahuja L.R., Reddy V.R., Saseendran S.A., Yu Q., Editors. Response of crops to limited water: Understanding and modeling water stress effects on plant growth processes, ASA, CSSA, SSSA, Madison, WI, USA. *Advance in Agricultural systems modeling*, 301-355

PURWANTO, B.S. & JUNAIDAH. 2015. Effect of the combination of some fertilizers on chlorophyll content of Gemor (*Nothaphoebe coriacea*) *Indonesia, Asian Journal of Applied Science,* 3(4), 699-703.

PURWANTO, I. 2007. MengenalLebih Dekat Luguminoseae, Yogyakarta, Kanisiu

RAEMAEKERS, R.H. 2001. Crop production in Tropical Africa, Directorate General for International Cooperation, Ministry of Foreign Affairs, External Trade and International cooperation.

RAO, S.C., MACKOWN, C.T. & BILACK., J.E. 2002. Biomass and Nitrogen traits of summer pigeon peas and winter wheat grown for three rotations in containers. Communication, soil science. *Plant Analysis*, 33 (5 & 6), 897-912.

RAVINDRANATH, N.H. & OSTWALD, M. 2007. Methods for Below ground biomass. C Inventory Methods Handbook for Greenhouse Gas Inventory, C Mitigation. *Round Wood Production projects*, 149 -156.

RENAWAKE, A.L., DAHANAYAKE, N.J. & KUMARI, R.D.G. 2010. Assessment of submergence tolerance of some traditional and modern rice cultivar in Sri Lanka, 8th Academic session, University of Ruhuna, p187.

RENWICK, L.LR., KIMARO, A.A., HAFNER, J.M., ROSENSTOCK, T.S. & CAUDIA, A.C.M. 2020. Maize pigeon pea intercropping outperforms monocultures under drought. Frontier Sustainability Food Systems, 41.

REYNOLDS-HENNE, C LANGENEGGER, A., MANI, J., SCHENK, N., ZUMSTEG, A. & FELLER, U.2010. Interactions between temperature, drought and stomatal opening in legumes. *Environmental and Experimental Botany*, 68, 37-43

ROBERTS, T.C. & JOHNSON, E.A., 2015. Resources, conservation and recycling. *Journal of Conservation and Recycling*, 105, (275 -281).

RUSINAMHODZ, L.M., CORBEELS, M.T., VAN WIK, NYAMANGARA, J. & GILLER KE. 2011. Long-term maize-pigeon pea intercropping increases productivity and rainfall infiltration in degraded sandy soil in central Mozambique. In:10th African Crop Science Society Conference Proceedings. From soil to soul crop production for improved African livelihoods and a better environment for future generations, 10th-13th October 2011, Maputo, Mozambique. ACSS. Mozambique: s.n., Resume, p.240. African Crop Science Conference, 10 Maputo, Mozambique, 10 October 2011.

SAS (Statistical Analysis Software). 2016. Institute Inc. SAS @ 9.4 LANGUAGE, 2016; Concepts, Six Edition, Cary: SAS Institute Inc.

SAXENA, K.B., CHOUDHARY, A.K., SAXENA, R.K, & VARSHNEY, R.J. 2018. Breeding pigeon pea cultivars for intercropping: synthesis and strategies. *Breeding Science*, (68), 159-167.

SAXENA, K.B., KUMAR, R.V. & SULTANA, R. 2010. Growth and production of pulses. *Soils, Plant Growth and Crop production*, 3,1-9.

SAXENA, K. 2008. Genetic improvement of pigeon pea a review. *Tropical Plant Biology,* 1, 159-178.

SAXENA, K., BOHRA, A., CHOUDHARY, A.K., SULTANA, R., SHARMA, M., PAZHAMALA, L.T. & SAXENA, R.K. 2020. The alternative breeding approaches for improving yield gains and stress response in pigeon pea (*Cajanus cajan*). Plant breeding, 140, 74-84.

SCHIEMENZ, K. & EICHLER-LÖBERMANN, B. 2010 Biomass ashes and their phosphorus fertilizing effect on different crops. *Nutrient Cycle Agroecosystem,* **87**, 471–482

SCOTT, H.D. 2000. Soil physics. Agricultural and Environmental applications. Published at Iowa State University Press, USA.

SHONOWER, T.G., ROMEIS, J. & MINJA, E.M. 1999. Insect pest of pigeonpea and their management. *Annual Revue Entomology*, 44, 77-96.

SIDDIQUE, M.R.B., HAMID, A., & ISLAM, M.S. 2001. Drought stress effects on water relations of wheat, Botanical. *Bulletin. Academia. Sinica,* 41, 35-39.

SILIM, S.N. & OMANGA, P.A. 2001. Response of short–duration pigeon pea lines to variation in temperature under field conditions in Kenya. *Field Crops Research, 72, 97-108*.

SINGH, A., FROMM, I., JHA, G.K., VENKATESH, P., JEWARI, H., PADARIA, R. & EGGER, U. 2020. Understanding pigeon pea (*Cajanus cajan*) production conditions, stakeholder's preferences for varietal traits and their implication for breeding programmes in India. J*ournal of Plosone*, 15 (2).

SINGH P.K., KUMAR S., KUMAR A. & KUMAR S. 2014. Effect of phosphorus and Sulphur fertilization on growth, nutrient uptake, their recovery and use efficiency by pigeon pea [*Cajanus cajan* (L.,) Millsp.,] genotypes. *Asian Journal of Biological and Life Sciences*, 3, (70-76).

SINGH, D., MATHIMARAN, N., BOLLER, T. & KAHMEN, A. 2020. Deep rooted pigeon pea promotes water relation, and survival of shallow rooted finger millet during drought- Despite strong competitive interactions at ambient water availability. https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0228993

SINGH, R., MALIK, J.K., THENUA, O.VS. & JAT, H.S. 2013. Effect of phosphorus and bio-fertilizer on productivity, nutrient uptake, and economies of pigeon pea (*Cajanus cajan*) and mungbean (*Phaseolus raditus*) intercropping system. *Legume Research and International Journal,* 36 (1), 41- 48.

SINGH, R.S. & YADAC, M.K. 2008. Effect of phosphorus and biofertilizers on growth, yield, and nutrient uptake of long-durations pigeon pea under rainfed conditions. *Journal of food legumes*, 21 (1), 46-48.

SNAPP, S.S. 2003. Pigeon pea for Africa: A versatile vegetable. Horticultural Science

SOGBEDJI, J.M., VAN E.S, H.M. & ANDAGBEBO, K.L. 2006. Cover cropping and nutrient management strategies for maize production in Western Africa. *Agronomy Journal*, 98, 883-889.

SOIL CLASSIFICATION WORKING GROUP. 1991. Soil classification. A taxonomic system for South Africa. *Institute for Soil, Climate and Water*, 38:1-6.

STATISTA, 2022. Number of people undernourished in South Africa from 2000 to 2022. Galal, S. 2022. www.statista.com.

STEPHEN, O.D., OZEGBE, B., OSAWE, G.O. & MICHAEL, C.G. 2014. Residual effect of phosphorus fertilizer on yield of pigeonpea (*Cajanus cajan*) in Ultisol. *American Journal of Experimental Agriculture*, 4, 1783-1792.

STEVENS, N.J., PEREZ-FERNADEZ, MA., MARCILLO, R.L., KLEINERT, A., HILLS, P., BRAND, D.J., STEENKAMP, E.T. & VALENTINE, A.J. 2019. Root and nodules response differently to P starvation in the Mediterranean-type legume *Virgilia divaricate*. *Frontiers in Plant Science*, 10, 73.

SUBBARAO, G.V., NAM, NH., CHAUHAN, Y.S. & JOHANSE, N.C. 2000. Osmotic adjustment, water relations and carbohydrate remobilization in pigeon pea under water deficits. *Journal of Plant Physiology,* 157 (6),651-659,

SUDHARANI, Y., MOHAPATRA, P., PRAMANIK, K. & MAITRA, S. 2020. Effect of Different Phosphorus Levels on Growth and Yield of Cowpea (*Vigna unguiculata* L.) Genotypes*. International Journal of Management, Technology and Engineering,* 2876-2880

SURESH NAIDU, K., BHADAURIA, H., KHADIA, S., SURESH, K., BHADAURIA, H. S., RAVINDRA, Y. & SATISH, K. 2015. Drought-induced changes in Root and Shoot Growth of Pigeonpea [*Cajanus cajan* (L.) Millspaugh] Heterosis, Combining Ability and Stability Analysis in Okra [*Abelmoschus esculentus* (L.) Moench] View project Seasonal impact on production of alkaloids in Tulsi (Ocimum sanctum L.) and Ardusi (Adhatoda vasica Nees.) View project Drought-induced Changes in Root and Shoot Growth of Pigeonpea [*Cajanus cajan* (L.) Millspaugh] (Vol. 33, Issue 4).

TAIRO, E. V. & NDAKIDEMI, P. A. 2013. Possible benefits of rhizobial inoculation and phosphorus supplementation on nutrition, growth and economic sustainability in grain legumes. www.usa-journals.com

TAYYAB, M.A., QASIM, M., AMED, N. & AHMAD, R. 2016. Salt stress responses of pigeon pea (*Cajanus cajan*) on growth yield and some biochemical attributes. *Pakistan Journal of Botany*, 48(4), 1353-1360.

THUYNSMA, R., KLEINERT, A., KOSSMANN, J., VALENTINE, A. J. & HILLS, P. N. 2016. The effects of limiting phosphate on photosynthesis and growth of *Lotus japonicus. South African Journal of Botany,* 104, 244-248.

UNKOVICH, M., BALDOCK, J. & FORBES, M. 2010. Variability in Harvest Index of Grain Crops and Potential Significance for Carbon Accounting: Examples from Australian Agriculture. In *Advances in Agronomy*,105, 173–219. Academic Press Inc.

VANAJA, M., MAHESWARI, M., SATHISH, P., VAGHEERA, P., LAKSHMI, N. J., KUMAR, G. V., SALINI, K., JAINENDER, N. S. & YADAV, S. K. 2015. Variability in Phenology, Physiology and Yield Response of Different Maturity Duration Pigeon Pea Genotypes at Elevated CO 2. *Climate Change and Environmental Sustainability*, 3(2), 131.

VASHISTH, S., JAGDISH, J., PATHANIA, M., SHARMA, SP., MUNGHATE, R.S. & SHARMA, H.S. 2016 Climate change effects on pest incidence in pigeon pea. International Crop Research Institute for the Semi-Arid Tropics (ICRISAT), Petancheru. 502 324, Telangana, India. 2016.

VIERA, G. H. S., SILVA, A. S., JANI, A. D., PREZOTTI, L. & MONACO, P. A. V. 2021. Surface residues: Effects on soil moisture and temperature1. *Revista Caatinga,* 34(4), 887–894. https://doi.org/10.1590/1983-21252021v34n416rc

VITTAL, K.P.R., ALI, M., CHARY, G.R., SANKAR, G.R.M., RAMARKRISHINA, Y.S., SRIJAYA, T., SAMRA J.S & G. SINGH. 2004. District–wise promising technologies for rain-fed pigeon pea based production system in India. All India Co-ordinated research project for dryland agriculture, Central Research Institute for dryland Agriculture, *Indian Council for Agricultural Research*, (Hyderabad), 132.

WANG, Y., SPERRY, J. S., VENTURAS, M. D., TRUGMAN, A. T., LOVE, D. M. & ANDEREGG, W. R. L. 2019. The stomatal response to rising CO 2 concentration and drought is predicted by a hydraulic trait-based optimization model. *Tree Physiology,* 39, 1416–1427.

WHITBREAD, A. M., JIRI, O. & MAASDORP, B. 2004. The effect of managing improved fallows of *Mucuna pruriens* on maize production and soil carbon and nitrogen dynamics in sub-humid Zimbabwe. *Nutrient cycling in Agroecosystem,* 69, 59-71.

WIECZOREL D.J., ZYSZKA-HEBERECHT, B. & KAFKA, A. 2022. Determination of phosphorus compounds in plant tissue from calorimetry to advanced. *instrumental analytical Chemistry Plant methods,* 18, 22.

WILSON, C., HUI, D., NWANERI, E., WANG, J., DENG, Q., DUSEJA, D. & TEGEGNE, F. 2012. Effects of planting dates, densities, and varieties on ecophysiology of pigeonpea in the South-eastern United States. *Agricultural Sciences,* 03(02), 147–152.

XIN, X., BELLALONI, N., MCCLURE, A.M., TYLER, D.D. & MENGISTU, A. 2006. Phosphorus fertilisation differently influences fatty acids, protein and oil in soybean. *American Journal of plant sciences,* (7), 1476-1486.

YASER, T.A., WASAYA, A. & HUSSAIN, M. 2018. Evaluation of physiological markers for assessing drought tolerance and yield potential in bread wheat. *Physiology Molecular Biology Plants,* 25, 1163–1174.

YIN, X., BELLALOUI, N., MCCLURE, A. M., TYLER, D. D. & MENGISTU, A. 2016. Phosphorus Fertilization Differentially Influences Fatty Acids, Protein, and Oil in Soybean. *American Journal of Plant Sciences*, 07(14), 1975–1992

YUDE, C., KAIWEI, H., FUJI, L. & JIE, J. 1993. The potential and utilization prospects of kinds of wood fodder resources in Yunman. *Forestry Research,* 6, 346: 350.

ZAHRAN, H.H. 1999. Rhizobium-Legume symbiosis and Nitrogen fixation under severe conditions and in an arid climate. *Microbiology and Molecular Biology Review*, 63(4), 968-989.

ZHANG, Q., PENG, S. & LI., Y. 2019. Increase rate of light induced stomatal size in the genus Oryza. *Journal of Experimental Botany*, 70 (19), 5259-5269.

APPENDICES

Appendix 3.2 to 3.22: Questionnaire used to collect information in both Provinces

A SURVEY ON PIGEON PEAS (*CAJANUS CAJAN (L.)* MILLSPAUGH*)* PRODUCTION, FARMER'S PRACTICES, UTILIZATION AS WELL AS POTENTIAL MARKETS IN LIMPOPO AND MPUMALANGA PROVINCES, SOUTH AFRICA

A. GENERAL INFORMATION (RESPONDENT)

Name of the respondent: …………………………………………………………

Contact details: …………………………………………………………

Province: …………………………………………………………

District: ………………………………………………………….

Municipality: ………………………………………………………….

Village: ………………………………………………………….

Ward Number: …………………………………………………………

Geographical coordinates: …………………………………………………………

Date: …………………………………………………………

B. FARMER'S DEMOGRAPHICS/ PERSONAL INFORMATION (Please mark using an x)

Q1**.** What agricultural activity .

are the farmers engaged in? (Category of farmer)

1. Subsistence/backyard garden ☐ 2. Smallholder/Emerging ☐ 3. Commercial ☐

Q2. Gender of the farmer

1. Male ☐ 2. Female ☐

Q3. How old is the farmer? Age (Years)

1. Below 30 ☐ 2. 30-40 ☐ 3. 40-50 ☐ 4. 50-60 ☐ 5. Above 60 ☐

Q4. What is the farmer's level of farming experience/skills? (Years)

1. Below 3 ☐ 2. 4 to 6 ☐ 3. 7 to 10 ☐ 4. Over 10 ☐

Q5. What is the farmer's main source of income?

1. Farming/agricultural activities ☐ 2. Wage/salaried employed ☐ 3. Other business ☐ 4. Social grant ☐ 5. Agricultural labor ☐ 6. Other ☐

Q6. Do you own agricultural land?

1. Yes ☐ 2. No ☐

Q7. What is your farm size? (Ha)

1. Less than 1 ☐ 2. 2 to 5 ☐ 3. 6 to 10 ☐ 4. 11-20 ☐ 5. Above 20 ☐

Q8. Where do you plant pigeon peas?

1. Lease ☐ 2.Backyard/garden ☐ 3. Other ☐

Q9. Please indicate the type of land ownership

1. Individual ☐ 2. Communal ☐ 3. Community property association (CPA) ☐ 4.Lease ☐ 5. Private ☐ 6. Cooperative ☐ 7. Trust ☐ 8. Close corporation ☐ 9.Family ☐ 10. Other ☐

C. PIGEON PEA VALUE ADDING AND PROCESSING

Q1. Are you involved in pigeon pea processing?

1. Yes☐ 2.No ☐

Q2. Which pigeon pea available processed products do you know?

1. Flour ☐ 2. Frozen veggies☐ 3. Dried Veggies☐ 4. Dried grains☐

Q3. How do you prepare pigeon peas?

1. Soup☐ 2. Vegetable/morogo ☐3. Sump☐ 4. Snack☐

Q4. Would you preserve products for use at a later stage?

1. Yes ☐ 2.No ☐

Q5 Have you trained in pigeon pea processing techniques?

1, Yes☐ 2.No☐

Q6. If not, are you willing to be trained?

1. Yes ☐ 2.No ☐

D. PIGEON PEA PRODUCTION AND UTILISATION

Q1. What is the area of your farm used to grow pigeon peas last season? (in ha)

1. Less than 0.25 ☐ 2. 0.5 to 0.9 ☐ 3. 1 ☐ 4. 2-4☐ 5. Above 5☐

Q2. Do you irrigate pigeon peas?

1. Yes ☐ 2.No ☐

Q3. If yes, where do you get water for irrigation? Source of water

1. River/ dam/canal ☐ 2. Municipal water☐ 3. Borehole☐ 4. Harvested water ☐ 5. Other☐

Q4.What was pigeon pea yield (kg) in the last season?

1. Less than 1 ☐ 2. 2-10 ☐ 3. 15 to 30☐ 4. 50 to 100☐ 5. 200-500☐ 6. 600 to 1000☐ 7. Above 1000☐

Q5. How do you rate your last season's yield?

1. Very low ☐ 2. Moderate ☐ 3. High ☐

Q6. What were the natural hazards that negatively affected your yield level last season?

1. None ☐ 2.Drought ☐3. Excessive Temperatures (heat stress)☐ 4. Flood☐
5. Other ☐

Q7. What yield in kilogram do you normally get if not affected by natural hazards?

1. Less than 1 ☐ 2. 2-10 ☐ 3. 15 to 30☐ 4. 50 to 100☐ 5. 200-500☐ 6. 600 to 1000☐ 7. Above 1000☐

Q8. Indicate how many plants of pigeon peas/area were planted.

1. Less10 ☐ 2. 20 -40 ☐3. 50 -100☐ 4. Above 150 ☐ 5. Other☐

Q9. What are your plans for the future in terms of yield that you want to achieve?

1. ☐ Increase production scale/no. of plants/area

2. ☐ Apply irrigation during dry seasons

3. ☐ Use improved seed varieties

4. ☐ Apply fertilizers according to fertilizer recommendations

Q10. Choose one of the most important characteristics in selecting a pigeon pea variety.

1. High yield ☐

2. Taste ☐

3. Grain quality ☐

4. Early maturing ☐

5. Disease tolerance ☐

Q11. Refer to Q9…. could you please place pigeon pea characteristics in the rank of importance (position 1 to 5)

1. High yield ☐

2. Taste ☐

3. Quality ☐

4. Early maturing ☐

5. Disease tolerance ☐

Q12. Specify why are you growing pigeon pea. **N.B you can tick more than once**

1. Consumption ☐ 2.income ☐ 3. Soil improvement ☐ 4. Fodder ☐ 5. Mulch/cover crop ☐ 6. Income and consumption 7.Other ☐

E. PIGEON PEA PRODUCTION PRACTICES

Q1. When was your last soil analysis/ test? (Years)

1. Never ☐ 2. 1-3 ☐ 3. More than 5 ☐

Q2. How do you prepare your soil?

1. Conventional ☐ 2.minimum tillage ☐ 3. No-till ☐ 4. Other ☐

Q3. Where do you source your pigeon pea seeds?

1. Bought ☐ 2. Recycling ☐ 3. From Neighbour ☐ 4. Other ☐

Q4. If seeds are recycled, how do you store them?

1. Using indigenous methods ☐ 2. Using Chemicals ☐ 3.Other ☐

Q5. Which season are you planting pigeon peas?

1. Summer ☐ 2. Autumn ☐ 3. Winter ☐ 4. Spring ☐

Q6. How much seed kg^{-1} did you plant ha^{-1}

1. Less than 1 ☐ 2. 2-10 ☐ 3. 11 – 25☐ 4. 30 to 75☐ 5. Unknown☐

Q7. Which pigeon pea variety did you plant last season?

1. Local (landraces) ☐ 2.Hybrid☐ 3. Open-pollinated variety (OPVs)☐ 4. Unknown☐

Q8. Have you changed your variety since last year?

1. Yes☐ 2.No☐

Q9.Do you have access to information on pigeon pea production practices or management?

1. Yes☐ 2.No☐

Q10. If yes, where do you access information?

1. Department of Agriculture☐ 2. Research institutions ☐ 3. NGOs ☐ 4.Private companies☐ 5. Literature☐ 6. Other☐

Q11. Which cropping system are you practicing in producing pigeon peas?

1. Sole ☐2. Intercropping ☐ 3. Rotational ☐ 4.Mixed☐

Q12. If intercropped, rotated, or mixed with which crops?

1. Grains ☐2. Vegetables ☐3. Fruit trees ☐4.Fodder ☐ 5. Indigenous trees ☐ 6. Other☐

Q13. Do you control weeds when producing pigeon peas?

1. Yes ☐ 2.No ☐

Q14. If yes, how frequently?

1. Once ☐ 2.Twice ☐ 3.Three times or more☐

Q15. Which methods are used to control weeds?

1. Manual ☐2. Herbicides/chemicals ☐3.Mechanical☐ 4. Cropping system☐

Q16. What is the major constraint that results in low pigeon pea production?

1. Unavailability of improved seed ☐ 2. Mechanization ☐ 3. Pests ☐ 4. Diseases ☐ 5. Poor Soil fertility ☐ 6 High production costs ☐ 7. Other ☐

Q17. How do you control pests/diseases when producing pigeon peas?

1. Never ☐ 2. Pesticides/insecticides ☐ 3. Use of cropping systems ☐ 4. Other ☐

Q18.How do you harvest your pigeon pea?

1. Manual ☐ 2. Mechanical (harvester) ☐

Q19. Have you used commercial fertilizers in producing pigeon peas?

1. Yes ☐ 2.No ☐

Q20. What type of fertilizer have you used?

1. NPK ☐ 2. Phosphate ☐ 3.Nitrogen ☐ 4. Compost ☐ 5. Kraal manure ☐ 6. None ☐

Q21. Have you applied according to the fertilizer recommendation?

1. Yes ☐ 2.No ☐

Q22.How much have you applied (kg/ha)

NPK	**kg/ha mark with X**	**Phosphate**	**kg/ha mark with X**	**Nitrogen**	**kg/ha mark with X**	**Compost**	**kg/ha mark with X**	**Kraal manure**	**kg/ha mark with X**
0	1	0	1	0	1	0	1	0	1
10	2	10	2	10	2	10	2	10	2
20-30	3	20-30	3	20-30	3	20-30	3	20-30	3
More than 50	4	More than 50	4	More than 50	4	More than 50	4	More than 50	4

Q23. When have you applied fertilizers?

1. At planting☐ 2. Top dressing☐3.Twice (planting and topdressing)☐ 4. No application☐

Q24. Have you changed your fertilization programs since you have started planting pigeon peas?

1. Yes ☐ 2. No☐

Q25. If yes, what type of fertilizer have you use last season?

1. Inorganic/commercial fertilizers ☐ 2. Kraal/ chicken manure☐ 3. Compose ☐

F. POTENTIAL MARKETS

Q26. State labor required in pigeon pea production

Planting	**No./ha mark with X**	**weeding**	**No./ha mark with X**	**Fertilizing**	**No./ha mark with X**	**Harvest-ing**	**No./ha mark with X**	**Processing**	**No./ha mark with X**
0	1	0	1	0	1	0	1	0	1
1-5	2	1-5	2	1-5	2	1-5	2	1-5	2
6-8	3	6-8	3	6-8	3	6-8	3	6-8	3
More than 10	4	More than 10	4	More than 10	4	More than 10	4	More than 10	4

Q27. Are you selling pigeon pea products?

1. Yes ☐2.No☐

Q28. Where have you sold your pigeon pea products?

1. Locally ☐ 2. National ☐3. Export☐ 4.Consumption ☐ 5 Other☐

Q29. Are market opportunities available for pigeon peas?

1. Yes☐ 2.No☐

Q30. How much per kg of pigeon pea?

1. Below R10 ☐ 2. R15☐ 3. Above R15 ☐ 4.determine by market price☐

Name of Enumerator: ………………………………

Contact details: ……………………………........

Date and time: ……………………………….....

Signature: :…………………………