

PROCESSING OF POLYPHENOL-RICH SORGHUMS FOR FOOD

by

TRUST BETA

Submitted in partial fulfillment of
the requirements for the degree

PhD Food Science

in the

Faculty of Biological and Agricultural Sciences

(Department of Food Science)

UNIVERSITY OF PRETORIA

Pretoria

1999



Dedication

This dissertation is dedicated to my three siblings who died during the course of my research:

- 1) Senitah Beta, who passed away on 17 August 1997, when I was conducting the steeping and germination experiments in Pretoria;
- 2) Sennie Beta, who passed away on 29 June 1998, when I was carrying out the milling experiments at Matopos; and
- 3) Norman Garikayi Beta, who passed away on 5 September 1998, prior to my departure for a China conference, where I intended to present a paper on sorghum phenolics.

Acknowledgments

I particularly wish to express my sincere thanks to my mentor, John R.N. Taylor, for giving me the opportunity to carry out this work under his constant support and supervision during its execution.

I am also indebted to Lloyd W. Rooney of Texas A&M University, Department of Soil and Crop Science, for assisting with the framework of this research and his contribution to the grain quality evaluation.

I am grateful to Lilian T. Marovatsanga of the University of Zimbabwe, Institute of Food and Nutrition, for her support during my absence on study leave from the University of Zimbabwe.

I am deeply indebted to the McKnight Collaborative Crop Research Program for sponsoring most of this work carried under the project entitled “The Ecological Biochemistry of Proanthocyanidins and Related Flavonoids in the Zimbabwean Small-Scale Farming System”.

Finally, my gratitude goes to Harold Corke of the University of Hong Kong, Department of Botany, for sponsoring the starch work reported in this thesis and his valuable guidance during my thesis write-up.

ABSTRACT

PROCESSING OF POLYPHENOL-RICH SORGHUMS FOR FOOD

by

TRUST BETA

Promoter: Professor J.R.N. Taylor

Co-supervisors: Professor L.W. Rooney; Dr L.T. Marovatsanga

Department: Food Science, University of Pretoria, Pretoria 0002

Degree: PhD Food Science

Phenolic compounds in sorghum play an important agronomic role. They are divided into three groups: phenolic acids, flavonoids, and condensed tannins. The cultivation of polyphenol-rich sorghums reduces pre-harvest losses due to bird predation and post-harvest storage losses. Condensed tannins bind proteins, thus reducing nutritional and functional value. Phenolic compounds may also impart undesirable colours in sorghum products during food processing. Sixteen sorghum varieties widely cultivated in Zimbabwe were examined for levels of phenolic compounds and kernel characteristics, to consider how to improve the acceptance and utilisation of sorghum for food in Zimbabwe and southern Africa as well as overall food security.

Three varieties, DC-75, Mutode, and Chirimaugute had high levels of condensed tannins. Chibonda had polyphenols that could not be extracted with methanol alone. A positive correlation was observed between pericarp thickness and polyphenol content ($r>0.64$).

Most varieties had an intermediate to floury (soft) endosperm texture. Zimbabwean sorghums were found to lack ideal agronomic and processing physico-chemical characteristics defined in terms of high polyphenols, plus hard endosperm and thin pericarp. Research was carried out to develop effective methods of processing the available polyphenol-rich sorghums. Chemical treatments, using HCl (0.25M), formaldehyde (0.017M), NaOH (0.075M) and water as control, were applied in steeping for malt or starch production. Conditioning moisture and chemical treatment were also used in milling. Three out of the sixteen varieties were selected for processing, each representing a tannin-free, high- and medium-tannin sorghum.

All chemical treatments reduced the polyphenol content of the grain after steeping. Treatment with NaOH or formaldehyde (HCHO) was more effective than water or HCl. Available DP was low in malt from tannin-containing varieties that had been treated with water or HCl. Malting alone, was not an effective method of reducing the enzyme inhibitory power of the sorghum tannins. Steeping in dilute NaOH was effective in deactivating high-tannin sorghums, reducing the steeping period through increased grain water uptake and enhancing malt DP. NaOH appears to be an alternative to HCHO for treatment of high-tannin sorghums in the malting industry.

Roller milling and abrasive decortication reduced the polyphenol content as the grain's outer layers were lost as bran. Chemical treatment and conditioning moisture up to 20 % did not significantly reduce the polyphenol content after abrasive milling. However,

treatment with NaOH or HCHO significantly reduced the polyphenol content of roller-milled flour. Moisture and chemical treatment appear to be useful in roller milling but not in abrasive milling.

Chemical treatments were used to improve the physico-chemical properties of starch isolated from high-tannin sorghums. The pink colour of starch from polyphenol-rich sorghums could not be removed but was further brightened by NaOH treatment. NaOH caused an intense colour for all but SV2. The tan plant colour of SV2 was important as a way to reduce colour in starch processes. NaOH steeping gave starches with higher peak viscosity (PV), cool paste viscosity (CPV) and setback than when water, HCl and HCHO were used. HCl-treated starches had higher PV temperature, and took longer to reach PV. The time to reach PV and PV temperature were markedly reduced by treatment with NaOH. Thus NaOH caused some form of partial pre-gelatinisation. Treatment with alkali could be advantageous in lowering temperatures needed to gelatinise sorghum starch. Dilute alkali steeping during wet milling could enhance the properties of starch isolated from tannin-free and tannin-containing sorghums. Polyphenol content and kernel characteristics of sorghum varieties influenced starch properties.

Dilute alkali steeping during malting or wet milling for malt or starch production could offer advantages in improving the functionalities of products made from polyphenol-rich sorghums.

Table of Contents

	Page
PRELIMINARY PAGES	
1. Title page . . . . .	.ii
2. Declaration page . . . . .	.iii
3. Dedication page . . . . .	.iv
4. Acknowledgments. . . . .	.v
5. Abstract	vi
6. Table of Contents . . . . .	.ix
7. List of Tables . . . . .	.xiii
8. List of Figures . . . . .	.xvii
 TEXT	
1. General Introduction . . . . .	.1
2. Objectives . . . . .	.6
3. General Literature Review . . . . .	.7
3.1 Sorghum grain morphology . . . . .	.7
3.2 Colour of sorghum grain . . . . .	.9
3.3 Chemistry of sorghum phenolic compounds . . . . .	.9
3.4 Qualitative and quantitative analysis of phenolics . . . . .	.12
3.5 Techniques to reduce or minimise the effects of phenolic compounds . . . . .	.21
3.6 Summary . . . . .	.28

4. Chapters

I) Phenolic compounds and kernel characteristics of Zimbabwean sorghums

Abstract . . . . .	.30
Introduction . . . . .	.31
Materials and Methods . . . . .	.32
Results and Discussion . . . . .	.37
Conclusions . . . . .	.42
Literature cited . . . . .	.43
Tables and figures . . . . .	.46

II) Effects of chemical treatments on polyphenols and malt quality in sorghum

Abstract . . . . .	.53
Introduction . . . . .	.54
Materials and Methods . . . . .	.55
Results and Discussion . . . . .	.58
Conclusions . . . . .	.64
Literature cited . . . . .	.66
Tables and figures . . . . .	.70

III) Effect of chemical conditioning on the milling of high-tannin sorghum

Abstract . . . . .	.77
Introduction . . . . .	.78
Materials and Methods . . . . .	.79
Results and Discussion . . . . .	.82
Conclusions . . . . .	.89
Literature cited . . . . .	.91
Tables and figures . . . . .	.95

IV) Effect of steeping treatment on pasting and thermal properties of starches from sorghums of different tannin content

Abstract . . . . .	.103
Introduction . . . . .	.104
Materials and Methods . . . . .	.105
Results and Discussion . . . . .	.107
Conclusions . . . . .	.112
Literature cited . . . . .	.113
Tables . . . . .	.116

V) Physico-chemical properties of starch isolated from sorghum varieties of different polyphenol content and kernel structure

Table	Abstract . . . . .	.119
1.1	Introduction . . . . .	.121
1.1.1	Materials and Methods . . . . .	.122
	Results and Discussion . . . . .	.126
1.2	Conclusions . . . . .	.134
	Literature cited . . . . .	.135
1.3	Tables and figures . . . . .	.139
5.	General Discussion . . . . .	.147
6.	Conclusions and Recommendations. . . . .	.160
7.	References. . . . .	.163
8.	Publications from this work . . . . .	.186

11-2	Effect of stepwise increase in the concentration of formaldehyde (HCHO) (0.05, 0.1, 0.2, 0.4, 0.8, 1.6, 3.2, 6.4, 12.8, 25.6, 51.2, 102.4, 204.8, 409.6, 819.2, 1638.4, 3276.8, 6553.6, 13107.2, 26214.4, 52428.8, 104857.6, 209715.2, 419430.4, 838860.8, 1677721.6, 3355443.2, 6710886.4, 13421772.8, 26843545.6, 53687091.2, 107374182.4, 214748364.8, 429496729.6, 858993459.2, 1717986918.4, 3435973836.8, 6871947673.6, 13743895347.2, 27487790694.4, 54975581388.8, 109951162777.6, 219902325555.2, 439804651110.4, 879609302220.8, 1759218604441.6, 3518437208883.2, 7036874417766.4, 14073748835532.8, 28147497671065.6, 56294995342131.2, 112589990684262.4, 225179981368524.8, 450359962737049.6, 900719925474099.2, 1801439850948198.4, 3602879701896396.8, 7205759403792793.6, 14411518807585587.2, 28823037615171174.4, 57646075230342348.8, 115292150460684697.6, 230584300921369395.2, 461168601842738790.4, 922337203685477580.8, 1844674407370955161.6, 3689348814741910323.2, 7378697629483820646.4, 14757395258967641292.8, 29514790517935282585.6, 59029581035870565171.2, 118059162071741130342.4, 236118324143482260684.8, 472236648286964521369.6, 944473296573929042739.2, 1888946593147858085478.4, 3777893186295716170956.8, 7555786372591432341913.6, 15111572745182864683827.2, 30223145490365729367654.4, 60446290980731458735308.8, 120892581961462917470617.6, 241785163922925834941235.2, 483570327845851669882470.4, 967140655691703339764940.8, 1934281311383406679529881.6, 3868562622766813359059763.2, 7737125245533626718119526.4, 15474250491067253436239052.8, 30948500982134506872478105.6, 61897001964269013744956211.2, 123794003928538027489912422.4, 247588007857076054979824844.8, 495176015714152109959649689.6, 990352031428304219919299379.2, 1980704062856608439838598758.4, 3961408125713216879677197516.8, 7922816251426433759354395033.6, 15845632502852867518708790067.2, 31691265005705735037417580134.4, 63382530011411470074835160268.8, 126765060022822940149670320537.6, 253530120045645880299340641075.2, 507060240091291760598681282150.4, 1014120480182583521197362564300.8, 2028240960365167042394725128601.6, 4056481920730334084789450257203.2, 8112963841460668169578900514406.4, 16225927682921336339157801028812.8, 32451855365842672678315602057625.6, 64903710731685345356631204115251.2, 129807421463370690713262408230502.4, 259614842926741381426524816461004.8, 519229685853482762853049632922009.6, 1038459371706965525706099265844019.2, 2076918743413931051412198531688038.4, 4153837486827862102824397063376076.8, 8307674973655724205648794126752153.6, 16615349947311448411297588253504307.2, 33230699894622896822595176507008614.4, 66461399789245793645190353014017228.8, 132922799578491587290380706028034457.6, 265845599156983174580761412056068915.2, 531691198313966349161522824112137830.4, 1063382396627932698323045648224275660.8, 2126764793255865396646091296448551321.6, 4253529586511730793292182592897102643.2, 8507059173023461586584365185794205286.4, 17014118346046923173168730371588410572.8, 34028236692093846346337460743176821145.6, 68056473384187692692674921486353642291.2, 136112946768375385385349842972707284582.4, 272225893536750770770699685945414569164.8, 544451787073501541541399371890829138329.6, 1088903574147003083082798743781658276659.2, 2177807148294006166165597487563316553318.4, 4355614296588012332331194975126633106636.8, 8711228593176024664662389950253266213273.6, 17422457186352049329324779900506532426547.2, 34844914372704098658649559801013064853094.4, 69689828745408197317299119602026129706188.8, 139379657490816394634598239204052259412377.6, 278759314981632789269196478408104518824755.2, 557518629963265578538392956816209037649510.4, 111503725992653115707678591363241807529902.08, 223007451985306231415357182726483615059804.16, 446014903970612462830714365452967230119608.32, 892029807941224925661428730905934460239216.64, 1784059615882449851322857461811868920478433.28, 3568119231764899702645714923623737840956866.56, 7136238463529799405291429847247475681913733.12, 14272476927059598810582859694494951363827466.24, 28544953854119197621165719388989902727654932.48, 57089907708238395242331438777979805455309864.96, 114179815416476790484662877555959610910619729.92, 228359630832953580969325755111919221821239459.84, 456719261665907161938651510223838443642478919.68, 91343852333181432387730302044767688728495783.936, 182687704666362864775460604089535377456991567.872, 365375409332725729550921208179070754913983135.744, 730750818665451459101842416358141509827966271.488, 1461501637330902918203684832716283019655932542.976, 2923003274661805836407369665432566039311865085.952, 5846006549323611672814739330865132078623730171.904, 11692013098647223345629478661730264157247460343.808, 23384026197294446691258957323460528314494920687.616, 46768052394588893382517914646921056628989841375.232, 93536104789177786765035829293842113257979682750.464, 187072209578355573530071658587684226515959365500.928, 374144419156711147060143317175368453031918731001.856, 748288838313422294120286634350736906063837462003.712, 1496577676626844588240573268701473812127674924007.424, 2993155353253689176481146537402947624255349848014.848, 5986310706507378352962293074805895248510699696029.696, 11972621413014756705924586149611790497021399392059.392, 23945242826029513411849172299223580994042798784118.784, 47890485652059026823698344598447161988085597568237.568, 95780971304118053647396689196894323976171195136475.136, 191561942608236107294793378393788647952342390272950.272, 383123885216472214589586756787577295904684780545900.544, 766247770432944429179173513575154591809369561091801.088, 1532495540865888858358347027150309183618739122183602.176, 3064991081731777716716694054300618367237478244367204.352, 6129982163463555433433388108601236734474956488734408.704, 12259964326927110866866776217202473468949912977468817.408, 24519928653854221733733552434404946937899825954937634.816, 49039857307708443467467104868809893875799651909875269.632, 98079714615416886934934209737619787751599303819750539.264, 196159429230833773869868419475239575503198607639501078.528, 392318858461667547739736838950479151006397215279002157.056, 784637716923335095479473677900958302012794430558004314.112, 156927543384667019095894735580191660402558886111600862.224, 313855086769334038191789471160383320805117772223201724.448, 627710173538668076383578942320766641610235544446403448.896, 1255420347077336152767157884641533283220471088892806897.792, 2510840694154672305534315769283066566440942177785613795.584, 5021681388309344611068631538566133132881884355571227591.168, 10043362776618689222137263077132266265763768711142455182.336, 20086725553237378444274526154264532531527537422284910364.672, 40173451106474756888549052308529065063055074844569820729.344, 80346902212949513777098104617058130126110149689139641458.688, 160693804425899027554196209234116260252220299378279282917.376, 321387608851798055108392418468232520504440598756558565834.752, 642775217703596110216784836936465041008881197513117131669.504, 1285550435407192220433569673872930082017762395026234263339.008, 2571100870814384440867139347745860164035524790052468526678.016, 5142201741628768881734278695491720328071049580104937053356.032, 10284403483257537763468557390983440656142099160209874106712.064, 20568806966515075526937114781966881312284198320419748213424.128, 41137613933030151053874229563933762624568396640839496426848.256, 82275227866060302107748459127867525249136793281678992853696.512, 164550455732120604215496918255735050498273586563357985707393.024, 329100911464241208430993836511470100996547173126715971414786.048, 658201822928482416861987673022940201993094346253431942829572.096, 1316403645856964833723975346045880403986188692506863885659144.192, 2632807291713929667447950692091760807972377385013727771318288.384, 5265614583427859334895901384183521615944754770027455542636576.768, 10531229166855718669791802768367043231889509540054911085273153.536, 21062458333711437339583605536734086463779019080109822170546307.072, 42124916667422874679167211073468172927558038160219644341092614.144, 84249833334845749358334422146936345855116076320439288682185228.288, 168499666669691498716668844293872691710232152640878577364370456.576, 336999333339382997433337688587745383420464305281757154728740913.152, 673998666678765994866675377175490766840928610563514309457481826.304, 1347997333357531989733350754350981533681857221127028618914963652.608, 2695994666715063979466701508701963067363714442254057237829927305.216, 5391989333430127958933403017403926134727428884508114475659854610.432, 10783978666860255917866806034807852269454857769016228951319709220.864, 2156795733372051183573361206961570453890971553803245790263941844.176, 4313591466744102367146722413923140907781943107606491580527883688.352, 8627182933488204734293444827846281815563886215212983161055767376.704, 17254365866976409468586889655692563631127772430425966322111534753.408, 34508731733952818937173779311385127262255544860851932644223069506.816, 69017463467905637874347558622770254524511089721703865288446139013.632, 138034926935811275748695117245540509049022179443407730576892278027.264, 276069853871622551497390234491081018098044358886815461153784556054.528, 552139707743245102994780468982162036196088717773630922307569112109.056, 1104279415486490205989560937964324072392177435547261844615138224218.112, 2208558830972980411979121875928648144784354871094523689230276448436.224, 4417117661945960823958243751857296289568709742189047378460552896872.448, 8834235323891921647916487503714592579137419484378094756921105793744.896, 17668470647783843295832975007429185158274838968756189513842211587489.792, 35336941295567686591665950014858370316549677937512379027684423174979.584, 70673882591135373183331900130116740633099355875024758055368846349959.168, 141347765182270746366663800260233481266198711750049516110737692699918.336, 282695530364541492733327600520466962532397423500099032221475385399836.672, 565391060729082985466655201040933925064794847000198064442950770799673.344, 1130782121458165970933310402081867850129589694000396128885901541599346.688, 2261564242916331941866620804163735700259179388000792257771803083198693.376, 4523128485832663883733241608327471400518358776001584515543606166397386.752, 9046256971665327767466483216654942801036717552003169031087212332794773.504, 18092513943330655534932966433309885602073435104006338062174424665589547.008, 36185027886661311069865932866619771204146870208012676124348849331179094.016, 72370055773322622139731865733239542408293740416025352248697698662358188.032, 144740111546645244279463731466479084816587480832050704497395397324716376.064, 289480223093290488558927462932958169633174961664101408994790794649432752.128, 578960446186580977117854925865916339266349923328202817989581589298865504.256, 1157920892373161954235709851731832678532699846656405635979163178597731008.512, 2315841784746323908471419703463665357065399693312811271958326357195462017.024, 4631683569492647816942839406927330714130799386625622543916652714390924034.048, 9263367138985295633885678813854661428261598773251245087833305428781848068.096, 18526734277970591267771357627709322856523197546502490175666610857563696136.192, 37053468555941182535542715255418645713046395093004980351333221715127392272.384, 74106937111882365071085430510837291426092790186009960702666443430254784544.768, 148213874223764730142170861021674582852185580372019921405332886860509569089.536, 296427748447529460284341722043349165704371160744039842810665773721019138179.072, 592855496895058920568683444086698331408742321488079685621331547442038276358.144, 1185710993790117841137366888173396662817484622976159371242663094884076552716.288, 2371421987580235682274733776346793325634969245952318742485326189768153105432.576, 4742843975160471364549467552693586651269938491904637484970652379536306210865.152, 9485687950320942729098935105387173302539876983809274969941304759072612421730.304, 18971375900641885458197870210
------	---

List of Tables

Table		Page
1	Main assays used for determination of phenolic compounds . . . . .	.13
I-1	Polyphenol content and phenolic acid content of 16 sorghum varieties as measured by different methods . . . . .	.46
I-2	Pericarp colour, endosperm colour, endosperm texture and pericarp thickness of Zimbabwean sorghums . . . . .	.47
I-3	Correlation analysis between polyphenol content and kernel characteristics . . . . .	.48
II-1	Effect of steeping sorghum varieties, Chiri and DC-75, for 8 h in HCl (0.9%, v/v), HCHO (0.05%, v/v), and NaOH (0.3%, w/v), on grain moisture content (% wet weight basis) . . . . .	.70
II-2	Effect of steeping sorghum varieties, Chiri and DC-75, for 8 h in HCl (0.9%, v/v), HCHO (0.05%, v/v), and NaOH (0.3%, w/v), followed by germination, on the condensed tannin content as measured by the butanol-HCl assay (A/g, dry basis) measured by . . . . .	.71
II-3	Effect of steeping sorghum varieties, Chiri and DC-75, for 8 h in HCl (0.9%, v/v), HCHO (0.05%, v/v), and NaOH (0.3%, w/v), followed by germination, on the condensed tannin content as measured by the vanillin-HCl assay in catechin equivalents (g/100 g, dry basis) . . . . .	.72
II-4	Effect of steeping sorghum varieties, Chiri and DC-75, for 8 h in HCl (0.9%, v/v), HCHO (0.05%, v/v), and NaOH (0.3%, w/v), followed by germination, on the condensed tannin levels as measured by the vanillin-HCl assay with blank	

- subtraction in catechin equivalents (g/100 g, dry basis)73
- II-5** Effect of steeping sorghum varieties, Chiri and DC-75, for 8 h in HCl (0.9%, v/v), HCHO (0.05%, v/v), and NaOH (0.3%, w/v), followed by germination, on the diastatic power (peptone extraction) of sorghum malt (SDU/g, dry basis) .74
- II-6** Effect of steeping sorghum varieties, Chiri and DC-75, for 8 h in HCl (0.9%, v/v), HCHO (0.05%, v/v), and NaOH (0.3%, w/v), followed by germination, on the diastatic power (water extraction) of sorghum malt (SDU/g, dry basis) .75
- III-1** Effect of conditioning sorghum varieties, DC-75 and Chiri, to 16 and 20%, using water, HCl (0.9%, v/v), HCHO (0.05%, v/v), and NaOH (0.3%, w/v), prior to abrasive decortication and roller milling, on the offal and meal yield (% extraction)95
- III-2** Effect of conditioning sorghum varieties, DC-75 and Chiri, to 16 and 20%, using water, HCl (0.9%, v/v), HCHO (0.05%, v/v), and NaOH (0.3%, w/v), prior to abrasive decortication or roller milling, on the tannin content of the meal as measured by the butanol-HCl assay (A/g, dry basis)96
- III-3** Effect of conditioning sorghum varieties, DC-75 and Chiri, to 16 and 20%, using water, HCl (0.9%, v/v), HCHO (0.05%, v/v), and NaOH (0.3%, w/v), prior to abrasive decortication or roller milling, on the polyphenol content of the meal or offal as measured by the vanillin-HCl assay in catechin equivalents (g/100 g, dry basis)97
- III-4** Effect of conditioning sorghum varieties, DC-75 and Chiri, to 16 and 20%, using water, HCl (0.9%, v/v), HCHO (0.05%, v/v), and NaOH (0.3%, w/v), prior to

	abrasive decortication or roller milling, on the tannin content of the meal as measured by the vanillin-HCl assay with blank subtraction in catechin equivalents (g/100 g, dry basis) . . . . .	.98
III-5	Effect of conditioning sorghum varieties, DC-75 and Chiri, to 16 and 20%, using water, HCl (0.9%, v/v), HCHO (0.05%, v/v), and NaOH (0.3%, w/v), prior to abrasive decortication or roller milling, on enzyme inhibition (%) by the polyphenols in the meal . . . . .	.99
III-6	Effect of conditioning sorghum varieties, DC-75 and Chiri, to 16 and 20%, using water, HCl (0.9%, v/v), HCHO (0.05%, v/v), and NaOH (0.3%, w/v), prior to abrasive decortication and roller milling, on meal color as measured by the Hunter Lab (L values) . . . . .	.100
IV-1	Effect of steeping sorghum varieties, SV2, Chirimaugute, and DC-75, in HCl (0.9%, v/v), HCHO (0.05%, v/v), NaOH (0.3%, w/v), on the pasting properties of starch . . . . .	.116
IV-2	Effect of steeping sorghum varieties, SV2, Chirimaugute, and DC-75, in HCl (0.9%, v/v), HCHO (0.05%, v/v), NaOH (0.3%, w/v), on the hardness of starch gels . . . . .	.117
IV-3	Effect of steeping sorghum varieties, SV2, Chirimaugute, and DC-75, in HCl (0.9%, v/v), HCHO (0.05%, v/v), NaOH (0.3%, w/v), on the thermal properties of starch . . . . .	.118
V-1	Pasting and swelling properties of starches isolated from Zimbabwean sorghum varieties . . . . .	.139

V-2	Pearson correlation coefficients (r values) of the sorghum starch properties, grain structural characteristics and polyphenol content . . . . .	.140
V-3	Endosperm texture, starch amylose content and gel properties of Zimbabwean sorghum varieties . . . . .	.141
V-4	Thermal properties of starches isolated from Zimbabwean sorghum varieties . . . . .	.142
V-5	Hunter L, a, and b colour values of starches isolated from Zimbabwean sorghum varieties of different kernel properties and polyphenol content . . . . .	.143

16. REFERENCES

1-2 SEM: Scanning electron microscopy

1-3 SEM: Scanning electron microscopy

II-1 (a) The endosperm of sorghum grain is composed of two layers, the scutellum and the cotyledon. The scutellum is the larger of the two and is the primary source of energy for the developing embryo. The cotyledon is the smaller of the two and is the primary source of protein for the developing embryo.

III-1 Preparation of starch from sorghum grain

III-2 Description of sorghum grain and starch properties

V-1 RVA: Rapid viscosity analyzer

V-2 Pearson correlation coefficients (r values) of the sorghum starch properties, grain structural characteristics and polyphenol content

V-3 Endosperm texture, starch amylose content and gel properties of Zimbabwean sorghum varieties

V-4 Thermal properties of starches isolated from Zimbabwean sorghum varieties

V-5 Hunter L, a, and b colour values of starches isolated from Zimbabwean sorghum varieties of different kernel properties and polyphenol content

List of Figures

Figure		Page
1	Basic flavonoid ring . . . . .	.10
2	Structure of condensed tannin . . . . .	.11
I-1	(a) RP-HPLC chromatographic patterns of varieties: 1, DC-75; 2, Chirimaugute; 3, Mutode; 4, Mukadzidzoka; 5, Chibonda; 6, Iganu; 7, Ntelwane; 8, Brown Tsweta . . . . .	.49
I-1	(b) RP-HPLC chromatographic patterns of varieties: 9, Katandanzara; 10, Mukadziusaenda; 11, Nyamidzi; 12, Kasvikisire; 13, Chihumani; 14, SV1; 15, SV2; 16, NL330 . . . . .	.50
I-2	SEM photographs of varieties Katandanzara, Mukadziusaenda, and Chibonda depicting: (a) corneous endosperm; (b) intermediate endosperm; and (c) floury endosperm, respectively . . . . .	.51
I-3	SEM photographs of varieties Chibonda, SV2, and SV1 depicting: (a) thick pericarp, (b) intermediate pericarp, and (c) thin pericarp . . . . .	.52
II-1	(a) Basic structure of a flavonoid ring; and (b) rearrangement reactions for proanthocyanidins to form ‘phlobatannins’ in mildly basic solutions . . . . .	.76
III-1	Procedures used for abrasive decortication and roller milling of sorghum . . . . .	.101
III-2	Diagrams illustrating the principles used in (a) abrasive decortication; and (b) roller milling . . . . .	.102
V-1	RVA pasting profiles of sorghum starches compared to maize starch. Sorghum varieties DC-75 and Chirimaugute are tannin-containing, and SV2 is tannin-free . . . . .	.144

V-2	(a) Photographs illustrating different colours of sorghum starches from tannin-containing (DC-75, Mutode, Chirimaugute and Chibonda) and tannin-free (SV2) varieties	.145
V-2	(b) Photographs illustrating different colours of sorghum starches from tannin-free varieties (Katandanzara, Kasvikisire, Tsveta, Mukadzidzoka, Mukadziusaenda)	.146